ELECTRODE - TISSUE INTERFACE: THE METHOD OF ACHIEVING STABLE AND REPEATIBLE ELECTRODE IMPEDANCE

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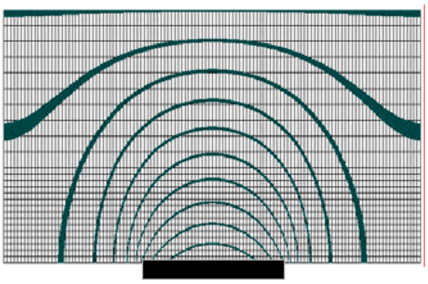
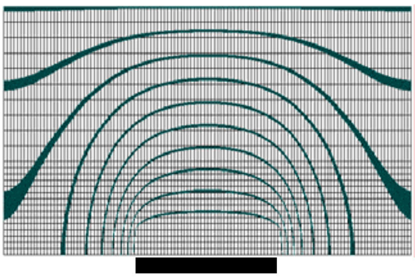
Abstract: A three- and four-electrode probes are considered. An influence of the electrode impedance on results of apparent impedance measurements is presented in the paper. Modification of potential distribution in the examined medium due to different impedance of double layer created at the electrode-tissue interface is also examined. It is found that special precautions should be taken when modifying construction of a measurement probe.

Introduction

Measurements of electrical parameters of biological materials are generally made by means of four electrodes probes for frequency range up to tens of MHz. It is commonly considered that the four-electrode technique eliminates an error due to a polarization of phenomenon. A precise inspection reveals that this assumption is not fulfilled for a certain configuration of measurement probe [1,2]. It is due to a modification of the current density distribution, mainly beneath and in the vicinity of the current electrode by electrode-tissue interface impedance. Thus, the potential distribution is also modified according to strict relationship between current density and potential. The area of modified potential depends on many factors, e.g. electrode size, distance between electrodes, etc.



a)



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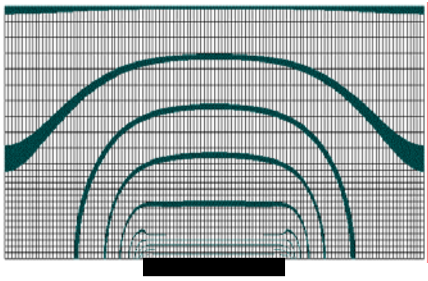

c)

Figure 1: Potential distribution involved by current flowing through the metal electrode, for different metal-tissue interface impedances

This phenomenon is illustrated in figure 1. Potential distribution has been calculated, using FE method, for two different models of electrode described by the following equations:

$$\sigma \frac{\partial \phi}{\partial \mathbf{n}} = \frac{I}{S_e} \quad (1)$$

and

$$\phi + z_e \sigma \frac{\partial \phi}{\partial \mathbf{n}} = \phi_e \quad (2)$$

where: ϕ - potential, σ - conductivity of the medium, z_e – impedance of the electrode–tissue interface, ϕ_e – potential of the electrode, **n** – a unit vector normal to the electrode surface. There is a serious difference in potential distribution shown in Fig. 1a) and 1b). The former result, obtained for the relation (1), is unreliable as the metallic electrode (marked by black bar) is not an equipotential surface. The latter result obtained for model described by the relation (2) is more reliable however, it shows a strong dependence of potential distribution on impedance of electrode – tissue interface, z_e. It follows from the results given in Fig. 1b) and 1c) that the potential distribution has also changed on the surface of the medium adjacent to the electrode. This has happened in spite of unchanged conductivity of the medium, σ. Thus, potential measured in this region contains information not only on σ but on z_e as well. Other problems deal with so-called reference electrode, e.g. for three electrode technique. A reference electrode has, typically, a large surface in order to reduce its interfacial impedance. However, a close inspection of result presented in Fig. 1c) reveals that the highest

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current density is located at edges of the electrode (a phenomenon known from physics) [3]. This involves a problem of determination actual (effective) area of the reference electrode.

Method

Potential distribution in a conductive medium is described by the equation

$$\nabla \cdot \mathbf{j} = 0 \qquad (3)$$

where **j** is the current density.

Two cases are examined. Firstly, band electrode of infinite length placed on a uniform half space characterised by conductivity σ is considered. Secondly, an annular probe is examined. Potential distribution is achieved by solving a 2-D FEM model, with mixed boundary conditions for both cases [4].

The first case has been solved means of Femlab 2.3.0.148. A 2-D inhomogeneous mesh, consisting of 8800 elements, has been generated. Aside examining the potential distribution for an uniformly distributed impedance of double layer other cases have been also examined (Figs. 2, 3). Conductivities considered in the model are respectively for metal σ_m=10000 S/m (much higher than other considered), gel, σ_g=0.1 S/m, isolation, σ_i=0 S/m, and examined medium (tissue) σ_t=1 S/m. A non-uniform mesh has been generated. An increased mesh density is located in the areas of expected nonlinear behaviour of the potential.

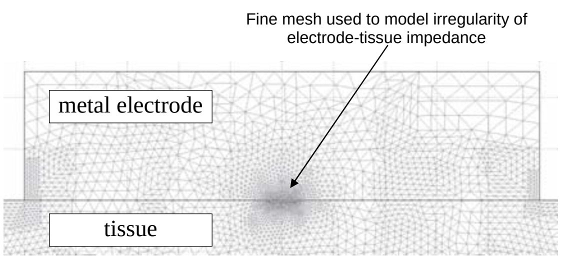

Figure 2: The mesh generated be means of Femlab

An effect of electrode shape on the potential distribution and thus the current density also has been examined (Fig. 3). Additionally, the sensitivity of arc-shaped electrode to perturbation in gel conductivity has been estimated.

Similar studies have been performed for annular probe. Another mesh, consisting of 8890 element has been generated using Femlab. However, a different solver, developed for cylindrical co-ordination system, has been utilized. Influence of double layer non-uniform impedance on potential distribution, especially, on the surface of examined medium has been studied.

A more details of the second model are presented in Figure 4. This model allows examining relations between potentials, e.g. V(ME2)/V(ME3), as a function of the model parameters, i.e. σ_1, σ_2, σ_e, characteristic dimensions of the probe and the examined medium.

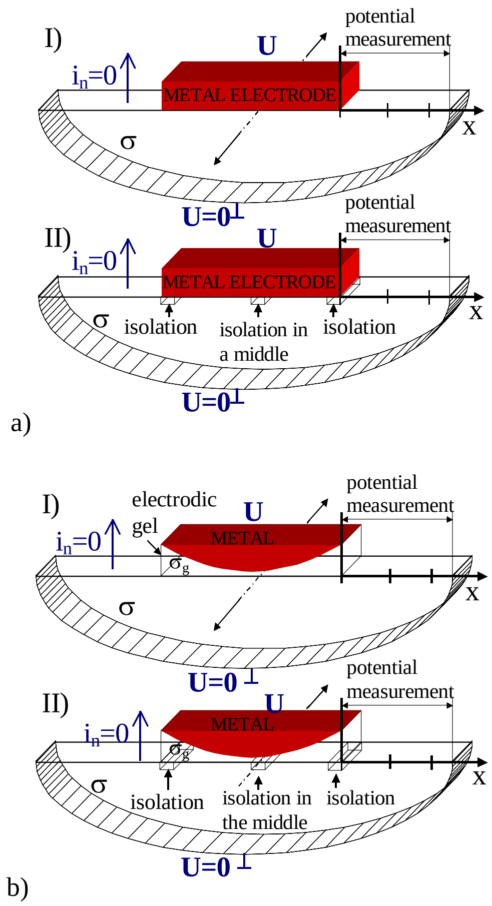

Figure 3: The considered models: a) for metal band electrode b) for metallic arc-shaped stripe electrode. Boundary conditions are also presented.

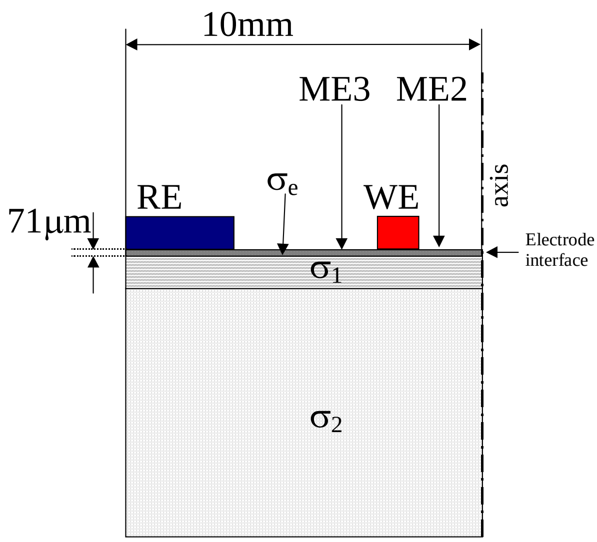

Figure 4: Model of the layered and annular electrodes (only part is shown), RE – the reference electrode, WE – the working electrode, ME2, ME3 – measuring electrodes

An impedance of electrode-tissue interface can be modelled either as uniform or non-uniform (thus different for each electrode.

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A further modification of the studied annular probe is presented schematically in Fig. 5. The shape of RE has been modified in purpose to obtain almost uniform current density at its surface.

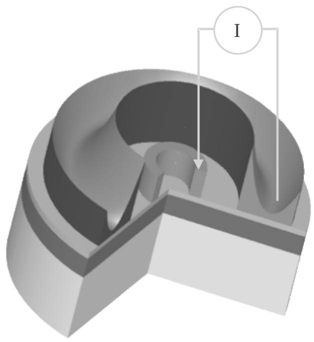

Figure 5: A schematic presentation of the probe with modified shape of RE

Results

Finite element method and full electrode model (i.e. described by equation (2)) has been used to determine the potential distributions presented in this paragraph. Potential distribution in the vicinity of the metal electrode strongly depends on impedance of double layer creating at the electrode-tissue interface.

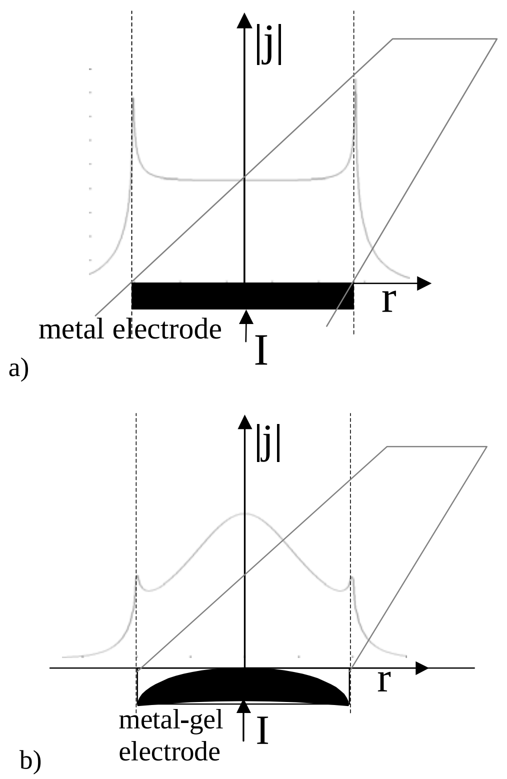

Figure 6: Distribution of current density: a) metal rectangular-shaped electrode, b) the arc profiled metal electrode. Current excitation, i.e. an identical value, I, is assumed for both cases

This problem has been studied in many papers, e.g. [5,6,7]. The importance of the electrode shape is illustrated in the paper (Fig. 6). A change in shape of electrode involves a different potential distribution and as a result also the current density distribution is changed (Fig. 6). Thus, changing the electrode shape and using gel of particulary chosen conductivity allows obtaining a more uniform current distribution and elimination of the edge effect.

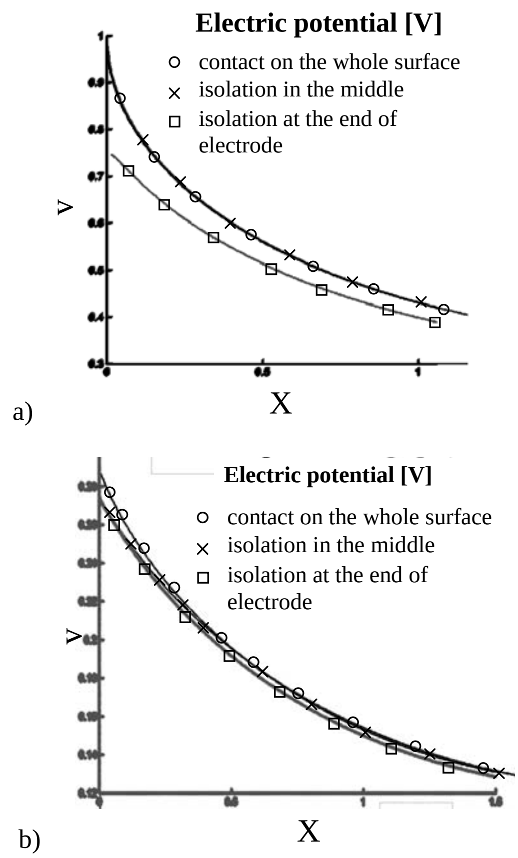

Figure 7: The potential distribution on the surface of the medium in the area adjacent to the electrode as shown in Figures 2 and 3: a) for the metal rectangular shaped electrode b) for the arc-profiled electrode

As a result, it has been found that the arc-shaped electrode is less sensitive to a local perturbation of electrode – tissue impedance. The metal, rectangular-shaped electrode is particularly sensitive to perturbations located at the border of the electrode. It seems that this result can easily proved using Geselowitz sensitivity theorem [8]. The measured impedance changes, involved perturbation of double layer conductivity, are proportional to gradient of potential, according to this theory. In turn, gradient of the potential for the considered case determines current density. It can be noted that the higher value of current density in ROI, the higher sensitivity to conductivity changes can be expected for this region.

The non-uniform current density affects the effective area of the electrode. A certain part of the total current flowing through electrode can be prescribed only to the part of the electrode. Moreover, a threshold of a linear behaviour of the electrode may be exceeded. This threshold is formulated in terms of current density. Thus, increasing surface of the reference electrode may not lead to an expected stabilisation of its behaviour.

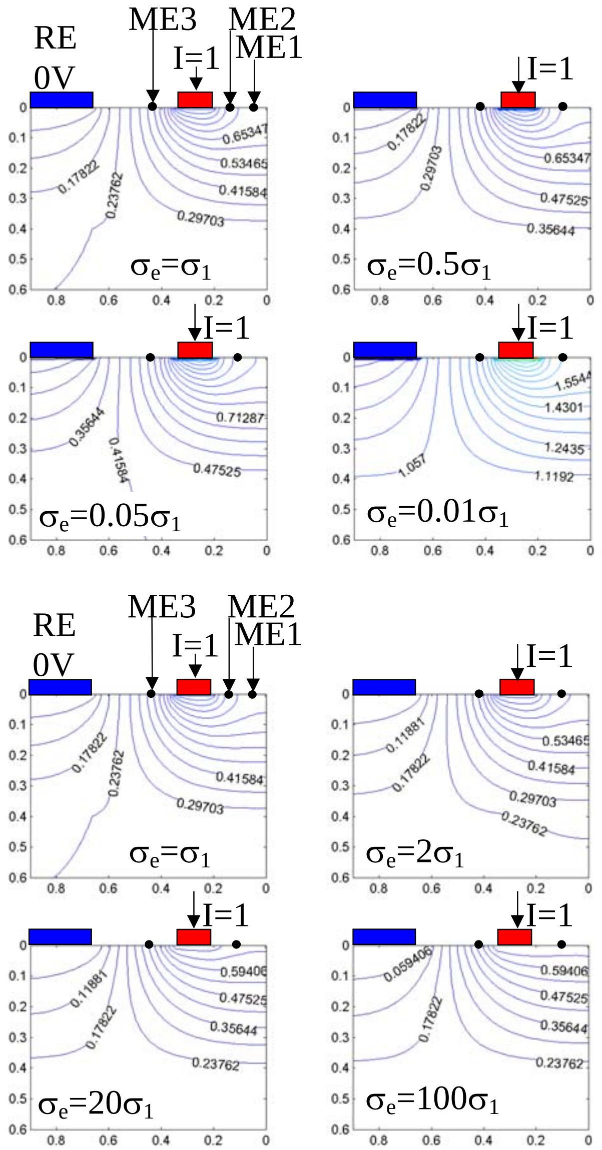

Figure 8: Potential distributions obtained as a function of ratio σ_1/σ_e for the model presented in Fig. 4.

The apparent impedance measured using a three-electrode probe (Fig. 4) is described by the following relationship:

$$Z = \frac{U_{ME}}{I} \quad (4)$$

where: U_{ME} – potential measured by ME in reference to RE, I – current flowing between WE and RE.

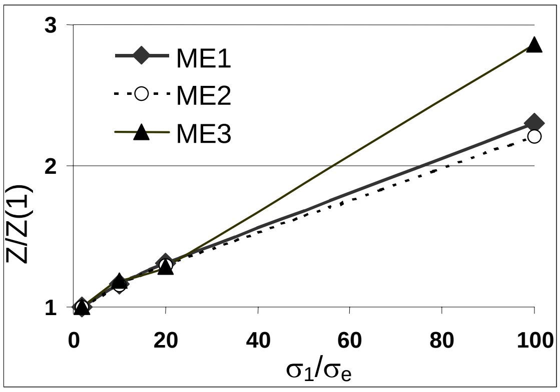

Figure 9: Dependence of apparent impedance measured at different location of ME as a function of σ_1/σ_e. Localisation of ME1, ME2, and ME3 is given in Fig. 8.

Dependence of apparent impedance, measured for the same configuration of excitation electrodes, i.e. WE and RE, however for a different localisation of ME, on conductivity ratio σ_1/σ_e is evidenced.

Example of potential distribution obtained for arc-shaped RE is similar to that presented in Fig. 8 however, it is almost independent on electrode-gel layer impedance. It suggests that the WE should be manufactured in the same way.

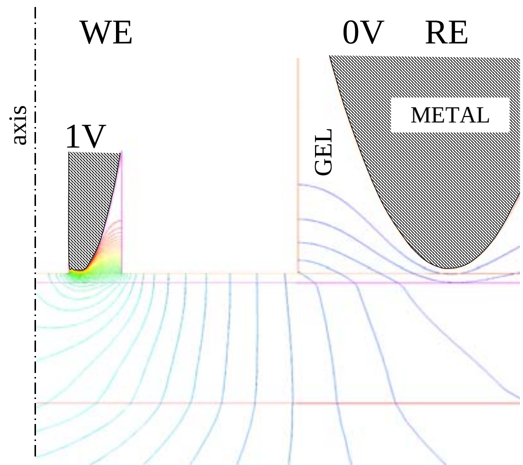

Figure 10: Potential distribution obtained for arc-shaped electrodes

Conclusions

It has been found that a so-called probe constant even that of four-electrode and three-electrode ones can be seriously affected by electrode-tissue impedance. To minimize this effect both RE and WE electrode should be adequately shaped.

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