Use of bioelectrical impedance in hydration status assessment: reliability of a new tool in psychophysiology research

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Abstract

Adequate hydration is crucial in maintaining optimal physical and mental functioning and the need for a fast and reliable hydration status assessment in behavioral medicine research has become increasingly important. The goal of this study was to determine the reliability of bioelectrical impedance assessment (BIA) in assessing total body water (TBW), extracellular water (ECW) and intracellular water (ICW) and to assess whether individuals can be reliably classified as being hypohydrated or hyperhydrated using lower and upper quartiles, respectively. TBW, ECW and ICW were assessed via BIA (Bodystat, Isle of Man, UK) in 52 male and 48 female college students on 2 separate days within 1 week. Results revealed strong test–retest reliability for TBW ($r=0.983$), ECW ($r=0.972$) and ICW ($r=0.988$) (all P's < 0.001). Following the initial and follow-up assessments, participants were then classified as being either hypohydrated or hyperhydrated based on the percentage of body weight accounted for by TBW. Test–retest reliability of hydration status within classifications was then assessed by gender. Test–retest reliability was found for TBW, ECW and ICW among hypohydrated ($r=0.985$, $r=0.972$ and $r=0.99$, respectively) and hyperhydrated ($r=0.994$, $r=0.989$ and $r=0.994$, respectively) males (all P's < 0.001). Significant test–retest correlations were also found for females classified as being hypohydrated ($r=0.97$, $r=0.956$ and $r=0.976$, respectively) and hyperhydrated ($r=0.973$, $r=0.976$ and $r=0.976$, respectively) (all P's < 0.001). These findings suggest that hydration status, as indexed by bioelectrical impedance technique, is reliable across time and is also reliable within individuals who are chronically hyperhydrated or hypohydrated.
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1. Introduction

Second only to the air we breathe, proper hydration is one of the most important factors in maintaining homeostasis within the body as well as sustaining optimal physiological and psychological performance. Appropriate daily hydration with

water is necessary for maintaining energy levels, regulating body temperature, digestion and absorption of nutrients, elimination of toxins and waste, joint lubrication, reproduction and neural conductivity (Kleiner, 1999; Felesky-Hunt, 2001). For an adequately hydrated adult, 35–45% of body weight is accounted for by intracellular water (ICW), extracellular water (ECW) accounts for 20–30%

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of body weight and therefore total body water (TBW) accounts for 55–65% of overall body weight (Berne and Levy, 1988; Pierson et al., 1998). In order to maintain proper daily hydration levels, the National Research Council recommends a fluid intake of at least 2900 ml per day for the average male and 2200 ml per day for the average female (Food and Nutrition Board, 1989).

Interestingly, regardless of the reported importance of proper hydration in maintaining good health, epidemiological data appears to indicate that a majority of individuals in the United States are mildly dehydrated due to not drinking enough water on a daily basis (Nationwide Food Consumption Survey, 1984; Levallois et al., 1998). Chronic mild dehydration (1–2% loss in body weight due to body water loss) can result in gastrointestinal discomfort, loss of appetite, cramping, irritability and dizziness while a 4–8% body weight loss has been reported to contribute to urinary stone development, breast, colon and urinary tract cancers, mitral valve prolapse and hypertension (Kleiner, 1999; Felesky-Hunt, 2001). Significant dehydration has also been found to result in diminished mental performance including short term memory deficits, impaired problem solving ability, and diminished visual-motor tracking and physical performance (Sharma et al., 1986; Gopinathan et al., 1988; Kleiner, 1999). Since poor hydration status can also affect the thickness or viscosity of blood in the vascular compartment, it is also possible that mild dehydration may exacerbate the stress-hemoconcentration effects that have been repeatedly observed during acute psychological and physical stress (Patterson et al., 1995a,b). Therefore, from a behavioral health perspective, poor hydration status is probably the single most overlooked, modifiable health behavior among humans.

Possible reasons for the lack of basic and applied behavioral research assessing the effects of hydration status on physical and mental health are that traditional hydration status assessment techniques are expensive and time consuming, require extensive technical skills, or are only crude assessments of TBW. These techniques fall into one of two categories: direct and indirect measures. Direct measures include measuring body water by radio-active isotope dilutions such as tritiated water ($3H_2O$) and heavy water dilutions, which include sodium bromide (NaBr) and deuterium oxide (D_2O) (Young et al., 1973) and are considered the 'gold standard' of body water measurement. The greatest advantage of direct measures is that they are actual measures of body water and are, therefore, believed to be the most accurate means of determining hydration status. However, most of the direct measure techniques require ingestion or intravenous administration of potentially hazardous agents, are time consuming, require extensive analysis of blood samples, and do not allow for multiple assessments over short periods of time as is commonly needed in psychophysiological research (Bartoli et al., 1993).

Indirect methods include biological measures such as plasma volume, urine osmolality and urine color from which body water is estimated. These techniques are very different from each other in that each measures a different aspect of overall hydration status. For example, the assessment of calculated plasma volume via hematocrit and hemoglobin measurement has been used as a determinant of hydration status (van Beaumont, 1972; Dill and Costill, 1974) and has been reported to be related to direct measures of TBW (Beijering et al., 1997). However, plasma volume is defended by the body in an attempt to maintain cardiovascular stability, and therefore plasma is not affected by hypohydration until a certain degree of body water has been lost (>3% of body weight) (Francesconi et al., 1987; Armstrong et al., 1994). Another indirect method is the measurement of solute load or osmolality of urine from the first void of the day, which has been found to vary according to hydration status such that hypohydrated individuals have greater urine osmolality than euhydrated individuals (Shirreffs and Maughan, 2000). Finally, urine color, estimated from a color chart, has been demonstrated to provide a reasonable 'field estimate' of hydration status. Unfortunately, urine osmolality and color can be influenced by a number of factors unrelated to hydration status, including foods, medications and illness. Each of these techniques provide quick assessments and are easy to use, but they do not have the accuracy or specificity of the direct

measures (Shirreffs, 2000) and are considered gross assessments of hydration status.

A relatively new technique for assessing hydration status is bioelectrical impedance. Bioelectrical impedance (BIA) is capable of measuring TBW and extracellular body water, from which intracellular body water can be mathematically calculated. Bioelectrical impedance assesses body water by sending a mild electrical current delivered across a range of frequencies, ranging from 5 to 500 kHz, through the participant's body via electrodes placed on the right hand and foot. The 5 kHz signal has been found to accurately assess ECW while the 200 kHz signal is adequate for assessing TBW (Deurenberg et al., 1993, 1995; Ward et al., 2000). More importantly, bioelectrical impedance is safe, fast and simple in that the actual measurement takes approximately 5 min, requires the placement of only four surface electrodes, and involves minimal technical training.

Bioelectrical impedance has been extensively validated against several other hydration assessment techniques such as hydrodensity, anthropometry, and isotope dilutions. Research on the validity of BIA has revealed that bioelectrical impedance yields results similar to those produced by hydrodensity (Brodie et al., 1998; Liang and Norris, 1993) and anthropometry (Brodie et al., 1998; Foster and Lukaski, 1996). More importantly, BIA has repeatedly been found to be highly correlated with sodium bromide and deuterium oxide isotope dilutions (Armstrong et al., 1997; Patel et al., 1994, 1996; DeLorenzo et al., 1997; Deurenberg et al., 1995; Johnson et al., 1992; Khaled et al., 1997; Ellis and Wong, 1998; Simons et al., 1999). Given the demonstrated validity of BIA, it is interesting to note that to our knowledge no studies have been conducted to assess the test–retest reliability of BIA which would be particularly important in psychophysiological research since it often requires multiple assessments of physiological measures over time. Therefore, the goals of this study were to: (1) assess the test–retest reliability for bioelectrical impedance measures of ECW volume (liters), TBW volume (liters) and ICW volume (liters) over a 1-week period, and (2) test the reliability of ECW volume (liters), TBW volume (liters) and ICW volume (liters)

among individuals who were categorized as being either hypohydrated or hyperhydrated.

2. Method

2.1. Participants

One hundred undergraduate students (52 males, 48 females) between the ages 18 and 30 (mean age of 19.2 ± 1.2) were recruited from an undergraduate psychology course for the study. Participants had to be in good physical health and within 20% of their ideal body weight (mean body mass index (BMI) of 23.8 ± 2.7). Due to the possibility that the electrical frequencies used to assess TBW and ECW could produce incorrect defibrillator responses (National Institutes of Health, 1996), individuals with pacemakers were not allowed to participate. To control for any short term dietary or post prandial effects on body water variables, participants were also asked to fast for 4 h prior to the study and to abstain from drinking alcoholic beverages or engaging in strenuous physical exercise for 12 h prior to the study session. Female participants were scheduled to attend study sessions during the follicular phase of their menstrual cycle (3–16 days after the start of menses) to control for hormonal and fluid retention effects and women who were pregnant were excluded from the study.

2.2. Physiological measures

2.2.1. Height/weight

Height and weight measurements were taken using a standard hospital balance beam scale and stadiometer. Height was measured to the nearest centimeter and weight to the nearest quarter pound, and BMI was calculated using the standard formula: (kg/m^2).

2.2.2. Hydration assessment

The Multiscan 5000 multifrequency bioelectrical impedance monitor (Bodystat Ltd, Isle of Man, UK), which measures a range of 100 frequencies between 5 and 500 kHz, was used to measure TBW and the distribution of ECW and ICW. The Multiscan 5000 measures bioelectrical impedance

by passing a mild electrical current (800 µA) across a range of frequencies (5–500 kHz) through the participant's body via four electrodes, two placed on the right hand and two placed on the right foot. Impedance from the 5 kHz signal is then used to determine ECW and the 200 kHz signal is used to determine TBW. Smye et al. (1993) compared four different commercially available multiple frequency bioelectrical impedance monitors including BodyStat and found that the BodyStat Multiscan 5000 had the least amount of measurement error (<10% across a range of skin resistance up to 6 kΩ).

2.3. Procedure

2.3.1. Participant screening

During the telephone screening, potential participants were asked several questions in order to determine eligibility and for scheduling purposes. During the telephone screening, participants were scheduled for both visits at which time they were told to abstain from food and beverage for 4 h before each session and also to abstain from alcohol and strenuous exercise for 12 h before each session. Participants also received a reminder call the day before each session.

2.3.2. Session 1

Upon arrival the participant read and signed the informed consent form. Height and weight measurements were taken and the participant was instructed to lie down on a massage table with feet apart and hands at their sides. The timer was started and then the experimenter asked several questions designed to determine if the participant abstained from food, beverage, alcohol and exercise for the correct period of time. The participant then began a 20-min rest period. A tetrapolar arrangement of gel electrodes (2.0×7.5 cm^2) was applied to the skin after alcohol preparation. Electrodes were placed (1) on the dorsal surface of the right foot 2 cm proximal from the metatarsophalangeal joint of the third toe, (2) on the anterio-dorsal surface of the right ankle over the axis of the medial and lateral malleoli, (3) on the dorsal surface of the right hand 1 cm proximal from the metacarpophalangeal joint of the third finger and

(4) on the dorsal surface of the right wrist 7.5 cm proximal from the hand electrode 3. After a 20-min supine rest period, multifrequency impedance measurements of compartmental body water were taken. The bioelectrical impedance measurements took approximately 5 min to complete and the participant was asked to lie still during that time. Following the BIA assessment, participant was unhooked from the impedance monitor and reminded of their second session.

2.3.3. Session 2

Upon arrival the participant signed and dated the informed consent form and the protocol from session 1 was repeated. After the bioelectrical impedance measurements were completed, the participant read a debriefing statement, all questions regarding the study were answered, and was then free to leave.

2.3.4. Data reduction and analysis

The study used a test–retest design. Pearson correlations were calculated for the 2 sessions comparing ECW, ICW and TBW over the 1-week period. Gender was also used as a factor to determine if any gender differences in hydration status existed.

As stated above, the second aim of the study was to assess the reliability of ECW, ICW and TBW among individuals who were categorized as being chronically hypohydrated or hyperhydrated. Quartiles were calculated from the percentage of weight accounted for by TBW for visit 1 to determine if participants could be classified as hypohydrated or hyperhydrated. Reliability was then assessed within the hydration classifications to determine if the measures were stable within each category over a 1-week period. Quartiles were calculated for males and females separately because men tend to have a higher percent TBW than women. For males, the cutoff for being hypohydrated was 51.35% and the cutoff for being hyperhydrated was 55.77%. For females, the cutoff for being hypohydrated was 45.00% and the cutoff for being hyperhydrated was 49.35%. Pearson's correlations were then conducted to assess the test–retest reliability of the body water measures
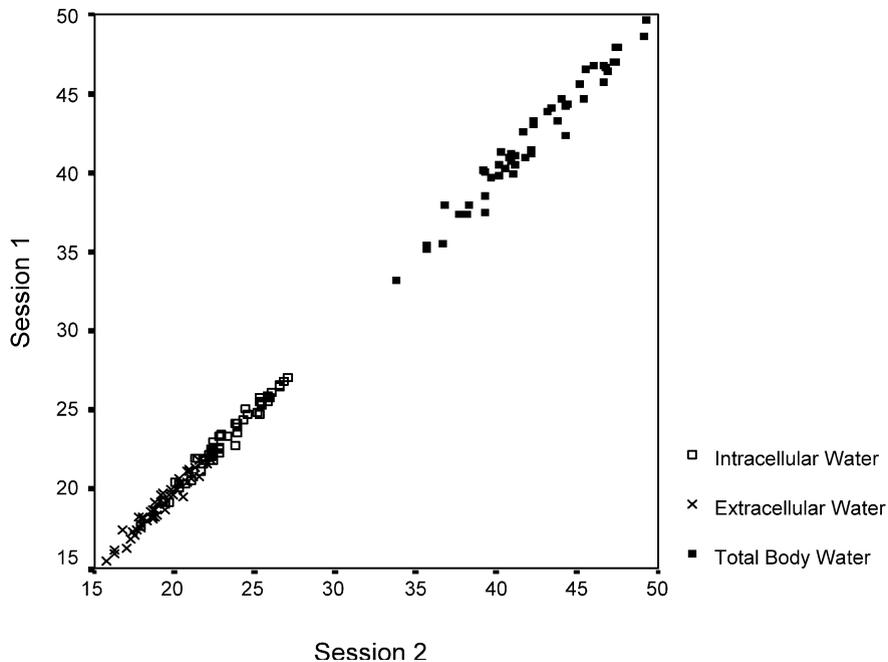
Fig. 1. Reliability of body water for males.

within the hypohydrated and hyperhydrated categories.

To our knowledge, there are no published norms regarding percent TBW in the human body and no specified cutoffs for determining whether a person is hypohydrated or hyperhydrated based on percent TBW. However, using the bioelectrical impedance data from NHANES III, Chumlea et al. (2002) reported the hydration status of individuals according to absolute TBW values (in liters). For the age group 18–20, they reported TBW mean for males 43.2 ± 5.8 and TBW for females 31.9 ± 4.2. This is comparable to our means of 42.3 ± 3.9 for males and 29.1 ± 2.7 for females.

3. Results

3.1. Test–retest reliability

For the full sample, test–retest reliability was found for TBW ($r = 0.99$, $P < 0.001$, $n = 100$), ECW ($r = 0.99$, $P < 0.001$, $n = 99$) and ICW ($r = 0.99$, $P < 0.001$, $n = 99$). Because males have greater amounts of body water than females, the

percentage of body water by weight, which indicates the percentage of an individual's weight that is accounted for by body water, referred to as %BW, was also calculated. For the full sample, %TBW ($r = 0.98$, $P < 0.001$, $n = 100$), %ECW ($r = 0.96$, $P < 0.001$, $n = 99$) and %ICW ($r = 0.99$, $P < 0.001$, $n = 99$) were also found to be highly reliable over a 1-week period.

For males, all the body water measures were significantly correlated for visits 1 and 2. TBW ($r = 0.98$, $P < 0.001$, $n = 52$), ECW ($r = 0.97$, $P < 0.001$, $n = 51$) and ICW ($r = 0.99$, $P < 0.001$, $n = 51$) were reliable over a 1-week period as were %TBW ($r = 0.94$, $P < 0.001$, $n = 52$), %ECW ($r = 0.94$, $P < 0.001$, $n = 51$) and %ICW ($r = 0.94$, $P < 0.001$, $n = 51$). Fig. 1 shows body water reliability for the male participants.

The females showed patterns similar to those of males with all the body water measures being significantly correlated for visits 1 and 2. TBW ($r = 0.98$, $P < 0.001$, $n = 48$), ECW ($r = 0.97$, $P < 0.001$, $n = 48$) and ICW ($r = 0.98$, $P < 0.001$, $n = 48$) were reliable over a 1-week period as were
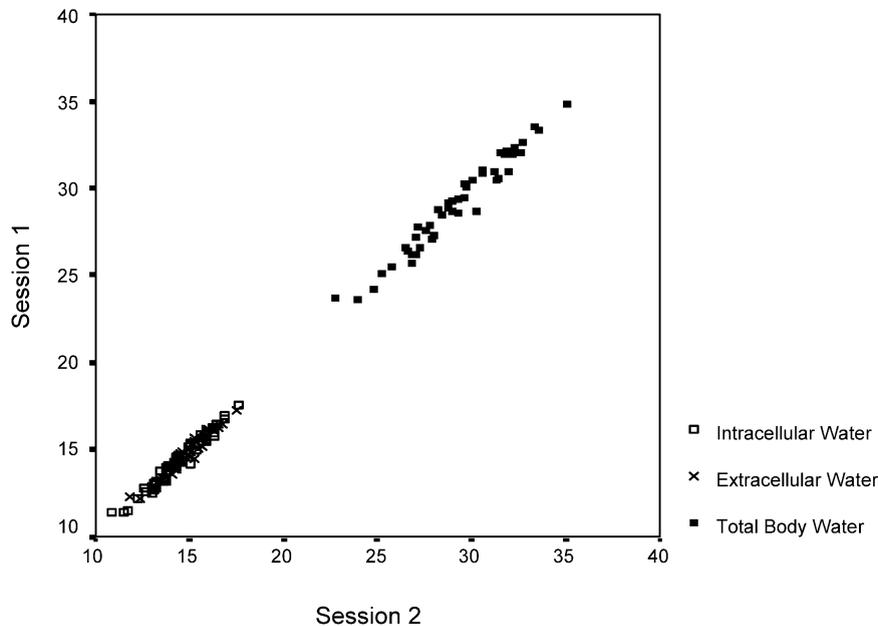
Fig. 2. Reliability of body water for females.

%TBW ($r = 0.97$, $P < 0.001$, $n = 48$), %ECW ($r = 0.97$, $P < 0.001$, $n = 48$) and %ICW ($r = 0.96$, $P < 0.001$, $n = 48$). Fig. 2 displays the reliability of TBW, ECW and ICW for the female participants.

There also appears to be gender differences in the distribution of ECW and ICW. In males, 45% of TBW was accounted for by ECW and 55% was ICW. For females, ECW and ICW comprised equal proportions of TBW (i.e. 50% each). This may be due to the fact that females were tested during the follicular phase of the menstrual cycle and research suggests that the distribution of ECW and ICW may change during the menstrual cycle (Lusseveld et al., 1993).

3.2. Test–retest reliability within hypohydration and hyperhydration categories

For the males who were classified as being hypohydrated, the body water measures were significantly correlated for visits 1 and 2. TBW ($r = 0.98$, $P < 0.001$, $n = 13$), ECW ($r = 0.97$, $P < 0.001$, $n = 13$) and ICW ($r = 0.99$, $P < 0.001$, $n = 13$) were again shown to be reliable over a 1-week period for hypohydrated males as were %TBW ($r = 0.68$,

$P < 0.01$, $n = 13$), %ECW ($r = 0.65$, $P < 0.05$, $n = 13$) and %ICW ($r = 0.76$, $P < 0.01$, $n = 13$).

For the males who were classified as being hyperhydrated, the body water measures were significantly correlated for visits 1 and 2. TBW ($r = 0.99$, $P < 0.001$, $n = 13$), ECW ($r = 0.99$, $P < 0.001$, $n = 13$) and ICW ($r = 0.99$, $P < 0.001$, $n = 13$) were reliable over a 1-week period for hyperhydrated males as were %TBW ($r = 0.90$, $P < 0.001$, $n = 13$), %ECW ($r = 0.93$, $P < 0.001$, $n = 13$) and %ICW ($r = 0.85$, $P < 0.001$, $n = 13$). Fig. 3 displays %TBW reliability for hypohydrated and hyperhydrated males.

For the females who were classified as being hypohydrated, the body water measures were significantly correlated for visits 1 and 2. TBW ($r = 0.97$, $P < 0.001$, $n = 12$), ECW ($r = 0.96$, $P < 0.001$, $n = 12$) and ICW ($r = 0.98$, $P < 0.001$, $n = 12$) were found to be reliable over a 1-week period for hypohydrated females as were %TBW ($r = 0.96$, $P < 0.001$, $n = 13$), %ECW ($r = 0.96$, $P < 0.001$, $n = 13$) and %ICW ($r = 0.94$, $P < 0.001$, $n = 13$).

For the females who were classified as being hyperhydrated, the body water measures were significantly correlated for visits 1 and 2. TBW ($r = $
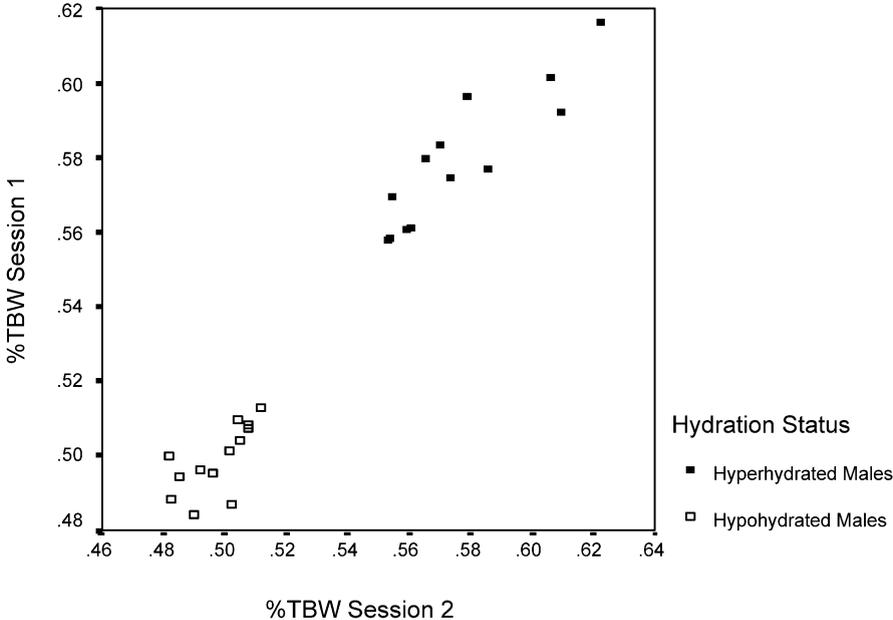
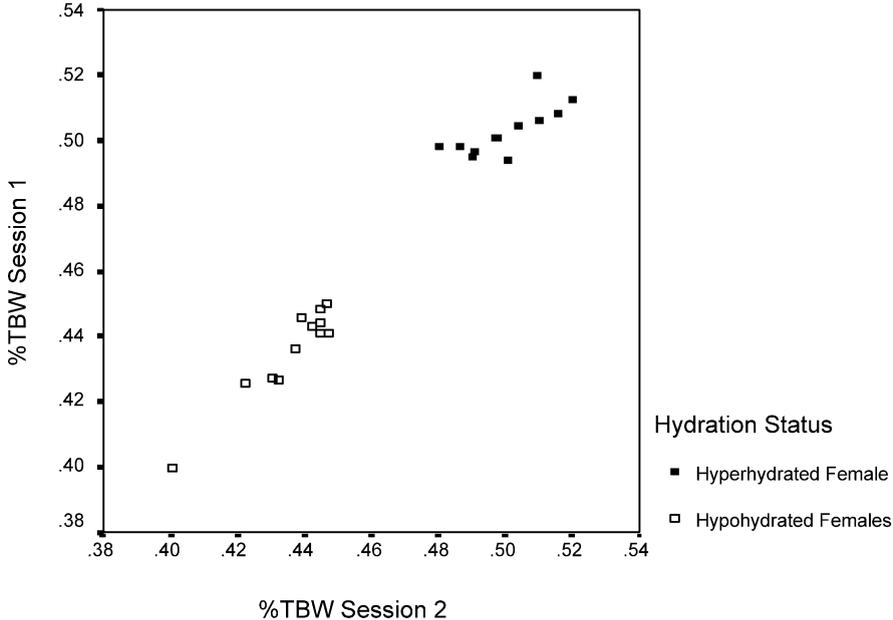Fig. 3. Reliability of %TBW for hypohydrated and hyperhydrated males.

Fig. 4. Reliability of %TBW for hypohydrated and hyperhydrated females.

0.97, $P < 0.001$, $n = 12$), ECW ($r = 0.97$, $P < 0.001$, $n = 12$), ICW ($r = 0.97$, $P < 0.001$, $n = 12$) were reliable over a 1-week period for hyperhydrated females as were %TBW ($r = 0.74$, $P < 0.01$, $n = 13$), %ECW ($r = 0.86$, $P < 0.001$, $n = 13$) and %ICW ($r = 0.68$, $P < 0.05$, $n = 13$). Fig. 4 displays %TBW reliability for hypohydrated and hyperhydrated females.

4. Discussion

The results of this study indicate that bioelectrical impedance is a highly reliable method for determining hydration status in healthy individuals. Furthermore, this study revealed that for most young healthy individuals, hydration status appears to be fairly stable over a 1-week period. It is important to point out, however, that this study assessed bioelectrical impedance reliability in a relatively young group of healthy college students and that future research is needed to assess the reliability of hydration status assessments across different age groups to include children, middle-aged adults and the elderly as cutoffs for hypohydration and hyperhydration vary with age (Chumlea et al., 2002).

This study also revealed that bioelectrical impedance can be used to reliably classify individuals as being either chronically hypohydrated or hyperhydrated across time. As stated previously, chronic hypohydration is believed to contribute to many health maladies and diseases such as cardiovascular disease, hypertension and diabetes. If this is true, the utility of being able to reliably identify chronically hypohydrated individuals would greatly enhance the ability of health care providers and therapists to provide early behavioral interventions designed to increase hydration behaviors which may, in turn, lower their risk for future health problems and possibly disease development. Furthermore, bioelectrical impedance may also serve as an important tool for health care professionals in assessing patient compliance with hydration enhancement regimens by providing immediate feedback on changes in TBW status. Therefore, another logical step in the assessment of bioelectrical impedance application is to determine whether bioelectrical impedance can successfully detect small incremental changes in hydration status changes over long periods of time such as months or years.

Due to the fact that most of the reported negative health effects of improper hydration status stem from being acutely dehydrated (Greenleaf et al., 1979; Senay, 1972), research into the ability of bioelectrical impedance to detect acute changes in hydration status during short-term rehydration is warranted. Interestingly, preliminary analysis of a recent study conducted in our lab that was designed to assess changes in body water from a pre-fluid load assessment to various time points up to 60 min after the fluid load has shown that bioelectrical impedance can detect an acute change in hydration status (Shanholtzer and Patterson, 2003).

The high reliability and validity of multifrequency bioelectrical impedance technology as a safe, simple and inexpensive method of body water assessment has both methodological and clinical implications for future psychophysiological research. Although several studies have demonstrated that stress-induced changes in plasma volume can account for the changes found in cholesterol, fibrinogen, proteins and blood cells during acute laboratory stress (Patterson et al., 1993, 1995a,b; Muldoon et al., 1992; Marsland et al., 1997; Bachen et al., 2002), TBW or hydration status has never been taken into account as a potential mediating factor for stress-hemoconcentration and, therefore, needs to be explored. From a clinical standpoint, bioelectrical impedance may prove to be useful in examining individual differences in hydration status among at-risk (i.e. hypertension, stroke) individuals. However, to our knowledge no studies have assessed body water differences among at-risk individuals. Future studies are needed to assess possible individual differences in extracellular or total body water, which may help in explaining reported individual differences factors such as blood viscosity and hematocrit levels (Rosing et al., 1970; Tofler et al., 1987; Jern et al., 1991) which are known to be affected by hydration status.

In conclusion, the results of this study indicate that body water assessments using bioelectrical impedance techniques afford a fast, simple, accu-

rate, valid and reliable method for evaluating individual differences in extracellular, intracellular or total body water hydration status, all of which is of growing importance in psychophysiological and behavioral medicine research.

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