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Effects of Heat Exposure on Body Water Assessed using Single-Frequency Bioelectrical Impedance Analysis and Bioimpedance Spectroscopy

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ABSTRACT

International Journal of Exercise Science 10(7): 1085-1093, 2017. The purpose of this study was to determine if heat exposure alters the measures of total body water (TBW), extracellular water (ECW), and intracellular water (ICW) in both single-frequency bioelectrical impedance analysis (BIA) and bioimpedance spectroscopy (BIS). Additionally, we sought to determine if any differences exist between the BIA and BIS techniques before and after brief exposure to heat. Body water was evaluated for twenty men (age=24±4 years) in a thermoneutral environment (22°C) before (PRE) and immediately after (POST) 15 min of passive heating (35°C) in an environmental chamber. The mean difference and 95% limits of agreement at PRE demonstrated that BIS yielded significantly higher body water values than BIA (all $p<0.05$; TBW=1.8kg; ECW=0.6±1.3kg; ICW=1.2±3.7kg). However, the effect size (ES) of the mean differences at PRE were small and the r-values were high ($r\geq0.97$). TBW and ICW remained significantly higher at POST for BIS (both $p<0.05$; 1.4±3.2kg and 1.1±3.7kg, respectively) whereas ECW was not different ($p>0.05$; 0.2±1.5kg). Additionally, the ES of the mean differences at POST were trivial to small and the r-values were high ($r\geq0.96$). When analyzing the changes in body water before and after heat exposure, POST values for BIS were significantly higher than PRE (all $p<0.001$; TBW=0.6±0.8kg; ECW=0.4±0.3kg; ICW=0.3±0.6kg). Similarly, POST values for BIA were significantly higher than PRE (all $p<0.001$; TBW=1.0±0.6kg; ECW=0.7±0.4kg; ICW=0.4±0.4kg). BIA and BIS provide similar body water estimates. However, the increase in POST body water values indicate more research is needed before either method can be used for estimating body water after heat exposure.

KEY WORDS: Bioimpedance analysis, body composition, hydration, total body water, extracellular water, intracellular water

INTRODUCTION

The assessment of body water through single-frequency bioelectrical impedance analysis (BIA) and bioimpedance spectroscopy (BIS) is a common practice in field settings due to their portability and simplicity of administration. Both BIA and BIS provide estimates of total body water (TBW), extracellular water (ECW), and intracellular water (ICW) in order to quantify body composition (17, 21). The principles of predicting body composition via bioelectrical impedance devices are similar (19). For instance, most single-frequency BIA devices pass a 50 kHz current through the body to calculate impedance (i.e., resistance and reactance). After obtaining impedance values, built-in regression equations predict various body composition compartments. However, the BIS method is considered to be superior to single and multi-frequency BIA methods since the calculation of fluid volumes is not based on equations, but on Cole modeling (9) and mixture theories (13).

The evaluation of body water provides practical and important information to the health fitness professional. For example, it is important for strength and conditioning specialists and athletic trainers to determine adequate hydration of athletes due to its importance for thermoregulation. Therefore, assessing body water becomes a useful tool for physically active individuals that are exposed to hot environments during physical activities. However, a proper understanding of the influence of environmental factors on impedance measures is essential for accurate analysis. For example, athletes who train in hot conditions experience regular shifts in hydration status before and after competitive events.

Importantly, high and low ambient temperatures have been shown to impact bioelectrical impedance devices (3, 4, 12, 16), in that higher ambient temperatures result in lower resistance values and a higher calculated TBW (3, 12). For example, Buono et al. (3) reported that impedance values (i.e., resistance) for single-frequency BIA decreased as ambient temperature temperatures (i.e., 15 °C, 20 °C, 25 °C, 30 °C, and 35 °C) increased. Thus, impedance values were highest in an ambient temperature of 15 °C and lowest in 35 °C, which would indicate higher body water estimates in the latter condition. The negative correlation between ambient temperature and impedance is likely due to the process of thermoregulation, which is highly dependent on an acute hydration status response when exposed to heat (5).

Recent advances in bioelectrical impedance technology have led to recommendations that single-frequency BIA can be used in varying climates (e.g., desert, arctic, high altitude, etc.) without concern of degrading accuracy and reliability. However, empirical evidence to substantiate this claim does not currently exist. To this point, the evaluation of BIA and BIS sensitivity to previous heat exposure is not fully understood. Previous research has measured impedance (i.e., resistance) and body water values in extreme ambient temperatures (e.g. 15 and 35°C), which is not traditionally recommended by bioelectrical impedance manufactures since wide variances in ambient temperature have been shown to introduce measurement error.

During field applications of BIA or BIS, it is very likely that participants unknowingly expose themselves to varying ambient temperatures (e.g. differences between outside ambient temperature vs. testing center ambient temperature) prior to testing. Therefore, the understanding of BIA and BIS sensitivity to heat exposure occurring prior to testing in a thermoneutral environment becomes important for accurate measures. Lastly, all research thus far has focused solely on single- and multi-frequency BIA and no information is available on more advanced bioelectrical impedance methods (i.e., BIS). Subsequently, it is unknown whether BIS is affected in a similar manner as single-frequency BIA after a brief heat exposure. Therefore, the purpose of this study was to determine if heat exposure alters the measure of TBW, ECW, and ICW in both BIA and BIS. Additionally, we sought to determine if any differences exists between the BIA and BIS techniques before and after an exposure to heat. Since higher frequencies (i.e., 500 kHz) have been shown to be less influenced than lower frequencies (i.e., 50 kHz) when skin temperature is increased (12), it was hypothesized that BIS would result in smaller directional body water changes than BIA after exposure to heat.

METHODS

Participants

Twenty college-aged adult males (age = 24 ± 4 years, height = 175.0 ± 6.0 cm, weight = 79.0 ± 10.6 kg) participated in this study. Body fat percentage and fat-free mass of participants were 22.6 ± 3.8% and 61.5 ± 8.3 kg, respectively for BIA and 17.9 ±5.5% and 64.9 ± 9.9 kg for BIS. Recruitment occurred through word of mouth. In order to be eligible for participation, participants were instructed to avoid caffeinated drinks and exercise 12 h prior to testing. Furthermore, participants were asked to abstain from eating and drinking, except water, 3 h prior to testing and had to be free from cardiovascular, pulmonary, or metabolic diseases. Prior to any collection of data, participants completed a health-history questionnaire and provided written informed consent as approved by the host university Institutional Review Board. According to an a priori analysis, the sample size of the current study was sufficient based on a power of 0.8, alpha level of significance of 0.05, and an effect size of 0.3 (12).

Protocol

Following the informed consent each participant's urine specific gravity (USG) was measured using a hand-held refractometer (Atago SUR-NE, Atago Corp Ltd., Tokyo, Japan) in order to ensure proper hydration. USG values were required to be < 1.020 in order to be considered adequately hydrated (6, 15). The USG values (mean ± SD) for participants were 1.012 ± 0.006. Following USG testing, participants were not allowed to drink fluids for the duration of BIA and BIS testing. After ensuring hydration, participants had nude body mass measured with a digital weighing scale (Tanita BWB-800, Tanita Corporation, Tokyo, Japan). Next participants were asked to dress in shorts and a t-shirt and had height measured with a stadiometer (SECA 213, Seca Ltd., Hamburg, Germany). Following height and weight measurements, participants had BIA (Quantum IV, RJL systems, Clinton MI) and BIS (Imp™ SFB7, ImpediMed Limited, Queensland, Australia) measurements taken in a thermoneutral environment (22°C, 40% Relative Humidity) before (i.e., PRE) the acute exposure to passive heating.

During BIA and BIS measurements, participants were required to lie supine on a gurney, face up with arms at their sides and legs spread, not in contact with any other part of the body. BIA and BIS measurements were taken on the right side of the body in a randomized counter balanced order after participants rested for a minimum of 5 min. The right hand and foot were wiped with an alcohol pad to reduce skin oils and impedance of signal. Once each surface dried, eclectrodes were placed at the distal ends of each participant's hand and foot following the manufacturer's guidelines. For BIA, one electrode was placed on the right wrist beside the ulnar head and another on the first joint of the middle finger. A third electrode was placed on the right foot beside the medial malleolus and the fourth electrode was placed on the base of the second toe. For BIS, two single tab electrodes (provided by manufacturer and different than BIA) were placed at the distal end of the participant's right wrist and hand and right ankle and foot, with 5 cm between each respective set of electrodes. After proper electrode placement, BIA and BIS were measured at PRE in order to estimate TBW, ECW, and ICW. Body water for BIA was estimated with the Chumlea et al. (7) equation, which is built-in to the device used in the current study.

Following the PRE BIA and BIS measurements, participants entered an environmental chamber (35°C, 40% relative humidity) and sat quietly for 15 min. After the acute exposure to passive heating, participants immediately exited the environmental chamber back into the thermoneutral environment and provided a second nude body mass measurement to determine if changes in body mass occurred (i.e., sweat losses). Next, participants dressed back into their athletic attire and laid supine on a gurney. Once properly situated on the gurney, electrode placement sites were wiped dry and cleaned with alcohol for a POST heat exposure measurement (i.e., TBW, ECW, and ICW). All POST BIA and BIS measurements were conducted approximately 5 min after exiting the environmental chamber. The routine of immediately exiting the chamber, drying off sweat, measuring nude body mass, etc. was similar for all tests in order to minimize the variance in the amount of time participants were in the chamber and the time they were waiting to be measured at POST.

Statistical Analysis

Data for all participants were analyzed by SPSS Statistics version 22.0 (Chicago, IL). A paired-samples T-test was used to test the mean difference of TBW, ECW, and ICW between BIA and BIS at each time point (e.g. TBW BIA PRE – TBW BIS PRE; TBW BIA POST – TBW BIS POST). The significance of the changes in body water for each device from PRE to POST was also determined with paired-samples T-test (e.g. TBW BIS POST – TBW BIS PRE). The effect size of the mean difference of TBW, ECW, and ICW was determined according to Cohen's *d*. Hopkin's scale was utilized for determining the magnitude of the effect size (ES): 0-0.2 = trivial, 0.2-0.6 = small, 0.6-1.2 = moderate, 1.2-2.0 = large, >2.0 = very large (14). Regression procedures were used to determine the Pearson product moment correlation coefficients (*r*) and intraclass correlation coefficient (ICC). The 95% limits of agreement were determined according to the Bland-Altman method for PRE and POST TBW, ECW, and ICW measurements (1). Significance for all comparisons was set at an alpha level of ≤ 0.05.

RESULTS

PRE Comparisons: The comparison of BIA and BIS at PRE for body water values (kg) is shown in Table 1. All BIA body water values were significantly lower than BIS at PRE ($p < 0.05$). The ES of the differences at PRE were small and the correlation coefficients were near perfect. The 95% limits of agreement for TBW, ECW, and ICW were ±3.3, 1.3, and 3.7 kg, respectively.

Table 1. Comparison of BIS and BIA body water values (kg) at PRE (n = 20).

							95% Limits of Agreement	
	Method	(Mean ± SD)	p	Cohen's d	r	CE ± 1.96 SD	Upper	Lower
TBW	BIS	47.6±7.4	---	---	---	---	---	---
	BIA	45.8±6.4	<0.001	0.26	0.98	-1.8±3.3	1.5	-5.1
ECW	BIS	19.5±2.7	---	---	---	---	---	---
	BIA	18.9±3.2	<0.05	0.20	0.99	-0.6±1.3	0.7	-1.9
ICW	BIS	28.1±4.8	---	---	---	---	---	---
	BIA	26.9±3.2	<0.05	0.29	0.97	-1.2±3.7	2.5	-4.9

BIS = bioimpedance spectroscopy; BIA = bioelectrical impedance analysis, TBW = total body water; ECW = extracellular water; ICW = extracellular water; PRE = body water before passive heating; SD = standard deviation; CE = Constant error; Upper = upper- and Lower = lower- boundary for 95% confidence interval.

POST Comparisons: The comparison of BIA and BIS at POST for body water values (kg) is shown in Table 2. BIA yielded significantly lower TBW and ICW values than BIS ($p < 0.05$). However, there was no difference between methods for ECW ($p = 0.120$). The ESs of the differences at POST was trivial for ECW and small for TBW and ICW and the correlation coefficients remained near perfect. The 95% limits of agreement for TBW, ECW, and ICW were ±3.2, 1.5, and 3.7 kg, respectively.

Table 2. Comparison of BIS and BIA body water values (kg) at POST (n = 20).

							95% Limits of Agreement	
	Method	(Mean ± SD)	p	Cohen's d	r	CE ± 1.96 SD	Upper	Lower
TBW	BIS	48.2±7.3	---	---	---	---	---	---
	BIA	46.8±6.5	<0.05	0.20	0.98	-1.4±3.2	1.8	-4.6
ECW	BIS	19.8±2.6	---	---	---	---	---	---
	BIA	19.6±3.2	0.12	0.06	0.98	-0.2±1.5	1.3	-1.8
ICW	BIS	28.4±4.8	---	---	---	---	---	---
	BIA	27.3±3.3	<0.05	0.26	0.96	-1.1±3.7	2.5	-4.8

BIS = bioimpedance spectroscopy; BIA = bioelectrical impedance analysis, TBW = total body water; ECW = extracellular water; ICW = extracellular water; POST = body water after passive heating; SD = standard deviation; CE = Constant error; Upper = upper- and Lower = lower- boundary for 95% confidence interval.

POST – PRE Comparisons: The differences in body water values (kg) for each device, which were determined as POST - PRE (e.g. BIS TBW POST – BIS TBW PRE), are shown in Table 3. All POST body water measurements were significantly higher than PRE for each device (all $p < 0.001$). Body mass at POST was significantly lower than PRE ($p = 0.01$; POST = 79.3 ± 10.3 kg; PRE = 79.4 ± 10.3 kg). The ES of the mean differences for body water and body mass changes were trivial. The intraclass correlation coefficients were near perfect and the 95%

limits of agreement for BIS TBW, ECW, and ICW were ±0.8, 0.3, and 0.6 kg, respectively, and 0.6, 0.4, and 0.4 kg, respectively for BIA.

Table 3. POST – PRE (CE) body water values (kg) for BIS and BIA (n = 20).

								95% Limits of Agreement	
	Method	POST	PRE	p	Cohen's d	ICC	CE ± 1.96 SD	Upper	Lower
TBW	BIS	48.2±7.3	47.6±7.4	<0.001	0.08	0.99	0.6±0.8	1.4	-0.2
	BIA	46.8±6.5	45.8±6.4	<0.001	0.15	0.99	1.0±0.6	1.6	-0.4
ECW	BIS	19.8±2.6	19.5±2.7	<0.001	0.11	0.99	0.4±0.3	0.7	0.1
	BIA	19.6±3.2	18.9±3.2	<0.001	0.21	0.99	0.7±0.4	1.1	0.3
ICW	BIS	28.4±4.8	28.1±4.8	<0.001	0.06	0.99	0.3±0.6	0.9	-0.3
	BIA	27.3±3.3	26.9±3.2	<0.001	0.12	0.99	0.4±0.4	0.8	0.0

BIS = bioimpedance spectroscopy; BIA = bioelectrical impedance analysis, TBW = total body water; ECW = extracellular water; ICW = extracellular water; PRE = body water before passive heating; POST = body water after passive heating; ICC = intraclass correlation coefficient; SD = standard deviation; CE = Constant error; Upper = upper- and Lower = lower- boundary or 95% confidence interval.

DISCUSSION

The purpose of this study was to determine if heat exposure alters the measure of TBW, ECW, and ICW in both BIA and BIS. Additionally, we sought to determine if any differences exists between the BIA and BIS techniques before and after an exposure to heat. The novelty of the current study is the directional changes associated with TBW, ICW, and ECW for both BIA and BIS and that BIS had a lower magnitude of change with an acute exposure to heat. Another finding is that the ESs were smaller for POST comparisons than PRE for both devices at each time point. Body water values for BIA were signficanlty lower than BIS at PRE. Therefore, the larger magnitude of change for BIA resulted in better agreement between both devices (e.g., non-significant ECW values) following the exposure to heat. These findings support the proposed hypothesis of the current study, which was that BIS would result in smaller directional body water changes than BIA after exposure to heat. However, results also indicate that the utility of both bioelectrical impedance devices following heat exporsure may result in erroneous body water values.

Previous research has compared single-frequency BIA and BIS to criterion methods such as deuterium oxide (20, 22). However, the direct comparison of BIA and BIS is limited (2, 8, 11). Boos et al. (2) and Donadio et al. (11) each reported that single-frequency BIA has good agreement with multi-frequency BIA when used for estimating body water. Contrarily, Cloetens et al. (8) reported that single-frequency BIA should not be used interchangeably with BIS. However, the study by Cloetens et al. (8) evaluated fat mass, fat-free mass, and body fat percentage and no information was provided on body water. Thus, direct comparisons of single-frequency BIA and BIS for body water have yet to be made before and/or after heat exposure, which is one of the novel findings of the current study.

Previous studies have evaluated the effects of ambient temperature on bioelectrical impedance devices and primarily reported only the changes in impedance values (i.e., resistance and reactance) (3, 10, 12). Uniquely, the current study utilized BIS, which is considered superior in

hydration measurements to single- and multi-frequency BIA devices due to Cole modeling (9) and mixture theories (13, 19). The evaluation of ambient temperatures' impact on BIA devices is well established (3, 4, 12, 16). However, no data is available on previous heat exposure prior to thermoneutral testing. Caton et al. (4) and Gudivaka et al. (12) each reported higher TBW measurements in a hot environment when compared to thermoneutral environment while using a low (i.e., 50 kHz) impedance measurement. Buono et al. (3) investigated the influence of various temperatures (i.e., 15 °C, 20 °C, 25 °C, 30 °C, and 35 °C) on a single-frequency hand-to-foot BIA device and found that impedance measurements and ambient temperature had a negative correlation (e.g. as ambient temperature increased the resistance values decreased). In the study by Gudivaka et al. (12), investigators heated and cooled skin temperature while examining the changes in impedance (i.e., resistance) at various frequencies with a multi-frequency BIA device.

It is outside the scope of the current study to examine the mechanisms that influence bioelectrical impedance measurements following heat exposure. However, a few postulations will be provided. One proposed mechanism for differences in bioelectrical impedance could be due to an increased skin temperature and skin blood flow (3, 4, 12, 16). Caton et al. (4) found that a higher skin temperature resulted in an increased TBW measurement via BIA when compared to a cooler skin temperature while Gudivaka et al. (12) reported that multi-frequency BIA impedance measurements had a negative correlation with skin temperature (i.e., as skin temperature increased the impedance measurements decreased). Similarly, Liang et al. (16) reported that an increase in skin temperature or an increase in skin blood flow provided a lower impedance value measurement. Likewise, Matthie (18) reported that a core temperature change of 1°C could cause a 2% change in resistance and concluded that BIS results should be interpreted with caution when either skin or core temperature is suspected of significant changes from baseline. Thus, the current study is simply confirming these results and comparing BIA and BIS when PRE and POST heat exposure body water measurements are taken in a thermoneutral environment.

Future research should seek to develop a regression formula that can correct for bioelectrical impedance-derived body water values after heat exposure, due to the application this technology brings to the field setting. The development of a regression equation that corrects for body water following passive heating would need to be specific to the device (e.g., BIA and BIS) and device manufacturer. For example, developing algorithms and devices that can accurately capture changes in body water after a bout of exercise that results in dehydration would be helpful in field applications where bioelectrical impedance technology has the most utility. The time period needed for bioelectrical impedance values to return to baseline and capture the changes in body fluid loss following passive heat exposure is also needed. Furthermore, determining whether active heating (i.e., exercise) requires a longer time period than passive heating to detect changes in body water is warranted.

A limitation of the current study could be that core and skin temperature were not measured. However, the assessment of core and skin temperature in a field or clinical setting might not be practical or readily available for practitioners. As a result, it was the intention of the current

study to simply highlight the effect of heat exposure on bioelectrical impedance-derived body water values taken in a thermoneutral environment regardless of mechanisms. Another limitation is that follow-up measurements were not assessed making it difficult to determine when values return to baseline and when practitioners should assess body water after heat exposure. Nonetheless, the current study added to the literature by demonstrating that advances in bioelectrical impedance technology are still needed before these devices can be used following an exposure to heat.

In conclusion, the current study found that single-frequency BIA and BIS provided similar body water values when compared to each other before and after a brief exposure to heat. Importantly, body water measurements for each device at POST were all higher than PRE values despite a small decrease in body mass after the acute exposure to heat. Due to this finding, it is recommended that practitioners avoid using these devices for body water values shortly after an acute period of heat exposure. The minimal amount of time (i.e., 15 min) spent passively heating (i.e., 35°C, 40% relative humidity) in an environmental chamber for the current study was shown to alter body water values examined via the bioelectrical impedance devices. As a result, when evaluating body water via bioelectrical impedance devices, technicians should ask participants about heat exposure experienced on day of testing and consider the results of the current study.

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