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Acoustical Method of Whole-Body Hydration Status Monitoring¹

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Abstract

An acoustical handheld hydration monitor (HM) for assessing the water balance of the human body was developed. Dehydration is a critical public health problem. Many elderly over age of 65 are particularly vulnerable as are infants and young children. Given that dehydration is both preventable and reversible, the need for an easy-to-perform method for the detection of water imbalance is of the utmost clinical importance. The HM is based on an experimental fact that ultrasound velocity in muscle is a linear function of water content and can be referenced to the hydration status of the body. Studies on the validity of HM for the assessment of whole-body hydration status were conducted in the Appalachian State University, USA, on healthy young adults and on elderly subjects residing at an assisted living facility. The HM was able to track changes in total body water during periods of acute dehydration and rehydration in athletes and day-to-day and diurnal variability of hydration in elderly. Results of human studies indicate that HM has a potential to become an efficient tool for detecting abnormal changes in the body hydration status.

Keywords

body hydration; hydration monitor; ultrasound velocity

1. INTRODUCTION

1.1. History

There are numerous therapeutic and diagnostic medical applications of ultrasound but it has never been used for monitoring body water content. The proposed method of ultrasonic assessment of body hydration status is based on the experimental fact that ultrasound velocity through soft tissue is a linear function of the tissue water content [1–4]. Because muscle provides the largest body reservoir for water, the assessment of water imbalance may be conducted by measuring ultrasound velocity in muscle. In the course of dehydration, the body system protectively shunts blood towards the most vital organs (brain, liver, kidney and heart) and away from peripheral organs such as the intestines, muscles and skin [5]. Hence, the earliest sign of dehydration may be seen in muscle, the target of ultrasonic hydration assessment. The feasibility of ultrasonic monitoring of body water balance was confirmed

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by two pilot studies involving adult patients with lower limb edema [6] and in a study on the changes in the hydration status of athletes during acute dehydration and rehydration [7]. The study with edema patients undergoing dialysis showed a 5 m/s increase in ultrasound velocity with a 5% decrease in body mass. The study on athletes, demonstrated that ultrasound velocity through human muscle tissue can determine changes in acute dehydration and rehydration status in male collegiate wrestlers. Promising results of these studies became the basis and motivation to further explore the ultrasonic technology for assessment of the body hydration status which may potentially have a significant long-term impact on the morbidity and mortality of at high-risk population, especially newborns, elderly, and athletes.

1.2. Significance

Dehydration is a critical public health problem [8–10]. Many elderly over age of 65 are particularly vulnerable as are infants and young children. It is estimated that dehydration accounts for 10% of hospital admissions in those over the age of 65 [8, 11, 12]. Furthermore, this diagnosis has been associated with a mortality of up to 50% and recognition that identification and management of hydration status in the elderly is challenging [13–15]. Unfortunately, the reliability and validity of current hydration assessment methods and criteria such as thirst, skin turgor, blood pressure, pulse, urine specific gravity, and bioimpedance are limited; the methods are also inaccurate or expensive [16, 17]. Given that dehydration is both preventable and reversible, the need for an easy-to-perform method for the detection of water imbalance is of the utmost clinical importance.

The dehydration of newborns is a significant clinical problem; it is a leading cause of infant morbidity and mortality worldwide. In the United States, infantile dehydration accounts for 10% of children hospital admissions and is a major cause of newborn readmissions after discharge [18]. Physical signs of moderate to severe dehydration in children are evident only at a significant 6 to 10% water loss. A neonate's hydration status is a critical piece of information that guides a baby's health assessment and management [19].

Early detection of water imbalance can inform physicians of underlying diseases such as diabetes, heart failure or kidney dysfunction so they can prevent the resulting physiological complications. The opposing treatment strategies for dehydration vs. water intoxication make it especially important that any water imbalance is identified early and correctly.

A special area of interest is sports medicine, where monitoring dehydration that may result in injuries like fatigue, cramps, and heat stroke is of urgent importance during high endurance loads in hot and humid conditions. Another reason for hydration tests in sportsmen is to ensure a well-hydrated state prior to weight certification. In almost any sport, athletes undergoing dehydration may suffer a loss of performance [20, 21] and experience flushing, low endurance, rapid heart rates, elevated body temperatures, and rapid onset of fatigue.

Another special area of interest is in military application, in monitoring soldiers total body hydration during deployment and training, long-term endurance exercise or performance in hot conditions. Soldiers may commonly dehydrate (by 2 to 5% of body weight) due to high

rates of water loss from environmental exposure and performing stressful physical work [22, 23]. Dehydration by modest amounts (2% of bodyweight) will decrease cognitive and physical work capabilities, and larger water deficits can have devastating effects on performance and soldier health. Likewise, over-hydration can cause serious health problems (hyponatremia) and many of its symptoms mimic dehydration.

1.3. Methods for Hydration Status Assessment

The currently available methods and tools to assess hydration status are not well suited for quantitative measurements of body hydration changes for field use (rapid, technically simple, and not easily confounded). Advanced laboratory techniques for hydration assessment are impractical to use in the daily monitoring of hydration status because of the need for blood or urine samples, time consuming analysis and the need to use large equipment. The test results of devices for bioelectrical impedance and conductance measurement, which are the most frequently used for water balance assessment, have significant dependence on the anthropometric features of the subject and on electrolyte balance. A study comparing bioelectrical impedance data with clinical judgment of hydration status in 103 acute geriatric hospital inpatients demonstrated that there is little concordance between the clinical and the bioelectrical evaluation of the hydration status [24]. Concordance between the results of clinical judgment and bioelectrical impedance measurements was only 43.7%.

The aims of this study were to further advance the technology of body hydration assessment based on measurement of ultrasound velocity in muscle, build a compact hand-held self-contained device, and test it in benchtop and in vivo human studies.

2. ULTRASONIC HYDRATION MONITOR

The general concept of the ultrasonic hydration monitor (HM) developed in this study and the measurement method are illustrated in Fig. 1. In a stand-alone mode HM can keep in the memory up to 100 measurements for up to 50 subjects. Collected data on ultrasound velocity have a timestamp from the internal real time clock. Connecting the HM to PC provides an automatic update of internal clock time and uploading collected data to PC. As shown in Fig. 1, the preferred area for measurement is calf, the soleus muscle area. Measurement location should be chosen such as to avoid a bone in the path of ultrasonic beam.

The HM block diagram is shown in Fig. 2. The device consists of a controller mounted in the handle along with interchangeable and detachable probes. It works under a Central processing unit (CPU) that controls all aspects of device functionality (sending burst pulse, selecting arrival time point, measuring pulse time-of-flight, calculating ultrasound velocity, displaying and storing measurement results with a timestamp, and providing communication with PC and power supply).

The HM includes a set of 4 ultrasonic probes with a range of acoustic bases: 60, 80, 100, and 120 mm. A probe with the optimal measurement base should be selected for each subject to ensure airtight and comfortable contact with the skin surface in both application points of the probe. The HM probes are shown in Fig. 3a miniature electronic board is mounted inside

each probe. The embedded EEPROM chip employs “plug and play” technology: the probes can be interchanged without any additional need to reconfigure or recalibrate the device. The probe technical information (its identification and calibration) are stored in the memory and allows the HM controller to identify the probe and be ready for measurement right after the device is assembled.

The probe’s electronic board provides triggered generation of an excitation pulse. The ultrasonic transducers are placed at the opposite tips of C-shaped probe. Ultrasound is emitted as a 3 MHz tone burst modulated by a skew Gaussian envelope, so the pulse width was close to 2 μ s. The probe’s frame shape was designed taking in account the following two requirements. First, the stability of the acoustic base should vary no more than about 0.01% under the level of mechanical stresses that might occur in the examination processor due to temperature variations or mechanical load applied. Second, the travel time of ultrasonic pulse through the probe frame should differ that for the acoustic pulse through the tissue to exclude the interference of the received signals. The error for the velocity measurements due to these factors does not exceed 1 m/s.

The HM handle/controller is shown in Fig. 4. The controller communicates with the probes’ board to emit and receive ultrasonic signals and to recognize the connected probe and choose the operating parameters needed to work with this particular probe. The controller allows for communication between the HM, an external PC, and with the battery charger. The Li-polymer rechargeable battery installed in the controller provides at least 5 hours of continuous work. The multi-functional button (see Fig. 4a) allows screen selection by pressing the control button up or down, or side to side.

3. HM BENCH TESTING

The average dehydration induced body water weight loss is about 2%. Above that level the subject may feel vague discomfort and oppression, along with slight decreases in cognitive and physical work capabilities [22, 23]. Consequently, the sensitivity of the hydration monitor should be better than the clinically relevant level of dehydration of 2%. Available data on the variations of ultrasound velocity in the human calf indicate that 2% percent of total body water loss results in a velocity increase in the range 2–3 m/s [7, 24]. Accordingly, in testing the HM device, the acceptable level of ultrasound velocity measurement error in the muscle was set as 1 m/s.

3.1. Calibration

Aqueous solutions of NaCl with concentrations in the range 0–160 g/L which provide ultrasound velocity in the range 1480–1630 m/s [25] were used for HM calibration. Fig. 5 shows an example of the experimental calibration curve of HM. The calibration function is linear with a slope of 7.7 CPU units per 1 m/s. Therefore, the device can provide resolution better than 0.2 m/s (corresponding to CPU resolution). Ultrasound velocity V is calculated using the formula $V = L/(\bar{T} - t)$, where L and t are calibration coefficients related to the ultrasonic pulse travel distance and the device time constant; and $\bar{T}$ is the mean value of the ultrasound pulse time-of-flight which is measured by CPU with accuracy 6 ns and is sufficient for achieving the accuracy better than 1 m/s.

3.2. Testing on Tissue Mimicking Phantoms

For the performance bench testing, several sets of gelatin based tissue-mimicking phantoms were manufactured. The phantoms in the form of rectangular blocks with dimensions $50 \times 30 \times 105$ mm were prepared from 10% gelatin aqueous gel with addition, when necessary, NaCl to adjust the ultrasound velocity, that was kept approximately 1500 m/s. To investigate the influence of ultrasound attenuation in the sample on the accuracy of HM a set of phantoms with different concentration of the aluminum oxide powder was prepared. The range of concentrations from 0 to 0.01% changing the attenuation coefficient from 0.25 to 1.6 dB/(cm MHz) was used, fully covering the range typical for muscle (typically 1.0 dB/(cm MHz) and below).

A Standard Gage repeatability and reproducibility (R and R) study was conducted [26]. The data of tests were analyzed with analysis of variance (ANOVA) single factor analysis. The test of the influence of the attenuation coefficient on the device performance and the reproducibility of the velocity measurement showed that the influence is negligible. Other tests included the reproducibility of measurements evaluated by 20 velocity measurements for each phantom, inter-operator variability test conducted with 5 operators each making 25 measurements, and device-to device reproducibility conducted with 3 prototypes of HM. The analysis of R and R data made using ANOVA-based spreadsheet [27]. The standard deviation of the measuring system did not exceed 0.6 m/s. Thus HM measurement performance met the initially set requirement of the reproducibility of measurements of the order of 1 m/s.

3.3. Safety

Diagnostic ultrasound devices must have spatial peak temporal average intensity $I_{spta} < 0.72$ W/cm², spatial peak pulse average intensity $I_{sppa} < 190$ W/cm² and mechanical index $MI < 1.9$ [28]. These characteristics for HM are $I_{spta} < 60$ μ W/cm², $I_{sppa} < 60$ mW/cm² and $MI < 0.03$, which are orders of magnitude below the acceptable level.

4. HUMAN STUDIES

Human studies on the validity of HM for the assessment of whole-body hydration status were conducted in the Appalachian State University on healthy young adults and on elderly subjects residing at an assisted living facility. Description of the study details is presented in [24]. The goal of the study on athletes was to test the ability of HM to track changes in total body water during periods of acute dehydration and rehydration and day-to-day and diurnal variability of hydration in elderly. The goal of the study on elderly in assisted living facility was to determine normal daily variation of the individual hydration level.

4.1. Adjusting in vivo Measurements Protocol

Having in mind complex anatomy of the extremity and presence of several groups of muscle in the calf, it is important to provide more specific recommendation on the HM measurement point because of a possible variations of ultrasound velocity from point to point. For this purpose the profile of ultrasound velocity was measured on several subjects. Two examples of such profiles are shown in Fig. 6. The profiles are bell-shaped and there is

a flat zone corresponding to 55–65% of the distance from bottom to the knee, H. This zone is considered optimal for the HM measurement in terms of minimal ultrasound velocity variations. In human studies, the measurement sites were determined using a standard body measurement tape and then marked with a surgical skin marker. Marks were made to ensure the probe was placed on the limb in as close to the same orientation as possible at every time point. The marks were made after a test measurement was taken to ensure that there was proper reproducibility of repeated measurements. It was shown that for reliable acoustical contact it was sufficient to simply dip the tips of the probe in water before the measurement.

4.2. Study on Young Adults

The purpose of this study was to determine if ultrasound velocity could detect changes in total body water (TBW) amongst male and female athletes after undergoing an acute dehydration and two hour rehydration protocol. Fifty-six NCAA Division one male wrestlers and 26 female soccer athletes served as subjects for this study. TBW was assessed using body mass, plasma osmolality, urine specific gravity, and urine osmolality. The experiment followed a repeated measures design with all subjects serving as their controls. After completing baseline measurements participants were assigned a mass loss goal of 3% of male body mass (BM) and 2% of female BM. The participants then underwent a supervised exercise regimen to induce the prescribed mass loss. Upon exercise completion, subjects followed the same measurement order as baseline.

After completing the rehydration protocol, the ultrasound velocity, plasma osmolality, urine specific gravity, and urine osmolality measurements were completed at 60 and 120 min after fluid consumption commenced. Dependent variables were analyzed using a one-way repeated-measures analysis of variance (ANOVA). Figures 7–8 adapted provide some representative results of the study on athletes. Data shown in Fig. 7 indicate that assessment of changes in the body water balance by measurement of ultrasound velocity in muscle, which takes just a few seconds, is comparable and possibly superior to that by advanced laboratory techniques, such as plasma osmolality, which are time consuming, need blood or urine samples, and need to use large equipment. Ultrasound velocity change was over 2 m/s per clinically relevant level of dehydration of 2%. High correlation of data on changes of ultrasound velocity in muscle and body mass changes during acute dehydration and rehydration in athletes illustrated in Fig. 8 is encouraging and supports the possibility of monitoring of body hydration status using ultrasonic measurements.

4.3. Study on Elderly

The main objective of the study was to determine normal daily variation of the individual hydration level in longitudinal study on elderly in assisted living facility and assess a range of variation of individual hydration baselines for elderly in a normal physiologically hydrated state. Twenty elderly subjects above 65 years of age residing at an assisted living facility were enrolled in the study. Measurements were performed by a trained operator on subjects sitting in resting position by applying the HM to their calf muscle. Measurements were scheduled 3 times per day and also 3 consecutive days to look at within and between day variability of the measurements. The ultrasound velocity was compared with TBW, an indirect measure of hydration estimated from bioelectrical impedance (IMP) analysis. The

data obtained in this study showed a strong correlation between the average change of ultrasound velocity, IMP and TBW (estimated from IMP analysis) in diurnal variability (morning—afternoon—evening). Correlation coefficient for ultrasound velocity in diurnal variability with IMP was 0.85 and with TBW was 0.84. Correlation coefficients for ultrasound velocity in day after day variability with IMP was 0.91 and with TBW was 0.98. Results of this study demonstrate that the ultrasonic HM technology might be a potentially efficient tool for detecting abnormal changes in the body hydration status of at-risk elderly and might have a significant long-term impact on the morbidity and mortality of this high-risk population.

5. DISCUSSION

Results of this study demonstrate that ultrasound velocity in muscle is a potential noninvasive marker of whole-body hydration. The increase in ultrasound velocity in a dehydrated state found in the present study is consistent with that of the previous investigation of changes of ultrasound velocity in human muscle in chronic renal patients before and after hemodialysis [6]. The ultrasound velocity in soleus muscle after hemodialysis with corresponding weight loss 3.8 kg or 5% of body mass was increased by 5 m/s. This value is close to that obtained in the current study: about 1.1 m/s in average per 1% of body dehydration. Independent of the method used to induce dehydration (i.e., hemodialysis or acute hypertonic dehydration) similar increase in ultrasound velocity in muscle is observed.

Main deficiency of the hydration status assessment using through-transmission ultrasonic method, which is implemented in the HM, is great individual variability of ultrasonic data. The ultrasound velocity measurement data is highly dependent on the individual anthropometric features of the subject. It also depends on positioning of the probe: variation in the acoustic path results in significant changes in the measured velocity values. This means that measured absolute values of ultrasound velocity may hardly serve as a quantitative characteristic of the body hydration status. Only longitudinal studies, that is assessing the changes of measured ultrasound velocity in time for the same subject and at the same body location, may produce reliable and meaningful results. Therefore an accurate and reproducible positioning of the probe is a precondition for assessing changes in hydration status in time. Not accurately standardized position of the leg or arm and variations in the pressure exerted by the probe on the tested site may also affect the results. Other factors, which might affect the accuracy of the method, include the temperature dependence of ultrasound velocity in muscle. In a study by Kenny et al. [29], it was determined that intramuscular temperatures of the *vastus lateralis* stayed elevated from resting conditions for up to an hour post exercise on the order of 0.92, 1.05, and 1.77°C with progressively decreasing depth from the femur. Therefore, it is possible that changes in intramuscular temperature could have caused a false increase or decrease of ultrasound velocity at the level of $\pm(1.0 \dots 1.5)$ m/s in some individuals. However this level of error resulting from the variations of temperature in muscle is within the range of normal physiological variation of body hydration, which is 2% of TBW and corresponds to about 2.2 m/s of ultrasound velocity change.

Main factor contributing to individual variability of ultrasound velocity in the through-transmission mode of measurement is related to the differences in regional muscle and adipose tissue distribution. Ultrasound velocity in adipose tissue, ranging from 1400–1450 m/s, is much lower than in muscle, which is typically in the range of 1550–1600 m/s [30]. Therefore even slight differences in the amount of adipose tissue along the acoustic path may significantly affect the measurement result. To make ultrasonic method capable of assessment of absolute value of total body water it is necessary to exclude the contribution of the surrounding tissues into the measured velocity. It is impossible to achieve in the through-transmission method but there are other modes of acoustic measurements to get ultrasound velocity in a small volume within the muscle, eliminating the contributions of surrounding structures. There are numerous devices developed for remote monitoring of the change of temperature in tissues during thermotherapy by measuring local ultrasound velocity [31–35]. In the physiological range of temperatures (35–40°C), the velocity/temperature slope is about 1 m/s per 1°C. Ultrasonic methods developed for remote monitoring of temperature have sensitivity better than 1 m/s for local ultrasound velocity in muscle, which is sufficient for assessment of total body water content changes better than 1%. Such devices may become the basis of further development of ultrasonic methods of monitoring whole body hydration status.

6. CONCLUSIONS

The HM, a compact handheld ultrasonic device for monitoring the hydration status of human body has been developed. Benchtop tests on tissue mimicking phantoms have shown that HM may provide measuring error of about ± 1 m/s. The HM was able to track changes in total body water during periods of acute dehydration and rehydration in the soleus muscle of athletes, as well in daily changes of hydration status of elderly people. Due to individual anatomical peculiarities of the internal structures of the calf, the absolute value of ultrasound velocity shows substantial variation, therefore only the change of ultrasound velocity can characterize variations of the individual hydration status. Obtained data are encouraging and confirm that ultrasound velocity in muscle may be an effective means of assessing changes in TBW throughout the day and between days. This may mean that the current technology could be used to detect when an individual starts becoming dehydrated and needs to take in fluids to prevent further water loss.

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Fig. 1.
General concept of HM: (a) general view of HM; (b) a diagram illustrating the method of measurement; (c) HM in use.

Fig. 2.
HM block diagram.

Fig. 3.
The HM smart probes.

Fig. 4.
HM Controller: (a) front view; (b) connectors compartment view.

Fig. 5.
HM calibration curve.

Fig. 6.

Typical ultrasound velocity profile along the calf of two subjects greatly differing in height and weight. Optimal measurement zone is marked gray.

Fig. 7. The changes of ultrasound velocity and plasma osmolality throughout the trial in male athletes (a) and female athletes (b).

Fig. 8.

The changes of ultrasound velocity in calf (circle) and body mass (square) of male and female athletes throughout the trial show high correlation.