1st International Conference on Sensing Technology
November 21-23, 2005 Palmerston North, New Zealand

Auto balancing bridge method for bioimpedance measurement at low frequency

J Prado, C Margo, M Kouider, M Nadi
Electronic Instrumentation Laboratory of Nancy
Henri Poincaré University - Nancy 1, France
Email: juan.prado@lien.uhp-nancy.fr

Abstract

The main objective of this work is to evaluate a cell for dielectric properties measurement of biological material. A prototype was designed based on Titanium electrodes connected to an LRC meter. The prototype was designed for applications from 42 Hz to 1 MHz. The system was also tested with a simplified electrical RC model. The experimental results are compared to finite element simulation. Polarisation impedance effects are also analysed.

Keywords: dielectric properties, bioimpedance, polarisation, bioelectromagnetism

1 Introduction

Impedance measurement is commonly used for electronic circuits, components, material or electrolytic solution characterisation. This method is also of great interest in biomedical engineering [1]. Dielectric properties of biological tissue, electrical conductivity σ and relative permittivity ε_r, could be determined by the way of impedance measurement made in vivo or ex vivo. Several techniques were used to achieve impedance measurement according to the frequency range [2]. As an example, dielectric properties of aqueous electrolyte solutions are of considerable importance for understanding of hydration, and complexation behaviour of ions. Related elementary mechanisms in liquids depend on properties as electric conductivity and are of great interest for a variety of applications. Much attention has also been given to the dielectric properties of cells and biological tissues [3]. We propose here the auto balancing bridge method for impedance measurement for small quantities of biological fluids at low frequency in order to determine their dielectric characteristics.

2 Conductivity and Permittivity theoretical approach

The permittivity and the conductivity of a biological sample are not directly accessible. A contrary, its impedance value Z_X is measurable and we can thus derive the equations for the conductivity and the relative permittivity as a function of the measured impedance. The biological sample is placed into a measurement cell with a given geometry. Here, we first consider a cylindrical or rectangular measurement cell with identical electrodes at the ends. The conductivity and the relative permittivity of the samples are usually determined as follows. Let the electrodes be separated by a distance D [m] and the electrode area A [m^2] with a sinusoidal current I applied to the cell. The total current density (equation 1) is given by

$$J = (\sigma + j \cdot \omega \cdot \varepsilon)E \quad [A/m^2] \tag{1}$$

Where $\varepsilon = \varepsilon_r\, \varepsilon_o$, $\omega = 2\pi$ f, σ Conductivity of saline solution [S/m], ε Permittivity [F/m], ε_r Permittivity relative [dimensionless],ε_o Permittivity of void = 8.854187818X10-12 [F/m], ω Angular velocity [rad/sec], f frequency of voltage source E [Hz], E Electric field [V/m].

We also assume that J = I /A and we define the cell constant factor K_{cell} (equation 2) as a function of its geometry and dimensions.

$$K_{cell} = D / A \tag{2}$$

$$Z_X = \frac{V}{I} = K_{cell} \frac{1}{(\sigma + j \cdot \omega \cdot \varepsilon)} \tag{3}$$

To determine the σ and ε values (equations 4 and 5) it is necessary to calculate Z_X (equation 3) with the values of I and V. Direct relations exist between electrical conductivity σ and permittivity ε versus impedance Z_X.

To distinguish between real and imaginary parts we obtain finally:

$$\sigma = K_{cell} \cdot G \tag{4}$$

$$\varepsilon = K_{cell} \cdot \frac{1}{\omega} \cdot B \tag{5}$$

Where G is the Conductance (equation 6) and B Susceptance (equation 7) [m/S^{-1}]

Therefore:

$$G = \frac{1}{[Z_X]} \cdot cos(\varphi) \quad (6)$$

$$B = -\frac{1}{[Z_X]} \cdot sin(\varphi) \quad (7)$$

The measured impedance is constituted by the addition of the desired impedance of the biological tissue Z_X and the polarisation impedance $Z_p = R_p + 1/j\omega C_p$. It is thus possible to determine Z_X in amplitude and phase.

3 Measurement method principle

The general principle is shown on fig. 1. The current flowing through the device under test (DUT), flows also through the resistor R, The potential at the point L is maintained at zero volts because the current through R balances with the one flowing throught the DUT. The impedance is calculated using voltage measurement at high terminal and that across R [4].

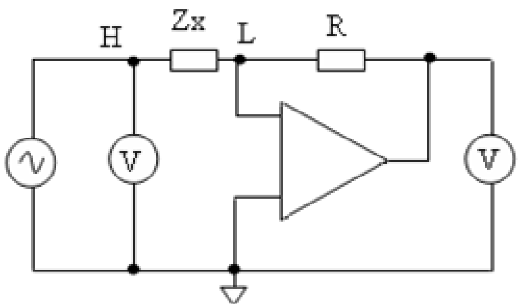


Figure 1: Auto balancing bridge method.

In our case the sample of biological material placed inside the measurement cell act as the "DUT." The impedance is measured at different frequencies. The measuring electrodes are placed at predetermined positions and the volume and the distances between electrodes are well known. In the present study the technique was used to measure the dielectric properties of saline solutions in the 42 Hz to 1 MHz range. In practice, the highest operating frequency is limited by the phase differences induced by stray capacitances of the measuring circuits that can mask the relevant reactive signal. The two components (phase and magnitude) of the impedance Z_X are to be determined. We worked with saline solution because this electrolytic is present in *in vivo* and *in vitro* fluids and because their dielectric values are well referenced [5].

3.1 The polarisation impedance

When using metal electrodes, as it is generally the case, a metal electrolyte interface is present. The contact of the electrodes with the biological tissue or the electrolyte leads to electrochemical phenomena. Metal ions tend to migrate into solution and for ions in the electrolyte to combine with the metal. This results a charge distribution in the immediate vicinity of the electrodes and thus in an additional impedance called "polarization impedance" [6]. This well known phenomena is specific for a given electrode-electrolyte interface. The potential due to polarisation impedance is dependent upon the metal-electrolyte combination, current density, and frequency [7][8][9].

3.2 Equivalents circuits

As a result of Warburg's pioneering studies in 1899, it was proposed that single electrode/electrolyte interface could be represented by a series RC circuit as shown in Fig. 2 [10]. However, the R and C values are frequency and current – density dependent.

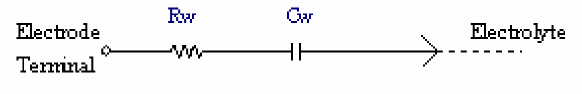


Figure 2: Warburg equivalent circuit.

Electrode polarisation affects biological impedance measurements up to 100 KHz. Hence it is desirable to present complete curves of Rp and Cp over the total frequency range from 42 Hz up to 1MHz. Such measurement has been carried out by previous authors with a variety of electrodes of different sizes.

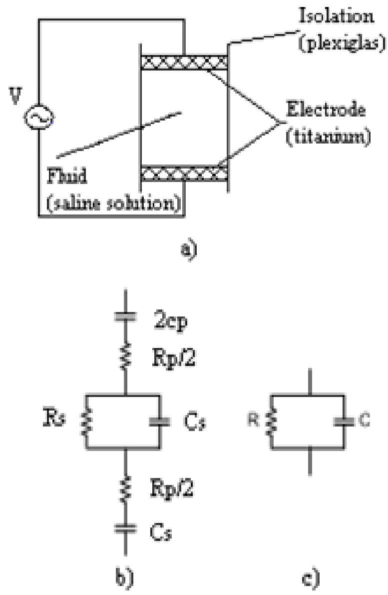


Figure 3: Measurement cell and equivalent electrical circuit.

Figure 3 shows the cell with electrolyte exhibiting electrode polarisation at the interface between electrodes and test solution (Figure 3a), the equivalent electrical circuit depicting the polarisation impedance Rp and Cp, in series with the sample Rs and Cs (Figure 3b) and the total observed capacitance C and resistance R in terms of an equivalent parallel circuit (Figure. 3c) [7].

In order to avoid or limit the polarization phenomena, it is possible to use gold or black platinum electrodes [11]. For technical facilities, we used here titanium electrodes. However, polarization effects were not always precised at low frequency and may be erroneously identified in the absence of any knowledge about electrode polarisation. Indeed, a substantial amount of biological impedance data continues to be in error and reflects confusion about the relative contribution of electrodes polarisation to the total measured impedance.

4 Simulation

Electric field distribution was simulated using an electromagnetic module of FEMLAB software (version 3.0a, 04/2004) based on Maxwell equations for a quasi-static hypothesis. The measurement cell was assumed a rectangle mesh containing 10678 tetrahedral elements and 956 number boundary elements was generated from FEM (Finite element methods) with Lagrange quadratic elements. Equipotential lines and direction and intensity of the electric field in the cell (Fig. 4 and 5) were simulated in order to analyse the behaviour of the cell as function of its parameters. The impedance, Z_X , is calculated from the current I, across the sample which is obtained from domain integration of the current density (Z_X =V/I).

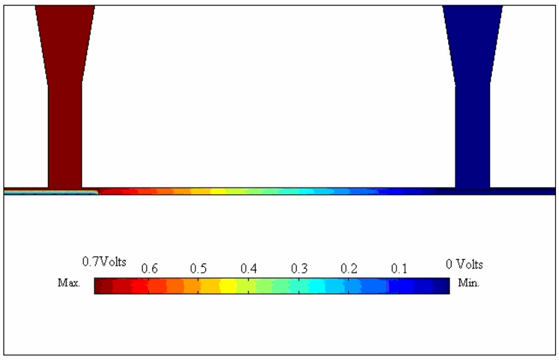


Figure 4: Electric field in the measurement cell

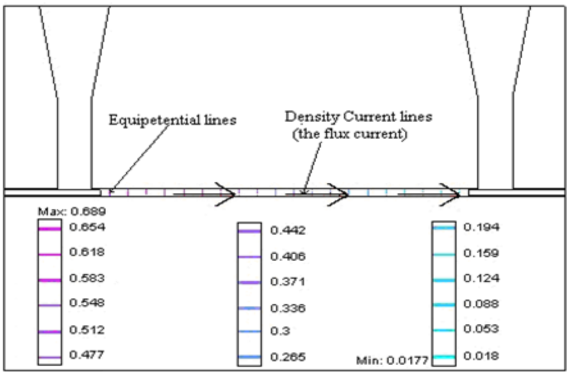


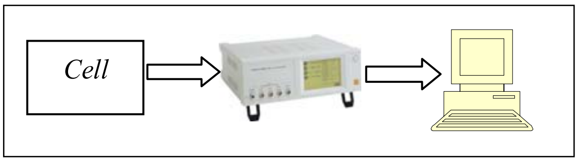
Figure 5: Current density and Equipotential lines

5 Experimentation

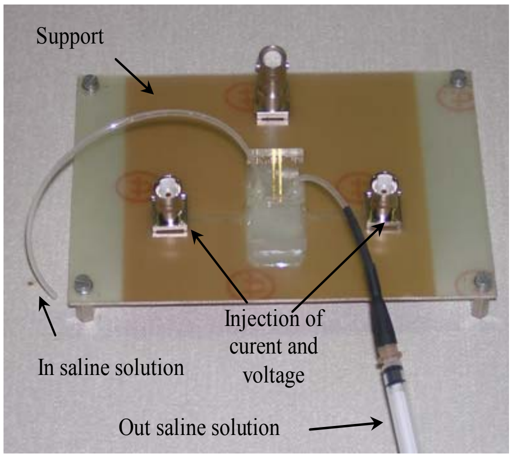
5.1 Material

The measurement system is showed on fig. 6. The measurement cell includes a Plexiglas micro tank, Titanium electrodes and a epoxy printed circuit board with socket for electronic connexion. The whole set is connected to a HIOKI 3532-50 LCR HiTESTER impedance meter to measure the impedance of the saline solutions at different frequencies. HPVEE software was used for data analysis.

.



a)



b)

Figure 6: a) System Prototype, b) Measurement cell.

The measurements were carried out with a cylindrical measurement cells with identical electrodes at the ends. The diameter of the electrodes was 2mm. The impedance of the saline solution was measured with a distance of 10.5 mm between the electrodes. The cell constant K_{cell} was thus determined according to these parameters for a cylindrical geometry..

5.2 Results

The figure 7 illustrates the results, impedance and phase with measurement cell with Titanium electrodes. The source is 0.707 V alternating current volts peak-to-peak [12][13]. The 42 Hz to 1 MHz frequency range was automatically analyzed for 58 points and a logarithmic scanning [14]. Figure 8 shows the results for the relative permittivity and the conductivity. We worked with a sample of saline solution (NaCl ; HI 70301 ; 12 S/m) and at a 23°C. Figure 9 presents the graphic simulated with Femlab, for the NaCl solution and our measurement cell. Values of the equivalent circuit R_S and C_S (see figure 2b) are respectively of 3554.45 Ω and 0.162 pF. The effects of polarisation electrodes are more evident in the low frequency range (under 3 kHz) [15].

It is possible to get interesting results in the first measurement. To test the validity of the approach we performed 10 series of measurements and calculated the average to obtain curves of figures 7 and 8. We observe in these graphs (figures 9 and 10) that the resistance calculated with the Femlab simulation (4141Ω) is greater than what we found in experimentation. This is related to the behaviour of the HIOKI 3532-50 (50Ω) impedance meter at low frequency. With real biological material the effective impedance increases contact considerably compared with saline solutions [16][17].

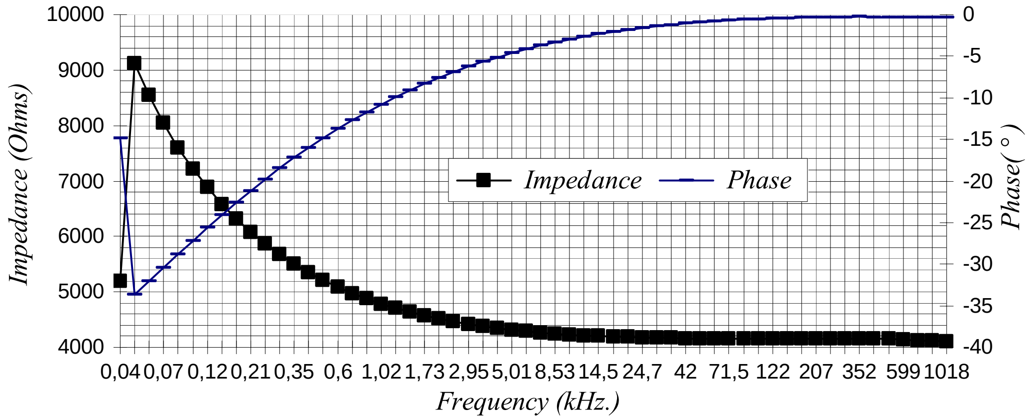


Figure 7: Impedance and Phase for Titanium electrodes with saline solution.

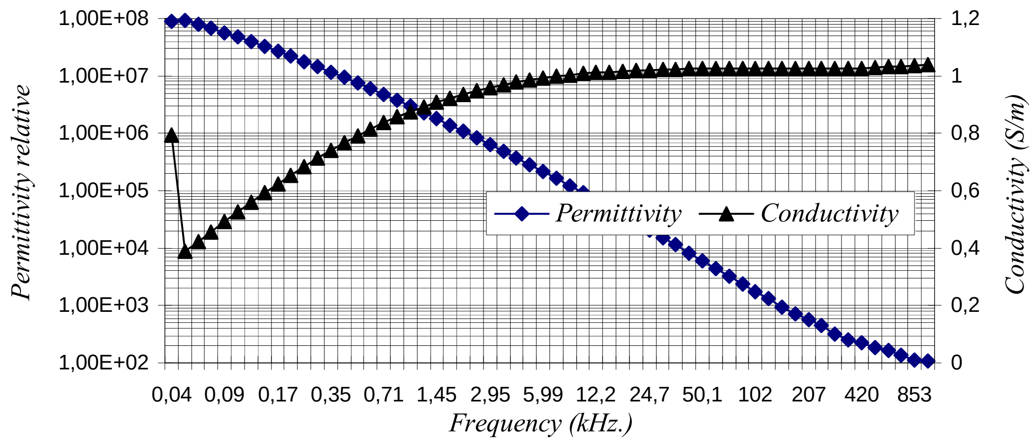


Figure 8: Electrics properties of saline solution (type HI 3030).

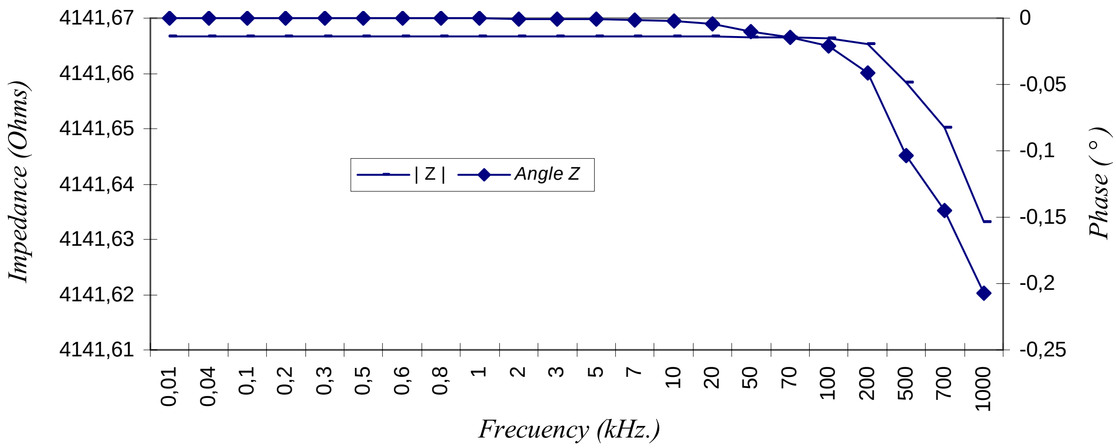


Figure 9: Simulation of the impedance variations using FEMLAB (εr = 78 and σ = 1,12).

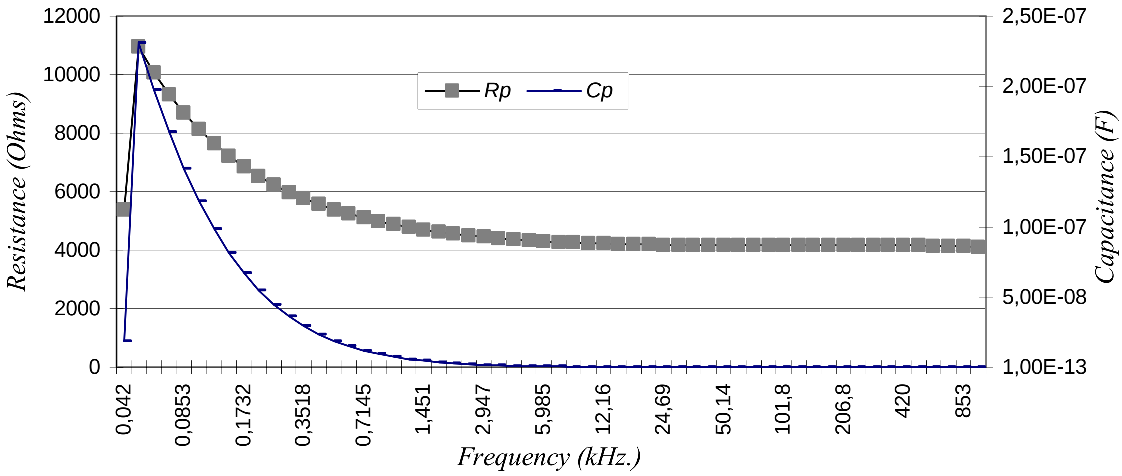


Figure 10: Capacitance and resistance of polarisation (f < ~3kHz).

6 Conclusions

We have studied the possibility to estimate contact impedance polarisation of electrodes simultaneously with internal electrical properties of a biological fluid. A simple model using a FEM based approach that could be used to dimension the measurement cell was proposed but has to be perfected for other kinds of configuration.

7 References

[1] *Proceedings of the XII International Conference on Electrical Bioimpedance & V Electrical Impedance Tomography, Gdansk, Poland, (2004).*

[2] Foster, K. R., Schwan, H. P., "CRC Handbook of biological effects of electromagnetic fields", *Charles Polk and Elliot, Eds.,* pp 25-102 (1995).

[3] Nörtemann, K., Hilland, J., Kaatze, U., "Dielectric Properties of aqueous NaCl Solutions at Microwave Frequencies", *J. Med. Chem.,* vol 101, pp 6864-6869 (1997).

[4] Honda, M., "*Impedances measurement handbook*'', Edition Hewlett Packard (2003).

[5] Carter, J. S., Linker, C. J., Turkle-Husling, T., Howard, L. L., "Comparison of impedance at the microelectrode-Saline and Microelectrode-Culture Medium Interface", *IEEE trans on Biomed. Eng.* vol 11, pp 1123-1129 (1992).

[6] Schwan, H.P., "Alternating current electrode polarisation", *Biophysik,* vol 3, pp 181-201 (1966).

[7] Ackmann, J. J., Seitz, M.A., "Methods of complex impedance measurements in biologic tissue", *CRC Crit. Rev. Biomed. Eng.,* vol 11(4), pp 281-311 (1984).

[8] Fricke, H., "The theory of electrolytic polarisation", *Phil. Mag.*, vol 14, pp 310-318 (1932).

[9] Mcadams, E.T. and Jossinet J., "Electrode-electrolyte impedance and polarisation", *Innov. Tech. Biol. Med.,* vol 12, n° special 1 (1991).

[10] Warburg, E., "Uber das Verhalten Soginannter Unpolarisirbarer Elektroden Gegen Wechselstrom", *Ann. Phys. Chem.,* vol 76, pp 473-499 (1899).

[11] Geddes, L. A., "*Electrodes and the measurement of bioelectric events*", Wiley Interscience, New Yor (1972).

[12] Geddes, L. A., DaCosta, C. P., and Wise, G., "The impedance of stainless steel electrodes", *Med. Biol. Eng.,* vol 9, pp 511-521 (1971).

[13] Ragheb, T., Geddes, L. A., "Electrical Properties of Metallic Electrodes", *Med. Biol. Eng. Comput.*, vol 28(2), pp 182-186 (1990).

[14] Kouider, M., Nadi, M., Kourtiche, D., Prado, Olivarez. J., and A. Rouane, A. "Hardware and software implementation for auto-calibrated measurement system", *IEEE sensor, the second international conference, vol 1*, Oct. 22-24, pp 611-616 (2003).

[15] Gabriel, S., Lau, R.W., Gabriel, C., "The dielectric properties of biological tissues: II. Measurements in the frequency range 10 Hz. to 20 GHz", *Phys. Med. Biol.,* vol 41, pp 2251-2269 (1996).

[16] Tirado M., Grosse C., "Conductivity dependence of the polarisation impedance spectra of platinum black electrodes in contact with aqueous NaCl electrolyte solution", *Colloids and Surfaces A: Physicochem. Eng. Aspects,* vol. 222, pp 293-299 (2003).

[17] Hamzaoui, L., Rigaud, B., Granie, M., Martinez, E., Morucci, J. P., "Tissue characterization by spectrometric measurements of the electrical Bioimpedance", *Innov. Tech. Biol. Med.,* vol 16, n° special 2 (1995).