A Novel Approach for Removing the Hook Effect Artefact from Electrical Bioimpedance Spectroscopy Measurements

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Abstract. Very often in Electrical Bioimpedance (EBI) spectroscopy measurements the presence of stray capacitances creates a measurement artefact commonly known as Hook Effect. Such an artefact creates a hook-alike deviation of the EBI data noticeable when representing the measurement on the impedance plane. Such Hook Effect is noticeable at high frequencies but it also causes a data deviation at lower measurement frequencies. In order to perform any accurate analysis of the EBI spectroscopy data, the influence of the Hook Effect must be removed. An established method to compensate the hook effect is the well known Td compensation, which consists of multiplying the obtained spectrum, \(Z_{\text{meas}}(\omega)\) by a complex exponential in the form of \(\exp[j\omega Td]\). Such a method cannot correct entirely the Hook Effect since the hook-alike deviation occurs over a broad frequency range in both magnitude and phase of the measured impedance, and by using a scalar value for \(Td\). First a scalar only modifies the phase of the measured impedance and second, a single value can only corrects the Hook Effect at a single frequency. In addition, the process to select a value for the scalar \(Td\) by an iterative process with the aim to obtain the best Cole fitting lacks solid scientific grounds. In this work the Td compensation method is revisited and a modified approach for correcting the Hook Effect including a novel method for selecting the correcting values is proposed. The initial validation results confirm that the proposed method entirely corrects the Hook Effect at all frequencies.

1. Introduction

Electrical Bioimpedance Spectroscopy is a typical approach currently and potentially in use in several applications of Electrical Bioimpedance (EBI) analysis like total body composition [1], electronic biopsies [2], as well as pulmonary edema [3].

In order to perform any useful data analysis, in addition to use an appropriate analysis method the data should be free from interferences and from artefacts. It is rather common to obtain EBI measurements affected by a characteristic deviation especially noticeable at high frequencies [4] and [5]. Such a deviation is commonly known as Hook Effect because it reassembles to a hook when the impedance spectrum is represented on an impedance plot. Its origin is related to parasitic capacitances influencing on the EBI measurements and its compensation has been studied previously [6].
The *Hook Effect* artefact distinctly modifies the impedance spectra at high frequencies but it affects the complex EBI data at any AC frequency and consequently interfering any posterior EBI data analysis; especially Cole-based analysis that requires to fit the corrupted data with two dominant dispersions into a single-dispersion system: the Cole function.

Currently, the method for correcting the influence of the *Hook Effect* on EBI data is the so-called Td compensation [6], which is worldwide spread and has several limitations.

2. Methods and Model

The error on the estimation of the impedance in a simple measurement model, including a stray capacitance in parallel with the Tissue Under Study (TUS), has been analytically studied using the software packages of Mathematica and Matlab. The *Hook Effect* introduced in the impedance spectrum by the parasitic capacitance has been observed and the compensation of such estimation error by the Td compensation method has been analyzed.

Combining the models proposed by Scharfetter in 1997 for artefacts [6] and Martinssen in 2004 [7] in admittance and neglecting the electrode polarization impedance of the later, it is possible to obtain a simple model equivalent to a current divider. The model used for the study is depicted in Figure 1.

![Figure 1. Model of study](image)

The TUS impedance models an experimental measurement obtained with 4-Electrode wrist to ankle EBI measurement fitted to a Cole function (1) with the following Cole parameters \( R_0=449.6 \, \Omega \), \( R_{\infty}=296.7 \, \Omega \), \( \alpha=0.7186 \) and \( \tau = 5.2727 \times 10^{-6} \), equivalent to a characteristic frequency of 30.2 kHz.

\[
Z_{TUS}(\omega) = R_0 + \frac{R_\infty - R_0}{1 + (j\omega\tau)^{\alpha}}
\]

\[
Z_{meas}(\omega) = \frac{V_{meas}(\omega)}{I_{meas}(\omega)} = \frac{I_{TUS}(\omega) + Z_{TUS}(\omega)}{I_{TUS}(\omega) + I_{leak}(\omega)}
\]

The measured impedance is obtained by expression in (2). Note that the current causing the voltage sensed by the impedance meter, \( V_{meas}(\omega) \) is not the same current generated by the impedance meter.

3. Hook Effect

1.1. Origin and deviation of EBI spectrum

According to the models proposed by [6] and [7], and the model depicted in Figure 1, electrical current intended for stimulating the TUS leaks away from the measurement load through parallel electrical pathways enabled by parasitic capacitances. Such current leakage introduces an impedance estimation error that is frequency dependant [8], this impedance estimation error produces a deviation in the impedance spectrum, especially noticeable at high frequencies since it is at high frequencies when the parasitic leakage pathways become more conductive dragging more current away from the TUS. The produced deviation affects the EBI spectrum at all AC frequencies and it deviates both real and imaginary parts of the EBI spectrum. This means that both module and phase of the EBI spectra are deviated.
The deviation is especially noticeable in the spectra of both reactance and phase at high frequencies, such a deviation is what creates the so-called Hook Effect easily identified in the impedance plot of Figure 2.

4. Td Compensation

Td Compensation is a well known and spread approach used nowadays for correcting the Hook Effect, it consists on multiplying the obtained measured EBI spectra by a complex exponential in the form of $\exp[j\omega Td]$.

The main limitation of this approach is that $Td$ is a scalar and consequently multiplying a complex magnitude like the impedance by $\exp[j\omega Td]$ only modifies the phase of the measured impedance, while the Hook Effect affects both the phase and the module of the impedance spectrum. This implies that for a proper compensation of the produced error on the impedance estimation the value of $Td$ should be complex.

From the analysis of the Td compensation a second limitation arises that for a complete correction of the impedance estimation error, the value of $Td$ cannot be just a number but a function of frequency. This way Td compensation with $Td$ scalar only corrects the deviation produced on the phase by the Hook Effect at a single frequency. In addition a very important limitation of the Td compensation method is that there is no solid scientific method published for the selection of the value for $Td$.

5. The Hook Correction Method

In order to completely correct the impedance estimation error causing the Hook Effect, the value of $Td$ in $\exp[j\omega Td]$ should be complex and function of the frequency instead than just an scalar. A new method developed on the same basis than the Td compensation method is proposed together with a methodology to obtain the values of the correction function.

1.2. Correction Function

From the mathematical analysis performed on the effect caused on the impedance estimation error by the complex exponential $\exp[j\omega Td]$, it was obtained that a mathematical expression could indeed eliminate the impedance estimation error caused by the parasitic capacitance of the model $C_{PAR}$, correcting completely the Hook Effect. The Correction function $F_{Corr}(\omega)$ in (3) is a logarithmic complex function dependent on the natural frequency $\omega$, $C_{PAR}$ and $Z_{meas}(\omega)$, that when substitutes $Td$ on the complex exponential $\exp[j\omega Td]$ and multiplies the obtained complex EBI spectra $Z_{meas}(\omega)$, produces the following final expression (4) for correcting the Hook Effect:

$$F_{Corr}(\omega) = -\frac{\log[1 - j\omega C_{PAR}Z_{meas}(\omega)]}{\omega}$$

(3)

$$Z_{TUS}(\omega) = Z_{meas}(\omega) * e^{-\log[1 - Z_{meas}(\omega) * j\omega C_{PAR}]}$$

(4)
1.3. Parasitic Capacitance Estimation

The admittance of the model depicted in Figure 1, can be written as in (5). Analyzing the frequency dependence of the imaginary part of equation 5 i.e. the susceptance of measurement, it is known that $SC_{PAR}(\omega)$ increases linearly with frequency in the form $SC_{PAR}(\omega)=\omega C_{PAR}$ while $STUS(\omega)$ decreases at high frequencies. See Figure 3. Therefore at high frequencies the value of susceptance of the TUS is practically negligible and it is possible to estimate the value of the parasitic capacitance $C_{PAR}$ using (6) from the measurement.

$$Y_{\text{meas}}(\omega) = G_{TUS}(\omega) + j\left[S_{TUS}(\omega) + SC_{PAR}(\omega)\right]$$ (5)

$$C_{PAR} \approx \lim_{\omega \to \infty} \frac{\text{Lin}[Y_{\text{meas}}(\omega)]}{\omega}$$ (6)

6. Validation of the approach

Figure 4 shows the correction effect caused by the correction function for a $Z_{\text{meas}}(\omega)$ obtained with the previously introduced model and parasitic capacitance $C_{PAR} = 50$ pF. In the figure it can be observed that the Hook Effect is completely removed, obtaining a $Z_{\text{CORR}}(\omega)$ identical to $Z_{TUS}(\omega)$.

Figure 3. Susceptance plot of the TUS impedance (1) against the measured impedance (2) with a $C_{PAR}$ of 50 pF.

Figure 4. Correction effect of $FCorr(\omega)$ over $Z_{\text{meas}}(\omega)$ with a $C_{PAR}$ of 50 pF.
7. Discussion & Conclusion
The proposed method corrects the hook effect caused by the leaking of measurement current away from the measurement load through parasitic pathways at all frequencies in the complex impedance, i.e. both in magnitude and phase. In this way, the mathematical intrinsic limitation of \( T_d \) compensation, the currently in use correction approach, is overcome. In addition, the proposed method is based on a well-accepted model of artefacts, so its implementation is not arbitrary, which it is another advantage over the \( T_d \) compensation method.

The main limitation of the proposed method resides in the estimation of the parasitic capacitance from the susceptance of the measurement, which requires performing EBI measurements up to very high frequency, theoretically the best estimation is done with measurements up to \( \infty \). Ongoing work with experimental measurements suggest that the Correction Function is valid and that works fine with EBI measurements obtained up to 600 kHz.

8. References
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