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Adaptive Frequency Distribution for Electrical Bioimpedance Spectroscopy Measurements

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Abstract— **This paper presents a novel frequency distribution scheme intended to provide more accurate estimations of Cole parameters. Nowadays a logarithmic frequency distribution is mostly used in Electrical Bioimpedance Spectroscopy (EBIS) applications. However it is not optimized following any criterion. Our hypothesis is that an EBIS signal contains more information where the variation of the measurement regarding the frequency is larger; and that there ought to be more measuring frequencies where there is more information. Results show that for EBIS data with characteristic frequencies up to 200 kHz the error obtained with both frequency distribution schemes is similar. However, for EBIS data with higher values of characteristic frequency the error produced when estimating the values from EBIS measurements using an adaptive frequency distribution is smaller. Thus it may useful for EBIS applications with high values of characteristic frequency, e.g. cerebral bioimpedance.**

I. INTRODUCTION

Novel Applications of Electrical Bioimpedance Spectroscopy (EBIS) are emerging in the areas of tissue characterization and assessment of body composition. Very often, Cole-based analysis is the core of the EBIS application characterizing the impedance spectra through the Cole parameters. Examples of these applications are Body Composition Assessment (BCA) [1], lung edema detection [2] or arm lymphedema detection [3].

The accuracy of impedance spectrum estimation depends on several factors. Because the consequent Cole parameter estimation is done through fitting of the measurement to the Cole function [4], the number of frequencies and the value of frequencies measured influence not only the accuracy of the EBIS measurement but also, the subsequent Cole-based analysis.

Logarithmic or quasi-logarithm frequency distributions are often the distributions of choice and they are found in commercial Electrical Bioimpedance (EBI) spectrometers like the SFB7 and BCM manufactured by Impedimed and Fresenius Medical Care, respectively. Since Logarithmic frequency distribution place more frequencies in the lower ranges, it is very suitable for most of EBIS applications measuring biological tissues with low values of characteristic frequencies. However, applications requiring an accurate analysis at high frequencies and studies of tissues with high characteristic frequency, might suffer from lack of accuracy.

This paper presents a method to obtain a frequency distribution that, with special attention to the estimation of the Cole parameters, would enhanced the characterization of EBIS measurements within the β dispersion window range using a limited number of frequencies. The aim is to obtain the most accurate information from the measurement performed.

II. BACKGROUND & HYPOTHESIS

To obtain the minimum number of frequencies and their frequency values which allow performing an accurate, robust and reliable impedance spectroscopy characterization and EBIS analysis of biological tissue would enable EBIS applications in several scenarios.

Given its significance and potential influence in the development of EBIS technology, such topic is currently under investigation by other authors [5-7]. Ward & Cornish in [6] found that using a logarithm frequency distribution increasing the number of measurement frequencies improved the estimation of the Cole parameters significantly up to 15 frequencies. Beyond that, the improvement was found not significant.

In [5], it was shown that placing measuring frequencies around the characteristic frequency, *i.e.* where the frequency dependence of the EBI measurement is larger, produces more accurate measurements. The hypothesis is that allocating more measurements points in the frequency region representing the largest changes in impedance enhances the estimation. A novel frequency distribution scheme has been developed following this criterion. In this distribution the measuring frequencies are spaced in relation to the variation exhibited in the measured spectrum. Thus the frequency resolution is highest around the characteristic frequency and decreases towards lower and higher frequencies.

III. MATERIALS & METHODS

In this paper the method to obtain an adaptive and optimized frequency distribution is presented. Thereafter synthetic EBIS data for both frequency distributions, adaptive and logarithmic with different characteristic frequencies f_C, number of exciting frequencies and added random noise were generated. The Cole parameters were estimated from the different EBIS data produced and finally the results were studied performing a comparison between the errors obtained with both frequency distributions: Logarithm vs. Adaptive.

A. Cole function

In 1940 Cole [4] introduced a mathematical equation that fitted experimental EBIS measurements with only four parameters R_0, resistance at *DC*, R_∞, resistance at high

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frequency, α and τ, *i.e. the inverse of characteristic natural frequency* ω_C (1).

$$Z_{Cole}(\omega) = R_\infty + \frac{R_0 - R_\infty}{1 + (j\omega\tau)^\alpha} \tag{1}$$

The impedance generated by the Cole equation, $Z_{Cole}(\omega)$ is complex and non-linear with respect to frequency. Equation (1) experimentally fits EBIS measurements taken in a frequency range containing one main single dispersion. The Cole function is usually used for characterization of EBIS measurements and data representation. It produces a semicircular plot with depressed center in the impedance plane, such a plot is known as a Cole plot.

B. *Adaptive optimized frequency distribution*

Once the number of frequencies is selected they are distributed between the lower and upper limits of the frequency range along the modulus of the impedance, producing equal variation ΔZ and populating with a larger density of measuring frequencies close to f_C. To generate an adaptive optimized frequency distribution, prior information about the measuring load is required. In this work the values to generate the synthetic EBIS data were known.

In Fig. 1 an example of optimized frequency distributions adapted to a synthetic Cole Impedance with parameters: R_0=500 Ohm, R_∞=300 Ohm, α=0.7 and f_C=[30,100,300] kHz for circle, triangle and star markers respectively are plotted together with a logarithmic distribution (solid circles) along a logarithmic axis, 21 exciting frequencies were considered.

C. *Non-Linear Least Squares for Cole Parameters Estimation*

The Non-Linear Least Squares (NLLS) method aims to obtain the best coefficients for a certain model that fits the curve. The method aims to minimize the summed squared of the error between the measured values and the modeled data, as in (2). This fitting method has been used extensively before in several different models of EBIS [7-10].

$$\min \sum_{i=1}^{N} e_i^2 = \min \sum_{i=1}^{N} \left(\left|Z_i\right| - \left|\overline{Z}_i\right|\right)^2 \tag{2}$$

In this paper the model used is the modulus of the Cole function $\left|\overline{Z}_i\right|$ shown in (3). Thus $\left|Z_i\right|$ is the magnitude only of the measured EBI at the frequency *i.* and N is the total number of frequency data points included in the curve fitting.

D. *EBI Frequency distribution analysis*

Cole synthetic EBIS spectra were generated for the reference Cole parameter values R_0=500 Ω, R_∞=300 Ω, α=0.7 and changing f_C. Also an adaptively optimized frequency distribution was generated for such EBIS data. Afterwards using the produced adaptive and the logarithmic frequency distributions two EBIS dataset with n frequencies were generated using the reference values and adding gaussian noise with variance of 2% of the signal magnitude. Using the NLLS method, the modulus of the generated EBIS datasets have been fitted to the modulus of the Cole function estimating the Cole parameters which are suitable for comparison.

This process has been repeated for number of frequencies from 4 to 32 in steps of 4 and from 32 to 64 in steps of 8, and also for values of f_C between 30 and 300 kHz in steps of 10 kHz. Finally the Cole parameters estimated from every different combination of number of frequencies, value of f_C and frequency distribution are compared through the Mean Absolute Percentual Error (MAPE). Note that each EBIS dataset from each possible combination of *n* and f_C contains 100 EBI spectra with a different random noise.

$$|\bar{Z}(\omega)| = \sqrt{\left(R_\infty + \frac{(R_0-R_\infty)(1+(\omega\tau)^\alpha\cos(\alpha\pi/2))}{1+2(\omega\tau)^\alpha\cos\left({}^{\alpha\pi}/_2\right)+(\omega\tau)^{2\alpha}}\right)^2 + \left(\frac{(R_0-R_\infty)(\omega\tau)^\alpha\sin(\alpha\pi/2)}{1+2(\omega\tau)^\alpha\cos\left({}^{\alpha\pi}/_2\right)+(\omega\tau)^{2\alpha}}\right)^2} \tag{3}$$

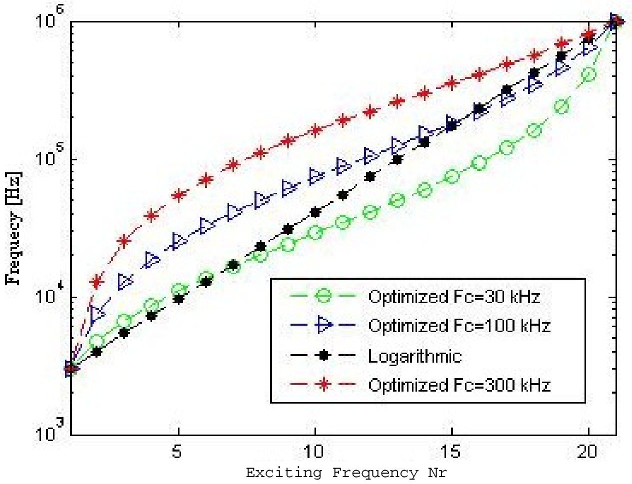

Fig. 1. Frequency measurement allocation obtained with Logarithmic distribution (solid circle) and optimized distribution adapted to a Synthetic Cole Impedance with f_C equal to 30, 100 and 300 kHz.

IV. RESULTS

Figures 2A and 2B show, respectively, the spectra of the modulus and the Cole plot of the reference synthetic Cole impedance plotted with continuous trace. In both figures, the EBIS values corresponding to both frequency distributions for 16 frequencies are shown. Values from the Adaptive distribution are plotted with stars solid markers and values from the Logarithmic distribution with triangular hollow marker. The figures also contain the modulus spectra and the impedance plot of the EBIS generated with the Cole parameters estimated from the EBIS datasets plotted in the same figures. The dotted line represents the spectrum generated from the Logarithmic distribution values and the dash-doted line represents the spectrum generated from the adaptive frequency distribution.

Fig. 3 contains four plots showing the MAPE obtained for each of the Cole parameters from both frequency distributions for several number of frequencies and different values of characteristic frequencies. In each plot the number

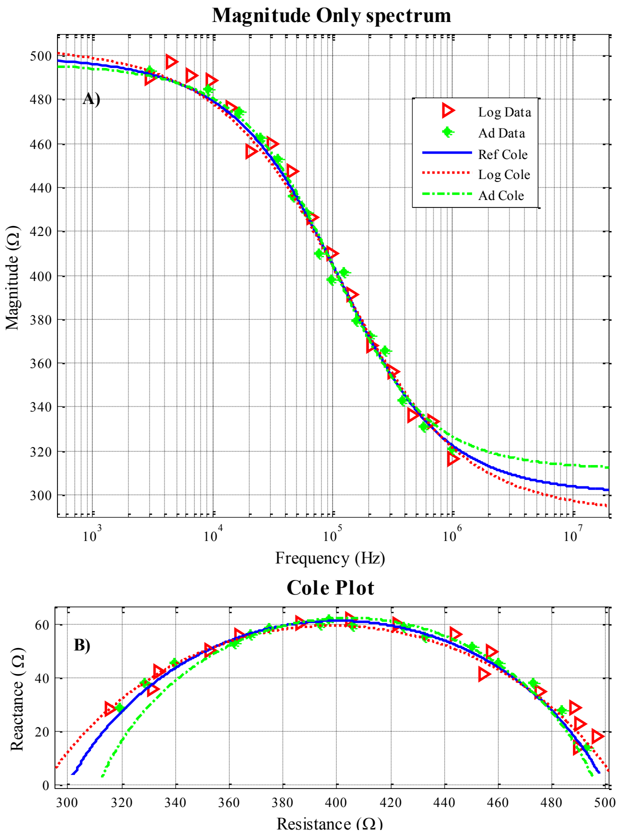

Fig. 2. Magnitude only spectra and Cole Plots of Synthetic data and Cole models with f_C value 100 kHz.

of measuring frequencies is indicated with different markers and the MAPE value is plotted vs. the value of the characteristic frequency of the corresponding EBIS data set.

Figure 3 shows the combinations of characteristic frequencies and number of frequencies that are representative for the overall study *i.e.* the calculations performed in the study contained more combinations of number of frequencies and values of f_C. see II.B. The characteristic frequencies represented are 50, 100, 150, 250, 250 and 300 kHz and the number of frequencies are 4, 8, 16, 32 and 64 represented by circles, dots, stars, crosses and triangles respectively.

Note that the frequency axes represent discrete values of f_C and the values obtained from the adaptive and logarithm distribution are plotted over the dotted bar and over the dashed bar, respectively.

In all four plots it is possible to observe the same trend, the obtained MAPE with both frequency distributions are very similar for values of f_C below 200 kHz. When the f_C of the EBIS data set increases over 200 kHz the adaptive optimized frequency distribution produced consistently more accurate estimations. In the plots it is also possible to observe how the MAPE decreases with an increasing number of frequencies up to characteristic frequencies of 250 kHz. For f_C values higher than 250 kHz increasing the number of frequencies does not represent any reduction of the MAPE.

V. DISCUSSION

A. Overall Performance

The under lying hypothesis for proposing the adaptive frequency distribution was that by allocating more measurement frequencies where the impedance spectrum change the most would produce a more accurate estimation of the Cole parameters. The obtained results confirm the hypothesis for EBI spectra containing values for the characteristic frequency over 200 kHz.

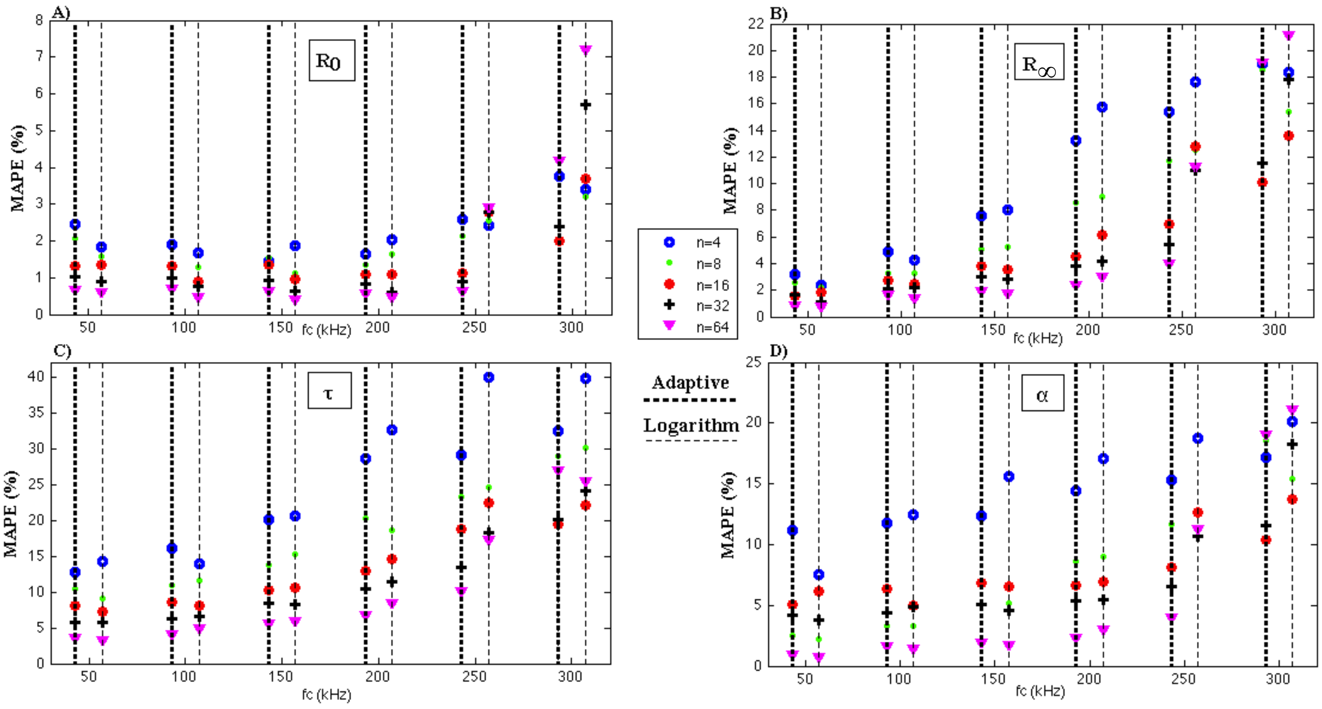

Fig. 3. MAPE values of each Cole parameter for combinations of different characteristic frequencies and number of frequencies

For lower values of characteristic frequency the adaptive frequency distribution do not produce any noticeable improvement over the logarithmic distribution. This occurs mainly because the logarithmic distribution places enough frequencies around the f_C, consequently characterizing with enough accuracy the EBI spectrum.

B. Increasing number of frequencies

In general, for both distributions an increasing number of frequencies reduce the MAPE of the estimations. This was expected and agrees with the work presented in Ward & Cornish [6]. One limitation in their work is that it was limited to the EBIS data for BCA application, i.e. typicaly with low values for f_C. Another limitation was that although a minimum number of frequencies for an efficient Cole parameter estimation was proposed, the study did not investigated the particular allocation of those frequency points.

The general observation that an increase of accuracy is obtained with increasing the number of frequencies does not occur for high values of f_C.

C. A priori information and allocation of the measurement frequencies

Regarding the allocation of frequencies, in [5] the authors proposed an approach to distribute the frequencies optimized for myocardium tissue impedance with an approximately f_C of 100 kHz and 21 frequencies that also improved the accuracy when characterizing the EBI measured spectrum. Despite the significant distinction in the criteria implemented for allocating the measurement frequencies in both approaches, since both cases place more measurement points around the characteristic frequency, the resulting frequency distribution schemes are very similar.

In practice, to generate an optimum frequency distribution allocating measuring frequencies around the spectral characteristics of the target tissue requires, apriori information. How that a priori information is acquired and introduced into the process of generating the frequency distribution used to perform the EBIS measurement will most probably influence the applicability of this approach.

VI. CONCLUSION

The results indicate than the adaptive frequency distribution proposed in this paper represents an improvement in the accuracy when estimating the Cole parameter from EBIS data with high characteristic frequencies. Therefore such an adaptive frequency distribution may be of special significance in EBIS applications with typically high values of f_C like cerebral Bioimpedance [11]. Experimental validation of this approach on cerebral EBIS measurements is ongoing.

Since research efforts are being focused on finding the optimum frequency distribution to generate multifrequency excitation, it would be interesting to compare the performance of the adaptive frequency distribution proposed here with the Logarithm-exponential distribution presented in [5]. The results of such study would probably be very useful in the quest of generating the perfect multifrequency excitation to develop short-time enabled applications of Electrical Bioimpedance Spectroscopy [12].

REFERENCES

[1] J. R. Matthie, "Bioimpedance measurements of human body composition: critical analysis and outlook.," *Expert review of medical devices* vol. 5, p. 22, 2008.

[2] L. Beckmann, D. van Riesen, and S. Leonhardt, "Optimal electrode placement and frequency range selection for the detection of lung water using Bioimpedance Spectroscopy," presented at the EMBC 2007. 29th Annual International Conference of the IEEE Engineering in Medicine and Biology Society, 2007.

[3] L. C. Ward, Czerniec S, and K. SL., "Operational equivalence of bioimpedance indices and perometry for the assessment of unilateral arm lymphedema.," *Lymphat Res Biol.* , vol. 7, p. 4, 2009.

[4] K. S. Cole, "Permeability and impermeability of cell membranes for ions.," *Quant. Biol.,* vol. 8, pp. 110–122, 1940.

[5] B. Sanchez, G. Vandersteen, R. Bragos, and J. Schoukens, "Optimal multisine excitation design for broadband electrical impedance spectroscopy," *Measurements, Science and Technology,* vol. 22, p. 11, 2011.

[6] L. C. Ward and B H Cornish, "Multiple Frequency Bielectrical Impedance Analysis how many Frequencies to use?," in *XII ICEBI Conference*, Gdansk, Poland, 2004, pp. 321-324.

[7] L. C. Ward, T. Essex, and B. H. Cornish, "Determination of Cole parameters in multiple frequency bioelectrical impedance analysis using only the measurement of impedances," *Physiol Meas,* vol. 27, pp. 839-50, Sep 2006.

[8] D. Ayllón, F. Seoane, and R. Gil-Pita, "Cole Equation and Parameter Estimation from Electrical Bioimpedance Spectroscopy Measurements - A Comparative Study," presented at the Engineering in Medicine and Biology Society, 2009. EMBC 2009. Annual International Conference of the IEEE Minneapolis, 2009.

[9] F. Seoane, R. Buendia, and R. Gil-Pita, "Cole parameter estimation from electrical bioconductance spectroscopy measurements," presented at the EMBC 2010, Buenos Aires, 2010.

[10] R. Buendia, Gil-Pita R, and Seoane F, "Cole Parameter Estimation from the Modulus of the Electrical Bioimpeadance for Assessment of Body Composition. A Full Spectroscopy Approach," *Journal of Electrical Bioimpedance,* vol. 2, p. *In Print*, 2011.

[11] F. Seoane, K. Lindecrantz, T. Olsson, I. Kjellmer, A. Flisberg, and R. Bågenholm, "Spectroscopy study of the dynamics of the transencephalic electrical impedance in the perinatal brain during hypoxia," *Physiological Measurement,* vol. 26, pp. 849-63, August 2005.

[12] M. Min, U. Pliquett, T. Nacke, A. Barthel, P. Annus, and R. Land, "Broadband excitation for short-time impedance spectroscopy," *Physiol Meas,* vol. 29, pp. S185-92, Jun 2008.