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Electrode Placement in Bioimpedance Spectroscopy

Evaluation of alternative positioning of electrodes when measuring relative dehydration in athletes

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Abstract - **In order to maintain a homeostatic environment in human cells, the balance between absorption and separation of water must be retained. Imbalance will have consequences on both the cellular and organ levels. Studies performed on athletes have shown coherence between their hydration status and ability to perform. A dehydration of 2-7% of total body weight resulted in a marked decrease in performance. Measurement and monitoring of hydration status may be used to optimize athlete performance. Therefore, in this current study bioimpedance spectroscopy is used to determine the hydration status of athletes. Trials were made to investigate alternative ways of electrode placement when performing bioimpedance spectroscopy in order to measure relative dehydration. A total of 14 test subjects underwent measurements before, during, and after a cycle test of 3x25min. Electrodes where placed to measure body impedance in three different ways: wrist-ankle (recommended method), wrist-wrist, and transthoracic. Furthermore, the relative loss in weight of the subjects during the trial was registered. The study showed no relation between relative weight loss and the wrist-wrist and transthoracic placement method, using bioimpedance spectroscopy to measure relative dehydration. The inability of the method to detect such relative changes in hydration may be due to the bioimpedance spectroscopy technology being extremely sensitive to changes in skin temperature, movement artifacts, thoroughness in placing the electrodes, and the physiological impact on the human body when performing exercise. Therefore, further research into the area of bioimpedance spectroscopy is needed before this methodology can be applied in monitoring active athletes. Hence, a simple weight measurement still seems a more useful way of determining a relative change of hydration in an active setting.**

Keywords - Bioimpedance Spectroscopy, Dehydration, Electrode placement, Athletes

I. INTRODUCTION

Dehydration in athletes is known to influence their performance [1-3]. Typically, athletes can loose as much as 2-7% of their bodyweight during strenuous exercise or competition, which can result in a marked decrease in performance [4]. Measuring the hydration status of athletes in real time during training and competition may therefore be useful for ensuring adequate fluid intake and thus optimize performance. Quantitative assessment of current hydration status is not trivial, but one possible approach for monitoring body water content is bioimpedance spectroscopy (BIS). Ideally when performing BIS, the subjects should be completely at rest during the measurement and the recommended placement of the electrodes should facilitate hand-to-wrist measurements. However, Kushner et al [5] showed that several mechanisms should be taken into account. In particular, the environment at the electrode placement, such as sweat and temperature, seems to have an impact on BIS recordings. This may pose a particular challenge when applying BIS on exercising individuals with increased skin temperature and sweat secretion [6]. Therefore, investigating how the placement of the electrodes affects the BIS recordings on exercising athletes seems imperative.

A. *Aim of study*

The aim of this study is to describe how alternative locations of the electrodes placed on exercising athletes influences BIS and how the locations correspond to the recommended wrist-ankle placement.

B. *Principles of measuring dehydration with bioimpedance spectroscopy*

Bioimpedance spectroscopy can be used to estimate the total body water in the human body. A change in body fluid volume and compartmental distribution also changes the electrical characteristics of the biological tissue. By inducing a low power current (50 µA - 700 µA) through carefully placed electrodes, a multi-frequency sweep (5 kHz to 1 MHz) is carried out to determine the impedance of the body within this frequency range. The frequency dependence arises from the fact that the lipid cell membrane surrounding the cell acts as a capacitor where the intracellular water (ICW) and the extracellular water (ECW) act purely resistively. Figure 1 illustrates the electrical equivalent expressed by two resistors and one capacitor.

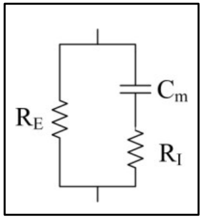

Figure 1 - Parallel 2R-1C model of biological tissue. R_E = extracellular resistance; R_I = intracellular resistance; C_m = the cellular membrane capacitance

At low frequencies, the current will mainly be conducted extracellular due to the isolating property of the membrane (capacitance). Hence, the extrapolated current at 0 Hz will express the resistance (R_0) in the ECW. At higher frequencies, (going towards ∞ Hz) the current will flow through and between the cells, (ICW and ECW combined) as the capacitor (cell membrane) short-circuits. The resistance measured at high frequencies (R_∞) therefore expresses the sum of ICW and ECW and is equal to the total body water (TBW) [7]. Thus, with reference to Figure 1 the impedances are:

$$Z_0 = Z_{RE} \tag{1}$$

$$Z_\infty = Z_{R_E} \| (Z_{C_m} + Z_{R_I}) \tag{2}$$

The two resistive values R_0 and R_∞ cannot be measured in practice and must be estimated by plotting the measured impedances at different frequencies from the frequency sweep in a Wessel diagram. The impedance consists of a real part, the resistance, and an imaginary part, the reactance. Based on the model in Figure 1, the equivalent impedance at DC (f = 0 Hz) is purely resistive and equals R_E. Likewise, at higher frequencies the equivalent resistance approaches R_E parallel to R_I, which is less than R_E. Thus, when plotting the impedance at various frequencies in a Wessel diagram (complex plane), part of a circle will ideally form. The intersections of the circle and the x-axis (real axis ~ resistance) is the R_∞ (with the lowest resistance), and R_0 (with the highest resistance). In theory, there will be no difference in phase at R_0 and R_∞ and thereby a phase angle of 0° [8]. When analyzing recorded data, circle fitting is applied to estimate approximations of R_0 and R_∞, which in turn are used to calculate the extra- and intracellular resistance, R_E and R_I, of the tissue. The previous assumption that $R_0 = R_E$ combined with Figure 1 yields that R_E and R_I simply are:

$$R_E = R_0 \tag{3}$$

$$R_I = R_0 \parallel R_\infty \tag{4}$$

Using this result for R_E and R_I along with the Hanai theory [9], the volume of ICW and ECW can be calculated as:

$$V_{ecw} = \frac{1}{1000} \cdot \left(\frac{{K_B}^2 \cdot \rho_{ecw}^2}{D_B}\right)^{1/3} \cdot \left(\frac{L^2 \cdot \sqrt{W}}{R_E}\right)^{2/3} \tag{5}$$

$$V_{icw} = V_{ecw} \cdot \left(\left(\frac{\rho_{tbw} \cdot (R_E + R_I)}{\rho_{ecw} \cdot R_I}\right)^{2/3} - 1\right) \tag{6}$$

Where K_B is a correction factor for standard anthropometric ratios [10] and ρ_{ecw} is a specific constant expressing the extracellular water resistivity in the body (male=40.5 $\Omega \cdot m$, female=39 $\Omega \cdot m$). D_B represents the body density set to 1.05 $kg \cdot l^{-1}$. L is the height and W the weight of the subject.
The sum of V_{ecw} and V_{icw} is TBW.

II. MATERIALS AND METHODS

A. Participants

In this study, 14 healthy young adults (6 males and 8 females) volunteered to participate after written and oral consent. The study complied with the Helsinki II declaration. The characteristics of the subjects are summarized in Table 1.

	Men *n = 6*		**Women** *n = 8*	
	Mean	**SD**	**Mean**	**SD**
Age (*year*)	23.8	±2.1	22.4	±2.7
Weight (*kg*)	78.7	±3.0	66.2	±10.1
Height (*cm*)	183.5	±4.6	175.0	±7.8

Table 1 - Characteristics of test subjects

B. Bioimpedance spectroscopy measurements

Dehydration was measured using Hydra 4200 (Xitron Technologies, San Diego, CA, USA) along with Xitron recommended single tab electrodes STE-292 (Impedimed, San Diego, CA, USA). The adhesive electrodes were applied to the wrist-ankle (WA) and the whole body measurement feature in the Hydra 4200 was used to estimate TBW (Figure 2) [11].

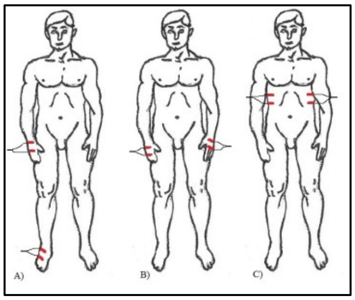

Figure 2 - Applying adhesive electrodes to A) wrist- ankle B) wrist-wrist C) transthoracic

Two alternative electrode placements were wrist-wrist (WW) and transthoracic (TT) (Figure 2).

C. Experimental design/setup

The study was carried out in two experiments, *1)* Enrollment trials and *2)* Dehydration trials. At least one day elapsed between the two trials. Before participating, the test subjects confirmed to their knowledge not to suffer from any type of cardiovascular diseases, having received bioimplants, or being pregnant.

1) Enrollment trials

The participants completed a $\dot{V}_{O_2}$*-max* test using Oxycon Pro (Carefusion, San Diego, CA, USA) through which their physical fitness rating was obtained. In order to make sure they would be able to complete the dehydration trial, the fitness rating of the subjects should be higher than 44 *ml/min·kg*$^{-1}$ for men and 35 *ml/min·kg*$^{-1}$ for women. The trials were made on an exercising bike (Ergorace, Kettler, Ense, Germany) where the load, measured in Watt, manually could be adjusted. When a $\dot{V}_{O_2}$*-max* measurement was performed, it was important that the test subjects reached their exhaustion level within 6-16 min. The 14 test subjects began the trial by warming up for 7 minutes at a load of 105 watts for men and 70 watts for women. The test subjects had to maintain a minimum cadence of 80 rpm for men and 75 rpm for women. After warming up, the load was increased every two minutes by 35 watts. This continued until the test subject fell below the minimum cadence or stopped entirely from exhaustion.

2) Dehydration trial

The test subjects were informed not to eat or drink 60 min prior to this trial. During the trials, the subjects had to keep a minimum activity level of 70% of their $\dot{V}_{O_2}$-*max*. This is equivalent to approx. 80% of the maximum heart rate measured during the enrollment trial [12]. The bioimpedance was measured four times during the trial: one before, two during, and one after. The electrode placement was WA, WW, and TT. The order of electrode placement for each recording was randomized to avoid systematic bias. To ensure consistency the following test protocol was conducted (Table 2).

Estimated time	Experiment progress	BIS-meas. number
10 min	Warm up	
1 min	Weighing	
4 min	Rest	
10 min	BIS-measurement on WA, WW, TT	1
25 min	Active	
1 min	Weighing	
4 min	Rest	
10 min	BIS-measurement on WA, WW, TT	2
25 min	Active	
1 min	Weighing	
4 min	Rest	
10 min	BIS-measurement on WA, WW, TT	3
25 min	Active	
1 min	Weighing	
4 min	Rest	
10 min	BIS-measurement on WA, WW, TT	4

Table 2 - Test protocol for hydration trial, showing time table and action of each module. Note that during the rest period sweat was dried off and the skin was wiped with alcohol where after new electrodes were mounted

D. Data analysis

Initially, the complete analysis depends on whether the recorded impedances form a half circle in a Cole-Cole plot. Therefore, the collected data from the different measurements (WA, WW, and TT) were processed and assessed for their ability to create such an approximated half circle. The multi-frequency sweep generated 50 data points to which the circle fitting was applied. The shortest distances from the points to the approximated circle were all numerically calculated as the root mean square (RMS) value normalized by the radius. These values were calculated for the methods WA, WW, and TT. WW and TT were then compared to WA, being the standardized reference. As a control parameter, the weight of the test subject was recorded before measuring the BIS..The loss in weight during the relatively short period of exercise indicates the amount of fluid loss and thereby the relative hydration status of the subject.

III. RESULTS

The results from the enrollment trials are summarized in Table 3.

	Men		**Women**	
	Mean	**SD**	**Mean**	**SD**
Fitness rating (*ml/min · kg^{-1}*)	54.8	±4.3	49.3	±8.3
Maximum heart rate (*bpm*)	193.5	±4.5	191.5	±4.1

Table 3- Enrollment trail summary

From the dehydration trial Figure 3 shows a typical Cole-Cole plot where the best approximated circle is fitted to the data for a test subject measured at WA.

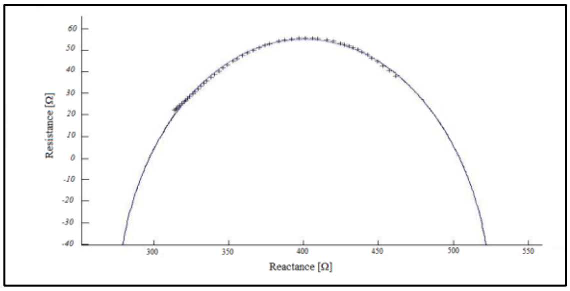

Figure 3 - Cole-Cole plot showing approximated half circle

A. Approximated half circle

Table 4 shows the mean value from all 14 test subjects showing the ability to form a half circle for each electrode placement. Data shows a tendency for WA and WW to form half circles equally well whereas TT is less able to do so.

WA		**WW**		**TT**	
Mean	SD	Mean	SD	Mean	SD
0.0085	±0.003	0.0098	±0.011	0.026	±0.023

Table 4 - Normalized RMS-values for the ability to form a half circle

B. TBW and Weight

The data in Table 5 show that there is a general increase in TBW for WA and WW from the first to the second BIS-measurement. The WW recording increases further from the second to the third measurement. However, overall there is a decrease in both WA and WW from the third to the fourth measurement. TT displays a decrease in TBW from the first to the second measurement and an increase in the last measurement. The weight shows a decrease for each time a measurement is taken.

BIS-mes.	**TBW_WA**		**TBW_WW**		**TBW_TT**		**Weight**	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
1	42.1	±9.3	43.6	±10.9	509.4	±155.7	71.6	±9.0
2	43.3	±9.5	44.6	±11.2	494.7	±147.3	71.2	±8.9
3	43.0	±9.6	45.4	±11.9	500.9	±149.0	70.8	±8.8
4	42.4	±9.4	45.2	±12.0	537.4	±105.2	70.3	±8.7

Table 5 - Average TBW (liters) and their average weight (kg) for all subjects, in different electrode locations

IV. DISCUSSION

This study investigated the ability of applying BIS in order to assess the hydration status of active athletes with various electrode placements. The setup for doing so varied from the prescribed protocols since the individuals were not at rest but rather active. Even though a resting period was included during the dehydration exercise protocol, it was observed that the participants still produced sweat prior to and during the different BIS-measurements. This caused the gel on the electrodes to dissolve and created a reduction in contact between the skin and the electrode. This may be one of the reasons for the diverging results, where a gradual decrease in TBW during the experiments would be expected (as a surrogate for dehydration). However, comparing the results from the WA method to the Cole-Cole plot theory, an increase in TBW at the first interval was found, whereas a reduction was observed for the remaining two [13]. Besides problems with electrode adhesion, this behavior could also be due to the variation of skin temperature at the first interval, affecting the BIS-measurement [6]. In future studies infrared cameras could be used to acquire the whole body temperature.

When comparing the TBW from the WA method to the weight loss, a relationship would be expected. However, this was not found. Besides the already mentioned problems, increase in heart rate and muscle temperature from the exercise may also result in a lower impedance of the muscle tissue, which could partly explain why this was not observed [5]. The different electrode placements revealed that the WW method exposed a reduction in impedance at the first and second intervals, whereas the last measurement had an increment. Ideally, this was not expected, but this could have been due to the ability of the hand to reach a steady state temperature resulting in lower impedance. Overall, there was a tendency for the WW method to give an increase in impedance at the last interval in contrast to the WA-method that measured an increase in the last two. Furthermore, the impedance values for the WW method were lower than for WA. Finally, comparing data from the TT to the WA-method, no relationship was observed. Hitherto, there seems to be no consistency or tendency in the BIS-measurements to act according to the theory about dehydration in tissue and the resulting impedance when applying this to active athletes.

V. CONCLUSION

No relationship between the electrode placements WA, WW, and TT was found. The TT method was less able to generate an approximated half circle in a cole-cole plot and was thereby not considered eligible as a method. The WW-method on the other hand showed an equally satisfying ability to create a half circle, but had difficulties in determine the same relative dehydration as WA. However, though these results may be indicative, more trials are needed to completely rule out WW as a hydration measuring method. A simple weight measurement still seems a more useful way of determining a relative change of hydration in an active setting, but is difficult to assess during exercise.

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