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Hydration Testing of Athletes

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Abstract

Dehydration not only reduces athletic performance, but also places athletes at risk of health problems and even death. For athletes, monitoring hydration has significant value in maximising performance during training and competition. It also offers medical personnel the opportunity to reduce health risks in situations where athletes engage in intentional weight loss. Simple non-invasive techniques, including weight monitoring and urine tests, can provide useful information. Bioimpedance methods tend to be easy to use and fairly inexpensive, but generally lack the precision and accuracy necessary for hydration monitoring. Blood tests appear to be the most accurate monitoring method, but are impractical because of cost and invasiveness. Although future research is needed to determine which hydration tests are the most accurate, we encourage sports teams to develop and implement hydration monitoring protocols based on the currently available methods. Medical personnel can use this information to maximise their team's athletic performance and minimise heat- and dehydration-related health risks to athletes.

1. Hydration Testing of Athletes

Every year severe dehydration results in the injury and death of many athletes. In the US, for example, a prominent professional football player died in 2001 from heat stroke.[1] At the time of death, his core temperature exceeded 42.5°C.[1] During the same 1-week time span in 2001, an interscholastic and a collegiate player died from the same cause. The National Center for Catastrophic Sports Injuries (NCCSI) reported four deaths among college and high school football players from heat stroke in 2000 and over the past 7 years the NCCSI has recorded 20 deaths from heat stroke.[2] According to the NCCSI, dehydration was a contributing factor in all of these deaths.[2] Equally as tragic were the deaths of three collegiate wrestlers during a 5-week span in the fall of 1997. According to the Centers for Disease Control and Prevention, the wrestlers had been attempting to lose 15% of their bodyweight through fasting and dehydration.[3] At the time of their deaths, each wrestler was using dehydration techniques to rapidly lose the remaining weight necessary to reach a lower weight class for competition. The deaths of all of these athletes could have been prevented.

The incidence of dehydration-related injuries is too numerous to be recorded.[2] Dehydration-related injuries include fatigue, cramps, heat exhaustion and heat stroke. In virtually every sport, athletes experience lost training time, performance decrements and, in some cases, hospitalisation related to dehydration. In a 2-year surveillance study of five major sports for high school-aged boys and girls, Powell and Barber-Foss[4] found that dehydration resulted in lost game or practice time for up to 1% of athletes.

Position statements by the American College of Sports Medicine (ACSM), the American Dietetic Association, the Canadian Dietetic Association and the National Athletic Trainers' Association (NATA) have been written to warn athletes, coaches and athletic trainers about the dangers associated with dehydration.[5-7] In addition, they have offered guidelines for staying well-hydrated while training and competing. They have not only included guidelines for the amount and rate of fluid consumption, but also addressed the palatability and nutritional composition of rehydration fluids. However, one shortcoming of the position stands has been the paucity of information on hydration testing. The typical recommendation is to consume fluids early and often with the goal of replacing the weight lost (from dehydration) during competition or practice. This recommendation is certainly valid but the all-too-frequent deaths and many near misses indicate that the hydration status of athletes should be monitored more closely. With this in mind, the purpose of this article is to:

- examine conditions under which hydration testing may be important;
- provide criteria for assessing hydration;
- evaluate several common methods for assessing hydration;
- offer recommendations for evaluating the outcome of a hydration test.

2. Conditions for Hydration Testing

Conditions under which hydration testing would be valuable fall into two broad categories. The first includes monitoring of athletes during training or competition to ensure health and safety. This situation can include self-monitoring by the athlete or monitoring by the team's medical staff. The second category includes the assessment of hydration status prior to certification in weight classification sports. This is done to ensure that athletes are in a well-hydrated state when weighed, and that their weight is not artificially lower due to dehydration. An artificially low weight puts the athlete in danger of losing too much weight prior to a competition.

With the modern age of athletics, there are a variety of training and competitive venues in which an athlete would benefit from the first type of hydration testing. One example would be the practice of multiple workouts within 1 day, particularly in hot/humid environmental conditions. This may have played a role in the deaths of the football players mentioned above. At the time the professional football player left the field, the heat index was 37.2°C (99°F).[1] This strenuous training style is not uncommon to athletes of all ages and skill levels. In addition, many athletes in sports such as tennis, soccer, volleyball, basketball, softball, and baseball frequently face conditions of having multiple competitions during a period of a few days (e.g. playoffs). While opportunities to replace fluids may be available to athletes in these situations, many athletes fail to return to a euhydrated state on a daily basis. This is because the thirst mechanism may not be enough to encourage proper restoration of body water in most exercising humans. This lag in fluid consumption in the face of dehydration has been termed 'involuntary dehydration'.[8] With this in mind, it is incumbent upon athletic teams to have proper hydration monitoring protocols in place. These protocols should include monitoring of athletes by medical staff and education programmes that teach athletes self-monitoring techniques.

With the recent deaths of three college wrestlers, there has been an increased interest in the second type of hydration testing. In response to the deaths of these wrestlers, the National Collegiate Athletic Association (NCAA) instituted changes that require an athlete to weigh-in and have their body composition tested at the beginning of the season. Based on their body composition, a minimum competitive weight is determined and the athlete must reach his competitive weight by the first competition.[9] This type of programme has also been instituted by several interscholastic state associations in the US during the last decade.[10] However, it has become clear that some wrestlers arrive for testing in a dehydrated state to secure a lower minimal weight. For example, in one study,

unannounced re-weighing of high school wrestlers within days of minimal weight testing showed that almost 25% had gained more than 1.4kg (3lbs), with a maximum gain of 8.2kg (18lbs).[10] To insure that wrestlers do not lose weight by dehydration prior to the initial weigh-in, high school and college wrestlers must produce a urine sample with a specific gravity ≤1.020 to indicate they are adequately hydrated at the time of testing. The governing body for US interscholastic wrestling, the National Federation of State High School Associations, has recently adopted this system of minimal weight testing paired with hydration testing.

While the two scenarios of hydration testing described above have different objectives, the goals remain the same. Coaches and medical staff want to ensure that the athlete is adequately hydrated during training and competition so that physiological conditions for physical performance are maximised and the risk of injury is minimised.

3. Criteria for Hydration

Water is the largest component of body mass, accounting for 50–70% of bodyweight.[11] Given that body water is exclusively contained within the fat-free mass compartment (fat mass is anhydrous), the percentage of body water increases as the percentage body fat declines. Thus, body water typically accounts for approximately 60–70% of bodyweight in males and 50–55% in females. On a cellular level of body composition analysis, body water can be partitioned between intracellular and extracellular compartments.[12] Approximately two-thirds of water resides in the intracellular compartment and one-third resides in the extracellular compartment.

A state of 'normal' body water content has been defined as 'euhydration'.[13] This state has not been described as a specific point, but rather a sinusoidal wave that 'indicates normal, daily water content'.[8] These definitions are primarily theoretical in nature, with no measurable criteria mentioned. As such, we will use a more concrete definition for the purposes of this review. Euhydration will be defined as the point at which an athlete has:

- a bodyweight that is relatively stable (within 0.45kg) day to day;[8]
- an adequate fluid intake to sustain normal urinary volume and concentration;
- relative stability of total body water (TBW), extracellular water (ECW) and intracellular water (ICW);
- normal blood chemistry.

Thus, this review will primarily focus on the usefulness of monitoring hydration through the monitoring of weight, urine, body water and blood.

No concrete definition or set of clinical symptoms has been proposed to define dehydration.[14] This is due, in part, to variations in the aetiology and symptoms of dehydration. In the sports medicine field, the level of dehydration is quantified by the amount of weight lost (usually by exercise) during a diurnal cycle. An athlete who loses 3% of their bodyweight is considered '3% dehydrated'. In addition to the quantity of weight loss, attention should be focused on the method of weight loss. How the weight was lost may affect the ability to monitor the extent of dehydration.

One type of dehydration, hypertonic dehydration, is characterised by blood hypernatraemia (serum sodium >145 mmol/L) and hyperosmolarity (serum osmolality >300 mmol/kg), as well as reductions in plasma volume.[14] This type of dehydration is most commonly seen after exercise in which heavy sweating has occurred. Plasma volume decreases because it is the source of water for the sweat and its osmolality increases because the sweat is usually more hypotonic than plasma.[15] Most of our comments will focus on detecting hypertonic dehydration.

Other forms of dehydration may be found in athletes in aesthetic-type sports and athletes who compete in weight classification sports. In isotonic dehydration, losses of both water and sodium occur, which results in a normal-appearing blood and urine chemistry. This type of dehydration can be the result of a complete fast or vomiting.[14] A third type of dehydration, hypotonic dehydration, is characterised by a lower than normal serum sodium and osmolality. This situation is likely to oc-

cur when sodium losses exceed water losses, such as when sodium intake is restricted or certain types of diuretic drugs are used.[14] Behaviours linked to isotonic and hypotonic dehydration, such as fasting, vomiting and diuretic use, have been reported in a wide range of male and female athletes at alarmingly high rates.[16-21]

4. Methods of Hydration Testing

4.1 Monitoring Bodyweight Stability

4.1.1 Rationale

Under conditions of caloric balance, diurnal changes in weight reflect loss of body fluids through sweating and insensible evaporation. For athletes in any sport, the majority of the fluids lost during exercise occur as a result of the body's thermoregulatory responses. This includes sweating and the resultant hypertonic dehydration. In addition to exercise, environmental conditions can have a significant effect on sweating, as do individual differences in sweat rate and adaptations to heat. As a result, the magnitude of the diurnal weight change can vary widely. In a euhydrated state there is a 1% fluctuation in weight during the course of a day,[8] but a heat-acclimated athlete exercising vigourously may lose 5% or more of his weight during a strenuous exercise session.[15]

4.1.2 Equipment

The simplest hydration testing is to monitor daily weight change using a professional quality scale. Weight fluctuations (losses) should not exceed 1% of bodyweight.[8]

4.1.3 Practicality

When athletes are completing multiple daily workouts or competing in multiple events during the course of a day, it is important to monitor weight changes and replenish fluid losses throughout the day. Both the NATA and ACSM have described methods for fluid replacement and the composition of the replacement fluid.[5,6] As described in the NATA position statement, it is important to recognise that there can be significant individual differences in weight loss among a group of athletes. In a training environment it is important for medical personnel to recognise and quantify these differences and provide adequate fluids appropriate to each individual's needs.

4.1.4 Accuracy and Precision

When monitoring hydration through weight changes, it is important to standardise the weigh-in protocol. During training, it is preferable that the athlete present prior to practice nude, or minimally clothed, and again following the workout in attire identical to that of the pre-workout. The athlete should towel-off excess sweat and not be wearing sweat-soaked clothing. As described by the ACSM and NATA position statements, weight lost during the training session should be regained by the next day's workout.[5,6] If there is a subsequent training session on the same day, the athletes should regain a significant portion of the weight lost prior to the second workout through the intake of food and fluids. There is an adverse, synergistic effect on physiological function when body fluids and energy stores are not replaced between workouts.

One limitation of this method is that the ingestion of fluids does not necessarily equate to equilibration of water in the extracellular and intracellular compartments. Popowski et al.[22] demonstrated that acute ingestion of fluids equal to a 5% weight loss did not return plasma osmolality to baseline values. In addition, research by Costill and Sparks[23] suggested that rehydration following a 6% weight loss during competition required 48–72 hours.

4.1.5 Conclusion

Monitoring weight using a standardised protocol is a simple, non-invasive and valid method for hydration testing. It can provide both clinicians and athletes with an effective tool for daily hydration monitoring. Since weight loss generally corresponds to water loss, weight monitoring is an effective tool for detecting hypertonic, isotonic and hypotonic dehydration.

4.2 Monitoring Urinary Volume, Colour and Composition

4.2.1 Rationale

Under conditions of progressive, hypertonic dehydration, urine shows acute changes in volume (Uvol), colour (Ucol), specific gravity (Usg), osmolality (Uosm) and conductance (Ucon). Under normal conditions, urine volume averages 1.5–2.5 L/day and is characterised by a specific gravity ≤1.020, osmolality <500 mOsm/L and a pale to light yellow (straw) colour.[24] With the onset of exercise, water conservation mechanisms are initiated in the kidneys to maintain plasma volume and ICW resulting in immediate effects on urinary volume and its physiological characteristics.

4.2.2 Equipment

Measurement of urinary markers of dehydration is inexpensive and requires minimal expertise from the technician. In addition, some of these methods are easily utitlised by athletes.

Urinary Volume

Quantitative measurement requires compliance by the athlete and cooperation in the collection process. However, qualitative assessment (i.e. frequency of 'normal' micturition) offers a simple non-invasive tool for assessing dehydration.

Urine Osmolality

This technique traditionally required a trained technician and a freezing point osmometer. The osmometer measures the amount of osmoles of solute particles per kilogram of solution. Only solutes that dissociate (e.g. NaCl) are detected, whereas particles such as glucose, urea and proteins are not. An alternative to the osmometer, the Sparta 5 conductance metre, has been validated by Shirreffs and Maughan.[25] It uses a five-point scale to provide a marker of Ucon. Unlike an osmometer, this device requires modest training for the technician and provides immediate feedback.

Urine Specific Gravity

Urine specific gravity is the density of a urine sample compared with the density of water. The specific gravity of the sample is dependent on its osmolality as well as its concentration of urea, glucose and protein. Several inexpensive methods exist for monitoring urine specific gravity, including hygrometry, refractometry and reagent strips. In hygrometry, a weighted glass float is used to determine the density of urine relative to pure water. It is no longer considered accurate or practical because it requires daily calibration, a larger urine sample (10–15ml) and is temperature sensitive.[26] Refractometry involves passing a beam of light through a urine sample and measuring how much the beam is refracted.[26] Refraction depends on the urine temperature and concentration. It requires a small sample volume and internally corrects for sample temperature, making it a practical and accurate alternative to more expensive methods. Reagent strips (e.g. Multistix™[1], Chemstrip™) offer a simple alternative for testing Usg compared with the more widely used refractometry method. These sticks estimate Usg based on the release of H^+ ions by the poly methyl-vinyl-ether/maleic anhydride, and the subsequent pH change as detected by the bromthymol blue which is contained in the reagent strip.[26] As the H^+ release increases, the bromthymol blue changes from blue-green to yellow-green. Comparison with the kit's colour chart allows for estimation of Usg between 1.000 and 1.030 to the nearest 0.005. The colour chart comparison requires subjective determination by the technician that has been considered a weakness when using this method. However, each of these methods requires modest technical skill easily mastered by clinicians or athletic trainers and the dipsticks offer a simple technique available to athletes.

Urinary Colour

Armstrong et al.[27] has validated a six-point Likert scale for monitoring Ucol. A pocket size copy of the colour scale can provide clinicians, or athletes, with a simple inexpensive method for assessing dehydration.

1 Use of tradenames is for product identification purposes only and does not imply endorsement.

4.2.3 Practicality

All of the methods for urine testing described above provide immediate feedback to an athlete and medical staff member. With the exception of the freezing point osmometer, equipment costs are minimal. Urinary techniques require skills easily mastered by a technician or athletic trainer. Techniques that are amenable to self-monitoring by the athlete include urine colour, the qualitative assessment of urinary volume and use of Usg dipsticks.

4.2.4 Accuracy and Precision

Recent research has focused on assessing the accuracy of urine parameters in detecting dehydration measured by weight loss or by blood-borne methods.[22,27,28] A summary of the changes observed in urine specific gravity and colour with stages of dehydration are documented in the NATA position statement.[6]

Several investigators have shown that urine parameters are correlated with the amount of weight loss by dehydration.[22,25,27] For example, although the increase in Usg and Uosm was delayed by a pre-protocol ingestion of fluids, Popowski showed a stair-step increase in Usg and Uosm with progressive weight loss up to 5% of bodyweight.[22] One investigation of military personnel tested in the field even suggested that changes in these urine parameters are a better marker of hypohydration than plasma osmolality.[29] Because some studies show that urine may lag behind blood in showing signs of dehydration, the debate of whether urine or plasma indices are better for detecting dehydration is still present in the literature.[22,27]

It is apparent from these investigations that urine tests unfortunately lack the precision necessary to meaningfully predict the extent of dehydration.[28] However, the use of a cut-off value can help to appropriately classify individuals into categories of euhydrated and dehydrated. As described in the NATA position paper, a Usg ≤1.020 is associated with mild dehydration.[6] Data from two unpublished investigations (Popowski LA et al. and Bartok C et al.) support this observation. In the first unpublished study by Popowski et al., 51 participants were tested at various times during the day. Urine specific gravity at three cut-off values (1.015, 1.020 and 1.023) was compared with plasma osmolality using a value ≤290 mOsm/L as the criterion of euhydration. Figure 1 shows the percentage of participants correctly classified as hydrated or dehydrated when the Usg is set at one of three values. Consistent with the NATA index of dehydration, they observed that 80% of individuals with plasma osmolality >290 mOsm/L had a Usg >1.020. However, these data also demonstrated that only 31% of individuals considered hydrated (i.e. plasma osmolality ≤90 mOsm/L) tested negative (Usg ≤1.020). In a separate unpublished study (Bartok C et al.) of 25 collegiate wrestlers who were tested in known euhydrated and dehydrated (2–5% dehydrated) conditions, the results were more promising. Using a Usg cut-off of 1.020, only one participant was classified as dehydrated when properly hydrated (false positive) and only one participant was classified as euhydrated when in the dehydrated state (false negative). Thus, by using individuals with known hydration states, this study demonstrated that Usg with a cut-off value of 1.020 appropriately classifies most individuals as hydrated or dehydrated.

Cut-off values for urine colour and osmolality have also been described. Armstrong et al.[28] de-

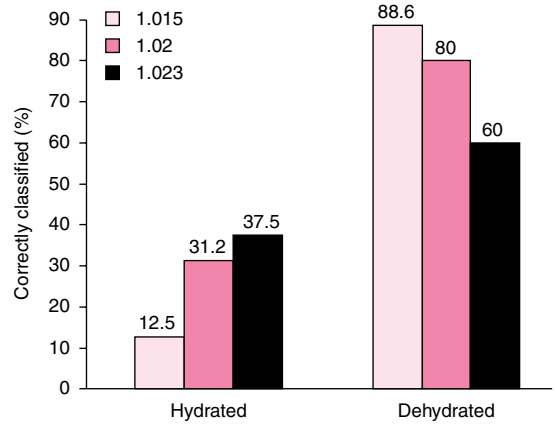

Fig. 1. Classification of hydration status at three urine specific gravity levels (n = 51).

termined that Ucol >3 on the Likert colour scale represents a state of dehydration. Shirreffs and Maughan[25] have shown that Uosm >900 mOsm/L or Ucon ≥4 is consistent with dehydration.

One concern with urinary measures is that acute ingestion of large volumes of hypotonic fluids may mask hydration status.[22,30] Thus, athletes who aggressively rehydrate following competition or workouts will produce urine that is dilute, despite being dehydrated. For example, one study in which participants lost 3–5% of bodyweight and then quickly rehydrated to starting weight showed that changes in urine osmolality, colour and conductivity mirrored the volume of fluids consumed rather than the amount of water retained by the body.[30] These results were mirrored in a study monitoring Uosm and Usg during rehydration.[22] These studies suggest that when a large volume of fluid is ingested in a short period of time, the kidneys respond to the relative 'fluid overload' by producing large quantities of urine before the body has had time to equilibrate the water with various body water compartments. Thus, the body does not have enough time to normalise intracellular and extracellular fluid chemistry. This physiological phenomenon, described by Popowski et al.,[22] is well known by many high school and college wrestling programmes as a way to create a false negative Usg at weight certification time. Clearly, this situation offers a limitation to using urine parameters to test for hydration status.

4.2.5 Conclusion

Urine specific gravity, osmolality, colour, conductivity and volume provide easy to use indices for testing hydration status among athletes. In the case of Uvol, Ucol and Usg with reagent sticks, these methods can be easily demonstrated to the athletes themselves. These methods also demonstrate potential as methods for hydration testing for purposes of detection of dehydration during weight certification. However, it is clear that the validity of urine parameters can be compromised by acute ingestion of large volumes of fluids prior to evaluation.

4.3 Blood-Borne Indicators of Hydration

4.3.1 Rationale

When dehydration is hypertonic in nature, such as with profuse sweating, it can be detected through changes in serum osmolality or serum sodium. In contrast, hypotonic and isotonic dehydration, produced by food restriction or diuretic use, would be difficult to detect except by serial haematocrit or haemoglobin measurements.

4.3.2 Equipment

Measurement of blood and serum parameters requires properly trained phlebotomists, safe and sterile technique, and access to laboratory equipment. Required equipment includes a freezing point osmometer for serum osmolality, an ion selective electrode for serum sodium, centrifuges and capillary tubes for haematocrit and a spectrometer for haemoglobin.

4.3.3 Practicality

Measurement of blood or serum parameters tends to be costly, invasive, labour intensive and requires a trained phlebotomist. In addition, blood drawing poses a small, but significant, risk of infection, bruising and vein damage.

4.3.4 Accuracy and Precision

Several studies have evaluated the sensitivity of blood-borne indices of dehydration during conditions of exercise and heat stress.[22,31] Studies have clearly shown that dehydration of greater than 3% bodyweight produces a marked increase in plasma osmolality.[22,31] However, the responsiveness of osmolality at dehydration of less than 3% bodyweight has been debated. In a study of over 200 male and female army personnel monitored during 44 days of field training, blood-borne indices of dehydration including plasma osmolality and haematocrit were not reliably related to highly concentrated urine samples.[29] The authors concluded that urinary indices may be more sensitive than blood indices because the urine was concentrated in an effort to maintain normal blood chemistry. This view was supported by the Armstrong et al.[27] study of mild hypohydration. They found no relationship between urinary indices of hydra-

tion (specific gravity, colour and osmolality) and blood indices (plasma osmolality, plasma sodium and haematocrit). In addition, despite the participants being dehydrated, blood indices were normal whereas urine indices detected the dehydration. They concluded that urinary indices were more sensitive to mild hypohydration than blood indices.

In contrast, a more recent study of 12 male athletes involving progressive dehydration from 1–5%, showed that plasma osmolality was highly responsive to a reduction in bodyweight by just 1%.[22] When these athletes had lost just 1% of bodyweight by exercising in the heat, they had a rise in plasma osmolality of nearly 7 mOsm/L. This change was comparable to the increase in osmolality as they progressed to 3% dehydration (5 mOsm/L) and to 5% dehydration (5.5 mOsm/L). Thus, the authors concluded that the blood osmolality was highly responsive to even low levels of dehydration.

One study of exercise in the heat has investigated plasma sodium levels as a marker of dehydration.[31] In this study, a loss of 3.7% bodyweight from 2 hours of cycling in the heat and 21 additional hours of fluid restriction resulted in an increase in plasma sodium levels, from 146 mEq/L at baseline to 151 mEq/L. An additional 20-minute bout of cycling after this dehydration phase resulted in an additional 1.5% bodyweight loss and a rise in plasma sodium to 154 mEq/L.

One study examined the usefulness of blood haematocrit and haemoglobin levels for monitoring dehydration.[32] This study compared haematocrit and haemoglobin levels to levels of TBW before and after a 14-day arctic mountain ascent and descent. These blood indices were well correlated with TBW levels throughout the study. This suggests that haemoglobin and haematocrit may be useful hydration indices for situations of isotonic or hypotonic dehydration.

4.3.5 Conclusion

Blood-borne factors such as serum osmolality, plasma sodium, haemoglobin and haematocrit may provide accurate information about the presence of dehydration, even when it is mild (1% of bodyweight lost). This is especially true when baseline/euhydrated values are established. However, repeated blood draws for dehydration monitoring is very impractical. It is time consuming, costly, requires trained personnel, and poses a risk of infection, bruising and vein damage to athletes. These limitations clearly outweigh the benefits of the information gained for routine hydration testing. Nevertheless, they may be considered excellent indices for research purposes.

4.4 Monitoring of Body Water Stores

4.4.1 Rationale

During exercise-induced dehydration, losses in TBW can be from both the intracellular and extracellular compartments. For example, one study showed that a bout of exercise in the heat produced greater losses from the extracellular (57%) than the intracellular (43%) compartment.[33] In addition, body water can shift from the intracellular space to the extracellular space in an effort to maintain circulating blood volume and normal plasma electrolyte concentration.[11]

In contrast, diuretic-induced isotonic dehydration is characterised by a greater loss in ECW and plasma volume than during exercise in the heat.[15] Because the diuretics increase the loss of electrolytes from the body, the osmotic pressure of the blood does not increase enough to promote fluid shifts from the intracellular to the extracellular compartment.

In theory, body water measurements would give the most accurate information about body hydration status. In particular, daily measurements would allow accurate tracking of body water over time and would encourage athletes to stay well hydrated on a daily basis. In addition, information regarding ICW and ECW changes could be used to further customise hydration plans.

4.4.2 Equipment

One field-ready method of TBW estimation is bioelectrical impedance analysis (BIA). In BIA, a 50 kHz alternating current is applied across the body and the resistance to the current is measured.

In some cases, the current is applied from the wrist to the ankle using disposable gel electrodes, however, some companies now manufacture leg-to-leg impedance systems with stand-on platforms and arm-to-arm systems using a hand-held device. Some units include built-in devices to calculate the estimated TBW and percentage of body fat, whereas others provide output of raw data (e.g. resistance) and the operator must select appropriate equations to predict body composition parameters.

The new generation multi-frequency analysers called bioelectric impedance spectroscopy (BIS) machines measure the resistance and reactance of the body when it is presented with currents that range in frequency typically from 5 kHz to 1 MHz. When the resistance and reactance at the different frequencies are modelled using a Cole-Cole plot, the resistances of ECW and ICW can be differentiated.[34] Through the use of equations, ECW, ICW and TBW can be predicted.

4.4.3 Practicality

Bioimpedance methods have received significant attention because they are safe, rapid, non-invasive and easy to administer. Typical costs can range from several hundred to the low thousands of dollars for BIA machines and approximately $US5000–10 000 (2002 values) for BIS machines.

4.4.4 Accuracy and Precision

The precision of most impedance analysers is approximately 0.5% when measuring test objects, and this increases another 1% when testing on humans.[34] The accuracy of most BIA machines is moderate, with prediction errors for TBW ranging from 1.5–2.5kg. Errors in prediction are due to lack of precision in measurement of resistance and height, as well as the error inherent in the prediction equation used. BIS machines tend to have slightly better accuracy (0.5kg) and precision (<1.0kg) than BIA machines.[35]

The accuracy and precision of impedance testing is highly dependent on the use of standardised testing procedures.[36,37] Standardisation of conditions includes:

- cleaning of the skin where the electrodes contact with alcohol wipes;
- accurate measurement of height and weight (if applicable);
- careful placement of gel electrodes to ensure proper position and full contact with skin (if applicable);
- minimisation of time in recumbent position before measurements are made (for recumbent measurements);
- consistency in angle of abduction of limbs (ideal is 30–45°) for recumbent measurements;
- fasting for 4 hours prior to measurements;
- comfortable room temperature;
- avoidance of exercise for several hours prior to measurements.

In addition, for optimal accuracy and precision, it is important to standardise hydration status[36,37] so that athletes are well-hydrated at the time of measurement. In BIA, little penetration of cells occurs at 50 kHz. Thus, the primary path of the current is extracellular, with TBW and ICW being predicted based on assumptions of normal fluid balance.[35] Indeed, when ECW and ICW ratios are disrupted (such as in dehydration), the error in TBW estimation can be substantially higher.[38-40] Studies of bioelectric impedance spectroscopy have shown that it may have potential in monitoring body water in dehydration beyond what BIA can do. One study found that BIS accurately quantified dehydration when it was hypertonic, but not when it was isotonic.[41] However, another study reported significantly better accuracy and precision under conditions of diuretic-induced dehydration.[35]

4.4.5 Conclusion

In summary, bioelectrical impedance techniques have many practical advantages such as ease of use, non-invasiveness and relative low cost. However, their application to hydration monitoring is fairly limited. First, athletes rarely meet the requirements for standardised testing conditions because they are often dehydrated and in the post-exercise state.[42] This will negatively affect the accuracy and precision of measurements. Sec-

ondly, care must be taken when using prediction equations for TBW. Non-athlete equations can lead to bias in the results, so appropriate equations must be used for the population of interest.[42] The common consensus is that bioelectrical impedance techniques lack the precision and accuracy necessary for meaningful hydration monitoring.

5. Recommendations

It is our opinion that hydration testing has value in the athletic arena. Over the past generation, we have recognised that fluid consumption and the type of fluid consumed are important to the athlete's performance and safety. More careful testing of hydration status can only serve to enhance both performance and safety. We recommend that teams have a written protocol in place that discusses the value of hydration testing related to performance and safety, as well as specifics about the testing methods. These protocols should be consistent with the NATA's recommendations.[6]

The advantages and disadvantages of each method of hydration testing are summarised in table I. It is important to note that all methods of hydration testing are not perfect. In particular, using field-ready, inexpensive and non-invasive tests results in reduced accuracy and precision. With this in mind, we recommend weight testing as a safe, inexpensive, accurate, precise and non-invasive option for daily hydration monitoring in athletes who are involved in weight independent sports. Other simple options for this athlete population could include monitoring of Ucol, Uvol or Usg (particularly by dipstick). These athletes could be instructed in the self-monitoring of weight, Ucol, Uvol and Usg as part of the team's hydration protocol.

For athletes involved in weight-dependent sports, hydration testing becomes more complicated and more important. Hydration testing prior to weight certification (e.g. the NCAA Wrestling Weight Certification Program), is an important tool to ensure the most accurate and precise minimal weight measurements.[9] The use of Usg at certification testing has obvious limitations, such as being sensitive to recent fluid consumption. However, we feel these limitations must be put in perspective with the risks of assigning a low minimal weight or having no hydration monitoring procedures in place. We feel the NCAA's current stand-

Table I. Advantages and disadvantages of hydration testing methods

Method	Advantages	Disadvantages
Weight	Easy, non-invasive	Does not measure incorporation of body water
	Inexpensive	Standardised conditions desirable
	Precise, accurate	
	Detects isotonic, hypertonic and hypotonic dehydration	
	Appropriate for self-monitoring	
Urine tests	Easy, minimally invasive	Detects hypertonic dehydration only
	Inexpensive	Lower accuracy and precision
	Appropriate for self-monitoring	Acute ingestion of fluids can invalidate tests
Blood tests	Precise, accurate	Invasive
	Can detect even mild dehydration	Not easy: phlebotomist required
	Detects isotonic, hypertonic and hypotonic dehydration	Expensive
		Outcomes not readily available
Impedance tests	Easy, non-invasive	Lower accuracy and precision
	Outcomes readily available	Expensive
		Requires standardised conditions
		Inaccurate in dehydration

ard for hydration, Usg ≤1.020, appropriately classifies most athletes.

6. Future Research Needs

Our ability to make appropriate hydration testing recommendations is limited by the paucity of research on hydration testing. We believe that future research in hydration testing is needed in the following areas.

6.1 Criterion Measures for Hydration Status of Euhydrated, Dehydrated and Rehydrated States

The simple monitoring of weight change is not sufficient. More work is needed to assess the sensitivity and specificity of criterion measures, such as plasma and urine osmolality, in these three hydration states. In particular, no methods have been validated for monitoring incorporation of rehydration fluids into the extracellular and intracellular spaces. Net weight gain (weight gain–urine output) is not sufficient as a rehydration criterion, because it may not reflect incorporation of fluid into the body water compartments.

6.2 Additional Blood and Urine Indices

Some data suggest that urinary parameters such as potassium, sodium and protein may be valuable hydration tests, but no validation studies exist.[43-45] Validation studies of new indices of hydration should include appropriate criterion measurements, such as TBW, percentage dehydration or plasma osmolality. Particular attention should be placed on finding field-ready methods that are easy, minimally invasive and low in cost.

6.3 Efforts to Refine Testing Protocols for Field-Ready Methods

It appears that the second daily void may be a more valid measure of hydration than the first morning void, but research that is designed to assess this question is lacking.[27]

6.4 The Effects of Acute Ingestion of Fluids on Urine Parameters of Hydration Status

These data are necessary to better understand how to most effectively determine hydration status at wrestling weight certification time. Given that weight certification for both high school and college wrestlers now includes hydration assessment by Usg, research that explores this question is needed.

6.5 Application of Bioelectrical Impedance Technology to Hydration Monitoring

Personal communications with high school wrestling coaches suggest that many are using BIA for daily hydration monitoring already. This has included tracking an athlete's resistance (in ohms) on a daily basis. Research is needed to document whether this, or other impedance methods, is accurate and precise enough to be a valid hydration monitoring technique.

7. Conclusions

In summary, we support the use of hydration testing as a tool to enhance athletic performance and decrease the health risks associated with intense training and competition regimens. Available methods offer useful information on hydration status particularly when athletes and medical personnel use them regularly and recognise individual differences in outcomes. Additional research is needed to document the sensitivity and specificity of these tests under field conditions, as well as to develop new field-ready methods. In addition, more research is needed to fully understand the effects that acute rehydration has on the accuracy of hydration assessment.

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References

1. Occupational Safety and Health Department. Report on the Minnesota Viking football training camp. St Paul (MN): Minnesota Department of Labor and Industry, 2001
2. Mueller FO. Annual survey of football injury research: 1931-2001. Chapel Hill (NC): National Center for Catastrophic Sports Injuries, 2002 Feb
3. Centers for Disease Control and Prevention. Hyperthermia and dehydration-related deaths associated with intentional rapid weight loss in three collegiate wrestlers: North Carolina, Wisconsin, and Michigan; November - December 1997. JAMA 1998; 279: 824-5
4. Powell J, Barber-Foss K. Sex-related injury patterns among selected high school sports. Am J Sports Med 2000; 28: 385-91
5. American College of Sports Medicine. Position statement: exercise and fluid replacement for athletes. Med Sci Sports Exerc 1996; 28: I-VII
6. Casa DJ, Armstrong LE, Hillman SK, et al. National Athletic Trainers' Association position statement: fluid replacement for athletes. J Athletic Training 2000; 35: 212-24
7. American College of Sports Medicine. Joint position statement: nutrition and athletic performance. Med Sci Sports Exerc 2000; 32: 2130-45
8. Greenleaf JE. Problem: thirst, drinking behavior, and involuntary dehydration. Med Sci Sports Exerc 1992; 24: 645-56
9. Wrestling Rules Committee. NCAA wrestling rules. Indianapolis (IN): NCAA Publications, 1999
10. Clark RR, Oppliger RA. Minimal weight standards in high school wrestling. Orthop Phys Ther Clin North Am 1998; 7: 23-45
11. Sawka MN. Physiological consequences of hypohydration: exercise performance and thermoregulation. Med Sci Sports Exerc 1992; 24: 657-70
12. Wang ZM, Pierson RN, Heymsfield SB. The five-level model: a new approach to organizing body composition research. Am J Clin Nutr 1992; 56: 19-28
13. Sawka MN, Pandolf KB. Effects of body water loss on physiological function and exercise performance. In: Gisolfi CV, Lamb DR, editors. Fluid homeostasis during exercise. Carmel (IN): Benchmark Press, 1990: 1-38
14. Weinberg AD, Minaker KL, American Medical Association CoSA. Dehydration: evaluation and management in older adults. JAMA 1995; 274: 1552-6
15. Sawka MN, Montain SJ, Latzka WA. Hydration effects on the thermoregulation and performance in the heat. Comp Biochem Physiol A 2001; 128: 679-90
16. Oppliger RA, Landry GL, Foster SW, et al. Wisconsin minimum weight program reduces weight cutting practices of high school wrestlers. Clin J Sports Med 1998; 8: 26-31
17. Steen SN, Brownell KD. Patterns of weight loss and regain in wrestlers: has the tradition changed? Med Sci Sports Exerc 1990; 22: 762-8
18. Brownell KD, Steen SN, Wilmore JH. Weight regulation practices in athletes: analysis of metabolic and health effects. Med Sci Sports Exerc 1987; 19: 546-56
19. Steen SN, Oppliger RA, Brownell KA. Metabolic effects of repeated weight loss and regain in adolescent wrestlers. JAMA 1988; 260: 47-50
20. Rosen LW, McKeag DB, Hough DO, et al. Pathogenic weight-control behavior in female athletes. Phys Sportsmed 1986; 14: 79-86
21. Sundgot-Borgen J. Eating disorders in female athletes. Sports Med 1994; 17: 176-88
22. Popowski LA, Oppliger RA, Lambert P, et al. Blood and urinary measures of hydration status during progressive acute dehydration. Med Sci Sports Exerc 2001; 33: 747-53
23. Costill DL, Sparks KE. Rapid fluid replacement following thermal dehydration. J Appl Physiol 1973; 34: 299-303
24. Strasinger SK. Urinalysis and body fluids. Philadelphia (PA): FA Davis Company, 1994
25. Shirreffs SM, Maughan RJ. Urine osmolality and conductivity as indices of hydration status in athletes in the heat. Med Sci Sports Exerc 1998; 30: 1598-602
26. Brunzel NA. Fundamentals of urine and body fluid analysis. Philadelphia (PA): WB Saunders Company, 1994
27. Armstrong LE, Maresh CM, Casellani JW, et al. Urinary indices of hydration status. Int J Sport Nutr 1994; 4: 265-79
28. Armstrong LE, Maresh CM, Gabaree CV, et al. Thermal and circulatory responses during exercise: effects of hypohydration, dehydration, and water intake. J Appl Physiol 1997; 82: 2028-35
29. Francesconi RP, Hubbard RW, Szlyk PC, et al. Urinary and hematologic indexes of hypohydration. J Appl Physiol 1987; 62: 1271-6
30. Kovacs EMR, Senden JMG, Brouns F. Urine color, osmolality, and specific electrical conductance are not accurate measures of hydration status during postexercise rehydration. J Sports Med Phys Fitness 1999; 39: 47-53
31. Armstrong LE, Soto JAH, Hacker FT, et al. Urinary indices during dehydration, exercise, and rehydration. Int J Sport Nutr 1998; 8: 345-55
32. Hackney AC, Coyne JT, Pozos R, et al. Validity of urine-blood hydrational measures to asses total body water changes during a mountaineering in the sub-Arctic. Arctic Med Res 1995; 54: 69-77
33. Nose H, Mack GW, Shi X, et al. Shift in body fluid compartments after dehydration in humans. J Appl Physiol 1988; 65: 318-24
34. Baumgartner RN. Electrical impedance and total body electrical conductivity. In: Roche AF, Heymsfield SB, Lohman TG, editors. Human body composition. Champaign (IL): Human Kinetics, 1996: 79-107
35. Gudivaka R, Schoeller DA, Kushner RF, et al. Single- and multifrequency models for bioelectrical impedance analysis of body water compartments. J Appl Physiol 1999; 87: 1087-96
36. Kushner RF, Gudivaka R, Schoeller DA. Clinical characteristics influencing bioelectrical impedance analysis measurements. Am J Clin Nutr 1996; 64 (3 Suppl.): 423S-7S
37. Anonymous. NIH Technology assessment statement: bioelectrical impedance analysis in body composition measurement. Bethesda (MD): National Institute of Health, 1994: 1-35
38. Thompson DL, Thompson WR, Prestridge TJ, et al. Effects of hydration and dehydration on body composition analysis: a comparative study of bioelectric impedance analysis

and hydrodensitometry. J Sports Med Phys Fitness 1991; 31: 565-70
39. Saunders MJ, Blevins JE, Broeder CE. Effects of hydration changes on bioelectrical impedance in endurance trained individuals. Med Sci Sports Exerc 1998; 30: 885-92
40. Koulmann N, Jimenez C, Regal D, et al. Use of bioelectrical impedance analysis to estimate body fluid compartments after acute variations of the body hydration level. Med Sci Sports Exerc 2000; 32: 857-64
41. O'Brien C, Baker-Fulco CJ, Young AJ, et al. Bioimpedance assessment of hypohydration. Med Sci Sports Exerc 1999; 31: 1466-71
42. Segal KR. Use of bioelectrical impedance analysis measurements as an evaluation for participating in sports. Am J Clin Nutr 1996; 64 (3 Suppl.): 469S-71S
43. Zambraski EJ, Tipton CM, Jordon HR, et al. Iowa wrestling study: urinary profiles of state finalists prior to competition. Med Sci Sports Exerc 1974; 6: 129-32
44. Zambraski EJ, Tipton CM, Tcheng TK, et al. Iowa wrestling study: changes in the urinary profiles prior to and after competition. Med Sci Sports Exerc 1975; 7: 217-20
45. Zambraski EJ, Foster DT, Gross PM, et al. Iowa wrestling study: weight loss and urinary profiles of collegiate wrestlers. Med Sci Sports Exerc 1976; 8: 105-8

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