Modeling parasitic effects with a RLC-RSC model in electrical impedance measurements

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Abstract. Electrode polarization, movement artefacts, cable impedance, parasitic capacitances, and electronic constraints are the main undesirable factors when performing an electrical impedance spectroscopy. Four different phantoms were implemented with electrical components. A 4-electrode probe was used for doing the measurement of the phantoms. The model RLC-RSC ((Resistor//Inductor//Capacitor)-(Resistor//(Resistor, Capacitor))) is proposed and then used for extracting the parameters from raw impedance data by using a particle swarming optimization (PSO) algorithm. The maximum root mean square of the relative error (RMSRE) was 0.80%, whereas 0.15% the minimum. It can be concluded that the model can significantly remove parasitic effects out of a phantom implemented with electrical elements and measured by a 4-point electrode probe.

1. Introduction
In electrical impedance spectroscopy (EIS) systems some unexpected effects may occur during the measurements, such as electrode polarization, movement artefacts [1], cable impedance, parasitic capacitances [2], and electronic constraints [3]. Impedance probes are the most common apparatus for performing EIS measurements [4].

Controlling all those effects is a difficult task, but important if a good extraction of the sample parameters are required [5]. The use of an electrical equivalent model in EIS, which best describe the material under study (MUT), is the ultimate goal of this technique. An application of such electrical model is that most EIS system use the Cole model [6] for tissue characterization. Cole model is a non-integer (0 < α < 1) polynomial function which best describes the biological sample (see equation 1). Most bioimpedance analysis consist of a resistance at zero frequency ($R_0$), a resistance at infinite frequency ($R_\infty$), a dispersion coefficient ($\alpha$) of the material under study and a relaxation time constant ($\tau = 1/f_C$).

$$Z(\omega) = R_\infty + \frac{R_0 - R_\infty}{1 + (f/f_C)^\alpha}$$ (1)

A simple interpretation of the Cole equation can be represented in terms of a RSC electrical equivalent circuit [7], as shown in figure 1(c). It corresponds to the Fricke Equivalent electrical circuit for the Cole equation, where $R_2$ represents the extracellular resistance in low frequencies ($R_2 = R_0 = R$), $R_3$ represents the intracellular resistance for high frequencies ($R_3 = S$), and $R_\infty = RS/(R + S)$. The objective of this paper is investigate this equivalent electrical model for reducing the parasitic effects of measured bioimpedance data from Cole equation. The RLC
(Z_{pe}) represents mostly the parasite effects in the measurements. Removing those effects is a quite hard work, but necessary for a consistent characterization of the material by using the Cole model.

2. **Methods**

2.1. Impedance measurement setup

Measurements were performed by using an impedance meter (model HF2IS), a transimpedance amplifier (model HF2TA) and an impedance probe. The output of the meter (Out1 in figure 1(a)) was setup to provide a sinusoidal voltage of 2 Vpp (peak-to-peak) from 1 to 3,000 kHz. The output voltage is converted to current by the HF2TA (transimpedance amplifier), which is recorded and averaged after 8 measuring frequency sweep. The diameter of the tetrapolar probe is 8 mm containing 4 gold electrodes, separated 2.4 mm apart. A circuit board (figure 1(b)) was developed in order to make a proper contact with the tested circuit elements, where 1, 2, 3, and 4 are the connection points.

![Diagram schematic of the model and measuring system](image)

**Figure 1.** Diagram schematic of the model and measuring system. (a) Measuring system for a MUT. (b) Circuit board connections (c) Fitted $R_2R_3C_1 - R_1LC_2$ model.

2.2. Parasitic impedances

Even using the four electrode technique, residual electrode polarization effect may occur, especially if the electrode impedances are not completely balanced [8]. Therefore, the model in the figure 1(c) was applied to compensate these effects. In this model the parasitic effects ($Z_{pe}$) are modeled by the RLC circuit (between the nodes 6 and 7). Particularly, the inductor L represents the peak effect which may occur at high frequency. The impedance of the material under test ($Z_{MUT}$) is characterized by the $R_2$, $R_3$ and $C_1$ components. The total equivalent impedance spectra from the circuit model is the equation 2, which can be manipulated to obtain the final expression shown in the equation 3.

$$Z(\omega) = \frac{R_2(R_3 + \frac{1}{j\omega C_1})}{R_2 + (R_3 + \frac{1}{j\omega C_1})} + \frac{j\omega L R_1}{R_1 + j\omega L} \cdot \frac{1}{\frac{1}{j\omega C_2}} \quad (2)$$

$$Z(\omega) = (-C_1C_2LR_1R_2R_3\omega^3 + j(LC_1(R_1R_2 + R_2R_3 + R_1R_3) + LC_2R_1R_2)\omega^2$$

$$+ (L(R_1 + R_2) + C_1R_1R_2R_3)\omega - jR_1R_2)/(−C_1C_2LR_1(R_2 + R_3)\omega^2$$

$$+ jL(C_1(R_2 + R_3) + C_2R_1)\omega^2 + (C_1(R_1R_3 + R_1R_2) + L)\omega - jR_1) \quad (3)$$
2.3. Materials and measurements
It was implemented 4 RSC circuits (phantoms) with nominal values of resistors, capacitors, and
inductors according to table 1. The respective column of each circuit represents the nominal
values for the inductances and the capacitances of each implemented circuit. Each phantom
is connected to the circuit board of figure 1(b) and an impedance spectra is measured. It
was implemented a Particle Swarm Optimization (PSO) algorithm in MATLAB, containing a
graphical user interface (GUI). The GUI permits the configuration of the parameters to be set
in the PSO algorithm for limiting its minimum and maximum values.

Table 1. Measured and fitted parameters for circuits 1 to 4, cut-off frequency ($f_C$) and the
resonance frequency ($f_R$).

| Circuit | 1     | 2     | 3     | 4     |
|---------|-------|-------|-------|-------|
| $C_1$ [nF] | 1.00  | 1.00  | 4.70  | 0.82  |
| $R_2$ [Ω] | 56.80 | 50.50 | 73.30 | 65.20 |
| $R_3$ [Ω] | 1.20  | 1.20  | 1.20  | 1.20  |
| $R_1$ [Ω] | 1.10  | 1.10  | 242.00| 61.90 |
| $L$ [µH]  | 100.00| 2.70  | 80.00 | 15.00 |
| $C_2$ [pF] | 15.00 | 271.00| 271.00| 271.00|
| $f_C$ [Hz] | 2.74  | 3.08  | 0.45  | 2.87  |
| $f_R$ [Hz] | -     | 25.00 | 0.34  | 2.50  |
| RMSRE    | 0.80  | 0.15  | 0.15  | 0.18  |

After the optimization of the algorithm, the $Z_{pe}$ value was found and then extracted from
the raw impedance spectra in order to obtain the $Z_{MUT}$ without the parasite effects (here modeled
by the RLC elements).

3. Results
Figure 2 shows the frequency response of phantom 4 and both nominal and fitted values for
phantom 3.

Figure 2. a) Mean impedance spectra of phantom 4; (b) Parameter values of phantom 3

A root mean square of the relative error ($RMSRE$) was calculated according to equation 4
[9], in order to evaluate the effectiveness of the parasitic effects cancelation, simulated by circuit
RLC. Figure 2(a) shows the spectra of one electrical circuit showing both $Z_{RSC}$ and $Z_{RLC}$ from the raw measured impedance. It can be seen that the $Z_{RLC}$ effects start to appear from 100 kHz. The parameters encountered for another circuit (in this case, circuit 4) are shown in figure 2(b). The cutoff frequency was estimated to be 400 kHz whereas 450 kHz for the measured one.

$$RMSRE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} \left( \frac{Z_{MEAS_i} - Z_{RLCRSC_i}}{Z_{RLCRSC_i}} \right)^2}$$ (4)

$Z_{MEAS}$ and $Z_{RLCRSC}$ are the magnitude from measured and fitted impedance, respectively, for 50 points in the frequency range. The maximum error was 0.80% whereas 0.15% was the minimum, which might be related to the resonance frequency and, consequently, to the value of the inductor $L$ in the RLC circuit.

4. Discussions and Conclusion
Phantoms have been used as good mimicking tissue model in EIS. They can be made of gelatin, agar, and others chemical components [10]. Its complex impedance can be simulated with an electrical phantom, which is simply an electrical circuit. An RSC circuit, for instance, models the behavior of phantoms using only 2 resistors and 1 capacitor.

Parasitic effects in the results of EIS measurements could misrepresent the information. In this case, RLC-RSC model was used to remove such effects, where the measurement setup presented was applied. The result showed in figures 2(a) parasitic effect at higher frequencies for measurements in the phantom 4. Similar results were presented by all implemented phantoms. It was expected the impedance spectra to decrease as increasing frequency, especially above 500 kHz, for all phantoms. Thus, applying such model, it removed significantly parasitic effects out for the phantom 4.

The same technique could be applied in EIS systems whose objective is, for instance, discriminating a normal biological tissue to a cancerous one, which, in turn, may increase significantly both sensitivity and specificity of the measuring system.

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