Analysis of Anomalies in Bioimpedance Models for the Estimation of Body Composition

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Abstract—**Bioimpedance analysis is a simple, safe and noninvasive method for Body Composition Estimation (BCE), which is of great interest for the monitoring of patients on renal replacement therapy. The most featured bioimpedance devices available are based on the bioimpedance spectroscopy technique, the extended Cole model and the Hanai Mixture theory. However, a set of anomalies using these methods has been found in this paper during the study of the evolution of body composition in patients on peritoneal dialysis. The main results obtained show that the estimates resulting from bioimpedance values that differ significantly from the single-dispersion Cole model have to be taken with some caution. This issue highlights the importance of medical assessment (technical or specialist) when interpreting any bioimpedance related data.**

Keywords—**Bioimpedance Spectroscopy, Body Composition Estimation, Cole Bioimpedance Model, Peritoneal Dialysis, Overhydration**

I. Introduction

Uremic patients treated with both hemodialysis (HD) and peritoneal dialysis (PD) show alterations in the metabolism of water with continuous variations in hydration status [1–3]. After a hemodialysis session is quite common for patients to have a significant fluid excess or to be in an undesirable state of dehydration, which can cause or aggravate any cardiovascular disease [4].

It is very important for renal patients treated by dialysis to assess the amount of fluid excess to determine how much should be removed through ultrafiltration to achieve a desired state of normohydration [4]. Bioimpedance methods are common techniques to estimate body composition because they have not the restrictions of solution methods [5–7] and provide more accurate estimations than the anthropometric methods [7]. Thanks to bioimpedance techniques, it is possible to obtain an estimation of body fluids and body composition in both normal and disease states. Bioimpedance measurements also have many practical advantages that have led to their rapid development [5, 6].

After years of research about bioimpedance analysis for dialysis patients, this technique has significantly increased its clinical use [1, 8], both for estimating body volumes as to assess patient's nutritional status. The clinical utility of the body composition analysis through bioimpedance techniques for patients treated with PD has been demonstrated in numerous studies [6, 9, 10]. In this context, this paper describes a number of "anomalies" in the BCE using the bioimpedance analysis, which have been identified during an evolution study of a group of PD patients. These anomalies were not detected by a bioimpedance device that uses the models described below, requiring the analysis of nephrologist specialists in order to evaluate their importance for patient welfare assessment.

II. Materials and Methods

A. Cole Bioimpedance Model

A simple model that describes the phenomenon of electric current conduction through the human body is represented by a parallel circuit in which a branch represents the current path through the extracellular medium and the other one the intracellular environment [1]. The extracellular path is modeled by a resistor (R_e, extracellular resistance) and the intracellular pathway by means of a resistor (R_i, intracellular resistance) in series with a capacity (C_m, membrane capacity) (see Fig. 1).

If the real part of the bioimpedance is plotted as a function of frequency versus the imaginary part in absolute values, the points obtained correspond to a semicircle (single-dispersion) in the first quadrant whose center is on the real axis (see Fig. 1). A more complete model of bioimpedance includes the effects of the variability of cell membranes, which are not perfect capacities due to different shape and size characteristics. This results in a shift pattern of the model in the center of the semicircle below the real axis, which can be expressed by the following equation (single-dispersion Cole model):

$$Z = R_\infty + \frac{R_0 - R_\infty}{1 + (j * \omega * (R_e + R_i) * C_m)^{1-\alpha}} \quad (1)$$

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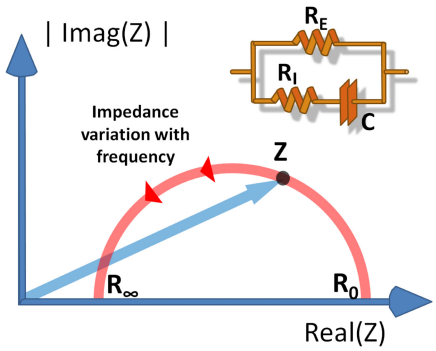

Fig. 1 Simple bioimpedance model and bioimpedance Cole diagram

R_0 is equivalent to R_e, R_∞ is the parallel of R_e and R_i, C_m is related to the characteristics of the cell membrane, $\omega = 2 * \pi * frequency$ and α is a parameter ($0 \leq \alpha \leq 1$) related to the shift of the curve.

A more realistic model also includes the effects of delays in the signals caused by the electrodes, the wires and the hardware, which can be modeled by a delay in phase (T_d) which increases linearly with frequency (extended Cole model).

$$Z' = Z * e^{-j\omega T_d} \tag{2}$$

B. Bioimpedance Spectroscopy for BCE

The first equations for the estimation of body fluid volumes were based on linear regressions defined from $Height^2/Resistance$ at 50 kHz. The regression parameters differed depending on the population group with which they were obtained [11]. Subsequent equations included other components to improve the accuracy of the estimations, such as weight, age, gender, ethnicity or anthropometric measurements of trunk and/or limbs.

Thomasset became the first to use the Cole model in order to differentiate between the extracellular water and the body water [1]. In 1992, the bioimpedance spectroscopy technique was introduced. This tecnique uses a multifrequency bioimpedance based Cole model and Hanai's mixture theory in order to estimate the extracellular water and the body water, avoiding the population imbalances obtained by linear regression approaches [1, 4]. In this method the determination of body fluid volumes is based on the fact that low-frequency electric current does not penetrate cell membranes, so it flows only for the extracellular compartment, while high-frequency current flows through both the extracellular and intracellular compartments. Therefore, the resistance at low and high frequencies are related to the Extracellular Water and the Total Body Water, respectively. By applying the mixtures theory of Hanai, the human body is considered as a superposition of a conductive medium (water, electrolytes, soft tissue, etc.) and a non-conductive (bone, fat, air, etc.). These considerations improve estimations by introducing the effects of non-conductive substances in body water, eliminating the apparent population specificity found in the regression equations and improving its sensitivity to changes in body hydration status [1].

Bioimpedance spectroscopy have been broadly used to quantify body composition, estimate fluid volume and locate mass anatomy (muscles, fat, water) in certain parts of the body. This technique is used by devices with higher features/prices in the market for the monitoring of dialysis patients, such as the Body Composition Monitor of Fresenius Medical Care [4].

C. Description of the Study

The initial objective of the study (cross sectional, observational) was to analyze the evolution of the hydration and nutritional status in a representative sample of prevalent PD patients. In the center of the study, all prevalent patients on PD were chosen as possible candidates for their inclusion. Patients were excluded if they had a cardiac pacemaker or metallic implants, were amputees or were pregnant. The study lasted a year and a half and the measurements were repeated with the same group of patients during their clinical routine practice. BCEs were performed by a single PD physician or nurse, using a portable body bioimpedance spectroscopy device: the Body Composition Monitor (Fresenius Medical Care). This device and the bioimpedance spectroscopy technique have been intensively validated against gold-standard methods [4, 6].

Table 1 shows the characteristics of the patients under study:

Table 1 Patient characteristics

10 men/10 women	Min	Medium	Max	σ
Age (years)	31	61.8	86	15.6
Weight (kg)	45.8	71.1	107	17.3
Height (cm)	140	160.5	184	9.3
Body Mass Index	20.4	27.4	41.8	5.5

The evolution of the patients was analyzed using the following parameters derived from data provided by the device: hydration level, Fat percentage [12], Fat Mass Index [13] and Fat Free Mass Index [14].

III. Results

Table 2 sumarizes the average ratings of BCEs of the patients.

Table 2 BCE patients results

10 men/10 women	Min	Medium	Max	σ
Overhydration (l)	-3.7	1.1	6	1.9
Percentage of Fat	8.8	34.5	53.6	9.8
Fat Mass Index	1.9	9.4	17.8	3.5
Fat Free Mass Index	11.5	17.4	24	3

This seems to indicate that the patients usually present on average a slight over-hydration and a good nutritional status, but with a slight excess of fat. When analyzing the evolution of the patients, there were no significant trends or characteristics, at least during the time of the study.

However, the technical analysis of the bioimpedance data shown that the cases in which they did not fit the model of single-dispersion Cole, the nutritional and hydration status of the patient undergone significant changes in valuations not too temporarily far. This technical analysis was clinically confirmed with the help of the nephrology specialists. Below there are two examples that highlight the anomalies detected.

A. Example A

Figure 2 show bioimpedance values for two consecutive measurements on a Cole diagram (only two are shown for the sake of clarity). The dashed line represents the fitting for a single-dispersion Cole model. One of the measurements (number 4) show a relevant mismatch at high frequency which is corrected by the extended Cole model (solid line) and a major phase delay ($T_d = 5.27nseg$).

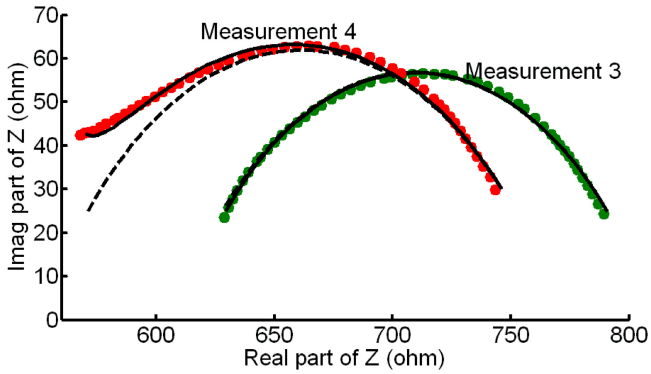

Fig. 2 Cole diagram of patient in example A

The body estimates in this case showed a significant variation with respect to other measures (see Fig. 3).

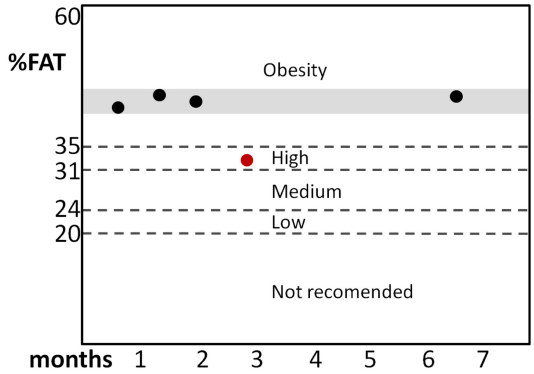

Fig. 3 Classification by percentage of FAT [12] of patient in example A

B. Example B

Figure 4 also shows bioimpedance values on two consecutive measurements on the Cole diagram. In this case the measurement 1 is corrected with a large phase lead ($T_d = -6.12nseg$).

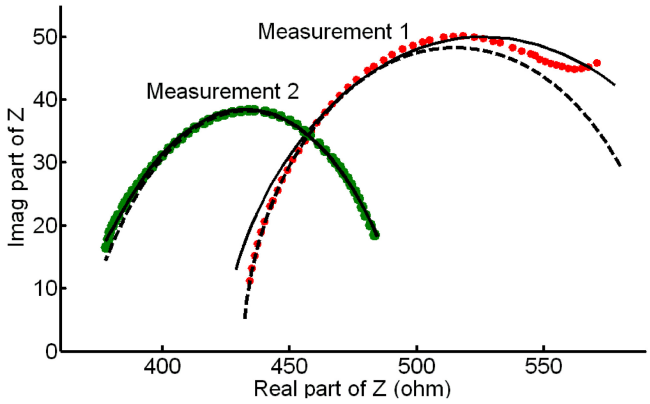

Fig. 4 Cole diagram of patient in example B

Assessments of BCE in this case also showed a significant variation with respect to the rest of measures (see Fig. 5).

IV. Discussion and Conclusions

The study described in this paper has analyzed the evolution of a group of peritoneal dialysis patients for over one year. BCEs were performed by a highly used device that employs the bioelectrical impedance spectroscopy technique, the extended Cole model and the Hanai Mixture theory. The results obtained have not shown relevant features to highlight regarding the clinical evolution of the patients. However, a number of anomalies were detected in those cases in which bioelectrical impedance values significantly differ compared

Fig. 5 Classification by Fat Mass Index [13] of patient in example B

to the single-dispersion Cole mole (the purpose of the extended Cole model is to correct and explain this effect). The anomalies were clinically evaluated in order to discard the related measurements for further studies.

BCEs were not compared with another reference method that could indicate a possible error in the measurement. However, in this paper the evolution of the patient has been analyzed, so that, assuming a progressive evolution of patient's condition, significant changes in the BCE on measures not too remote in time or regarding normal patient values in the patient may indicate a possible error in the estimation. If these estimates are considered to be mistaken, the possible sources of error can be multiple: defects in the electrodes or inappropriate placement on the body, the patient was not in the proper position, enough time was not spent so that the volume of fluid in the different compartments could be stabilized, etc.

According to the analysis carried out on the model parameters, the authors consider that those BCEs derived from the extended Cole model where the phase delay module T_d is greater than 5 nsec, must be taken with some caution. In these cases, it may be advisable to make a second estimate repeating the whole process of measurement (cleaning the skin, electrode placement, etc.) in order to compare the results obtained.

On the other hand, perhaps the peritoneal compartment of this particular type of patients has a greater influence and in certain situations it may be manifesting as a second dispersion. It is possible that more complex models (two dispersions maybe) could explain better these phenomena, and can provide more accurate measurements of BCEs for a higher number of situations.

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REFERENCES

1. Roa L M, Naranjo D, Reina L J, et al. Applications of bioimpedance to end stage renal disease (ESRD). *Studies in Computational Intelligence.* 2013;404:689-769.
2. Liu L, Zhu F, G Raimann J, et al. Determination of fluid status in haemodialysis patients with whole body and calf bioimpedance techniques. *Nephrology.* 2012;17:131-140.
3. Chua H R, Xiang L, Chow P Y, et al. Quantifying acute changes in volume and nutritional status during haemodialysis using bioimpedance analysis. *Nephrology.* 2012;17:695-702.
4. Wabel P, Chamney P, Moissl U, Jirka T. Importance of whole-body bioimpedance spectroscopy for the management of fluid balance. *Blood Purification.* 2009;27:75-80.
5. Earthman C, Traughber D, Dobratz J, Howell W. Bioimpedance spectroscopy for clinical assessment of fluid distribution and Body cell mass. *Nutrition in Clinical Practice.* 2007;22:389-405.
6. Sipahi S, Hur E, Demirtas S, et al. Body composition monitor measurement technique for the detection of volume status in peritoneal dialysis patients: The effect of abdominal fullness. *International Urology and Nephrology.* 2011;43:1195-1199.
7. Moissl U M et al. Body fluid volume determination via body composition spectroscopy in health and disease. *Physiological Measurement.* 2006;27:921-933.
8. Laegreid I K, Bye A, Aasarod K, Jordhoy M. Nutritional problems, overhydration and the association with quality of life in elderly dialysis patients. *International urology and nephrology.* 2012;44:1885-1892.
9. Parmentier S P, Schirutschke H, Schmitt B, et al. Influence of peritoneal dialysis solution on measurements of fluid status by bioimpedance spectroscopy. *International Urology and Nephrology.* 2013;45:229-232.
10. Biesen W et al. Fluid status in peritoneal dialysis patients: The European body composition monitoring (EuroBCM) study cohort. *PLoS ONE.* 2011;6.
11. Kyle U G et al. Bioelectrical impedance analysis - Part I: Review of principles and methods. *Clinical Nutrition.* 2004;23:1226-1243.
12. Lohman Houtkooper L B Going S B. Body fat measurement goes hi-tech: not all are created equal. *ACSM's Health Fitness J.* 1997;1:30-35.
13. Kyle U G, Nicod L, Raguso C, Hans D, Pichard C. Prevalence of low fat-free mass index and high and very high body fat mass index following lung transplantation. *Acta Diabetologica.* 2003;40:S258-S260.
14. Coin A et al. Fat-free mass and fat mass reference values by dual-energy X-ray absorptiometry (DEXA) in a 20-80 year-old Italian population. *Clinical Nutrition.* 2008;27:87-94.

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