Parameter Identification for a New Circuit Model Aimed to Predict Body Water Volume

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***Abstract*—Intracellular and extracellular water volumes in the human body have been computed using a sequence of models starting with a linear first order RC circuit (Cole model) and finishing with the De Lorenzo model. This last model employs a fractional order impedance whose parameters are identified using the frequency characteristics of the impedance module and phase, the latter being not unique. While the Cole model has a two octaves frequency validity range, the De Lorenzo model can be used for three decades. A new linear *RC* model, valid for a three decades frequency range, is proposed. This circuit can be viewed as an extension of the Cole model for a larger frequency interval, unlike similar models proposed by the same authors.**

***Index Terms*—bioimpedance, circuit synthesis, frequency response, impedance measurement, passive circuits.**

I. Introduction

Accurate information about fluid distribution in different compartments of the body is very important in drug dosage, renal replacement therapy, and nutritional support. Dilution methods, magnetic resonance imaging, computer axial tomography, X-ray method used to determine the fat-free mass are expensive, time consuming, unfit for routine procedures, request laboratories and high trained technicians. The body impedance analysis method being simple, inexpensive, accurate and noninvasive has become largely used to predict the fluid distribution in different compartments of the body [1]-[6]: intracellular water (ICW), extracellular water (ECW) and total body water (TBW). Several variants of the body impedance analysis method have been reported: single-frequency and dual-frequency bioimpedance analysis (BIA), and multi-frequency bioimpedance analysis, called also bioimpedance spectroscopy (BIS).

Intracellular water (ICW) can be used to estimate body cell mass (BCM) which is an important indicator of nutrition status. The evaluation of extracellular water (ECW) is also important to predict changes in fluid distribution for people with wasting, obese people and people receiving dialysis [6].

The body impedance analysis method has not yet reached its full potential. Following the trend to improve the method by increasing the level of model accuracy, a new approach to the parameter identification for a linear *RC* model in bioimpedance spectroscopy is proposed in this paper.

This approach employs the approximation of the measured body admittance modulus $|Y_{RC}(j\omega)|$ with a physically realizable function followed by the circuit synthesis [7]. This model is a linear *RC* circuit with frequency independent values of resistances and capacitances. As the frequency dependence of the phase angle $arg(Y_{RC}(j\omega))$ can be computed from $|Y_{RC}(j\omega)|$ using the Bayard-Bode relationships [8], the measured values of $arg(Y(j\omega))$ are not needed for the parameter identification of this model. Two equivalent circuits of the human body, built using this approach, have been proposed previously [9], [10]. These are ladder circuits which cannot be considered as extensions of the Cole model. A new *RC* circuit, valid for a frequency range of three decades, which can be reduced to the Cole model for a narrow frequency interval, is proposed in this paper.

We build our model starting from measurement of the body impedance frequency characteristic $|Z_{RC}(j\omega)|$ reported in [3]. We proved that the influence of the measurement equipment including signal source, cables (modeled as transmission lines), and connectors is negligible so $|Z_{RC}(j\omega)|$ given in [3] is an accurate representation of the human body impedance modulus [9], [10].

Section II describes the known circuit models of the human body used for ICW and ECW volumes prediction. Aiming that this paper be self-contained, Section III describes an efficient method for *RC* admittance synthesis. The new *RC* circuit model of the human body is developed in Section IV.

II. Human Body Circuit Models

The frequency dependence of the body impedance can be explained taking into account the behavior of the organic tissue at low frequencies (LF) and at high frequencies (HF). In the LF range (1 KHz to 70 KHz), the cell membrane capacity has a high impedance value and the electric current flows mainly through ECW. In the HF range (70 KHz – 1 MHz), as this impedance decreases, the current flows through both ICW and ECW depending on their relative conductivities and volumes [11].

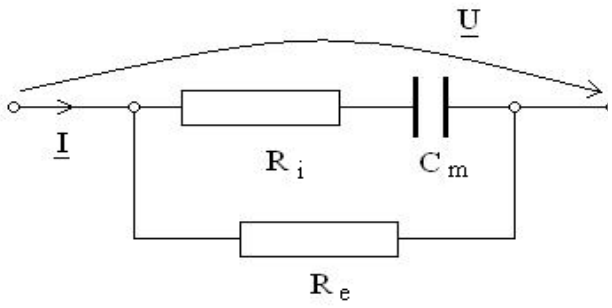

Figure 1. Cole model

At a first glance, this behavior can be modeled with a

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very simple linear electrical circuit known as the Cole model [2], [3], [4] which is shown in Fig. 1, where R_i stands for the resistance of the intracellular fluid, C_m is the capacity of the cellular membrane and R_e stands for the resistance of the extracellular fluid.

The AC equivalent resistance of this circuit at zero frequency is $R_0=Re$ and its AC equivalent resistance at infinite frequency is $R_\infty=(R_i*R_e)/(R_i+R_e)$.

Approximating R_0 with the measured AC resistance at the minimum frequency ω_m and R_∞ with the measured AC resistance at the maximum frequency ω_M, the ICW volume V_I and the ECW volume V_E are estimated as:

$$V_I = k_I \cdot Wt \cdot (Ht^2 / R_i) \quad (1)$$

$$V_E = k_E \cdot Wt \cdot (Ht^2 / R_e) \quad (2)$$

where Ht is the height, and Wt is the weight of the subject, and k_I and k_E are constants which can be determined by cross validation against other methods [2], [3].

The measurement results show that, in a wide frequency range (e.g. for two or three decades), the parameters in this circuit are frequency dependent and the relationships between the resistances of this model and the body water volumes are nonlinear. For example:

- the electrical permittivity depends on frequency as it is pointed out in Fig. 2 [3],

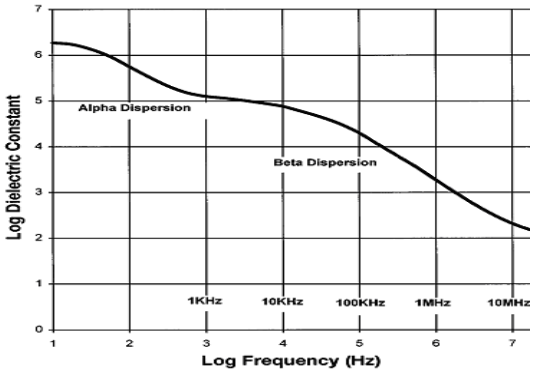

Figure 2. Dielectric constant of the muscle tissue vs. frequency

- the mixture effects have a greater influence on the skeletal muscle resistivity in the LF range than in the HF range [3],
- due to the complexity of the nonlinear relations between R_i and R_e and ICW and ECW volumes, some heuristic relations as (1) and (2), including the height and weight of the subject are used to compute body water volumes.

Over 500 KHz, the time delay between the excitation and its response cannot be neglected [3]. In this case a model with distributed parameters could be more accurate.

As it will be shown in Section IV, the frequency characteristic of the Cole model with frequency independent values R_i, C_m, and R_e cannot be fitted to the measured data on a three decades frequency range. In order to fix this drawback, a modified Cole model has been proposed in [3] in which the body impedance is considered as:

$$Z(j\omega) = \left(\frac{R_e}{R_e + R_i}\right)\left(R_i + \frac{R_e}{1+[j\omega C_m (R_e + R_i)]^{\alpha}}\right)e^{-j\omega T_d} \quad (3)$$

where ω is the angular frequency, T_d is the delay, and $\alpha \in [0.3,\ 0.7]$ is a coefficient whose value is chosen to fit the values given by (3) to the experimental data. As this formula doesn't lead to a single valued function $arg(Z(j\omega))$, the identification of its parameters based on measured frequency characteristics $|Z(j\omega)|$ and $arg(Z(j\omega))$ cannot be made. In our opinion the measurements of $|Z(j\omega)|$ and $arg(Z(j\omega))$ suggest a circuit like that in Fig. 1 having frequency dependent components, rather than this bizarre formula that has been obtained starting from the equivalent impedance of the linear circuit in Fig. 1 in which the power $\alpha<1$ is attached to one term while other terms remain unchanged. Taking into account that the frequency dependence of material parameters is not known for all kinds of tissues, the development of an accurate physical model is very difficult or even impossible.

We appreciate that a behavioral model, as a linear circuit which can be an extension of the Cole model, will be the best choice, taking into account that the intracellular and the extracellular water volumes are related to the real part of the model impedance computed at minimum and maximum frequencies [3], this impedance being well defined only for a model of this kind.

The parameters of a model with a given structure are extracted or identified using optimization methods. In general these methods minimize the distance between the measurement results and those obtained by simulation. In the case of semiconductor devices, the parameters of the large signal DC models or those of the small signal AC models are usually extracted using numerical techniques. Some symbolic methods have been used efficiently for parameter identification [12]-[14]. The circuit functions are generated using a symbolic method, obtaining analytical formulas in terms of s and model parameters. These parameters are computed using an optimization method to reach a global minimum of the distance between the measured and simulated values of the circuit functions for a set of test frequencies. The symbolic methods are very efficient for the computation of derivatives which are usually needed in the optimization procedure. The optimization can be performed using genetic algorithms [15]. Sometimes hierarchical techniques are employed to obtain combined DC-AC models [16].

III. SYNTHESIS OF RC ADMITTANCES

For the sake of completeness, the synthesis method developed in [7] is presented below. The characteristic $|Y_{RC}(j\omega)|$ has asymptotes whose slopes are 20 dB/decade, 0, 20 dB/decade, 0, a. s. o, the pole and zero values alternating on the negative real axis [8]. The average slope of a given characteristic can be estimated as a weighted mean of these two values. The approximation by asymptotes of $|Y_{RC}(j\omega)|$ has the maximum error of *3dB* at the asymptote intersection point [7].

A natural way to approximate $|Y_{RC}(j\omega)|$ is to consider a smaller asymptote number than that corresponding to the measured characteristic. A greater error ε between measured and simulated values leads to a simpler circuit.

The algorithm for the synthesis of a *RC* one-port has the following steps [7]:

1. computation of the first zero z_1
2. computation of the other poles and zeros
3. computation of the circuit parameters

The frequency range of interest is $[\omega_m, \omega_M]$. The smallest

module zero z_1 is set to ω_m. Sweeping the frequency axis with a step $\Delta\omega_m$, the algorithm checks the error between the *20 dB/decade* asymptote and the given characteristic. The first pole p_1 is assigned to the last value before that corresponding to an error of 2ε or greater. If this error occurs after the first angular frequency step $\Delta\omega_m$, then p_1 is placed in the vicinity of z_1. Afterwards, the first asymptote is translated so that a maximum error of ε is obtained. The other asymptotes are determined in order to fulfill the condition $error \leq \varepsilon$ for each asymptote.

IV. PARAMETER IDENTIFICATION FOR NEW *RC* CIRCUIT MODEL

The parameters of the Cole model with frequency independent values R_i, C_m, and R_e can be identified using the measured impedance values for three frequencies. As the resistance values at the minimum and maximum frequencies are used for ECW and ICW volume estimation in (1) and (2), we have chosen these three frequencies as $\omega_1=\omega_m$, $\omega_2=\omega_M$, and ω_3 corresponding to the intersection points between the measured characteristic and that of the Cole model (Fig 3). In this case it is obvious that the results obtained with this Cole model are not fitted to the measured data. Identifying the parameters of this Cole model in a different way i.e. using three frequencies in the middle of the frequency interval, significant errors appear at the minimum and maximum frequencies.

It follows that the Cole model is not suitable for ECW and ICW computation. The parameter identification for (3) is

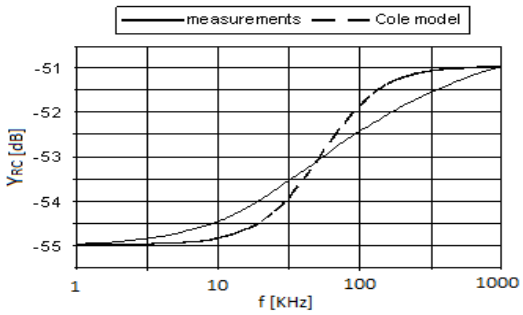

Figure 3. Comparison between the Cole model and the measured results

made in [3] (ignoring the uncertainty on phase) starting from both measured frequency characteristics $|Z(j\omega)|$ and $arg(Z(j\omega))$. A very good fitting of the model characteristics to the experimental data is obtained. The real parts of the body impedance in (3) at ω_m and ω_M are not AC resistances, so the formulas (1) and (2), aimed to be employed with the Cole model AC resistances cannot be used.

For the proposed method only the measured frequency characteristic $|Y(j\omega)|$ is used. In order to build this model, we employ the approximation method followed by the circuit synthesis as it is described in the previous section.

Using the above algorithm, the frequency characteristic $|Y(j\omega)|$ corresponding to the data in [3] has been approximated by the admittance in (4) with an error ε=0.95 dB using an average sweeping step $\Delta\omega_m$=8315 Hz. The synthesis of this admittance can be made by various methods.

$$Y_{RC}(s)=\frac{1.78e-3\left(1.59e-4\cdot s+1\right)\left(1.3e-5\cdot s+1\right)\left(4.31e-6\cdot s+1\right)\left(1.86e-6\cdot s+1\right)\left(7.58e-8\cdot s+1\right)}{\left(1.591e-4\cdot s+1\right)\left(1.154e-5\cdot s+1\right)\left(3.808e-6\cdot s+1\right)\left(1.647e-6\cdot s+1\right)} \quad (4)$$

The most interesting circuit seems to be that obtained by the Foster II method and is given in Fig. 4. The parameter values are: C5=5.9 pF, R5=27 MΩ, C4=2.14 nF, R4=4.78 kΩ, C3=0.945 nF, R3=4.03 kΩ, C2=0.51 nF, R2=3.23 kΩ, C1=0.195 nF, R1=561.5 Ω.

The resistance corresponding to the volume of the extracellular water can be computed for f_{min}=1 KHz and has a 560.97 Ω value, which is practically the same with R_E=562 Ω given by the Cole model.

The resistance corresponding to the volume of the intracellular water can be computed for f_{max}=1000 KHz and

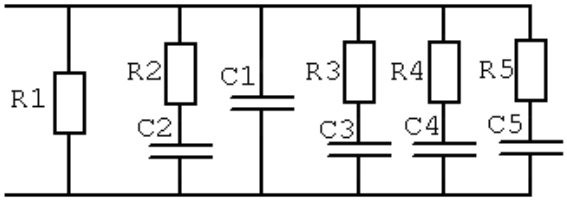

Figure 4. Foster II synthesis of the new circuit model

has a 314.97 Ω value, unlike R_I=352.69 Ω given by the Cole model. Due to the better agreement with experimental data, it is expected that the body water volume prediction will be improved considering these values in (1) and (2). A similar circuit (Fig. 5) is given in [3] without pointing out how the resistance and capacitance values can be computed starting from the measured data.

It is very interesting to observe that R1 has a similar value to Re in the Cole model, being the equivalent resistance for f=0. This circuit can be viewed as a generalization of the Cole model. The two branches model contains R_1, R_2, C_2,

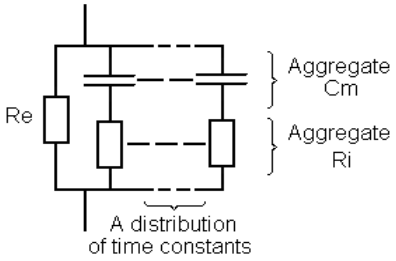

Figure 5. The extended Cole model [3]

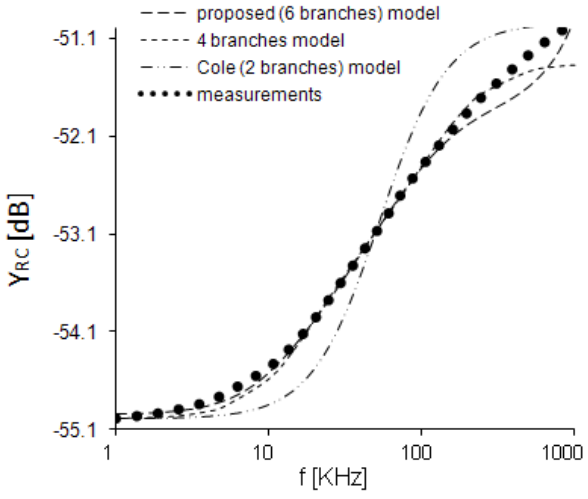

Figure 6. The measured frequency characteristic vs. those of some proposed models with 2, 4, and 6 branches.

and so on. As the frequency range of interest is extended to higher frequencies, a model with a greater number of

branches is needed. The simulated data obtained with models with various numbers of branches, obtained by imposing the same error ε on various frequency intervals are given in Fig. 6. In order to appreciate the agreement between the measured and simulated data, the measuring errors must be taken into account. Unfortunately, no information on these errors is given in [3].

V. CONCLUSIONS

We have shown that the Cole model for body water volume prediction, having frequency independent R_i, R_e, and C_m values, is inaccurate. The admittance module and phase of the modified Cole model, based on a bizarre formula, which cannot be used for the computation of $arg(Z(j\omega))$ are fitted to the measured values in [3].

The parameter identification for a new behavioral model of the human body used to compute ICW and ECW volumes has been performed in this paper. This model is a linear *RC* circuit with frequency independent elements, whose parameters can be identified starting from the measured values $|Y_{RC}(j\omega)|$, unlike the case of the modified Cole model which needs, in addition, the measured values of $arg(Y_{RC}(j\omega))$.

After the synthesis of a ladder *RC* model valid for a frequency range between 1kHz and 100 KHz [9], and its extension to a three decade frequency interval [10], we propose a new circuit model whose validity range is three decades, too. This new linear lumped *RC* circuit avoids using both intricate frequency dependent elements suggested by the physical interpretation of current conduction in human body and the bizarre impedance formula of the modified Cole model [3]. The proposed model contains some *RC* branches connected in parallel. This model can be simplified, taking into account that the influence of some branches is negligible in a certain frequency range, its ultimate simplification being the linear RC Cole model. It follows that this model can be considered as an extension of the linear RC Cole model, allowing a better prediction of the intracellular and extracellular water volumes.

The behavior of any kind of tissue can be in principle formulated as a fractional order system containing two resistors and a constant phase element described by a fractional power of s [17]. Although the impedance of this system reminds about the formula (3) discussed above, we appreciate that a linear *RC* circuit model, based on straightforward concepts, is more useful for intracellular and extracellular water volume prediction than that fractional order system.

The development of this new model illustrates the actual trend [11], [18] to make noninvasive investigation methods more precise in various areas of medicine. Coronary artery disease [19], colorectal cancer [20], and HIV infection [21] are some examples of this kind.

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