Impedance Spectroscopy and Cell Constant of the Electrodes for Deep Brain Stimulation

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Abstract: To achieve a deeper understanding of the mechanism of the deep brain stimulation (DBS) [1] scientists use more and more numerical simulations. DBS inhibits overreaching brain activity via electric pulses that send into the brain by electrodes [1]. Different electrode parameters such as geometry, frequency of stimulated impulse or applied voltage have a great influence on the size of the stimulated volume. To compare electrodes of different shape we use the cell constant [2] and the impedance spectroscopy [2]. The latter, describes properties of electrodes in frequency range. For our first model we have chosen sodium chloride solution as surrounding medium in the simulations. This solution accords to the physiological fluid in the brain.

Keywords: deep brain stimulation (DBS), impedance spectroscopy, cell constant, equivalent circuit, FEM.

1. Introduction

Deep brain stimulation (DBS) is an electrical stimulation of neurons in specific parts of the brain to treat movement disorders such as Parkinson's disease (PD), tremor and dystonia [1]. PD is a neurodegenerative disease caused by the destruction of nerve cells in a deep region of the brain (Substantia Nigra) [1]. This destruction results in synchronous firing of nerve cells in other parts of the brain (Subthalamicus Nucleus or Globus Pallidus). The primary symptoms of PD are tremor, rigidity and bradykinesia. In the beginning the illness is treated with medicaments. During the course of the disease medicaments loose their effecting and usually a medical stimulator, a so called "brain pacemaker", is implanted in Subthalamicus Nucleus or Globus Pallidus to reduce these symptoms. The stimulation system consists of three components: the lead, the generator, and an extension. The lead is the coil shaped conductor insulated in urethane whith four stimulation electrodes at the end and is placed in the specific part of the brain. The pulse generator, which is implanted under the skin of the chest, sends electrical impulses to the specific brain region. The impulses run along the extensions from the pulse generator to the lead in the brain.

For better understanding of the electrical process of DBS more and more numerical simulations are applied. The understanding of DBS is a basis for improving the geometry and the parameters of stimulated leads, which results in better healing. In our work we compare the two models of the electrodes for DBS (model 3387 and 3389, Medtronic®) in sodium chloride solution. This solution accords to the physiological fluid in the brain.

In this paper, we report about a simple model within isotropic medium, the theory and the main equations for our problem, the numerical solution and finally we represent our results.

2. Model

2.1 Problem type

Comparison of electrodes with different geometries is provided using the impedance spectroscopy or the cell constant [2]. Impedance spectroscopy is an electrochemical method for the analysis of the electrical properties of electrodes and their surrounding medium. This analysis provides quantitative information about the conductance, the static properties of the interfaces of a system, and its dynamic change due to adsorption or transfer of charge. The impedance of two charged electrodes in the medium is determined from the equivalent circuit shown in Fig. 1.
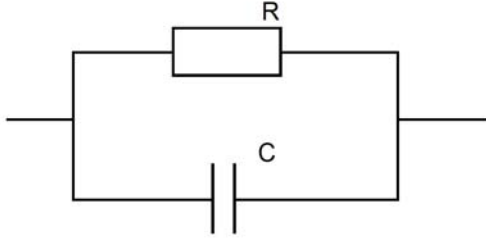
Figure 1. Equivalent circuit for electrodes of deep brain stimulation.

From the equivalent circuit the complex impedance Z is calculated (Eq. (1)):

$$Z = \frac{1}{\frac{1}{R} + j\omega C},\qquad(1)$$

where R is the resistivity of medium, ω is the angular frequency, C is the capacity of electrodes and j is the imaginary unit. Neglecting the influence of the permittivity, the resistivity is calculated from numerical simulation of the stationary flow fields. In this case the electric field is coupled to the electric current by Ohm's law [4], which results in Poisson's equation (2):

$$\nabla \cdot \sigma \nabla V = 0,\qquad(2)$$

where σ is specific conductivity and V is potential.

Poisson's equation is solved with help of the Conductive Media DC (emdc) application mode of the AC/DC (emes) Module. Whereas the voltage U between the electrodes is given, the current I has to be determined numerically to calculate the ohmic resistance R of the equivalent circuit from Ohm's law ($R = U / I$). The current results from integration of current density over the surface of the electrode (see also section 2.5.2).

The capacity is calculated from simulation of the electrostatic fields neglecting the influence of the conductivity. For calculation of the capacitance C of the equivalent circuit using the ratio of charge q divided by the voltage U ($C = q / U$), Poisson's equation (3) for the Electrostatics mode was solved within the AC/DC (emes) Module:

$$\nabla \cdot \varepsilon_r \varepsilon_0 \nabla V = 0,\qquad(3)$$

where ε_0 is the permittivity of vacuum, ε_r is the relative permittivity and V is the potential.

2.2 Geometry & Subdomain Parameters

The simulation model consists of four stimulated electrodes, the electrode's shaft and a cylinder with sodium chloride solution as surrounding medium. The geometry of the simulated lead is taken from the description of the Medtronic 3389 and 3387 electrodes (Medtronic® Inc, Minneapolis, MN, USA) [3] and consists of four metal contacts of platinum iridium each with a diameter of 1.27 mm, a height of 1.5 mm and an outer jacket tubing of urethane 80A (Fig. 2).
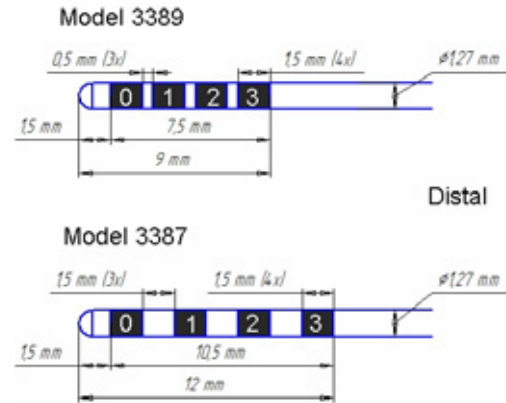

Figure 2. The 2D-electrodes for deep brain stimulation (drawn after Implant manual, Medtronic®).

For the calculation of resistivity and capacity we apply numerical integration over the specific surface at the electrode. Each of the electrodes is surrounded by a cylinder-sized closed surface for the integration that has roughly the dimension of the electrode. The separation between the contacts is 1.5 mm. 2D axisymmetric finite element models of the two DBS electrodes and its surrounding medium were created using COMSOL Multiphysics® 3.5a RC1 (Fig. 3).
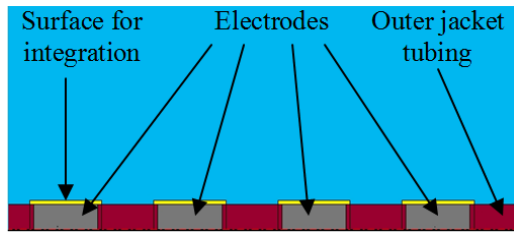
Figure 3. The 2D-simulation model (sector).

In the model we choose a cylinder of 70×77 mm in size with sodium chloride solution for the surrounding medium, according to the physiological fluid in the brain. For the calculation of the resistivity in the Conductive Media DC application mode the surrounding medium and each of the stimulating electrodes were modeled as conductors with conductivities of 0.005 S/m and 1e6 S/m respectively. The outer jacket tubing was modeled as an insulator with conductivity 1e-15 S/m. For the calculation of the capacity C in the Electrostatics application mode the relative permittivity is set to 80 for sodium chloride solution, 1 for platinum and 5 for urethane. Instead of the inhomogeneous and anisotropic materials of the brain the sodium chloride solution in this simulation is homogeneous and isotropic.

2.3 Boundary conditions

For both application modes the boundary conditions for the electrodes are the same. The typical electrode's polarity is bipolar (stimulation electrode "0" is negative, stimulation electrode "3" is positive) and unipolar (electrode "0" is negative, "case" is positive). In our model, two neighbors (electrode "0" and "1", see Fig. 2) of four stimulation electrodes were specified as electric potential of ± 1 V. Because the two remaining electrodes are floating, they are chosen as continuity. It means that they were not assigned a potential and were ungrounded. The electrode shaft was defined as continuity, too. We assume that our simulation takes place in a glass cylinder within sodium chloride solution. The walls of the glass were assumed as zero charge in the Electrostatics mode and as electric insulation in the Conductive Media mode at the boundary.

2.4 Mesh & Solver

The model was discretised with the triangle method. The number of mesh elements consists of 57295 elements. The cylinder was discretised with a maximal element size of 4e-4. Because of electric field values vary strongly on the crossover from electrode to sodium chloride solution, the stimulated electrodes and surface for integration have to discretised relatively fine. Maximum element size for each of the stimulated electrodes and surfaces of integration is 5e-5. To avoid numerical problems the integration does not take place on the surface of the electrode. Instead of that the surface of integration is positioned at the distance of 0.1 mm to the electrode surface. The main equations (see section 2.1) were solved using the iterative solver GMRES with algebraic multigrid preconditioner. The standard accuracy limit of 1e-6 had to be changed to 1e-8 in order to achieve convergence. The surface of integration was positioned at a distance of 0.1 mm from the electrode and the area in-between was discretised with finer mesh elements.

2.5 Postprosessing

2.5.1 Cell constant

One convenient characterization of the electrodes is an electrode geometry factor or so called cell constant γ [2]. The usability of the cell constant is easily described by the example of a plate capacitor (Fig. 4).
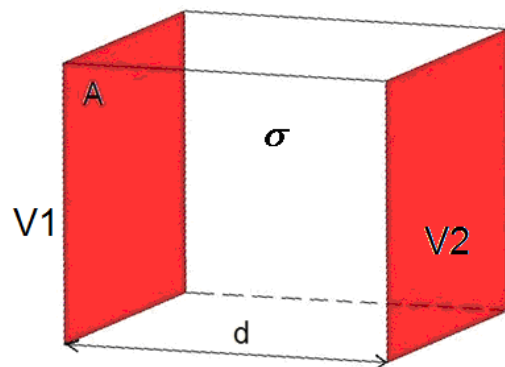

Figure 4. The plate capacitor.

If we have a chamber with two coplanar electrodes and medium with conductivity σ between the electrodes then according to Ohm's law the resistance R is determined using equation (4):

$$R = \frac{U}{I} = \frac{l}{\sigma A} = \frac{1}{\sigma \gamma},$$ (4)

where U is the applied voltage, I is the current through the medium, l is the distance between the electrodes, A is the area of electrodes, σ the specific conductivity of the medium and γ the cell constant. Rearranging equation (4) results in the cell constant:

$$\gamma = \frac{A}{l}.$$ (5)

Other applications lead to other dependency of the geometry. Equation (5) is valid for the plate capacitor. The more the actual electrode geometry differs from the plate capacitor the less equation (5) may be used. Therefore in general, the cell constant is computed from equation (6):

$$\gamma = \frac{1}{\sigma R},$$ (6)

were R is taken from a numerical field computation.

An advantage of the cell constant is the independency from material parameters (for isotropic medium) and reciprocal proportionality to the resistance. This allows calculating the cell constant from either a computed or a measured resistance and the conductivity of the medium. For DBS electrodes, the cell constant was determined numerically from the current from one electrode to another and the given potential difference. The current was obtained by integration over the surface of integration (see section 2.2).

We expect that the cell constant of model 3387 is bigger than that of model 3389. The reason for that is that model 3387 has a bigger distance between the stimulation contacts than model 3389 (see Eq. (5)).

2.5.2 Impedance spectroscopy

The impedance of the electrodes is usually as imaginary vs. real part of the impedance. As mentioned above, the electrode impedance can be determined from the equivalent circuit (shown in Fig. 1). The real part of the impedance is represented by the term R (resistance) and the imaginary part by the term $j\omega C$ (C capacity). Term R represents the ionic bulk conductance [2]. R and C are calculated from the current I and the charge q for the given potential difference U:

$$R = \frac{U}{I},$$ (7)

$$C = \frac{q}{U}.$$ (8)

The current I and the charge q were computed using the area integral over the current density $\mathbf{J}$ and the area integral over the dielectric displacement $\mathbf{D}$:

$$I = \iint_A \mathbf{J} \cdot d\mathbf{A},$$ (9)

$$q = \iint_A \mathbf{D} \cdot d\mathbf{A},$$ (10)

where $\mathbf{A}$ is the area of integration.

3. Results and Discussion

3.1 Impedance

In this part we present our results for models 3387 and 3389 of the electrodes used for DBS. Two of four electrodes are charged. Fig. 5 shows imaginary vs. real part of the impedance in the frequency range from 100 Hz to 5 MHz.
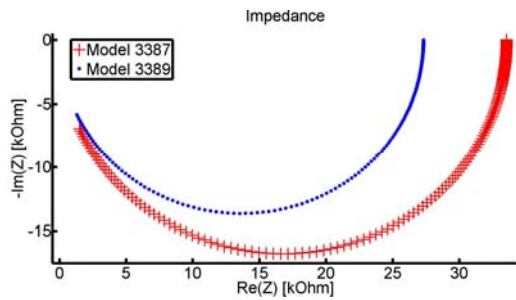
Impedance

Figure 5. Imaginary vs. real part of the impedance of electrodes used for DBS (model 3387 and 3389, Medtronic®).

The real part of the impedance dominates at low frequencies. The resistance, the capacity and the angular frequency at each point of the curve are related by the ratio $\omega = 1/RC$. Fig. 6 shows the real part of the impedance vs. frequency.
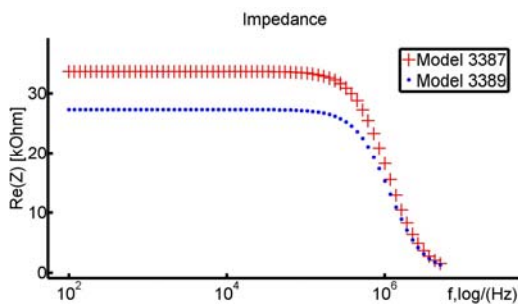

Figure 6. Real part of the impedance vs. frequency of electrodes used for DBS (model 3387 and 3389, Medtronic®).

The modeling and simulation of the impedance spectroscopy with help of an equivalent circuit affords information about the electric properties of media like the electrolyte and the electrochemical processes like charge transfer. The different electrode shapes or different distances between the electrodes cause that the same electrode surface can conduct current of different density. This has an impact on the spread of the electric field and its magnitude. This effect can then be considered using cell constant [2]. Evidently, the cell constant is one significant parameter for the stimulation current. The same impedance at reduced surface can be achieved by a decrease of the electrode's distance leading to the same coefficient. This is directly correlated with electric field distribution and the size of stimulated volume.

3.1 Cell constant

The calculated cell constants for model 3389 and 3387 are 0.0075 and 0.0061, respectively. As could be expected, the cell constant is bigger for model 3389 than for model 3387 which has a larger distance between the stimulation contacts. This means that model 3389 leads to a smaller stimulated volume than model 3387 (for details see section 2.5.1).

4. Conclusions

In this work a simple model for comparison of different geometries of electrodes for DBS was presented using parameters such as cell constant and impedance.

Modeling of electrode's effects for DBS is a rather complex task. For a better description of the stimulation effects, not only inhomogeneity and anisotropy, but also the complex electric properties of the brain tissue and electrochemical processes have to be taken into account. For example in the equivalent circuit the polarization resistance and the double-layer capacitance were not yet considered.

8. References

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9. Acknowledgements