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Application of Tetrapolar Electrode Systems in Electrical Impedance Measurements

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The specifics of using tetrapolar electrode systems for a wide class of electrical impedance measurements are discussed. The key factors affecting the error in solving the inverse electrical impedance problem using a tetrapolar electrode system are determined.

Introduction

Multichannel electrical impedance rheography provides noninvasive measurement of such parameters of blood flow as perfusion, stroke volume, and ejection fraction [1]. It also allows displacements of organ and tissue boundaries to be detected [1-3]. Measurement of these parameters is based on solving the inverse problem of electrical impedance probing to estimate the values of specific impedance and layer thickness within the framework of the accepted biophysical model. The error of specific impedance measurement in soft tissues in the range of 1.5 to 20 Ω·m [4] should not exceed the contribution of pulse blood filling to the specific impedance (0.01 to 0.1 Ω·m, i.e. ~1%) [5].

Tetrapolar electrode systems are especially often used for electrical impedance measurements (Fig. 1) [4]. In these systems, alternating current with an amplitude ≤10 mA and frequency in the range of 50-150 kHz passes through a pair of current electrodes. The voltage is measured from the potential electrodes using an instrumentation amplifier. The input current of an instrumentation amplifier does not exceed 100 pA. Thus, if a tetrapolar electrode system is used, polarization effects occurring at the electrode–skin boundary do not lead to an additional error in electrical impedance measurement.

Modern rheography techniques – precardiac impedance mapping [1], electrical impedance myography [2], and electrical impedance tomography [3] – use tetrapolar electrode systems with interelectrode distances of 10-160 mm in current and potential electrode pairs. However, these techniques do not take into account the increase in impedance measurement error caused by the electrode diameter (3-10 mm) being comparable to the size of the electrode system. It also leads to an increase in the error related to the mutual position of electrodes.

The specifics and methodological aspects of application of tetrapolar electrode systems should be studied to

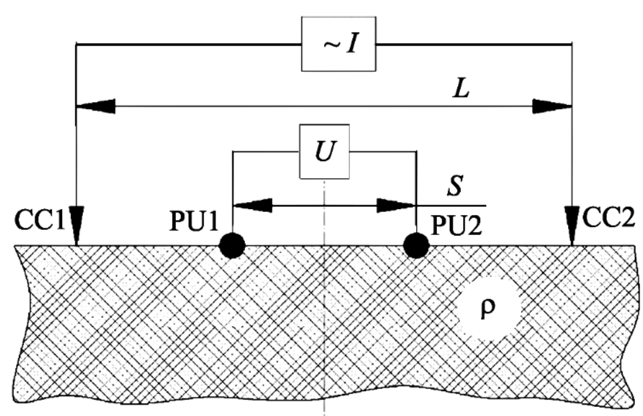

Fig. 1. Mathematical model of electrical impedance probing of semi-infinite continuous medium with specific impedance ρ: CC1, CC2 – current electrodes; PU1, PU2 – potential electrodes; L – distance between the current electrodes; s – distance between the potential electrodes.

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minimize the measurement errors, to estimate their contribution to the results of measurements and subsequent calculations, and to improve the accuracy of solving the inverse problem of electrical impedance probing.

Analytical Estimates

The distances L and s between the current and potential electrodes, respectively, and the electrode diameter d are the main parameters of a tetrapolar electrode system.

The ratio s/L is considered optimal when it leads to minimization of the relative error of measurement of the specific impedance ρ of the medium.

The optimal ratio s/L can be determined analytically based on the mathematical model of a semi-infinite homogeneous medium with the specific impedance ρ (Fig. 1). If a symmetric tetrapolar electrode system with point electrodes is used, the measured impedance between the potential electrodes is [6] (Fig. 1):

$$R = \frac{2\rho}{\pi}\left(\frac{1}{|L-s|} - \frac{1}{L+s}\right). \quad (1)$$

The absolute errors ΔL and Δs of positioning of electrode pairs are equal because the fitment holes for the electrodes have been made using the same manufacturing procedure. Thus,

$$\delta\rho\left(\frac{s}{L}\right) = \frac{\Delta\rho}{\rho} = \frac{\left|\frac{\partial\rho}{\partial L}\cdot\Delta L\right| + \left|\frac{\partial\rho}{\partial s}\cdot\Delta L\right|}{\rho} =$$

$$= \frac{1+\frac{s}{L}}{\frac{s}{L}\cdot\left(1-\frac{s}{L}\right)}\cdot\frac{\Delta L}{L} \to \min. \quad (2)$$

The minima of these functions are at

$$\frac{s}{L} = \sqrt{2}-1$$

and

$$\frac{s}{L} = \frac{1}{1-\sqrt{2}}.$$

The physical significance of the second minimum is that the electrode system remains optimal (i.e., providing minimal relative error of measurement of the specific impedance of the medium) if the positions of the current and potential electrodes are reversed. This accords well with the reciprocity principle, according to which swapping the current and potential electrodes should not affect the results of impedance measurement [6].

If the relative instrumental error $\delta R = \Delta R/R$ of impedance measurement is also taken into account, we obtain:

$$\delta\rho \geq \left(3+2\sqrt{2}\right)\cdot\delta L + \delta R. \quad (3)$$

In practice, it is easier to manufacture electrode systems with $s/L = 1/2$ or $s/L = 1/3$. In this case,

$$\delta\rho\left(\frac{1}{2}\right) = \delta\rho\left(\frac{1}{3}\right) \geq 6\cdot\delta L + \delta R. \quad (4)$$

In particular, at $L = 100$ mm, $\Delta L = 0.1$ mm and $R = 100\ \Omega$, $\Delta R = 1\ \mathrm{m}\Omega$, the relative error of measurement of the specific impedance is mainly determined by the accuracy of electrode positioning and equals approximately 1%.

A symmetric tetrapolar system provides the minimal error of measurement of the specific impedance. Indeed, let us consider a non-symmetric electrode system with the potential electrodes PU1 and PU2 shifted by a distance e with respect to the symmetry axis (Fig. 2).

If two more potential electrodes PU1′ and PU2′ are added to the system to attain symmetry, two symmetric tetrapolar electrode systems are obtained. Their impedances are related to the impedance measured by the non-symmetric electrode system as follows:

$$R(\mathrm{PU1}, \mathrm{PU2}) = \frac{R(\mathrm{PU1}, \mathrm{PU1'})}{2} + \frac{R(\mathrm{PU2}, \mathrm{PU12})}{2}. \quad (5)$$

Therefore,

$$\delta\rho\left(\frac{s}{L}\right) = \frac{\delta\rho\left(\frac{s+2e}{L}\right)}{2} + \frac{\delta\rho\left(\frac{s-2e}{L}\right)}{2} \to \min. \quad (6)$$

This sum of two non-negative terms reaches its minimum only when both electrode systems are optimal. Thus,

$$\frac{s+2e}{L} \to \sqrt{2}-1$$

and

$$\frac{s-2e}{L} \to \sqrt{2}-1,$$

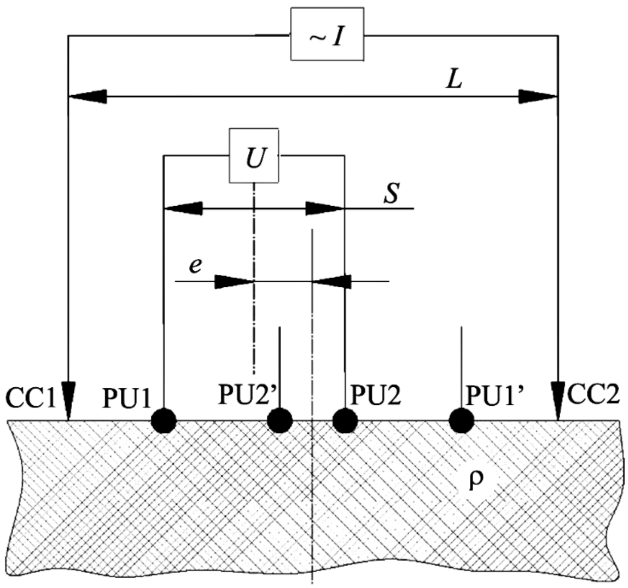

Fig. 2. Mathematical model of electrical impedance probing of semi-infinite continuous medium using a non-symmetric electrode system: CC1, CC2 – current electrodes; PU1, PU2 – potential electrodes; PU1′, PU2′ – potential electrodes added to attain symmetry; L – distance between the current electrodes; s – distance between the potential electrodes.

which is possible if and only if $e \to 0$. Thus, a non-symmetric electrode system provides minimization of the relative error of measurement of the specific impedance only if it can be reduced to a symmetric system.

The electrodes are of a finite size, which leads to an additional systematic error of measurement. If disc electrodes with diameter d are used, the impedance of a semi-infinite homogeneous medium (Fig. 1) is [4]:

$$R' = \frac{2\rho}{\pi \cdot d}\left[\arcsin\left(\frac{d}{L-s}\right) - \arcsin\left(\frac{d}{L+s}\right)\right]. \quad (7)$$

The relative systematic error of measurement of the impedance R can be estimated by comparing Eq. (7) to Eq. (1) for point electrodes:

$$\delta R = \frac{|R' - R|}{R} = \frac{\arcsin\left(\frac{d}{L-s}\right) - \arcsin\left(\frac{d}{L+s}\right)}{\frac{d}{L-s} - \frac{d}{L+s}} - 1. \quad (8)$$

In particular, at $s/L = 1/2$ and $d/L = 1/10$, the systematic error δR reaches 1%.

Discussion

The optimal interelectrode distance ratio for the electrode system

$$\frac{s}{L} = \sqrt{2} - 1$$

has been found using the semi-infinite homogeneous medium model. Inverse problems of electrical impedance probing are formulated for a layered medium or a medium with a spherical inclusion. The obtained equation (3) for estimating the relative error of measurement of the specific impedance ρ of the medium provides the lower estimate of the maximum achievable error $\delta\rho$ for any layer or inclusion, because the effect of the inclusion is always weaker than that of the semi-infinite medium.

Equation (3) allows the electrode system build quality (depending on the relative error δL of electrode positioning) to be assessed. For this purpose, it is necessary to measure the specific impedance of the calibration fluid (for example, saline solution) or to compare the measurement errors for two electrode systems from the same batch.

The ratio d/L can be decreased to reduce the systematic error δR. However, this process is accompanied by an increase in the probing current source loading, so that the source capacity should be taken into account. The load can be estimated as twice the contact impedance of a single disc electrode with diameter d for a semi-infinite homogeneous medium with the specific impedance ρ [4]:

$$R \geq 2 \cdot \frac{\rho}{2d} = \frac{\rho}{d}. \quad (9)$$

For example, if $\rho = 10\ \Omega \cdot$m and $d = 2$ mm, the load on the current source exceeds 5 kΩ, i.e., the limit of the effective range of modern impedance sensors.

The decrease in the electrode diameter d also gives rise to parasitic resistances and capacitances at the electrode/tissue contact interface [7-9]. These effects can be suppressed using liquid electrodes, which have rather large contact interface area, but come into direct contact with the biological object only at a small point (Fig. 3) [10].

The systematic measurement error can be eliminated by switching from statistical estimates of the specific impedance to estimating its time variation. For two different results of measurement of the specific impedance $\rho(t_1)$ and $\rho(t_2)$, the relative error of measurement of the specific impedance is determined as twice the random error in the impedance R:

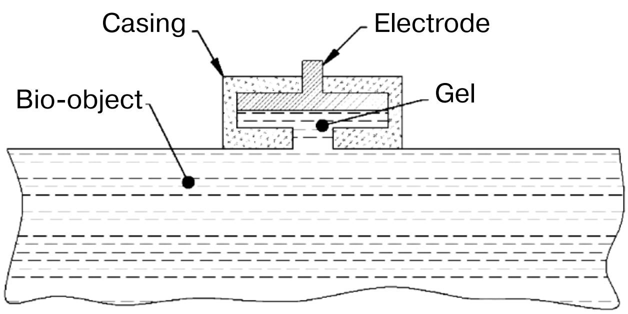

Fig. 3. Electrode design providing elimination of spurious polarization effects at a small contact diameter.

$$\delta\left(\overline{\Delta\rho}\right)=\frac{\Delta\left[\Delta\rho\left(t_1\right)-\Delta\rho\left(t_2\right)\right]}{\rho\left(t_1\right)-\rho\left(t_2\right)}=\frac{2\cdot\delta R\cdot\bar{\rho}}{\rho\left(t_1\right)-\rho\left(t_2\right)}=\frac{2\cdot\delta R}{\overline{\overline{\delta\rho}}},\quad(10)$$

where

$$\bar{\rho}=\frac{\rho(t_1)+\rho(t_2)}{2}.$$

Conclusions

The optimal ratio of interelectrode distances was determined analytically. Based on this ratio, the contributions of the systematic electrode positioning error and the random instrument error to the measured specific impedance of the medium were determined. Requirements for the design of electrode systems were formulated that allow the effect of procedure errors on the results of solution of the inverse electrical impedance problem to be minimized.

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