FORWARD AND INVERSE METHODS IN EVENT RELATED POTENTIAL IMAGING USING A RESISTOR MESH MODEL

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Abstract- **A spherical head model based on a resistor mesh is presented. Each resistor corresponds to the conducting electrical properties of a tissue volume. A current dipole is simulated by an electrical current source connected between two nodes in this mesh. The direct problem is solved and the accuracy of this model is evaluated in comparison with the analytical solution. The results show that the resistor mesh provides correct potential and scalp current density values. The model structure makes it easy to introduce conductivity heterogeneities such as stroke and skull anisotropy. First trials of an inverse method are also presented.**
***Keywords* - Resistor mesh, forward and inverse problems, scalp current density, event related potential, conductivity anisotropy.**

I. INTRODUCTION

In electroencephalography and event related potentials (EEG, ERP), the resolution of the so-called *forward problem*, that is the determination of scalp potentials from the simulation of a current dipole, is a preliminary step to the resolution of the so-called *inverse problem*, which aims at finding amplitude, localization and orientation of the intracerebral current source that generates the recorded scalp potentials. Various models have been proposed in the literature for computing electrical activity in the head, the most widely used consisting of three concentric spherical volumes [1]. Although this model is a gross simplification of the geometrical and electrical properties of the real head, this is the only one for which an analytical solution of the forward problem is available. For this reason and for simplification, we will call here this kind of model *analytical model*. For a decade, a range of numerical models, including finite difference, finite element and boundary element methods (FDM, FEM, BEM) have been developed. Most of them take in account the real geometry and conductivity of the head and all give rise to numerical solutions. We propose a new modelling approach based on a resistor mesh, each resistor representing a volume element of given geometry and conductivity.

Considering the analytical method as the reference method to validate head models, a three-sphere model has been implemented to represent the three basic tissues of the human head : brain, skull and scalp. The whole conducting spherical volume was sampled into a range of basic volume elements and each one was replaced by a set of resistors whose values reproduce the electrical properties of the volume elements. In this structure, heterogeneity and anisotropy can be easily introduced by changing the resistor values.

Analytical and numerical models from the literature use the forward method to solve the inverse problem. In other words, the inverse problem is an estimation problem in which the unknown source parameters are varied until the difference between the measured and calculated scalp potentials gets as small as possible [2]. The main interest of studying the forward problem is to provide initial data that are required to solve the inverse problem.

II. MODEL STRUCTURE

The resistor mesh was designed to reproduce a three-sphere model – basically homogenous and of isotropic conductivities – with radii of 72, 79 and 85 mm. The definition of the resistor mesh was achieved by sampling the whole spherical volume with $\Delta\theta = \Delta\varphi = 10°$ angular increments and considering 23 concentric spheres (Fig. 1). This resulted in 14,123 nodes connected by three types of resistors, defined following the unit vectors, $\mathbf{e_r}$ (radial direction), $\mathbf{e_\theta}$ and $\mathbf{e_\varphi}$ (tangential directions) of the spherical coordinate system. Each resistor represents a volume element of given conductivity. As an example, equation (1) defines radial resistor Rr, which connects node n_1 (of coordinates r_1,θ_2,φ_2) to node n_2 (r_2,θ_2,φ_2) and corresponds to a volume element of conductivity σ comprised between the surfaces defined by $\theta_2 - \Delta\theta/2$, $\theta_2 + \Delta\theta/2$, $\varphi_2 - \Delta\varphi/2$ and $\varphi_2 + \Delta\varphi/2$, and between spheres of radii r_1 and r_2

$$R_r = \frac{1}{\sigma}\cdot\frac{3\,(r_2 - r_1)^2}{(r_2^3 - r_1^3)}\cdot\frac{1}{2\sin(\theta_2)\sin(\Delta\theta/2)}\cdot\frac{1}{\Delta\varphi} \quad (1)$$

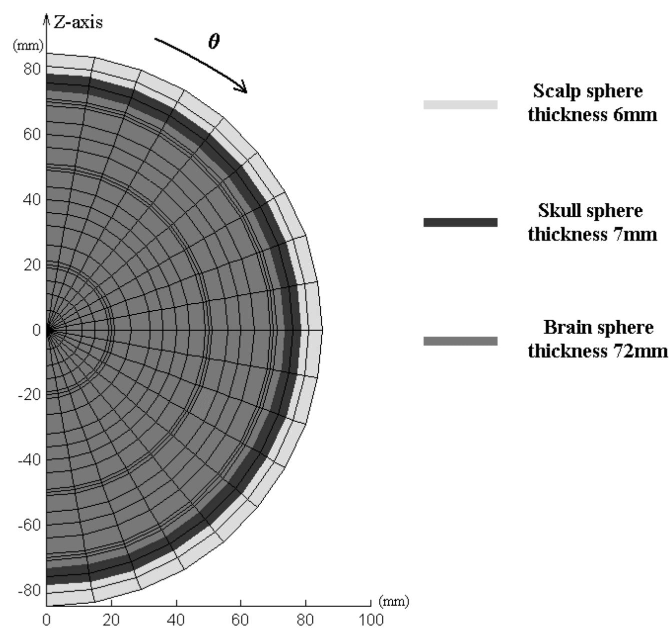


Fig. 1. Representation of a cross section of half of the resistor mesh, at $\varphi = 0°$ (sagittal right view).

0-7803-7211-5/01$10.00©2001 IEEE

Report Documentation Page

Report Date	Report Type	Dates Covered (from... to)
25 Oct 2001	N/A	-

Title and Subtitle Forward and Inverse Methods in Event Related Potential Imaging Using a Resistor Mesh Model	**Contract Number**
	Grant Number
	Program Element Number
Author(s)	**Project Number**
	Task Number
	Work Unit Number
Performing Organization Name(s) and Address(es) INSERM U455 Neurology Department, Purpan Hospital TOULOUSE Cedex France	**Performing Organization Report Number**
Sponsoring/Monitoring Agency Name(s) and Address(es) US Army Research, Development & Standardization Group (UK) PSC 802 Box 15 FPO AE 09499-1500	**Sponsor/Monitor's Acronym(s)**
	Sponsor/Monitor's Report Number(s)

Distribution/Availability Statement
Approved for public release, distribution unlimited

Supplementary Notes
Papers from 23rd Annual International Conference of the IEEE Engineering in Medicine and Biology Society, October 25-28, 2001, held in Istanbul, Turkey. See also ADM001351 for entire conference on cd-rom.

Abstract

Subject Terms

Report Classification unclassified	**Classification of this page** unclassified
Classification of Abstract unclassified	**Limitation of Abstract** UU

Number of Pages
4

The definition of tangential resistors was carried out in similar way. The resulting mesh includes 43,102 resistors. Owing to the fact that the synaptic current source/sink distribution within a small slab of cortex can be represented by a current dipole, we modelled it by an ideal electrical current source connected between two nodes. Although the values of skull and scalp conductivity are quite questioned [3], we applied a ratio of 80 between both, which is a value commonly used by the authors [1]. Scalp and brain conductivity was set to 0.33 $S.m^{-1}$, and skull conductivity to 4.2 $mS.m^{-1}$ [4].

III. FORWARD PROBLEM

Forward solutions were computed, for a set of current dipoles, in both the mesh model and the anaytical model exhibiting the same conductivities. In the first one, Kirchhoff's current law was applied by the Saber® simulator so that the sum of all currents through each node was equal to zero. In the second one, the solution was obtained by the analytical method using Matlab®. In both cases, current dipoles with the same dipolar moment were simulated to make comparison consistent. Basically, the moment of a current dipole is defined as the integration of current density $\mathbf{J_P}$ inside the volume of neural activation considered as infinitesimal. In the mesh model, this volume is represented by the resistor in parallel to which an electrical current source was connected. The moment of the current dipole $\mathbf{M}$ is therefore given by

$$\mathbf{M} = \mathbf{J_P}\,\mathrm{SL} \tag{2}$$

where S and L are respectively the surface and the length of the activation volume. Twenty-seven dipole configurations have been simulated, each one representing a different position of a dipole on X- and Z-axis and a so-called Q-line through the centre of the sphere oriented to $\theta = \varphi = 50°$. In each case, three eccentricities corresponding to r = 20mm, r = 50mm and r = 70mm have been taken. A radial and two tangential dipoles have been successively simulated at each eccentricity.

Validation of the proposed resistor mesh model has been carried out by comparing scalp potential and current density data computed with this model to the results provided by the analytical method. Simulation errors have been evaluated in relation to the analytical solution, using formulations of the magnification factor (MAG) and the relative difference measure (RDM), that derive from Meijs et al [5]. Providing V_{A_i} is the potential at node i given by the analytical solution on the three-sphere model and V_{S_i} is the corresponding simulated potential on the resistor mesh model, MAG and RDM are given by

$$\mathrm{MAG} = \sqrt{\frac{\sum_{i=1}^{n} V_{S_i}^2}{\sum_{i=1}^{n} V_{A_i}^2}} \quad (3) \qquad \mathrm{RDM} = \sqrt{\sum_{i=1}^{n}\left(\frac{V_{S_i}}{\sqrt{\sum_{i=1}^{n} V_{S_i}^2}} - \frac{V_{A_i}}{\sqrt{\sum_{i=1}^{n} V_{A_i}^2}}\right)^2} \quad (4)$$

where n is the number of nodes taken into account. These equations show that MAG is an index of potential magnitude comparison and that RDM pertains to fitting of potential spatial distribution between both models. RDM is also in direct connection to the correlation coefficient. Comparison of data from both models has been achieved taking n = 614, which corresponds to all scalp surface nodes in the mesh. If the fitting were perfect, MAG would be equal to one and RDM to zero.

Scalp current density, I_{SCD}, as defined in equation (5), has been proposed in the literature as an alternative approach to compensate for the spatial smearing of potential distribution due to the volume conduction of the various anatomical structures.

$$I_{SCD} = -\frac{\partial \mathbf{J_r}}{\partial r} = \frac{\partial(\sigma \mathbf{E_r})}{\partial r} = -\sigma \frac{\partial(-\partial V_r/\partial r)}{\partial r} \tag{5}$$

In this equation, $\mathbf{J_r}$ is the radial component of the current density, $\mathbf{E_r}$ the radial component of the electric field, ∂V_r the potential difference used to obtain $\mathbf{E_r}$ at two points separated by an infinitely small distance ∂r, and σ the conductivity of the scalp in the radial direction. In the mesh model, scalp current density can be calculated from the potential difference between scalp nodes and the nodes in the layer beneath using,

$$I_{SCD} = -\sigma \frac{U}{L^2} \tag{6}$$

where L is the equivalent length of the more eccentric radial resistor, U the potential difference across it, and σ the radial conductivity of the scalp. Calculation of MAG and RDM pertaining to scalp current density is obtained from equations (3) and (4), replacing potentials by I_{SCD}.

Fig. 2 shows MAG and RDM for scalp potentials and current density. Except for dipoles on Z-axis, MAG ranges from 0.99 to 1.03 for scalp potentials, and from 0.77 to 1.05 for scalp current density. The magnitude of potentials

c8rre85 deA t515.4(y9).3-4(a)8.G 2t81ea7G c8 5(a)0.2(f5)r, U t81ea7(e or

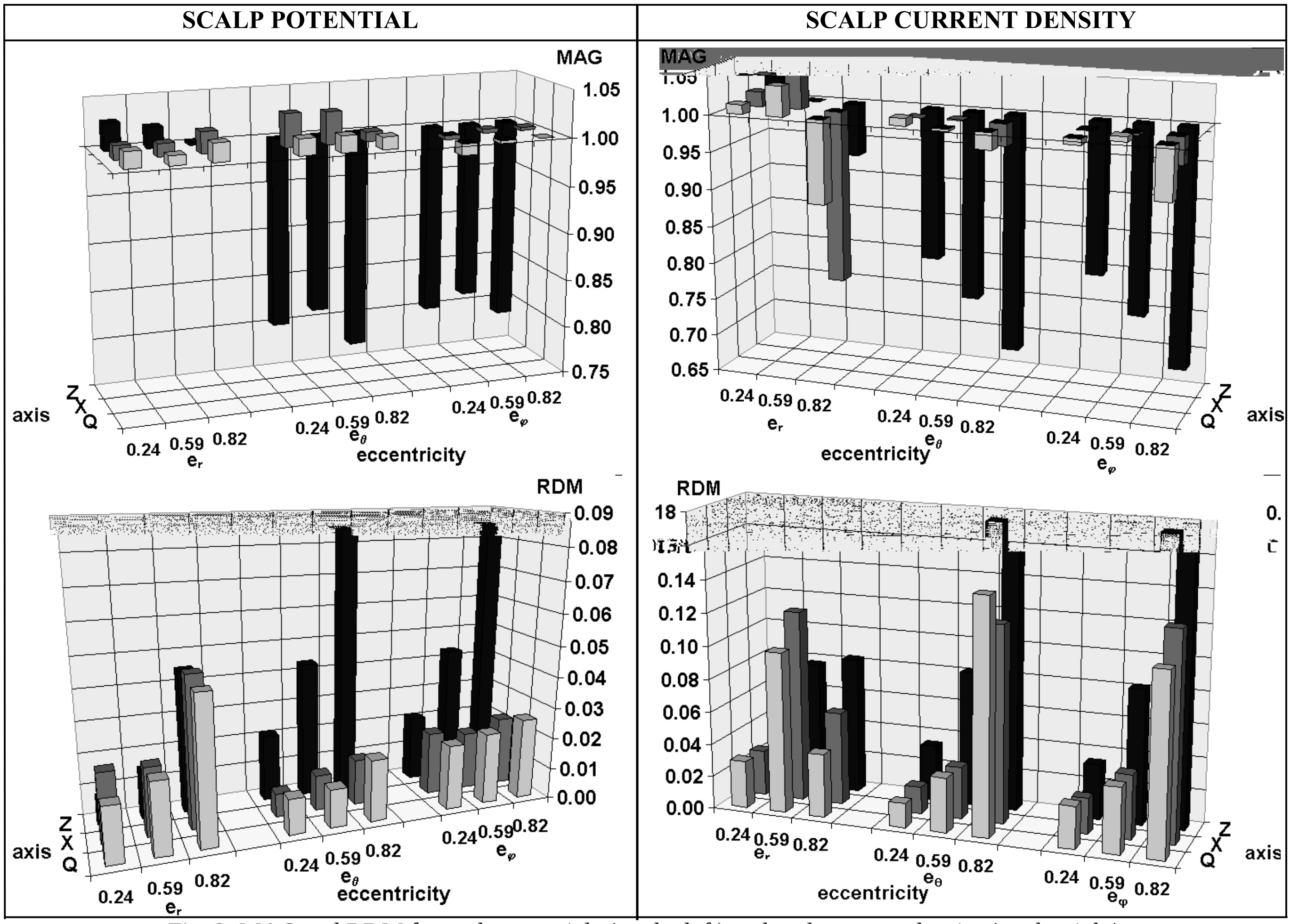


Fig. 2. MAG and RDM for scalp potentials (on the left) and scalp current density (on the right) calculated for 27 simulations: three dipoles on one of the three quoted axes; three orientations for each dipole.

Finally, spatial distributions of scalp surface potentials on the resistor mesh model and on the analytical model are very close with a correlation coefficient better than 0.996 for each of the 27 dipole simulations.

IV. CONDUCTIVITY ANISOTROPY AND HETEROGENEITY

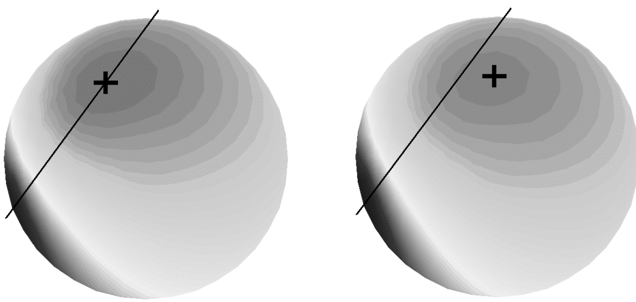
The low conductivity of skull makes this tissue playing a major part in the smearing of scalp potential distribution. That is why imaging techniques showing cortical surface potential and scalp current density maps have been developed. As a matter of fact, it is known that these two imaging modalities provide similar pictures. As the structure of our model makes it possible to compute as well current densities as surface potentials on any of the 23 resistor layers, comparison of cortical surface potential and scalp current density maps is easy. The weak smearing in both pictures in fig. 3 thus illustrates the interest of using scalp current density imaging as an insight beneath the skull with a view to improve dipole localization when solving the inverse problem.

Although all the tissues in the human head are anisotropic, we only have simulated skull anisotropy owing to its low conductivity and high anisotropy. The radial skull conductivity was kept to 4.2 $mS.m^{-1}$ when tangential conductivity was increased by a factor ten [6]. Simulations with an isotropic and an anisotropic equivalent skull have been carried out. Taking into account the anisotropy led to a decrease of the peak value of scalp potentials. This was confirmed by MAG values (the isotropic model being used as reference), that ranged from 0.93 to 0.89 when the dipole eccentricity increased from 0.24 to 0.82. Corresponding RDM increased from 0.01 to 0.1. For dipoles close to the scalp, the introduction of anisotropy leads to a lower maximum voltage and a larger spreading of spatial distribution.

(a) (b)

Fig. 3. (a) Cortical potential map (r=71 mm).
(b) Scalp current density map for the same dipole (r=85 mm).

A stroke has been simulated in the isotropic skull model modifying some resistors to make them equivalent to a blood volume of 7.6 cm^3 with a conductivity twice of the cortex one [5]. A range of simulations has been carried out. Fig. 4 shows the case, which led to the largest modification of voltage distribution. This case corresponds to a current dipole placed at 1 mm from the stroke and oriented on a line passing through it. We observed scalp voltage maps, comparing data from the model without stroke (fig. 4a) and those with the stroke (fig. 4b). Fig. 4 shows a significant shift of the spatial distribution of scalp potentials close to the dipole when a stroke is simulated. In this case, MAG and RDM calculated in reference to the case without stroke are respectively 1.08 and 0.21. This demonstrates that the presence of a stroke does not modify significantly the magnitude of voltage distribution but distorts and shifts it like if the current lines were "sucked up" by the high conductivity volume.



(a) (b)

Fig. 4. Scalp potential maps on the isotropic mesh model for a dipole oriented along the line, (a) without stroke and (b) with stroke. The cross indicates the maximum potential value.

V. INVERSE PROBLEM

Our approach to the inverse problem can be seen as a forward problem in which the initial data are scalp surface potentials. We have first considered the potential distribution on the outer sphere of the mesh resulting from the direct method for a given current source. Then, applying the Kirchhoff's current law at each of these nodes made it possible to obtain the potentials of the nodes in the resistor layer beneath the "scalp surface" one. Repeating this process from a layer to an other one down to the model, we have attempted to calculate the potential distribution in the whole mesh. Twenty-one dipoles have been thus successively simulated on the Q-line at a distance from the mesh center comprized between 50 and 70 mm, and our inverse method has been then applied. In all cases the orientation of the dipole was found correctly. Twelve of them were localized at the right position in the model. In 9 cases, the dipole was localized with an error in depth ranging from 1 mm to 5 mm. The magnitude of the localization error is linked to equivalent thickness between the spherical layers in the vicinity of the dipole and depends on its orientation. Furthermore, as we applied an inverse algorithm without any *a priori* information on the localization of the dipole, calculation of currents included an error that increased in the vicinity of the true position of the dipole. However, as this error also produced a strong inversion of potentials near to position of the dipole, we could use it as a localization index. The preliminary results look promising and suggest that the mesh model could help solving the inverse problem.

VI. CONCLUSION

When tangential dipoles are simulated, comparison of the direct method applied to the resistor mesh model with the analytical method gives MAG and RDM that are comparable to those obtained by Marin et al [6], who have evaluated a finite element model with a similar number of elements. When radial dipoles are simulated with high eccentricity, our model provides better results. Like FEM model, the discrete structure of the mesh limits simulation accuracy. This restriction is more visible in scalp current density maps than in voltage maps owing to the spreading effect of skull on the last.

The proposed inverse method looks promising because it permits to localize single current sources very closed to their true positions. This approach could be applied to several dipoles using the superposition principle. A real head mesh model is under development, including conductivity heterogeneities, that are of prime importance in ERP studies, especially when they are located in the vicinity of the expected dipoles. The mesh model could be used to simulate spatio-temporal layers of current dipoles, pathologies such as epilepsy, heterogeneities of connexity, and asymmety between cerebral lobes.

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