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Cole Parameter Estimation from Total Right Side Electrical Bioimpedance Spectroscopy Measurements – Influence of the Number of Frequencies and the Upper Limit

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Abstract— **Applications based on measurements of Electrical Bioimpedance Spectrocopy (EBIS) analysis are proliferating. The most spread and known application of EBIS is the non-invasive assessment of body composition. Fitting to the Cole function to obtain the Cole parameters, R_0 and R_∞, is the core of the EBIS analysis to obtain the body fluid distribution. An accurate estimation of the Cole parameters is essential for the Body Composition Assessment (BCA) and the estimation process depends on several factors. One of them is the upper frequency limit used for the estimation and the other is the number of measured frequencies in the measurement frequency range. Both of them impose requirements on the measurement hardware, influencing largely in the complexity of the bioimpedance spectrometer. In this work an analysis of the error obtained when estimating the Cole parameters with several frequency ranges and different number of frequencies has been performed. The study has been done on synthetic EBIS data obtained from experimental Total Right Side (TRS) measurements. The results suggest that accurate estimations of R_0 and R_∞ for BCA measurements can be achieved using much narrower frequency ranges and quite fewer frequencies than electrical bioimpedance spectrometers commercially available nowadays do.**

I. Introduction

SINCE the introduction of the Cole function (1) by K.S Cole in 1940 [1], the function and its parameters have been widely used on Electrical Bioimpedance (EBI) applications for data representation as well as analysis of spectroscopy and multi-frequency impedance measurements. From the origin of EBI Spectroscopy (EBIS), mostly applied to Body Composition Assessment (BCA), the use of EBIS has proliferated to several application areas of tissue characterization like skin cancer detection [2].

EBIS has not only proliferated to other areas but it has deep-rooted into BCA applications, especially through the use of the Cole parameters R_0 and R_∞ [3] from Total Right Side (TRS) EBIS measurements. Therefore the estimation of the Cole parameters has become a common and necessary step in EBIS-based BCA applications.

The estimation of the Cole parameters depends on the width of the frequency range and the number of measurement frequencies contained in the spectroscopy measurement. Since the number of frequencies and the frequency limits, especially the upper limit, put demands on the hardware and the acquisition process, customization of such parameters for a specific EBI applications would produce a more efficient EBI spectrometers.

In this work a study of the effect of reducing the value of the upper frequency limit and the number of frequencies on the estimation of the Cole parameters from TRS synthetic EBIS data is performed.

II. Materials and Methods

A. *Cole equation*

In 1940 Cole [1] introduced a mathematical equation that fitted experimentally EBI measurements with only four parameters R_0, R_∞, 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 on the frequency domain. It fits EBIS measurements on a single dispersion frequency range and it generates a depressed semi-circle when plotted in the impedance plane known as Cole plot, see Fig. 1.

B. *EBIS Measurements and Noise Model*

TRS tetrapolar EBIS measurements from 4 male healthy volunteers have been used to extract the Cole parameters to generate the synthetic data. The EBIS measurements were performed with the SFB7 bioimpedance spectrometer manufactured by Impedimed ltd. using repositionable Red Dot Ag/AgCl electrodes manufactured by 3M and keeping 5

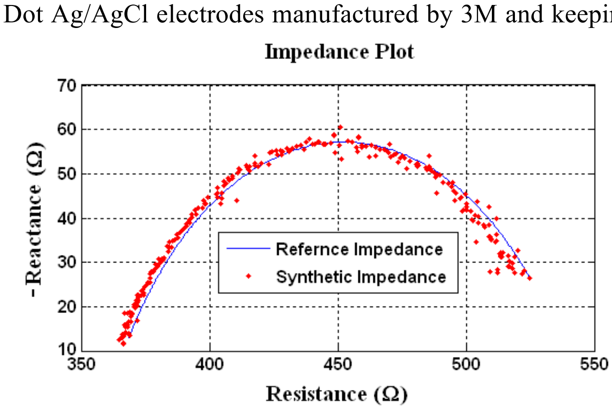

Fig. 1 Impedance plot showing the impedance resulting from the Cole parameters obtained from an experimental Total Right Side measurement and the synthetic EBI data generated

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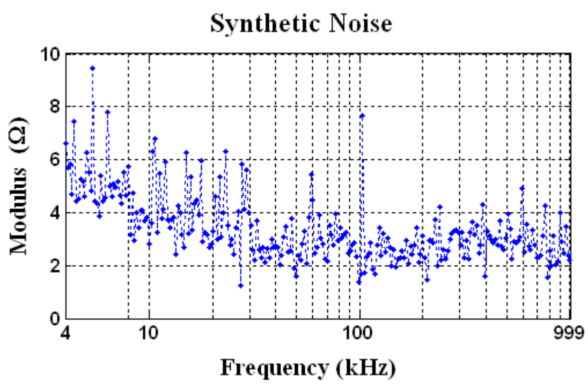

Fig. 2 Noise extracted from the TRS measurements and used for the generation of the synthetic EBIS data

cm between current injection and voltage detector electrodes. The frequency range of performed EBI measurements was 3.096 to 999 kHz and 100 complex EBIS measurements were obtained for each of the volunteers. The measurements did not exhibit any noticeable capacitive leakage or measurement artefacts

From each of the 100 TRS EBIS measurements, noise has been characterized using a generalized Gaussian noise model. First, a complete covariance matrix from the data has been estimated using the maximum-likelihood estimator. Second, this estimated covariance matrix has been used to generate new synthetic random zero-mean noise values, that have been added to the EBI data generated from the Cole Parameters extracted from the measurements as can be seen in Fig. 1, Fig. 2 shows an example of the synthetic noise generated in this way.

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

The Non-Linear Least Squares (NLLS) method aims to obtain the best coefficients for a given model that fits the curve, the method given by (2) aims to minimize the summed squared of the error between the measured data value and the modelled value. This approach has been validated previously, [4] and [5].

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

In this work the model used is the modulus of the Cole function $|\overline{Z_i}|$, shown in (3). Thus $|Z_i|$ is the modulus of the measured EBI at the frequency indicated by *i*.. N is the total number of frequency data points included in the curve fitting.

The advantage of a modulus based analysis is that allows the use of a bioimpedance spectrometer without phase detector.

This approach has been used for estimating the Cole parameters from both the TRS measurements and the EBIS synthetic data.

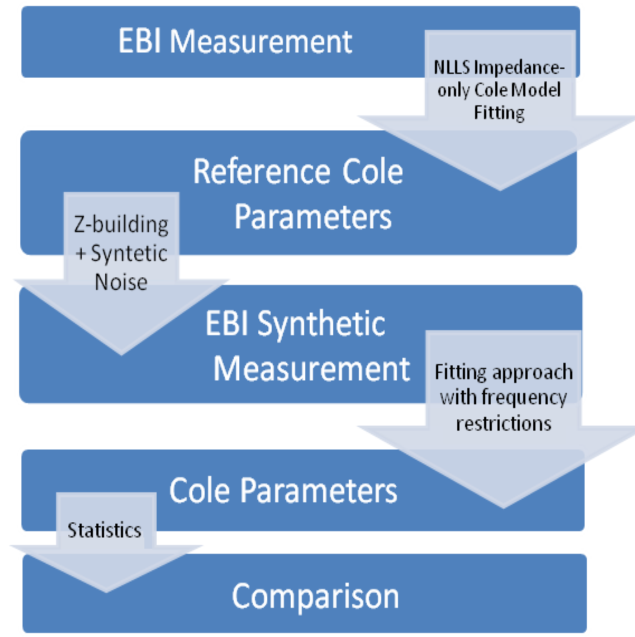

Fig. 3 Work Flow implemented in this study

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

D. *EBI Frequency Reduction Analysis*

The synthetic EBIS data is obtained using the Cole function with the experimental Cole parameters and adding the generated noise. The process is repeated 100 times producing 100 EBIS synthetic measurements for each of the four sets of experimental Cole parameters.

From the obtained synthetic EBI spectra the Cole parameters are estimated using the NLLS approach described in 2.C for the following frequency ranges: 4-999 kHz, 4-500 kHz, 4-250 kHz and 4-100 kHz. For each of the 4 frequency ranges, the number of frequencies used to perform the NLLS curve fitting has been varied according to the following list 256, 128, 64, 32, 16, 12, 8 and 4. Note that in all cases the frequencies were spaced exponentially like is done in the Impedimed SFB7. In Fig. 3 it is possible to observe the flow of the work implemented in this study.

This way, 32 sets of 100 Cole parameters have been obtained. The mean for each of Cole parameter has been calculated for the 32 different configurations and by comparing with the value of the experimental Cole parameters the Mean Absolute Percentage Error (MAPE) produced has been obtained as in (4).

$$MAPE = \sum_{n=1}^{N} \left| \frac{X - \overline{X}}{\overline{X}} \right| * 100 \qquad (4)$$

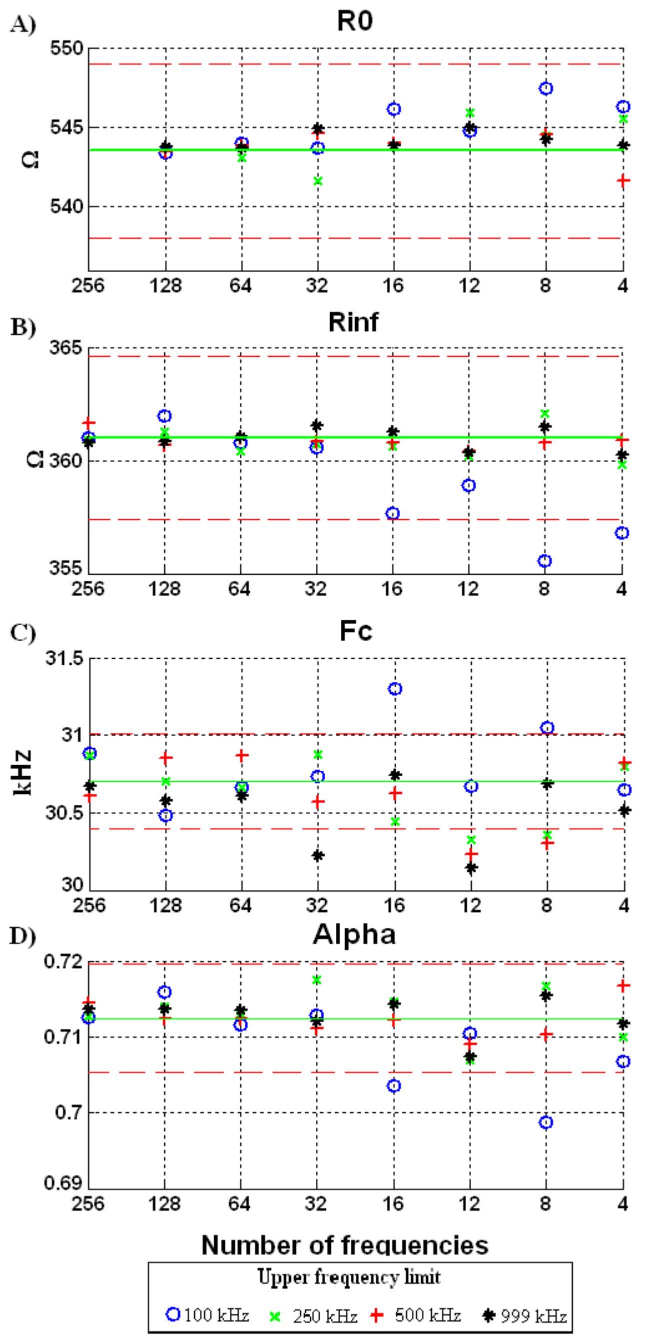

Fig. 4 Cole Parameter estimation for each combination of number of frequencies and lower frequency limit

Where X represents the estimated value of the Cole parameter under study i.e. R_0, R_∞, α or F_c, and $\overline{X}$ the original value of the parameter under study. N is the total number of estimations. Note that instead of τ, it is the characteristic frequency F_c, the parameter that is evaluated.

III. RESULTS

An illustrative example of the effect of decreasing the number of frequencies and the upper limit frequency on the estimation of the Cole parameters, from 1 set of EBIS synthetic measurements is presented in Fig. 4.

TABLE I. R_0 MAPE COMPARISON

Upper Freq	999 kHz	500 kHz	250 kHz	100 kHz
Number of Freqs	Mean	Mean	Mean	Mean
256	0.27	0.04	0.22	0.07
128	0.25	0.13	0.10	0.18
64	0.09	0.11	0.24	0.05
32	0.10	0.10	0.17	0.26
16	0.44	0.21	0.24	0.43
12	0.54	**1.52**	0.59	**1.03**
8	0.34	0.26	0.28	**2.12**
4	0.22	0.23	0.24	0.66

Note: In bold the Errors bigger than 1%

TABLE II. R_∞ MAPE COMPARISON

Upper Freq	999 kHz	500 kHz	250 kHz	100 kHz
Number of Freqs	Mean	Mean	Mean	Mean
256	0.21	0.13	0.21	0.09
128	0.24	0.19	0.18	0.33
64	0.10	0.13	0.23	0.70
32	0.15	0.10	0.08	0.65
16	0.31	0.41	0.25	**2.27**
12	0.32	**1.39**	0.56	**3.48**
8	0.37	0.31	0.34	**5.76**
4	0.23	0.12	**1.53**	**4.48**

Note: In bold the Errors bigger than 1%

The estimated values for R_0, R_∞, α and F_c are plotted in fig. 4.A) to 4.D) respectively. Horizontal lines indicate the original value and the 1 % deviation threshold, with continuous and dashed trace respectively. The number of frequencies is indicated in the abscissa and the different upper limits use different markers.

In the plots it is possible to observe that most of the estimations fall within the 1% deviation error and as a general trend the deviation increases when decreasing the number of frequencies. In all four plots the larger deviations

TABLE IV. ALPHA MAPE COMPARISON

Upper Freq	999 kHz	500 kHz	250 kHz	100 kHz
Number of Freqs	Mean	Mean	Mean	Mean
256	0.27	0.17	0.20	0.13
128	0.35	0.16	0.19	0.42
64	0.20	0.04	0.23	0.37
32	0.30	0.23	0.40	0.52
16	0.53	0.65	0.62	**1.30**
12	**1.33**	**3.29**	**1.02**	**1.68**
8	0.69	0.31	0.75	**4.20**
4	0.75	0.72	0.60	**1.75**

Note: In bold the Errors bigger than 1%

TABLE III. F_c MAPE COMPARISON

Upper Freq	999 kHz	500 kHz	250 kHz	100 kHz
Number of Freqs	Mean	Mean	Mean	Mean
256	0.48	0.49	0.75	0.28
128	0.69	0.93	0.40	0.78
64	0.75	0.78	**1.14**	**1.43**
32	0.72	0.84	0.24	0.73
16	**1.40**	0.86	0.55	**3.56**
12	**3.77**	**9.27**	0.92	**5.08**
8	**1.75**	**2.17**	**2.41**	**10.1**
4	**1.29**	0.50	**1.50**	**2.62**

Note: In bold the Errors bigger than 1%

are produced with the estimation done with the minimum upper frequency limit, *i.e. 100 kHz*.

In Tables I to IV the MAPE values obtained from averaging the error obtained for the four subjects are compared. Each of the tables contained the comparison for each of the Cole parameters and values of MAPE above 1 are highlighted in bold font. The reported MAPE values agree with the trend observed in Fig. 4A)-D), that is, larger values of MAPE for decreasing number of frequencies and lower values of upper frequency limit.

The error presents the same tendency in all the four subjects, getting a SD below 1% in most of the cases.

IV. Discussion

The MAPE results show that for most cases the estimation of the Cole parameters are very accurate. As it could be expected the estimation of the Cole parameters exhibit different dependencies regarding the reduction of the number of frequencies and the upper limit used.

It is not unexpected to observe that the estimation of R_0 does not exhibit a remarkable dependency on the upper frequency nor the number of frequencies. Such dependency is clearer for the estimation of R_∞, which exhibit the larger MAPE values for the lowest upper frequency limit and the small number of frequencies. In the case of the estimation of A*lpha*, similar dependencies than those exhibited by the estimation of R_0 and R_∞ are found.

Regarding the estimation of F_c the influence of reducing the number of frequencies to perform the curve fitting is more remarkable than decreasing the upper frequency limit. This is also expected since a higher number of frequencies near the characteristic frequency will help to fit the curve in that frequency range better.

Considering that for the estimation of the BCA parameters in most of the approaches R_0 and R_∞ are the parameters of interest [6], it is the progression of MAPE for the estimation of both parameters what should be taken into account when selecting a suitable number of frequencies and the lowest upper frequency limit for performing EBIS measurements.

From the results in Tables I and II 16, 12 and 8 frequencies using an upper limit of 250 kHz and 32 frequencies using the limit of 100 kHz seems to be suitable combinations. The limit of 16 frequencies has been previously reported as the limit number of frequencies beyond which not noticeable improvement is achieved producing a curve fitting to the Cole function [7].

In case that the estimation of the BCA parameters is done according to Cornish [8] using the value of the impedance at the characteristic frequency instead than R_∞, then the estimation of the F_c must be very accurate. In this case the suitable combinations are limited to 16 and 12 frequencies with 250 kHz, and 32 frequencies with an upper limit of 100 kHz.

When selecting this number of frequencies and upper frequency limits, it must be taken into consideration that the measurement frequencies are distributed exponentially within the measurement frequency range. The distribution of frequencies might influence also into the estimation of the Cole parameter and it is an issue that deserves to be studied in depth. Another issue to consider regarding the number of frequencies is the robustness of the estimation of the Cole parameters, which can be studied from the form the standard deviation obtained from the estimation. As it could be expected to increase the frequency resolution increases the preciseness of the estimations. Due to the lack of space, this aspect of the estimation will be studied properly in a future study, which will include also experimental EBI measurements.

V. Conclusion

Accurate estimation of the Cole parameters might be obtained from TRS impedance spectroscopy measurements performed in a frequency range remarkably much narrower than the range currently in use nowadays by commercial spectrometers like the SFB7 and the Body Composition Monitor manufactured by ImpediMed and Fresenius Medical Care respectively.

The number of frequencies used to perform TRS measurement can be also reduced significantly. The combination of both facts might lead to the implementation of simpler impedance devices, as well as easier EBIS analysis.

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