Exact Model of Electrodes for ECT Simulations

Robert Szmurło, Bartosz Sawicki, Jacek Starzyński, Stanisław Wincenciak

Abstract— **The papers discusses numerical simulation of electroconvulsive therapy (ECT). A realistic finite element model of human head with different models of stimulating electrodes is be presented. Special attention is paid to the influence of the model of electrodes on the results of simulation.**

I. Introduction

NUMERICAL simulation of the electroconvulsive therapy applied to the human head seems to be relatively easy. During this treatment electric currents are passed through the head between two electrodes placed on the patient's head. The time variation of the stimulus is a square pulse of less than millisecond width, repeated with frequency of dozens Hz. The Fourier spectrum of the stimulus can be limited to 20kHz. This allows us to reduce equations describing field to the single Laplace equation with Dirichlet boundary conditions on electrodes and uniform Neumann boundary condition on the rest of the skin surface. The numerical models of ECT with realistic models of the human head were already presented elsewhere [3], [2]. These research have confirmed the obvious insight that during ECT the extreme values of the electric field (and current density) appear near the electrodes. As a result of this observation one could ask how important is the model of the stimulating electrodes? The realistic models of the head does not contain electrodes. Need for investigation of different positions of the electrodes suggests external application of these electrodes to the head model.

The goal of this paper is to discuss the influence of the electrodes model on the results of stimulation. The universal model of the metallic electrode, which can be applied externally to the existing FEM model of the head will be presented. Different application of the boundary conditions and realistic simulation of the contact potential will be investigated.

II. Model of the head

The creation of the 3D FE grid in a head was based of head cross-sections. The sample data used in this paper was taken from the public domain Internet data base Visible Human [4]. 219 cross-sections of the head in JPG format were made resolution of 162 × 182 pixels.

Using tools based on digital image processing theory, a surface mesh that outlines the head structure had been constructed with help of Amira software [9]. The advanced front algorithm is used to generate 3D model of the head. Our experiments have shown that surface mesh with 50000 triangles gives reasonable, exact model consisting of 674807 tetrahedra elements and 119290 nodes. The final volume grid of the head is shown in Fig. 1.

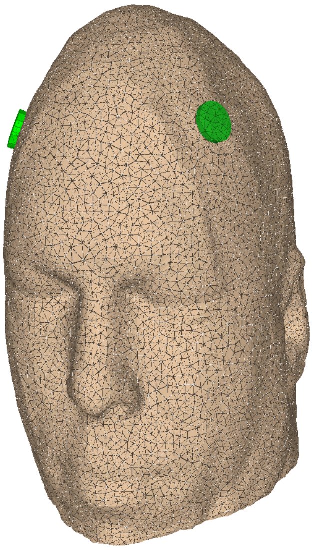

Fig. 1. Realistic model of the head built using data from the Visible Human database with electrodes simulated with the methodology described in this paper

III. Model of electrodes

A. The motivation

The process of the head model creation is time consuming and it would be advantageous to be able to apply model of electrodes to the ready model of the head. Thus the same model of the head could be used for many simulations with electrodes of different shapes and positions.

To obtain the field distribution the following Laplace equation with Dirichlet boundary conditions have to be solved:

$$\nabla \cdot \gamma \nabla \varphi = 0. \tag{1}$$

The simplest approach to simulation of electrodes applied on the skin surface is to set the Dirichlet ($\varphi = \varphi_0$) boundary condition in some external nodes of the FE grid. The main advantage of this approach is simplicity, the main drawback—the poor quality of the solution, especially in the vicinity of electrodes. This drawback can be observed in Fig. 2, where electric potential near of the simplest model of electrode is shown. It is obvious that

---

Authors are with the Institute of Theory of Electrical Engineering, Measurement and Information Systems, Warsaw University of Technology, ul. Koszykowa 75, 00-662 Warsaw, Poland, email: *szmurlor@iem.pw.edu.pl*

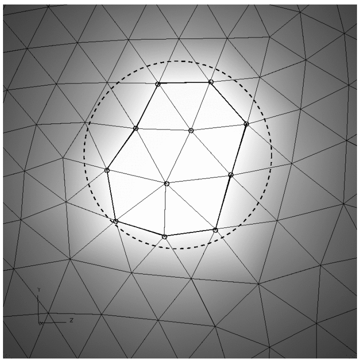

Fig. 2. The electric potential φ near of the simplest model of electrode. Potential is shown with shades of gray. Electrode contour is shown with dashed line. Nodes at which Dirichlet BC is set are marked.

the electrode model shown in Fig. 2 is not correct, because the real shape of the electrode can be very different than the simulated one and extreme values of the electric field which can appear if the boundary of "electrode" is sharp can seriously influence the field in the whole head.

The straightforward solution of the problem shown in Fig. 2 is to modify the FE grid in area where the potential is to be applied. Moving external nodes to the circle corresponding to electrode boundary, as shown in Fig. 3 allows one to smoothen the Dirichlet boundary and to make solution more realistic. However it needs modification of the FE grid. For sake of brevity from now we will call this approach "2D model of electrode". It seems that such modification of the grid is necessary, but one can ask if such model of electrode is sufficient to obtain the exact values of the stimulus within the brain.

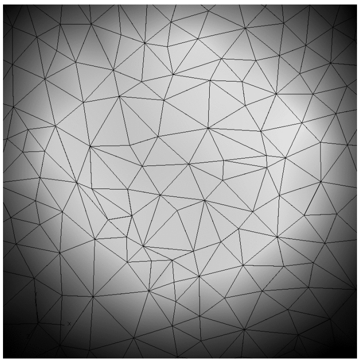

Fig. 3. The electric potential φ near of the more realistic, 2D model of electrode

B. Model of electrode-skin contact

Combination of the human skin, metal electrodes and electrode jelly seems to be relatively simple. Unfortunately deeper investigations unveils that this sandwich is, in fact, a little bit complicated. We can distinguish the following layers (see Fig. 4):

electrode	– round metal plate, very good conductor,
electrode jelly	– special gel used to reduce contact resistance between skin and electrode,
epodermis	– external part of skin, very thin, isolating layer,
epidermis	– main part of skin, low conducting.

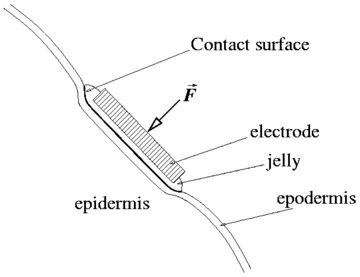

Fig. 4. Cross-section of the electrode applied to the skin

Analysis of Fig. 4 results in the following remarks:

- Electrode and jelly are very good conductors and we can assume, that electrical potential φ is constant there. There is no need to simulate them, but it is enough to set proper Dirichlet boundary condition on the "Contact surface" shown with the thick line in Fig. 4.
- Shape of electrode jelly is a problem. If there are not too much jelly, it can be assumed that it has the same shape of the electrode (usually it is a circle).
- Electrode is applied with some force $\vec{F}$, necessary to assure good contact with the skin. As the result of this force some deformation of the skin is observed. We simulate this deformation by flattening the skin surface under electrodes.
- Epodermis is the hardest problem here. This lifeless part of body is protecting soft tissues from external conditions, such as temperature, physical contact with other objects, and also gives good protection against external electric field. Epodermis should be modeled as very thin isolator, and its small thickness makes generation of the finite element mesh very difficult. Thus the authors decided to model only this part of epodermis, which is just under the electrode.
- Epidermis is main part of skin. It's size is comparable to other parts of head, so it is simply treated as separate, external layer in our head model (as shown in Fig. 1).

C. Discretization

We assume that electrode has shape of thin cylinder. The basis for transformation is constructing a sphere S, which has same center and radius as electrode base. Nodes on the surface of head model which are inside the sphere have direct contact with electrode. To obtain circular shape of electrodes all surface edges which intersected with sphere had to be eliminated. This was done by translating one node of each edge so its new position was on the sphere surface. Next copies of all selected nodes translated by a vector parallel to the electrode axis. This forms a very thin (as thin, as the epodermis layer) cylinder "glued" to the head. As a last step a layer of elements between selected and doubled nodes was created.

The idea of transformation can be more formally described in the following steps:

- Construct sphere S with same radius and center as the base of the electrode.
- Add special boundary indicator B_s to all external nodes of the head which have contact with electrode (i.e. are inside of S).
- Create a set S_n of nodes which belong to at least one surface edge intersecting with sphere and have boundary indicator B_s. (The S_n creates a rounded bounding box of nodes with B_s.)
- Eliminate edges which intersect with sphere—this allows to obtain regular shape of electrode:
  - Loop 1: For each node N_k from S_n select the edge along which distance between N_k and sphere surface is minimal. If the distance is less than 0.5 of edge length, then translate this node to the surface.
  - Loop 2: For each node N_k from S_n which was not translated, select the edge which opposite node $N_k^{'}$ is the nearest to the sphere surface. If the distance is less than 0.5 of edge length, the node $N_k^{'}$ is translated to the surface.
- Create a set S_f of surface faces, which contains all faces of elements which have direct contact with electrodes.
- For each face calculate the normal vector.
- For each node of S_n create a normal vector which is calculated as average from all normal vectors from adjacent faces (S_f).
- For each node of S_n create a "twin" node which is translated of original node by vector of length 3 mm (thickness of epodermis) and direction calculated in previous step. Set a special boundary indicator at this node. This boundary indicator will be used for simulation of external side of electrodes.
- Generate grid of elements between original set of nodes S_n and created "twin" nodes. The original and "twin" face create a prism, which can be easily filled with elements.
  - To facilitate the generation process, extra node in the middle of the prism is created.
  - For each prism 8 elements are created filling entirely the volume between original face and "twin" face.

The realistic 3D model of the electrode (epodermis layer) is shown in Fig. 5.

D. *Electrical parameters of model*

The electric parameters of the model are shown in Table I). Average contact resistance of human skin and metallic electrode is equal: R=100 [Ω/cm^2] [6]. We simulate this resistance by additional, 3 mm thick layer (the epodermis). The equivalent conductivity of this layer $\gamma_e = 0.33$ [S/m] was calculated to give 100 Ohms of equivalent resistance for 1 cm^2 of electrode.

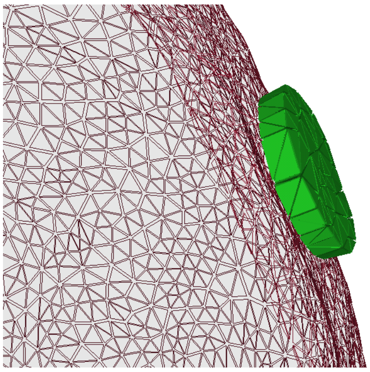

Fig. 5. 3D layer of epodermis "glued" to the head model

TABLE I
ELECTRIC PARAMETERS OF MODEL LAYERS

Tissue	γ [S/m]
Skin & CSF	0.33
Bone (Cortical)	0.02
Eyes	0.33
Cortex	0.33
Sinus	0.0001
Electrode	0.33

The boundary conditions were basically enforced on the external surfaces of the electrodes, but for comparison the solution with potential applied directly to the skin surface was also calculated.

IV. RESULTS OF EXPERIMENTS

To study the influence of the electrode model on the simulation results the following experiments were done: i) simulations with boundary conditions applied directly on the external surface of the head model (no epodermis) (see Fig. 6), ii) simulations with boundary conditions applied on external boundary of electrode (model of epodermis with different values of γ_e)—see Fig. 7, iii) simulations for different radius of electrodes (contact area).

The examples of the simulations results are shown on Fig. 6–8 and summarized in Table II. The total power dissipated in the head, calculated by

$$P = \int_V \gamma E^2 dv \qquad (2)$$

allowed us to asses the equivalent resistance R seen from the source of potential as $R = U^2/P$.

V. DISCUSSION AND CONCLUSIONS

The simulation needs to solve a relatively simple Laplace equation with Dirichlet boundary condition. However, due the size of the grid, solution of the equation system was not so easy. We have used iterative solvers (BiConjugate Gradient and GMRES) and Jacobi preconditioner from the Diffpack library [5]. For the grids of 674807 tetrahedra elements and 119290 nodes the solvers converged in 300-500 iterations.

Results of simulation allow to state that introduction of electrodes to realistic head model increases

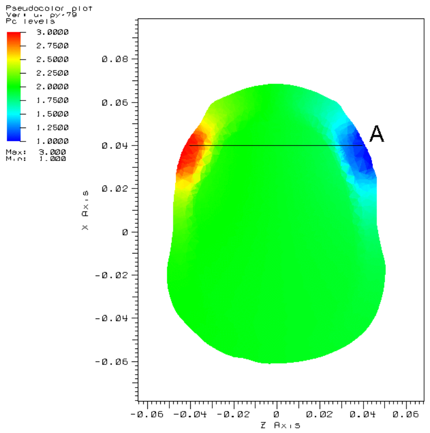

Fig. 6. Cross-section of potential distribution with Dirichlet conditions applied directly on head surface (no epodermis).

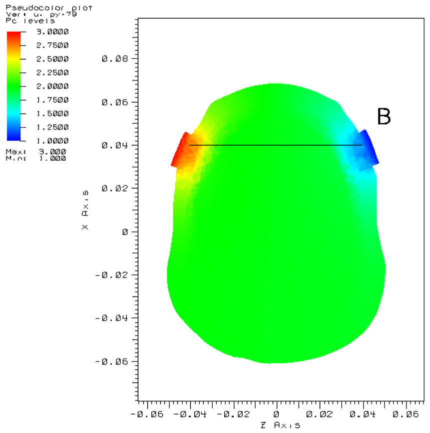

Fig. 7. Cross-section of potential distribution with Dirichlet conditions applied on external boundary of electrodes (epodermis approximation).

precision of simulation approximation. Comparing Fig. 6 and Fig. 7 one can easily notice, that model of electrode seriously influences results of simulation.

It is not easy to verify the results, however, comparing the values of the equivalent resistance of the head, as seen from the ECT supply terminals we see a good agreement with resistance of about 300 Ohms for electrodes of 2.5 cm diameter.

The presented method of addition of electrodes to existing model is relatively easy and does not require any effort in system matrix formulation.

REFERENCES

[1] A. Rassineux, P.Breitkopf, C. Chappuis, P. Villon, Volume mesh adaptation with a meshfree surface model, `http://www.imr.sandia.gov/papers/imr11/rassineux.pdf`, 2001

[2] M. Nadeem, T. Thorlin, Om P. Gandhi, M. Persson, Computation of Electric and Magnetic Stimulation in Human Head Using 3-D Impedance Method, IEEE Trans. on Biomedical Engineering, vol. 50, No. 7, Jul. 2003

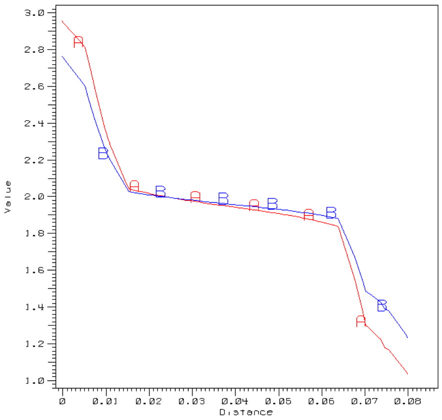

Fig. 8. Comparison of potential distribution with Dirichlet conditions applied directly on the skin (curve A) and with epodermis approximation (curve B).

TABLE II
TOTAL POWER (FOR $U = 2[V]$) AND RESISTANCE OF HEAD FOR DIFFERENT RADIUS r OF ELECTRODES AND TWO DIFFERENT MODELS: WITHOUT EPODERMIS AND WITH EPODERMIS (WIDTH 3 MM, γ_e=0.33 [S/M]).

	no epodermis		with epodermis	
r [cm]	P [W]	$R[\Omega]$	P [W]	$R[\Omega]$
0.65	0.01368	292.3	0.00898	445.3
0.7	0.01455	274.8	0.00966	414.1
0.75	0.01523	262.7	0.01039	385.0
0.8	0.01572	254.4	0.01095	365.1
0.85	0.01653	242.0	0.01180	339.0
0.95	0.01790	223.5	0.01319	303.2
1.0	0.01855	215.6	0.01429	280.0
1.1	0.01984	201.6	0.01542	259.3
1.2	0.02108	189.8	0.01649	242.5
1.3	0.02239	178.7	0.01792	223.2

[3] J. Starzyński, B. Sawicki, S. Wincenciak, A. Krawczyk, T. Zyss: *Simulation of Magnetic Stimulation of the Brain*, *IEEE Transactions on Magnetics*, vol. 38, No. 2, March 2002

[4] M. Chang and P. Coddigton. *The Visible Human Project*, The Northeast Parallel Architectures Center, Syracuse University, 1996, `http://www.npac.syr.edu/projects/vishuman/`

[5] H. P. Langtangen. *Computational Partial Differential Equations.* Springer-Verlag, 1999, ISBN 3-540-65272-4.

[6] J. Patrick Reilly *Applied Biolelectricity.* Springer-Verlag, 1998, ISBN 0-387-98407-0

[7] M. Nadeem, T. Thorleif, Om P. Gandhi, M. Persson: *Computation of Electric and Magnetic Stimulation in Human Head Using 3-D Impedance Method*, *IEEE Transactions Biomedical Engineering*, vol. 50, No. 7, July 2003

[8] R.Szmurło: *Report electrodes connected to realistic human head*, Institute of Theory of Electrical Engineering, Warsaw University of Technology, 2004, `http://www.iem.pw.edu.pl/~szmurlor/reports/elec_connect.pdf`

[9] Amira Homepage: `http://www.amiravis.com/`