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Monitoring change of body fluids during physical exercise using Bioimpedance Spectroscopy

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***Abstract*—During physical exercise body muscles are activated and heat is generated. In intensive physical activity, heat will be released by sweating to protect the body of overheating. Sweating and convection implies a water loss which can lead to dehydration. To avoid health problems as a result of dehydration, the body water content can be monitored to detect changes early in order to rehydrate in time. Bioimpedance Spectroscopy (BIS) is a comfortable measurement method to monitor the body composition under controlled conditions, that is used for different applications, like monitoring dialysis. Unfortunately, the physiological changes due to sportive activities can influence the BIS and complicate the measurement. In this article, a study is presented in which the fluid content of five test persons is monitored during physical exercise, whereas all test persons did not drink anything before and during sport. During training not only the body composition was measured using a BIS device but also the skin temperature was monitored with an infrared camera. As a result, it could be shown that such a combination of measurement systems allow to use BIS devices also during sport as significant monitoring systems for detecting a person's body fluid loss.**

I. Introduction

A balanced body composition is important for a persons' health, life quality and sportive performance. Especially insufficient water content can lead to dehydration with severe consequences, like vertigo, convulsions or cardiovascular problems. Athletes must be particularly careful since they can loose between 2% and 8% of their total body water during one training session [1]. To avoid dehydration not only the body weight should be measured but also other body compartments like extracellular water content (ECW), intracellular water content (ICW), fat mass and fat free mass. Bioimpedance Spectroscopy (BIS) allows monitoring these parameters in a non-invasive, rapid and inexpensive way. Studies have shown that BIS provides good estimation of the water content during changes in hydration status compared with other measurement methods [2, 3]. Unfortunately, precise BIS measurement results require controlled conditions in order to avoid the influence of external factors like temperature, skin perfusion or natural fluid shifts [4, 5]. One of the major influencing factors is temperature, which affects the properties and therefore impedance behavior of tissues. Cornish et. al. [6] investigated the influence of temperature on skin impedance. He showed that the skin resistance and reactance decreases by 35% and 18% within a temperature range of 20°C-40°C. Representing body fluids as electrolyte solution, Grimnes et al. could present an impedance change of +2%/°C [7]. Due to these investigations it can be assumed that also the whole body impedance will be influenced by temperature changes. Jürimäe et al. [8] showed that if physiological effects are uncontrolled and the body composition is measured just before and directly after sport exercises, no difference is visible. In such cases the body composition seemed unchanged. After 30 min of recovery, when the perfusion and skin temperature has normalized, the dehydration could be measured [8]. Within this paper BIS measurements were done not only before and after the sportive training but also during the physical exercise, to monitor the process of dehydration. To control physiological changes, the skin temperature was supervised with an infrared camera. The aim was to measure the stepwise dehydration of the test person under controlled conditions.

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II. Bioimpedance-Spectroscopy

Determination of body composition through BIS is based on the fact, that the electrical characteristics of the human body change according to the relative amount of body fluid and tissues. Different components like blood or muscle have a higher conductivity in comparison to bones or fat [7].

The content of water in human tissue can be divided into intracellular water (ICW) and extracellular water (ECW), which are separated by the cellular membrane. The ECW and ICW are predominantly electrically resistive entities, whereas the cellular membrane, due to its lipid layer, has an isolating (capacitive) behavior. According to that, the

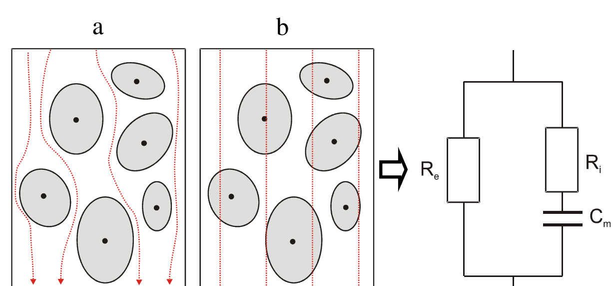

Fig. 1. Low (a) and high frequency (b) current flow through body

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behavior of an injected current will be different for low and high frequencies: low frequency alternating current flows only around the cells trough the ECW, whereas a high frequency current will also pass through the cell membrane and the ICW (see fig.1).
Based on this principle the electrical behavior of body tissue can be represented by the following electrical model (see fig.1), known as the Cole Cole model [9]. The values of the electrical model R_e, R_i and C_m could be found by measuring the body impedance at $\omega = 0$ (R_0) and $\omega = \infty$ ($R\infty$) frequencies and solving the equation for the parallel circuit (see (1) and (2)). Due to technological difficulties, frequencies between 5 KHz and 1 MHz are used instead. Thus, in practice curve fitting methods are needed to calculate the parameters of the Cole Cole model (R_e, R_i and C_m).

$$R_0 = R_e \tag{1}$$

$$R_\infty = \frac{R_e R_i}{R_e + R_i} \tag{2}$$

Using the Cole-Cole parameters, the basics of the Hanai Theory [10] and modeling the human body as a cylindrical volume, we get the following equations for the calculation of the extracellular water volume (V_{ECW}) and the intracellular water volume (V_{ICW}):

$$V_{ECW} = \frac{1}{1000}\left(\frac{K_b^{\,2}\rho_{ECW}^{\,2}}{D_b}\right)^{1/3}\left(\frac{H^2\sqrt{W}}{R_e}\right)^{2/3}. \tag{3}$$

$$V_{ICW} = V_{ECW}\left(\left[\frac{\rho_{TBW}(R_e+R_i)}{\rho_{ECW}\cdot R_i}\right]^{\frac{2}{3}} - 1\right). \tag{4}$$

$$V_{TBW} = V_{ICW} + V_{ECW}. \tag{5}$$

In these equations K_b is a correction factor for a whole body measurement, relating the relative proportions of the leg, arm, trunk, and height, ρ_{TBW} is the resistivity of the overall fluid (Ω·cm), ρ_{ECW} is the resistivity of the extracellular fluid (Ω·cm), H is the body height (cm), D_b the body density (kg/l) and W the body weight.

III. Experimental Setup

In this study, the hydration level of five test subjects, aged 24-25 was monitored during exercise with a crosstrainer (type “Ergo Lyps Medical” from Daum Electronics, Fürth, Germany). The aim was to produce dehydration under controlled conditions, trying to measure the water loss using BIS measurements. The test persons were requested to train with the crosstrainer for certain time periods (3 x 30 min + warm up time). In defined time intervals whole body BIS measurements with the Hydra 4200 from Xitron Technologies were made and pictures of the arm and thigh with an infrared camera (type “Vario CAM hr head” from Infratec, Dresden, Germany) were taken to supervise the skin temperature. Table 1 shows the personal data of the five patients. For the BIS measurements, four electrodes were

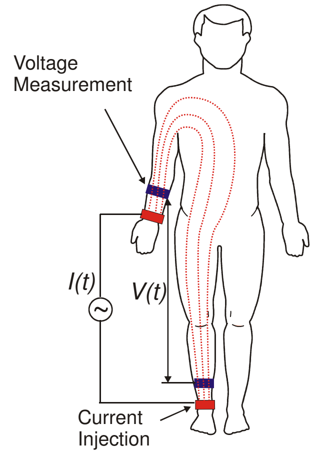

Fig. 2: Bioimpedance-Spectroscopy measurement setup

attached on the wrist and ankle. During a BIS measurement a sweep of small alternating currents was injected into the body using the outer electrode, as it is shown in the Fig. 2. Parallel to the current injection the voltage is measured using

Table 1
Patient data

Patient	Gender	Age	Start weight	Height	Weight loss during exercise
1	female	25	69.3 kg	1.70 m	1.1 kg
2	female	24	71.8 kg	1.77 m	1.6 kg
3	male	25	75.6 kg	1.89 m	1.5 kg
4	male	24	80.7 kg	1.78 m	0.8 kg
5	male	24	74.9 kg	1.71 m	1.4 kg

the other pair of electrodes. Knowing voltage and current the body impedance can be calculated. The infrared camera was used to supervise the skin temperature during the study. All test persons were not allowed to eat and drink 2h before and during the complete measurement procedure in order to cause a controlled dehydration. To have a gold standard as a reference, for the dehydration every test person was weighted before and after the training and the temperature in the gym room was kept stable. Table 2 shows the measurement protocol in detail.

Table 2
Measurement protocol

Time	Action	Measurement
5-7min	BIS measurement and infrared image	1
10 min	Warm up time using the Crosstrainer	
5-7 min	BIS measurement and infrared image	2
30 min	Exercise with the Crosstrainer	
5-7 min	BIS measurement and infrared image	3
30 min	Exercise with the Crosstrainer	
5-7 min	BIS measurement and infrared image	4
30 min	Exercise with the Crosstrainer	
5-7 min	BIS measurement and infrared image	5
15 min	Recovery time	
5-7 min	BIS measurement and infrared image	6

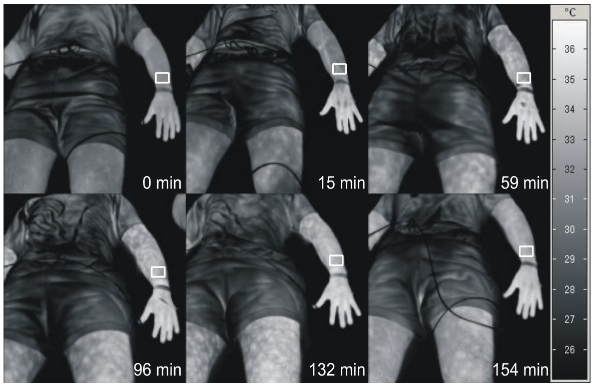

Fig. 3. Infrared images taken during the measurements

IV. RESULTS AND DISCUSSION

For each measurement interval, the skin temperature was analyzed using the infrared images. The measured whole body impedance was used to calculate the Cole-Cole parameters as well as the extra and intracellular water content (ECW, ICW). Fig. 3 shows exemplarily the infrared images taken from test person 5 during the measurements. Picture 1 was taken just before the warm up time (0 min). At that time all test persons were rested and relaxed. The skin temperature was between 27°C – 32°C. During the training the skin temperature rose due to increasing muscle activity and skin perfusion. The temperature increase becomes apparent in the lighter areas on the skin. It is very interesting to see that even after a recovery time of 15min (picture 6 - 154 min) the skin temperature is still very high. It is assumed that the recovery time for muscle and skin perfusion takes longer until the start condition are reached, even if the test persons felt already quite relaxed. This behavior could be measured for all test persons and can be also seen in the temperature plot. As an example Fig. 4 shows the temperature that was measured by the infrared camera at the white marked position on the arm (see Fig. 3), of test person 5 over the complete measurement time. Besides the increasing temperature that could be measured during the training (measurement 2 - 6), another effect appeared. Four of the five test persons showed the lowest skin temperature just after the warm up time, in which all test persons were training already for 10 min. An explanation for this behavior could be the convective heat transfer between the moving arms during sport and the air. In the warm-up time, it is supposable that such refrigerant effect prevails, since the body needs some time to warm-up and to increase skin temperature due to the vascular perfusion and muscle activities.

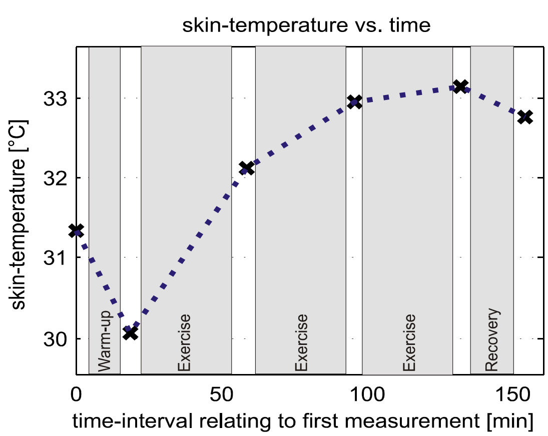

Fig. 4. Skin temperature curve of test person 5

Fig. 5 shows exemplarily the Cole-Cole parameters (R_e, R_i) that could be calculated from the measurements of patient 5 against training time. If we compare R_e and R_i of the first measurement against the last measurement, the values are quite similar as if no dehydration took place. This corresponds well to the results Jürimäe showed in his study [6]. Since it is known that skin and tissue temperature can influence the impedance measurements, for analysis only impedance measurements made with stable measurement condition, i.e. stable skin temperatures, should be compared and evaluated. Fig. 4 shows that after 60 min training the skin temperature of the test persons varied only within 1°C. So we defined such a variation as stable measurement conditions and used only the last four measurements for the evaluation. Comparing this temperature behavior with the calculated Cole-Cole parameters in Fig. 5, it can be seen that R_e increases continuously about 10-15Ω between the fourth and the last measurement (60 min – 155 min). An increasing R_e corresponds to a dryer extracellular space and therefore a water loss of the body. The R_i of test person 5 (shown in Fig.5) also increased during the last four measurements. However, this behavior was not clearly visible for all five test persons, which makes correct analysis difficult. For some of the test person, R_i decreased or stayed almost stable.

Using the Cole-Cole parameters, the total body water content was calculated and compared with the weight loss during the training. Since the test persons did not drink 2h

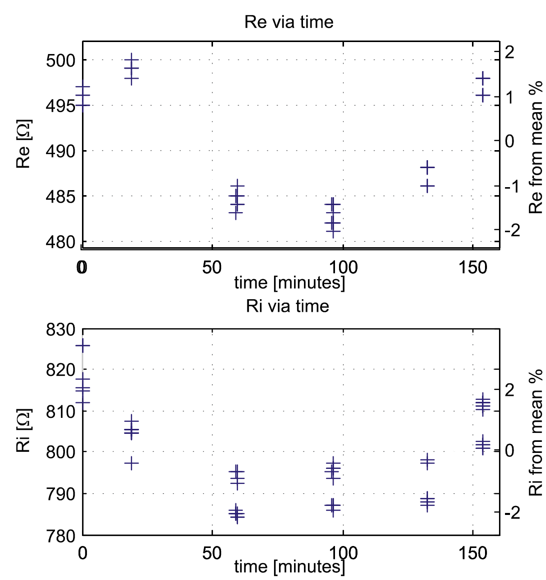

Fig. 5. Cole Parameter R_e, R_i of test person 5 during the training

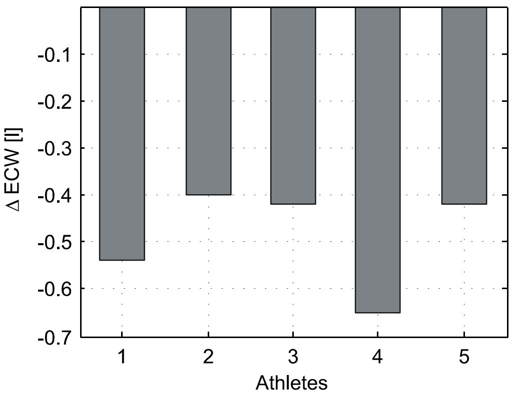

Fig. 6. Extracellular water content of 5 test persons during the training

before and during the training, all persons dehydrated and lost between 0.8kg-1.6kg body weight. Most of this weight loss was assumed as water loss. Fig. 6 and 7 show the calculated ECW and ICW change between the four last measurements for all five test persons. It is clearly noticeable, that in all cases the ECW parameter decreased strongly. All five persons lost between 0.4l – 0.65l ECW which leads to the assumption that the test persons began to dehydrate.

The ICW change was not uniform and the differences correspond to the Ri variations. If the test persons did only loose water during the training we would also expect a clear decrease of the ICW. However, this was not the case. A possible explanation for such a behavior could be the type of dehydration. Depending on the ratio of water and electrolytes in the sweat, the osmotic effect within the body cells leads to a compensation between intra- and extracellular space and therefore to positive or negative changes of ICW.

The total body water content (ICW+ECW) changes are smaller than the complete body weight loss of all five persons (see Table 1) measured before and after the training using a weight scale. This deviation can have different reasons. One explanation could be that the tissue conductivities that are used for the calculation of ECW and ICW change due to physiological changes, so that the standard algorithms can't be used anymore. It is also possible that additional physiological effects that were not taken into account yet could distort the measurement accuracy. Both assumptions should be further investigated with more test persons, and comparisons to other measurement methods should be used for validation.

V. Conclusion

Within this paper, a study was presented in which the hydration change of five test persons was monitored during exercise in order to detect dehydration. The use of an infrared camera to supervise the skin temperature of the test persons allowed defining the time interval in which the temperature conditions were stable and measurements could be evaluated. It was shown that generally within the first two

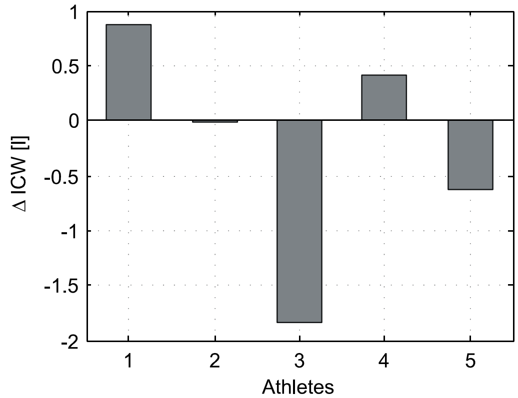

Fig. 7. Intracellular water content of 5 test persons during the training

measurements at the beginning of the training the temperature change was too high so that BIS measurements could not be compared. Analyzing the four comparable BIS measurements at the end of the trial, hydration changes in ECW and ICW could be presented that assume that the test person started to dehydrate during the training. The difference between body weight loss during the study and water change loss can not be completely explained yet, so that further measurements and evaluations are necessary in the future. However, it could be shown within this trial that continuous monitoring of body water content during sport using BIS combined with skin temperature measurements allows to measure loss of body water during physical exercise.

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