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Cole Function and Conductance-based Parasitic Capacitance Compensation for Cerebral Electrical Bioimpedance Measurements

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Abstract— **One of the most common measurement artifacts present in Electrical Bioimpedance Spectroscopy measurements (EBIS) comes from the capacitive leakage effect resulting from parasitic stray capacitances. This artifact produces a deviation in the measured impedance spectrum that is most noticeable at higher frequencies. The artifact taints the spectroscopy measurement increasing the difficulty of producing reliable EBIS measurements at high frequencies. In this work, an approach for removing such capacitive influence from the spectral measurement is presented making use of a novel method to estimate the value of the parasitic capacitance equivalent that causes the measurement artifact. The proposed method has been tested and validated theoretically and experimentally and it gives a more accurate estimation of the value of the parasitic capacitance than the previous methods. Once a reliable value of parasitic capacitance has been estimated the capacitive influence can be easily compensated in the EBIS measured data. Thus enabling analysis of EBIS data at higher frequencies, i.e. in the range of 300-500 kHz like measurements intended for cerebral monitoring, where the characteristic frequency is remarkably higher than EBIS measurements i.e. within the range 30 to 50 kHz, intended for body composition assessment.**

I. Introduction

From early applications of Electrical Bioimpedance Spectroscopy (EBIS) for assessing on body composition already in 1986 [1] the applications of electrical bioimpedance (EBI) and especially EBIS, have spread and proliferated significantly. Currently EBIS technology is used in many different applications areas like electronic biopsies of skin tissue [2], detection of pulmonary edema [3] and other novel uses of EBIS technology are emerging, *e.g. cerebral monitoring* [4]. Some of these applications like cerebral monitoring may require a reliable EBI spectrum up to higher frequencies, in the order of 500 kHz, rather than in the order of 100 kHz as in traditional EBIS applications like body composition assessment.

To perform any useful data analysis and especially spectroscopy analysis, the EBIS measurements should be free from artifacts. The capacitive leakage effect produced by parasitic capacitances is one of the most common artifacts associated with EBIS measurements and it produces a deviation in the obtained EBIS data that is often seen at high frequencies [5].

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Despite the early criticism of the approach [6] and the high frequency limitation pointed by Scharfetter [5], the so-called Td Compensation method introduced by De Lorenzo *et al*. in [7] has been the method of choice to compensate EBIS measurements with high frequency deviations.

Recently, another approach has been proposed and validated by Buendia *et al.* [8]. Even if the approach is effective for EBIS measurements at low frequencies, *i.e.* in applications with low values for the characteristic frequency, the method exhibit certain intrinsic limitation for correcting capacitive leakage in EBIS measurements at higher frequencies, as in the case of assessment of cerebral impedance.

In this work a novel approach for the estimation of parasitic capacitance from EBI measurements is proposed. The novel method is tested against the approach proposed in [8] with EBIS synthetic data and 2R1C circuits measurements and finally validated with experimental EBIS measurements of cerebral impedance. The method is specifically aimed at EBIS measurements with relatively high frequency content in the Beta dispersion range and presents encouraging preliminary results when it is applied to electrical bioimpedance cerebral measurements.

II. Methods and Materials

A. Correction Function

The Correction Function approach proposed as an alternative to Td Compensation uses a similar approach but corrects the deviations in both modulus and phase. Td compensation method multiplies the measured EBIS by imaginary exponential of the form $exp(-j\omega Td)$ this way modifying only the phase of the measurement. With the correction function method the measured EBIS is multiplied by a complex function that modifies both the modulus of the impedance and the phase, see (1).

$$Z_{Corr}(\omega) = Z_{Meas}(\omega)\frac{1}{1 - j\omega Z_{Meas}(\omega)C_{PAR}} \qquad (1)$$

The core of this correction is the value of a parasitic capacitance C_{PAR}, therefore an accurate estimation of C_{PAR} is paramount to obtain an EBIS properly corrected $Z_{Corr}(\omega)$, i.e. neither over- nor under-compensated.

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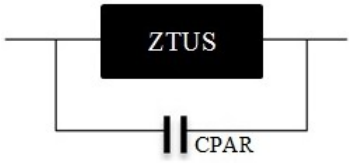

Fig. 1. EBI measurements model.

In [8], the value of C_{PAR} is estimated from the imaginary part of the admittance spectrum *i.e. susceptance*, of the measurement under the assumption that the electrical susceptance of any single dispersion system modeled with the Cole function will become zero at high frequencies.

When measuring EBI for body composition assessment with typical characteristic frequencies around 30-50 kHz the susceptance of the tissue at high frequencies can be neglected [8] and the value of the C_{PAR} can be extracted from the remaining susceptance spectrum which exhibit a value increasing with frequency and slope equally to C_{PAR} .

Experimental data shows when performing electrical bioimpedance measurements, which may produce EBIS spectra with characteristic frequency values around 300-500 kHz, neglecting the susceptance of the tissue to estimate the value of an eventual C_{PAR} is not a very accurate option and some other estimation method to obtain a precise value for C_{PAR} is required.

B. Model Based C_{PAR} Estimation.

The Cole function (2) was introduced by K.S Cole in 1940 [9] and it is widely used for EBI data representation. The Cole function consists of four parameters R_0, resistance at *DC*, R_∞, resistance at high frequency, α and τ *i.e. inverse of the characteristic frequency* ω_C.

$$Z_{Cole}(\omega) = R_\infty + \frac{R_0 - R_\infty}{1 + (j\omega\tau)^\alpha} \approx Z_{Meas}(\omega) \qquad (2)$$

According to the simplified model for EBI measurements containing parasitic capacitances presented in [10] and depicted in Fig. 1, the conductance spectra obtained from such EBIS measurement will be free from any influence caused by the parasitic capacitance C_{PAR}, therefore as shown in [10] all four Cole parameters can be extracted from fitting the conductance spectrum of the EBIS measurement to the conductance of the Cole function expressed in (3). Such parameter estimation will be done free from the influence of parasitic capacitance leakage.

$$G_{Cole}(\omega) = Y_0 + \frac{(Y_\infty - Y_0)\left(1+\frac{Y_\infty}{Y_0}(\omega\tau)^{-\alpha}\cos(\alpha\pi/2)\right)}{1+\frac{Y_\infty^2}{Y_0^2}(\omega\tau)^{-2\alpha}+2\frac{Y_\infty}{Y_0}(\omega\tau)^{-\alpha}\cos(\alpha\pi/2)} \qquad (3)$$

Using the values for the Cole parameters obtained in the fitting process to (3) into the Cole function (2) a full impedance version of the measured EBIS $Z_{Cole\_G}(\omega)$ can be generated. $Z_{Cole\_G}(\omega)$ will be completely free from any capacitive leakage effect.

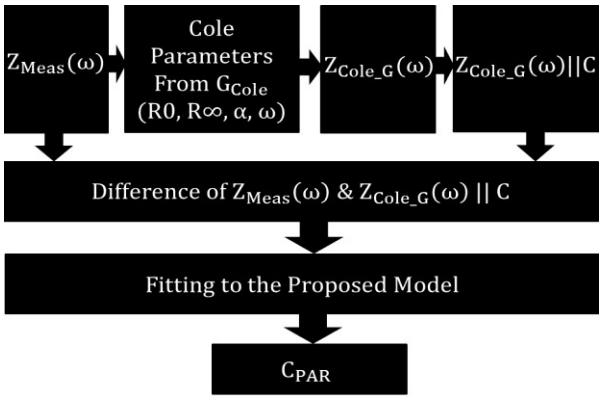

Fig. 2. Block diagram of proposed method.

Since according to the EBIS measurement model from Fig. 1 the difference between $Z_{Meas}(\omega)$ and $Z_{Cole\_G}(\omega)$ is caused by the current divider created by the parasitic capacitances represented by C_{PAR}, the value of C_{PAR} can be estimated by finding the C_{PAR} value that minimizes the error function in (4).

$$\sum_{\omega=1}^{n} \left| Z_{Meas}(\omega) - (Z_{Cole_G}(\omega) || \frac{1}{j\omega C_{PAR}}) \right| \qquad (4)$$

Equation (4) represents the error obtained from subtracting the equivalent impedance produced by the tissue impedance modeled as $Z_{Cole\_G}(\omega)$ in parallel with a capacitor C_{PAR} from the obtained EBIS measurement $Z_{Meas}(\omega)$.

The whole process of obtaining the value for C_{PAR} from the performed EBIS measurement is described in Fig. 2.

C. Validation and the Data Set.

In order to validate the proposed method for estimating the value of C_{PAR} three different sets of impedance data have been used.

- Synthetic Data generated in Matlab®
- Impedance measurements from a 2R1C circuit.
- Non-invasive cerebral EBIS measurements.

In all three data sets the C_{PAR} has been estimated using both the susceptance spectra and the proposed method in this paper and the resulting C_{PAR} values are compared.

1) Synthetic Data Generation in Matlab®.

Considering the measurement model depicted in Fig.1 and the Cole function in (2), impedance data have been generated for the Cole parameters with values R_0=604 Ω, R_∞= 402 Ω, α =0.5 and τ= 1.74×10^{-6}s for C_{PAR} values 47, 68 and 115 pF extracted from observations performed on experimental obtained measurements. The synthetic data have been generated at 255 logarithmic scaled frequency points in the frequency range from 3.096 to 1000 kHz adding white Gaussian noise with 1% relative magnitude to the impedance.

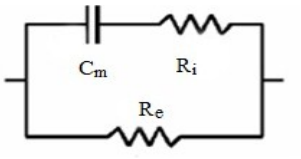

Fig. 3. 2R1C Test Circuit

2) Measurements on a 2R1C Circuit.

On a 2R1C-parallel circuit with R_e = 604 Ω, R_i = 1210 Ω and C_m = 1 nF from SFB7 test circuit values and according to Fig. 3 and with a capacitor added in parallel, C_{PAR}, with values 47, 68 and 115 pF, measurements were recorded using an SFB7 spectrometer manufactured by Impedimed.

3) Cerebral EBI Data.

EBIS measurements from 6 healthy volunteer subjects have been obtained using the four electrode technique and the SFB7 spectrometer in the frequency range from 3.096 to 1000 kHz. In total 35 set of EBI measurements were recorded this gave us an average of 5.8 measurements per subject. For each subject EBI data were record with 4 different electrode placements (EP) according to Fig. 4 and Table I, producing 4 different EBIS cerebral measurements. These measurements were taken with the approval of the regional ethical committee of Gothenburg.

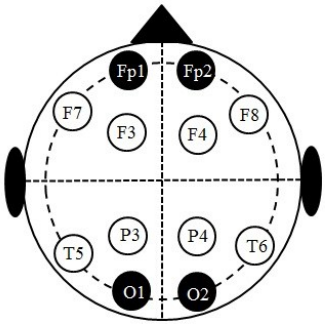

Fig. 4. Different electrode placement for performing the Cerebral EBIS measurements. Note the electrodes are located according to the 10-20 system EEG electrod placement.

TABLE I. PLACEMENT OF CURRENT AND VOLTAGE ELECTRODES FOR EBIS CEREBRAL MEASUREMENTS

	EP1	**EP2**	**EP3**	**EP4**
I+	Fp1	Fp1	Fp2	Fp2
I-	O1	O1	O2	O2
V+	F3	F7	F4	F8
V-	P3	T5	P4	T6

III. RESULTS

A. Comparison of C_{PAR} Estimation

In this section the results from comparing the estimations of C_{PAR} obtained applying both methods on all three data sets are presented.

1) C_{PAR} from Synthetic Data

Table II contains the values for C_{PAR} estimated with both approaches. It is seen that the values produced with the conductance model approach produces a perfect estimation while the values estimated from the susceptance spectra are 24 pF above the actual added value.

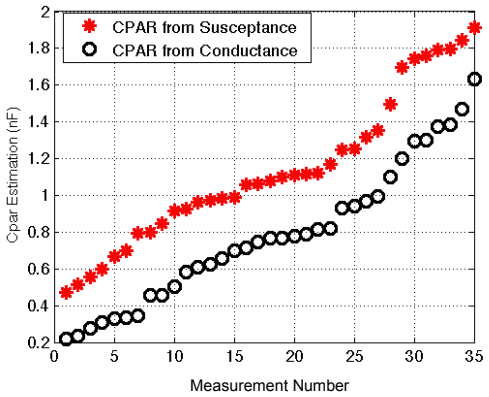

Fig. 5. Comparision of the C_{PAR} estimated from susceptance and conductance.

TABLE II. C_{PAR} ESTIMATED FROM SYNTHETIC DATA USING THE SUSCEPTANCE SPECTRA AND CONDUCTANCE MODEL

Added Value	47	68	115
C_{PAR} from Susceptance (B)	71	92	139
C_{PAR} from Conductance (G)	47	68	115

Note: values are in pF.

2) C_{PAR} from 2R1C Circuit Measurements.

Table III contains the values for C_{PAR} estimated with both approaches from the 2R1C circuit. Again the conductance model approach produces a very close estimation while the C_{PAR} values from the susceptance spectra are over-estimated between 20 to 24 pF approximately.

TABLE III. CPAR ESTIMATED FROM 2R1C CIRCUIT MEASUREMENTS USING SUSCEPTANCE SPECTRA AND CONDUCTANCE MODEL

Added Value	47	68	115
C_{PAR} from Susceptance (B)	67.4	92.1	137.7
C_{PAR} from Conductance (G)	48.3	72.9	118.3

Note: values are in pF

3) C_{PAR} from Cerebral Measurements

As shown in Fig. 5, the results from the C_{PAR} estimated from cerebral EBIS data shows that the value estimated from the susceptance spectrum, with asterisk marker, are larger than the values estimated from the conductance model, with circular marker, proposed in this paper.

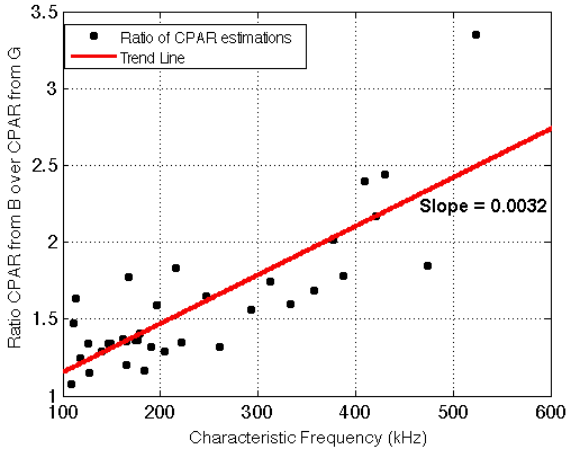

Fig. 6. Ratio of C_{PAR} estimated from susceptance and conductance versus the characteristic frequency.

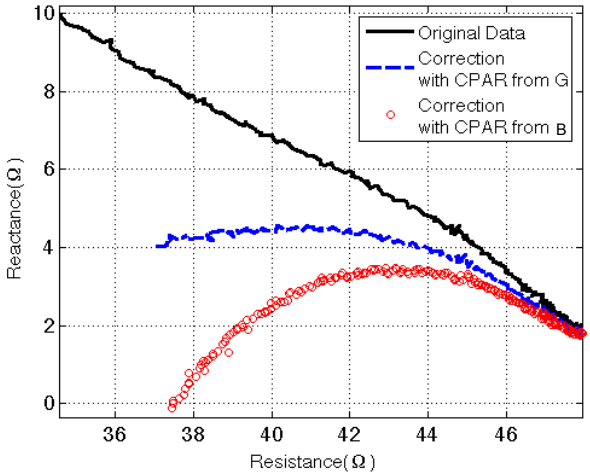

Fig. 7. Cole function of original EBIS versus corrected data using C_{PAR} from conductance (G) and susceptance (B) spectra.

In Fig. 6, the ratio C_{PAR} estimated from susceptance over C_{PAR} estimated from the conductance model is plotted versus the characteristic frequency of each given EBIS measurement for all 35 measurements. It can be observed how the overestimation for C_{PAR} produced by the susceptance spectrum method increases as the characteristic frequency of the EBIS measurement, indicating a certain frequency dependency.

B. C_{PAR} Correction Cerebral EBIS Measurements

The effects of correcting an EBIS measurement using the Correction Function in (1) with the C_{PAR} values obtained from both estimation methods can be observe in Fig. 7.

In the impedance plot from one of the EBIS measurements, continuous trace, it is possible to observe that the correction produced using the value estimated from the susceptance spectrum, plotted with circular markers, overcompensate the capacitive influence, turning the sign of the reactance to inductive values at high values.

IV. Discussion

The results clearly confirm that in case of EBI measurements with higher characteristic frequency, as in the case of cerebral EBI, estimating the value for C_{PAR} from the susceptance spectrum produces wrong estimation, confirming that susceptance from the tissue cannot be neglected for EBIS measurement with high values of characteristic frequency.

The obtained results demonstrate that the method proposed can indeed produce an accurate estimation of C_{PAR}, for the tissues with high characteristic frequency overcoming the limitations of the susceptance-based approach.

In this work, the validation tests have been done under the assumption that there are no other measurement artifacts apart from capacitive leakage affecting the EBIS measurements. If the EBIS measurement is tainted with low or high frequency artifacts like for instance, electrode mismatch [11] the estimation of the Cole parameters from the conductance spectrum would be influenced. It would be interesting to study the robustness of the whole correction approach proposed in this work.

V. Conclusion

Using the conductance of an EBIS measurement containing a main single dispersion together with the Cole function, it is possible to compensate a measured EBIS tainted with capacitive leakage effect. The proposed method enables the correction of EBIS data with high characteristic frequencies allowing a proper spectroscopy analysis of the EBIS data. Emerging novel applications of EBIS like Electrical Bioimpedance Cerebral Monitoring could benefit from the availability of such methods and pre-processing tools.

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