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# A geometrical method for modeling bioelectrical impedance measurements and remove the hook effect deviations

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***Abstract*. Objective: to describe a simple and straightforwardmethod to calculate the circle parameters that can be used to fitElectrical Bioimpedance Spectroscopy (EBIS) raw data to the complex plane and remove the hook effect, a deviation of that model especially seen at higher frequencies and considered as an artifact due to instrumental limitations. Approach: under the assumption that raw EBIS data in the middle frequencies best represent the beta dispersion, the authors of this article propose a geometrical procedure to calculate parameters for this dispersion and remove the hook effect. For this purpose, data obtained with two different devices were used with apparently very good results. Main results: the results of this study suggest that circle parameters for the beta dispersion can be obtained, but, also, that the residuals of the hook effect correction seem toadjust to a circle and, therefore, they could also be parameterized using the same approach. Significance: the method proposed in this article is very easy to perform and could help end EBIS users not familiar with mathematical models and fitting processes, to better understand and interprettheir data.**

Keywords— **Hook effect, Cole model, Electrical Bioimpedance Spectroscopy (EBIS), complex plane, fitting methods.**

## I. INTRODUCTION

According to [1], the history of electrical bioimpedance spectroscopy (EBIS) can be traced back to at least one century, 1910, when Hoeber reported the discovery of the $\beta$-dispersion. Currently, the future of EBIS looks very promising, especially because the spectrum of its possible clinical applications is very wide and growing [2, 3]. The first area where EBIS was partially accepted, both clinically and commercially, was for studies of body composition, mainly based on the principle that EBIS resultsare associated with body water content [4]. [5] concluded thatwhole body EBIS measurements can predict total body water [6], and, later, Lukaski *et al* [7] and other researchers began topublish different equations to assess body composition. These equations, though, are age, gender and ethnicity dependent and this factor has limited its wider use worldwide, as there isnot a universally valid equation. The best way of dealing with EBIS data is to parameterize them [8] and this requires a mathematical process that is difficult to understand and to carry out by people with a predominant biological background such as physicians, nurses and physiologists, amongst others. Another limitationfor a wider use of EBIS is the fact that, very often, experimental data do not completely fit well with the single dispersion Cole model, the most commonly accepted model when parameterization of data is carried out. One of the difficulties regarding the fitting is known as the hook effect [9, 10], especially notorious at high frequencies. So far, this effect has been considered as an artifact of the measurements,mainly due to different parasitic capacitances [11]. In this paper, we extend the method of parameterizationproposed by [12] to fit whole body EBIS measurements to thecomplex plane. This method has not yet been validated, but it looks very promising and we are confident that further research and validation will prove it right. In this article we propose the extraction of the parameters [13] and the subsequent removal of the hook effect from the main single central dispersion, characteristic of the frequencies in the middle range ($10 kHz \leq f \leq 100$ kHz). First step is to obtain circle parameter of the main dispersion, with raw data from frequencies in the middle range of the spectrum (10, 20 and 50 kHz). Secondly, residuals are obtained subtracting the corresponding theoretical values from the raw data. Thirdly, parameters for the circle of the residuals are calculated. Finally, both theoretical curves (main dispersion and residuals) are summed up to compare the results to the raw data.

## II. METHODS

### *A. Data*

Data used to illustrate the proposed method in this paper weretaken from our archives. All of them were whole body Bio- Impedance Analysis (BIA) measurements, taken either with aBIA 4200 Hydra Xitron analyzer (USA-California) or with aSECA mBCA 525 device (Germany-Hamburg).

### *B. Data fitting to the complex plane*

In order to fit raw data to an arch in the complex plane, the method proposed by [12] was used. Basically, it assumes that: a) there is a main dispersion in EBIS data better represented for values around the characteristic frequency, especially on its right side; b) this dispersion adjusts well to an arch, and c) the parameters of the circle to which the arch belongs (centre location and length of the radius) can be calculated if the coordinate values (resistance or R and reactance or Xc) of just three points of the arch are known. In this article, it is assumed that there are two dispersions with

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a circular pattern. A first one, which we would like to consider as the main dispersion and which fits well around frequencies in themiddle range of the spectrum (i.e. 10 kHz - 100 kHz), and a second one that fits well at higher frequencies (> 100 kHz), which correspond to those where the hook effect is more evident. For the first dispersion, data points at frequencies 10,20 and 50 kHz were used, while, for the second dispersion, data points at frequencies 100, 200 and 500 kHz were used. For the latter, values were those given by the subtraction of the modelled values of *X*c for the main dispersion from the actual raw data. The calculation of the circle parameters was carried out with a free-use widget provided by the Webpage Wolfram Alpha [14].

### *C. Raw data used in this paper*

Raw data taken with a Xitron Hydra 4200 BIA equipment andused to illustrate the method proposed in this study are shownin Table I, where frequencies are separated into three ranges:low, middle and high ($f < 10$ kHz, 10 kHz $\leq f \leq$ 100 kHz and$f$ > 100 kHz, respectively) [13, 15, 16]. The values of the three points used for the calculation of the circle parameters in both cases are given in terms of ohms, with resistance (*R*) as the *X* axis value and reactance (*X*c) as the *Y* axis value in the complex plane. To extract the hook effect from the raw data, the theoretical values for *X*c at each frequency were calculated using the Pythagorean theorem, where the hypotenuse was equal to theradius of the circle and the length of one of the sides was equalto *R* at that frequency minus the *X* value of the centre. From the obtained value, the *Y* value of the centre was added (it is always negative, as the circle is depressed) and the result was assumed as the theoretical value of *X*c.

TABLE I. DATA USED FOR THE CALCULATION OF PARAMETERS,TAKEN WITH A XITRON HYDRA 4200 BIA EQUIPMENT.

III.

| Low range ($f \leq 10$kHz) | | | Middle range (10 kHz < $f$ < 100kHz) | | | High range ($f \geq 100$kHz) | | |
|---|---|---|---|---|---|---|---|---|
| *f* (kHz) | *R* (Ω) | *Xc* (Ω) | *f* (kHz) | *R* (Ω) | *Xc* (Ω) | *f* (kHz) | *R* (Ω) | *Xc* (Ω) |
| 5 | 554.0 | 29.3 | 10 | 539.9 | 42.8 | 100 | 442.8 | 59.3 |
| 6 | 552.1 | 32.9 | 11 | 537.5 | 44.8 | 115 | 437.2 | 58.0 |
| 7 | 548.2 | 35.6 | 12 | 534.7 | 46.8 | 128 | 433.2 | 56.9 |
| 8 | 546.1 | 38.2 | 13 | 532.2 | 48.2 | 143 | 429.8 | 55.9 |
| 9 | 542.9 | 40.7 | 14 | 529.5 | 49.9 | 159 | 425.9 | 55.0 |
| | | | 15 | 527.5 | 51.1 | 177 | 423.1 | 54.0 |
| | | | 16 | 524.7 | 52.5 | 200 | 419.1 | 53.1 |
| | | | 18 | 520.5 | 54.6 | 220 | 416.9 | 52.5 |
| | | | 20 | 516.1 | 56.5 | 245 | 413.8 | 51.9 |
| | | | 23 | 509.8 | 58.6 | 273 | 411.1 | 51.4 |
| | | | 25 | 506.4 | 59.7 | 304 | 408.8 | 51.2 |
| | | | 28 | 500.7 | 60.9 | 339 | 406.1 | 51.2 |
| | | | 31 | 496.4 | 61.9 | 378 | 404.3 | 51.2 |
| | | | 35 | 490.0 | 62.7 | 421 | 401.8 | 51.6 |
| | | | 39 | 485.4 | 63.2 | 469 | 400.3 | 52.1 |
| | | | 43 | 480.2 | 63.4 | 500 | 398.8 | 52.6 |
| | | | 50 | 473.1 | 63.4 | 582 | 396.8 | 54.0 |
| | | | 54 | 469.6 | 63.4 | 649 | 395.3 | 55.4 |
| | | | 60 | 464.2 | 62.9 | 723 | 393.7 | 57.0 |
| | | | 67 | 459.7 | 62.4 | 806 | 393.0 | 58.8 |
| | | | 75 | 454.2 | 61.6 | 898 | 392.0 | 61.3 |
| | | | 83 | 450.4 | 60.9 | 1000 | 391.8 | 63.4 |
| | | | 93 | 445.3 | 59.9 | | | |

## III. RESULTS

The values used for the calculation of the circle parameters ofthe two dispersions are shown in Table II, along with the parameters themselves.

TABLE II. DATA USED FOR THE CALCULATION OF THE CIRCLE PARAMETERS FOR THE TWO DISPERSIONS CONSIDERED IN THISARTICLE AND THE PARAMETERS THEMSELVES.

| Dispersions | 1st | 2nd |
|---|---|---|
| Frequency for first point (kHz) | 10 | 100 |
| Frequency for second point (kHz) | 20 | 200 |
| Frequency for third point(kHz) | 50 | 500 |
| Raw data for 1st point (*R*, *X*c, both in Ω) | (539.9, 42.8) | (442.8, 2.6) |
| Raw data for 2nd point (*R*, *X*c, both in Ω) | (516.1, 56.5) | (419.1, 9.8) |
| Raw data for 3rd point (*R*, *X*c, both in Ω) | (473.1, 63.4) | (398.8, 30.1) |
| Center of the circle(X, Y) | (479.1, -35.5) | (446.6, 57.5) |
| Radius (*r*) of the circle | 99.1 | 55.1 |
| $R_\infty$ for the main dispersion(*X*c = 0 Ω) | 386.6 | ------ |
| $R_0$ for the main dispersion(*X*c = 0 Ω) | 571.7 | ------ |
| $\alpha$ for the main dispersion (dimensionless) | 0.64 | ------ |
| ($X_c$ at $\omega_c/r$) for the main dispersion (Ω) | 63.6 | ------ |

Figure 1 a) shows raw data obtained with the Xitron Hydra 4200B (Table I) and the fitted arch calculated with the parameters of the circle corresponding to the first dispersion. It clearly shows that the fitting of data at the right side of the figure (corresponding to low and middle frequencies) looks very good, while the hook effect appears at higher frequencies.

Figure 1 b) shows that the subtraction from the raw data of thetheoretical values obtained for $X_c$ with the equation for the main dispersion gives values very close to zero on the right side of the curve, i.e. at low and middle frequencies. This indicates a very good fitting of the data to the first dispersion in this side of the curve, but results deviate from zero (upwards) at higher frequencies (left portion of the curve). The deviation begins approximately midway between the distance separating the centres of the two semicircles. These residuals also fit very well to another arch of a circumference, and they were also also adjusted to an arch by the same method proposed by [12].

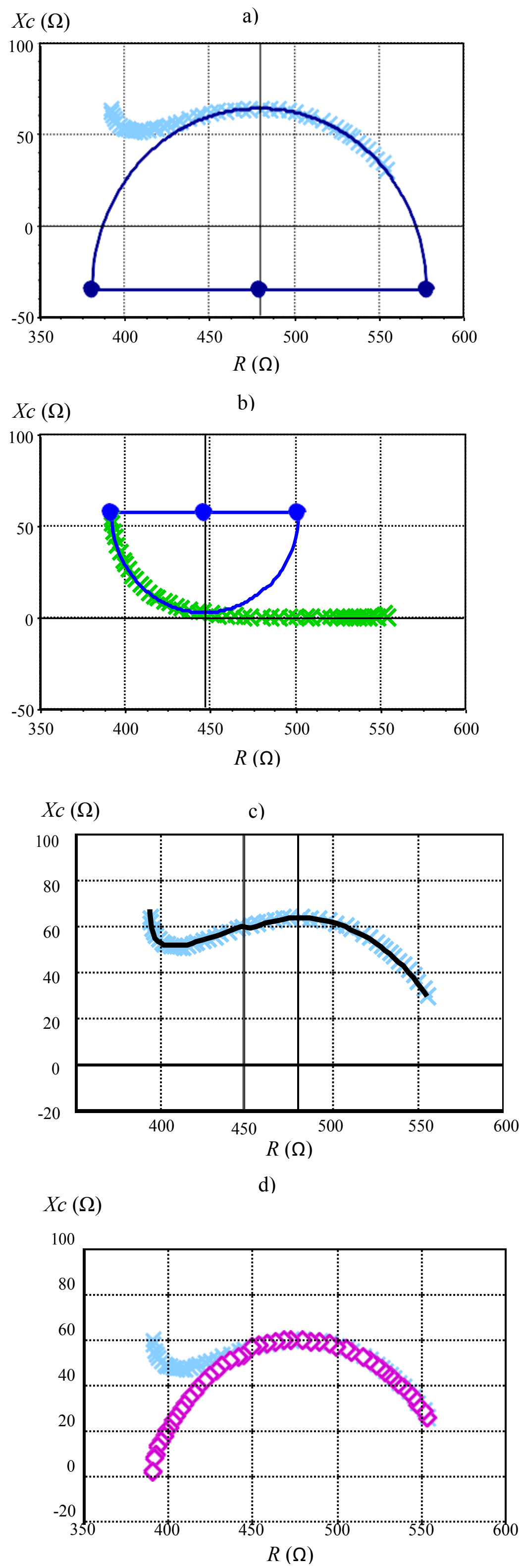
When values of the two theoretical curves are added up at higher frequencies, there is an excellent match between actual data and theoretical values (figure 1 c).

Finally, in figure 1 d), data after the removal of the hook effect are presented. This remotion was carried out by substracting the values corresponding to the second circle from the raw data.

## IV. DISCUSSION

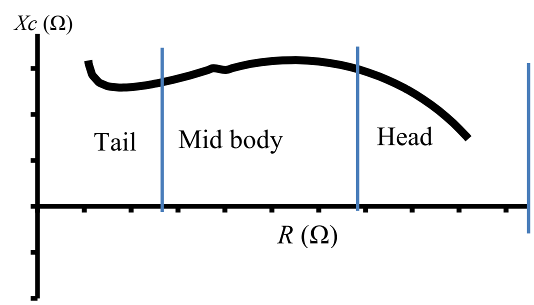
In the field of EBIS, a second dispersion is frequently mentioned in the literature. However, so far, the deviation of experimental data from a fitting arch, especially at higher frequencies, has been considered as an artifact due to the measurement devices [9-11].

Figure 1. Fitting of raw data using two dispersions. a) Main dispersion obtained with the values at 10, 20 and 50 kHz; b) fitting for the values obtained by subtracting the corresponding theoretical values from the raw data at frequencies where the hook effect is visible (in this case, beginning with 90 kHz, where the difference between raw and theoretical data is 2.5 Ω);c) overall fitting of the raw data by adding the values corresponding to the two dispersions considered in this article.




The authors of this article propose a method for removing the hook effect at higher frequencies. Nevertheless, as the residuals obtained subtracting the theoretical value from the raw data gives an arch, the method could possibly be extended for the calculation of the circle parameters for two dispersions (one at middle frequencies and the other at higher frequencies). Both methods, the one for obtaining the circle parameters thatfit to what we call here the main dispersion, and its use for obtaining the circle parameters for the second dispersion, arestill to be validated. This will require the collaboration of people in the physical and mathematical side of the EBIS field such as physicists, mathematicians and/or engineers. This taskis out of the scope of the present study, but it will be undertaken using data obtained with different devices and in different situations. In relation to the first dispersion, the values for $R_0$ and $R_\infty$ canbe easily calculated using the Pythagorean Theorem. The alpha parameter of the Cole equation could be related to the ratio of the reactance at the characteristic frequency to the "length" of the radius. This would oscillate between 1 (if the fitting gave a perfect semicircle) and 0 if there were no capacitance at all (giving a straight line as, in this case, *Z* would be equal to *R*). Raw data and its fitting, as presented in this paper, resemble an "S" shape commonly adopted by some worms as the *Lumbricus terrestris*, and we propose to divide it into three main regions that we would like to call, from right to left, as head, mid body and tail (see Figure 2).

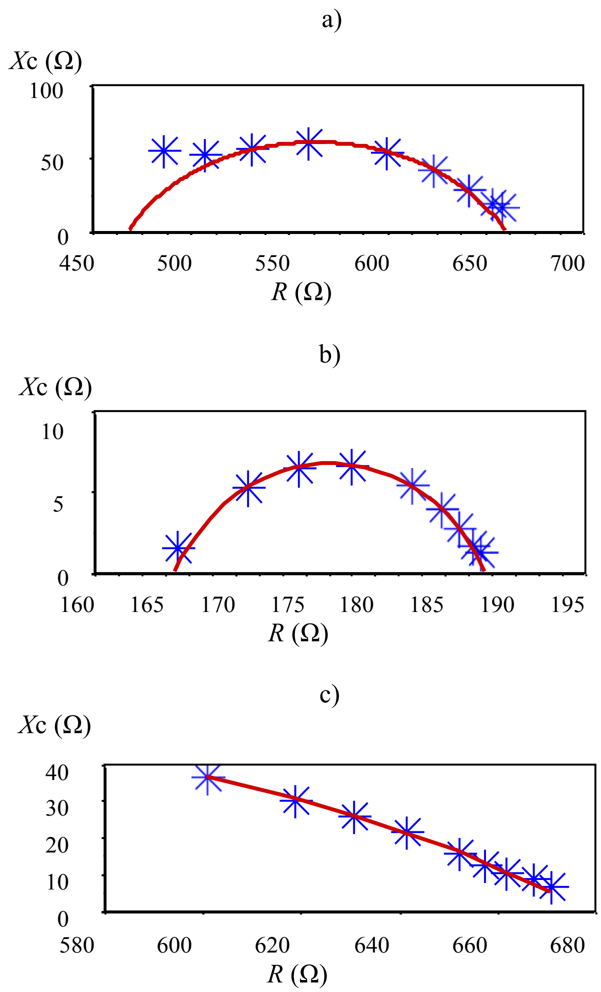
Figure 2. "S" shape form of ebis data showing the so called "hook" effect.




Based on this, we can classify the curves of raw data obtained by EBIS measurements into three different types: 1) When values at higher frequency reach the tail (Fig.3 a); 2) When values at higher frequencies only reach themiddle body (Fig. 3 b); 3) When values at higher frequencies are on the head(Figure 3 c).

The adjustment of data to a central or main dispersion, allows to detect deviations both at lower and higher frequencies and this opens the possibility of detecting and, eventually, removing them, in order to have a better representation of the actual characteristics of the objetbeing studied or, at least, of its main or central dispersion.

Figure 3. Fitting of raw data taken with a Seca mBCA 525.




## CONFLICT OF INTEREST

The authors declare that they have no conflict of interest regarding this article.

## V. CONCLUSIONS

This article presents the principles for a process to fit data from raw electrical bioimpedance measurements to the complex plane and modeling and removal of the hook effect. If two dispersions were to be considered, it could also be used to obtain the parameters of two circles that fit the raw data. The method has to be thoroughly validated and, if proven to be correct, it could facilitate a better understanding and interpretation of experimental data obtained by people in the biological side of the EBIS field (physicians, nurses and biologists, among others).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