Effects of Skull Thickness, Anisotropy, and Inhomogeneity on Forward EEG/ERP Computations Using a Spherical Three-Dimensional Resistor Mesh Model

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Abstract: Bone thickness, anisotropy, and inhomogeneity have been reported to induce important variations in electroencephalogram (EEG) scalp potentials. To study this effect, we used an original three-dimensional (3-D) resistor mesh model described in spherical coordinates, consisting of 67,464 elements and 22,105 nodes arranged in 36 different concentric layers. After validation of the model by comparison with the analytic solution, potential variations induced by geometric and electrical skull modifications were investigated at the surface in the dipole plane and along the dipole axis, for several eccentricities and bone thicknesses. The resistor mesh permits one to obtain various configurations, as local modifications are introduced very easily. This has allowed several head models to be designed to study the effects of skull properties (thickness, anisotropy, and heterogeneity) on scalp surface potentials. Results show a decrease of potentials in bone, depending on bone thickness, and a very small decrease through the scalp layer. Nevertheless, similar scalp potentials can be obtained using either a thick scalp layer and a thin skull layer, and vice versa. It is thus important to take into account skull and scalp thicknesses, because the drop of potential in bone depends on both. The use of three different layers for skull instead of one leads to small differences in potential values and patterns. In contrast, the introduction of a hole in the skull highly increases the maximum potential value (by a factor of 11.5 in our case), because of the absence of potential drop in the corresponding volume. The inverse solution without any a priori knowledge indicates that the model with the hole gives the largest errors in both position and dipolar moment. Our results indicate that the resistor mesh model can be used as a robust and user-friendly simulation tool in EEG or event-related potentials. It makes it possible to build up real head models directly from anatomic magnetic resonance imaging without tessellation, and is able to take into account head heterogeneities very simply by changing volume elements conductivity. *Hum. Brain Mapp.* 21:86–97, 2004. © 2003 Wiley-Liss, Inc.

Key words: EEG; modeling; skull conductivity; anisotropy

INTRODUCTION

Electroencephalography (EEG) and magnetoencephalography (MEG) provide complementary brain activity data with the high temporal resolution (1–2 msec) required in advanced brain functional studies [Nunez, 1990]. On the one hand, MEG records magnetic fields of tangential sources only, whose localization is almost unaffected by resistive barriers such as the skull. On the other hand, EEG records scalp potential variations induced by radial as well as tangential sources whose localization depends greatly on con-

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ductive properties of the skull [Huiskamp et al., 1999]. We apply an original model [Franceries, 2003] that offers useful features to assess easily the effects of skull thickness, resistivity, and inhomogeneity on EEG/ERP source localization. Localization of the electrical dipoles generating surface potentials, the so-called “inverse” problem, remains crucial for understanding the mechanisms of brain response to various stimuli; however, the number, amplitude, localization, and orientation of the reconstructed sources depend strongly on the geometric and electrical properties of the head model used. Various models have been proposed in the literature, the most widely used consisting of three concentric spherical volumes, depending on the number of different tissues taken into account [Cuffin, 1991; Oostenveld and Oostendorp, 2002] or more [Laarne et al., 2000; Liston et al., 2002]. The main advantage of this kind of spherical model is that an analytic solution is available that can be used for scalp potential evaluation [Ary et al., 1981]. Realistic head models, built from anatomic magnetic resonance imaging (MRI) and taking into account the real shape of tissues, have also been proposed. Three-dimensional (3-D) realistic head models obtained with MRI for EEG are now used to solve the inverse problem [Huiskamp et al., 1999; Kavanagh et al., 1978] with recent efforts improving computational efficiency [Mosher et al., 1999]. With the realistic head models, an analytic solution is not available and numerical methods must be used to solve forward and inverse problems. For that purpose, one can use the boundary element method (BEM), which defines the envelopes between the different conducting media [Buchner et al., 1995; Yvert et al., 1995], or the finite element method (FEM), which splits the head volume in elementary volume elements [Awada et al., 1997; Thevenet et al., 1991; Yan et al., 1991]. One advantage of FEM compared to BEM is that it is possible to introduce anisotropic conductivities [Thevenet et al., 1991]. An example of practical application of FEM is deblurring [Le and Gevins, 1993], which permits the estimation of potentials at the superficial cerebral cortical surface from EEGs recorded at the scalp. The finite difference method (FDM) has also been proposed [Schimpf et al., 2002; Vanrumste et al., 2001; Witwer et al., 1972] and seems to improve the accuracy in the determination of dipoles when a hole is present in the head [Oostenveld and Oostendorp, 2002]. BEM and FEM, however, require a tessellation of the head model as a first step. This tessellation produces unavoidably irregular elements in the volume sampling that generates computational errors. [Franceries et al., 2003].

Many studies have attempted to define the impact of various parameters included in these models. Introducing the real conductivities, as measured for example by electrical impedance tomography (EIT), reduces systematic errors on dipole position provided by the inverse solution up to the amount of 1 cm [Law, 1993; Gonçalves et al., 2001; van Burik and Peters, 2000]. The brain, skull, and scalp conductivity ratio 1:1/80:1 used commonly in the three-sphere head model [Roth et al., 1993] is probably inadequate because a series of in vivo measurements has shown that it should be

1:1/15:1 [Oostendorp et al., 2000]. These values are of prime importance when using analytic or realistic models. Important errors can also be observed when not taking into account the anisotropy of tissues, particularly for the skull [Franceries et al., 2001; Haueisen et al., 2002; Marin et al., 1998]. The nonuniformity of the bone thickness, which can vary in the same skull by a factor of six [Rush and Driscoll, 1968], or by a factor of three between frontal and temporal regions [Todd, 1924], can lead to additional localization errors [Cuffin, 1993] of about 1 cm. The presence of a hole in the skull has been assessed and proved to induce very large errors [Oostenveld and Oostendorp, 2002; Vanrumste et al., 2000], especially with cortical dipoles [Heasman et al., 2002]. In addition, simple but important acquisition characteristics can limit the quality of dipole fit in the inverse solution. For example, the number of electrodes in the cap used for recording and the noise level are important points to consider [Chauveau et al., 2001; Van Hoey et al., 2000]. A large number of electrodes improves localization, especially for shallow and tangential dipoles [Yvert et al., 1996].

FEM, BEM, FDM, or derived numerical methods permit the measurement of potentials inside the volume. But calculation time is quite long, and in addition, large errors are observed for cortical dipoles [Franceries, 2003]. Our resistor mesh model, which is a hybrid between the finite difference method (FDM) and the transmission-line-matrix method (TLM), permits the study of potentials inside the spherical volume with satisfying results compared to those produced by the analytic solution, whatever the source eccentricity [Franceries et al., 2003]. In our model, the head volume is split in volume elements, each one represented by an equivalent resistor the value of which takes into account the local geometric and electrical properties.

In the present application of our model, we concentrate on the skull-smearing effects on scalp potentials, by varying parameters of the bone layer. For that purpose, the potential maps at the scalp surface obtained by the resistor mesh model are compared to the analytic solution to validate our approach. This has been achieved in the first step by studying surface potentials in the dipole plane and on the dipole axis, for several eccentricities and several homogeneous bone thicknesses. The study has been conducted on an isotropic model and on a model that takes into account skull anisotropy. In the second step, the skull has been subdivided into three layers, and the corresponding computed potentials have been compared to those obtained with the one-layer model. In the third step, a hole has been introduced in the skull and the effects on the scalp potentials investigated. Finally, an inverse method has been applied to the scalp potentials obtained with these different models to evaluate the corresponding errors in terms of source position and dipolar moment.

MATERIALS AND METHODS

A three-sphere head model has been chosen to represent the three basic tissues of the human head: brain, skull, and scalp with respective conductivities of 0.33, 0.0042, and 0.33

Figure 1.

Q-axis and dipole plane used for the simulations. In Cartesian coordinates, x-axis is pointing to the right ear, y-axis to nose and z-axis to the top of the head. In spherical coordinates, angle θ is defined versus z-axis and ϕ is the angle toward x-axis of the projection in the horizontal XOY plane. We call Q-axis the line through the centre of the sphere oriented to $\theta = \phi = 50$ degrees. Q81, for instance, means that the dipole origin is at 69 mm from the centre for a standard head radius of 85 mm, corresponding to an eccentricity of 0.81.

Siemens/meter (S/m). The inner, middle, and outer radii of the three concentric spheres are, respectively, 72, 79, and 85 mm (standard model). The brain source is modeled by a dipole defined by six parameters: location ($r, \theta_{loc}, \phi_{loc}$), orientation (θ_{ori}, ϕ_{ori}) and amplitude (M). The dipolar moment is defined by $M = \int J dv = I d$, where I is the primary current source propagating between the two poles of the source and d the distance between poles. Bone thickness varied from 1.5–11.5 mm, keeping bone plus scalp thickness constant and equal to 13 mm.

The analytic solution has been programmed using *Matlab* with 1-degree resolution for θ and ϕ angles. This program calculates the surface potentials for any dipole placed in the spherical head model, using spherical coordinates (Fig. 1).

The resistor mesh model includes resistors oriented in the radial, tangential θ and tangential ϕ directions [Franceries et al., 2003]. The technique consists in sampling the three-sphere head model using spherical coordinates with 10-degree angular increments, considering 36 concentric layers. Figure 2 shows a cross section of the spherical mesh. Equivalent resistors have been calculated for each element of the sphere, taking into account the volume, the position and the conductivity of the element in the model. A 3-D mesh model is thus obtained including 67,464 resistors and 22,105 nodes. A differential current source $\pm I$ is applied on two nodes, mimicking a quasi-punctual dipole (Fig. 3). We obtain a resistor mesh model whose nodes between elements are a simplification of the continuity equations. This model follows Ohm's and Kirchhoff's laws and is only calculated once for each head. It is then possible to simulate this model in

Figure 2.

Cross section of half of the spherical resistor mesh, at $\phi = 0$ degrees (sagittal right view). Each segment represents a resistor. The nodes of the mesh correspond to the intersections of the segments. Skull and scalp are sampled with very thin layers to study their internal potential distribution.

Figure 3.

Application of the dipole in the resistor mesh model. The quasi-punctual dipole of the analytic model, placed at node N, is modeled by two current sources ($-i$ and $+i$) plugged between nodes (N-1) and (N+1) in the resistor mesh model. These nodes are distant from L mm so that the dipolar moment is $M = iL$.

response to the application of one or several dipoles using simulation software such as SABER (Synopsys, Mountain View, CA) or PSPICE (Cadence, San Jose, CA), or to program the Newton-Raphson algorithm using Matlab (Math-Works, Natick, MA). In the last case, we first need to calculate the admittance matrix Y , which is a sparse square symmetric matrix used in the calculations of the algorithm. This algorithm brings out potential values at all nodes in the spherical volume and calculation can be stopped when the relative error reaches a threshold that can be set as low as 10^{-15} . From our experience, very good results are obtained with a threshold of only 10^{-8} . Because we constructed our own model, we know the exact place and number of each node and resistor in the model. This seems to be of great help when studying potentials in the dipole plane or on the dipole axis, or at specific 10/20 electrode positions, once the complete 3-D simulation has been carried out.

RESULTS

Resistor Mesh Model Validation Versus Analytic Model for Scalp Potentials

Forward solutions were computed for four radial dipoles to obtain the maximum potential exactly on a node, which facilitates validation. Moreover, a radial dipole gives very sharp surface potential distributions for higher eccentricities. These conditions, which are the less favorable ones, have been chosen for testing. On Q-axis, four eccentricities (0.24, 0.47, 0.66, and 0.81) corresponding, respectively, to $r = 20, 40, 56$, and 69 mm (Fig. 1) have been considered with locations and orientations source as: $\theta_{loc} = \theta_{ori} = 50$ degrees, $\phi_{loc} = \phi_{ori} = 50$ degrees, and a dipolar moment $M = 10$ nA.m.

Forward solutions were computed, for these four radial dipoles and for 10 skull thicknesses from 1.5–11.5 mm, using both the resistor mesh model and the analytic solution on a three-sphere head model. Validation of the resistor mesh model has been achieved by choosing identical dipole parameters in both models, using the magnitude factor (MAG) and the relative difference measurement (RDM) [Meijs et al., 1989] for all centered (mean = 0) potentials at the scalp surface (614 nodes in the mesh). The MAG evaluates the mean relative gain between two sets of data. The RDM estimates the pattern variation independently of the amplitude. The perfect equality between two data sets gives 1 and 0 for MAG and RDM, respectively.

Results in Figure 4 show that MAG remains constant except for the highest eccentricity (0.81). For bone thicknesses in the range of 4–9 mm, all MAG and RDM curves are constant, proving the adequacy of the resistor mesh model to the analytic model. For eccentricity equal to 0.81, MAG is increased for very thin and for very thick bone. However, as this effect concerns only a few points, MAG and RDM remain globally very good.

Figure 5 displays the maximum of scalp potentials depending on bone thickness and eccentricity. The analytic model and the resistor mesh model show the same variation

Figure 4.

MAG and RDM for scalp potentials in the resistor mesh model versus the three-sphere head analytic model for four eccentricities (0.24, 0.47, 0.66, and 0.81) and 10 skull thicknesses from 1.5–11.5 mm.

Figure 5.

Maximum scalp potential values obtained with the resistor mesh model and with the three-sphere head analytic model, for four eccentricities (0.24, 0.47, 0.66, and 0.81) and 10 skull thicknesses from 1.5–11.5 mm. Dipolar moment is kept constant (10 nA.m).

shape; however, their difference increases, as expected, when eccentricity increases. This is due to the spatial resolution of our model, which becomes a limiting factor when eccentricity increases. This drawback can be avoided by reducing element size in the model [Franceries et al., 2003].

The curves in Figure 6 represent the surface potentials in the plane containing the dipole axis for two skull thicknesses (0.24 and 0.81), in common reference, which is the reference equal to the mean value of scalp surface potentials. At each eccentricity, surface potentials are calculated for 10 skull thicknesses varying from 11.5 mm (top curve) to 1.5 mm. For the sake of figure clarity, only curves showing a visible difference were displayed. For each eccentricity, plots are split in two parts: bone thickness of 11.5–7.0 mm (Fig. 6a,c) and from 7.0–1.5 mm (Fig. 6b,d). The maximum potential decreases when bone thickness decreases to 7 mm (Fig. 6a,c), and increases when bone thickness decreases further to 1.5 mm (Fig. 6b,d).

The maximum is lower for values of skull and scalp thicknesses close to the normal mean physiologic value, i.e., 7.0 and 6.0 mm for skull and scalp, respectively. It is around these values that potentials are the smallest at the scalp surface, as to minimize energy on the scalp. A negative consequence of this effect is that two different configurations can give the same result, as with curves 10.5–2.5 and 1.5–11.5 (eccentricity 0.24) or curves 9.5–3.5 and 2.5–10.5 (eccentricity 0.81), which are very similar. This means that local variations in thickness may not necessarily translate into different potential values at the surface.

Because the resistor mesh model is capable of easily computing potentials at all nodes with results very close to the analytic ones, internal potentials in the 3-D volume can now be investigated.

Potential Measurements Along the Radial Dipole in the Resistor Mesh Model

The two plots (Fig. 7a,c) and their zoomed part corresponding to the skull and scalp layers (Fig. 7b,d) in Figure 7 correspond to eccentricities 0.24 and 0.81, respectively. The slope of the potentials in skull is nearly vertical compared to

that in scalp, which is nearly horizontal. This effect is very marked for high eccentricities (0.81) and negligible for deep dipoles (0.24).

As expected, if we examine potential variations from source point injection toward the scalp, we observe a quick potential decrease long before entering the bone, because of current attenuation in brain tissues. The high resistivity of bone then elicits further another potential dip throughout the skull. The slope of the potential fading increases as bone thickness decreases. But the value of the current passing through the bone depends on both bone thickness and scalp thickness. Lastly, it should be noticed that for a given skull thickness, the slope of the decrease in potential increases with eccentricity.

Effect of Skull Anisotropy on Surface Potential Measurements in the Dipole Plane

To test the effect of skull anisotropy, simulations have been carried out for a bone thickness of 7 mm (normal model). Bone conductivity has been increased by a factor of 10 in tangential directions according to the results presented by Law [1993]. Figure 8 shows a decrease in the maximum of surface potentials, with this effect being larger for cortical dipoles than for deep dipoles. Curves are smoother when using anisotropic bone conductivity.

Effect of Introducing a Three-Layer Skull

Most models invoke only a one-layer skull. Akhtari et al. [2002] reported measurements of skull conductivity obtained by electrical impedance using the four-electrode method. Their results showed that skull presents at least three different conducting layers: the outer and inner parts of skull, which are compact with low conductivity, and the inside part, which is spongiform with higher conductivity. Reported values of conductivities cover quite important ranges, however, so we chose two different configurations with very different thicknesses and conductivities. For the first model (M1), conductivities correspond to the lower values of the reported ranges: 5.4 mS/m for the outer com-

Figure 6.

Surface potentials in the dipole plane for two eccentricities and 10 skull thickness. **A:** Eccentricity 0.24, bone thickness 11.5–7.0 mm. **B:** Eccentricity 0.24, bone thickness 7.0–1.5 mm. **C:** Eccentricity 0.81, bone thickness 11.5–7.0 mm. **d:** Eccentricity 0.81, bone thickness 7.0 to 1.5 mm. Abscissa θ varies from 10–170 degrees.

compact layer, thickness 2.5 mm; 16.2 mS/m for the spongiform layer, thickness 2 mm; and 2.8 mS/m for the inner compact layer, thickness 2.5 mm. For the second model (M2), we kept the conductivity of bone used in the three-sphere head model for outer and inner layers and reduced thickness, and for the spongiform layer, we took the middle value of the range and increased thickness: 4.2 mS/m for the outer and inner compact layers, thickness 1.5 mm each; and 29 mS/m for the spongiform layer, thickness 4 mm.

The spongiform layer has conductivity three to five times higher than that of the other two layers for M1 and seven times higher for M2. Results in Figure 9 using isotropic conductivity concern skull described as one or three isotropic layers. Only results for M2 are reported because the difference between M1 and the three-sphere head model with one bone layer is too weak to be visible in the figure. The differences obtained with M2 are substantial. The curve for three isotropic layers is higher than is the curve for one isotropic layer, which is due to the very small potential

decrease in layer B in comparison with decreases in layers A and C (Fig. 10). Although surface potentials are higher, however, the shape of the curve does not differ very much in comparison with the one-layer isotropic skull. The effect of anisotropy applied to the three-layer skull has also been tested and gives very similar results to the one-layer anisotropic skull.

Modification of Surface Potentials in the Presence of a Hole in the Skull

The initial three-sphere head model has been modified to introduce a hole in the skull close to the dipole. The hole consists of a square area of 1-cm width in which bone conductivity has been replaced by brain conductivity. The hole is defined by the θ and ϕ angles in the range 40–50 degrees. The radial dipoles are pointing at one corner of the hole ($\theta = \phi = 50$ degrees). In our resistor model, the hole is achieved simply by locally modifying the admittance matrix

Figure 7.

Potentials inside the 3D resistor mesh model. **A:** Along Q-axis at 0.24 eccentricity (Q24). **B:** Along Q24 axis (zoomed) in skull and scalp layers. **C:** Along Q-axis at 0.81 eccentricity (Q81). **D:** Along Q81 axis (zoomed) in skull and scalp layers.

Y. Figure 11 presents the results for the two radial dipoles used previously. There is an increase in the maximum value at the surface, less important for deep dipoles (Fig. 11a) than for cortical dipoles (Fig. 11b).

The maximum potential is much higher, with a factor of about 11.5 for an eccentricity of 0.81, and the potential

difference is also maximal for this eccentricity. As relative residual energy (RRE) defined by Vanrumste et al. [2000] is proportional to the square of the difference with the tested model, the inverse calculation would give larger position errors for the dipole at eccentricity of 0.81 than for dipole at 0.24. Our results agree fully with those of other authors

Figure 8.

Surface potentials in the dipole plane for the three-sphere model using one-layer isotropic skull and one-layer anisotropic skull.

Figure 9.

Surface potentials in the dipole plane for one-layer isotropic skull and for three-layer isotropic skull.

[Oostenveld and Oostendorp, 2002; Vanrumste et al., 2000]; however, in these studies the dipolar moment is known and kept fixed, with the aim being to evaluate potential variations due to model difference for the same dipole.

Error on Dipole Fitting After Source Reconstruction by an Inverse Method

When processing ERPs, the dipole moment is unknown. To conform to realistic data, we used potentials obtained at

the surface from 61 positions corresponding to the electrode cap of a 10/20 system. The aim was to evaluate the error in localization resulting from the inadequacy of the model in the inverse method using the *Besa* software, which integrates the simplex algorithm. With such a configuration using 61 electrodes, we can expect a maximum precision of about 1 mm [Yvert et al., 1997] if the model is adequate.

The *Besa* algorithm was applied without any a priori information on the dipole initial position, orientation, or

Figure 10.

Potentials along Q-axis dipole. **A:** Q24 for one- and three-layer isotropic skull. **B:** Q24 zoomed in skull and scalp. **C:** Q81 for 1 and three-layer isotropic skull. **D:** Q81 zoomed in skull and scalp.

Figure 11.

Surface potentials in the dipole plane with or without a hole in the skull. The three-sphere isotropic head model is modified locally for eccentricity 0.24 (a) and eccentricity 0.81 (b). The dot curve in (b) corresponds to the potentials of the isotropic curve magnified by a factor of 11.5.

dipolar moment. We were looking for a fixed dipole with all six parameters free. Results reported in Figure 12 and 13 concern the fit of the three-sphere head model (standard model).

We first fitted the model to itself, i.e., to isotropic one-layer bone, which is in fact the reference three-sphere head model. The small position error observed was due to error in our model, to *Besa* error, and to the electrode cap limitation. We found at most -1 mm error for the four eccentricities, a value that corresponds to the error expected from cap sampling constraint; our resistor model does not seem to introduce any additional error. Results concerning bone thickness are not reported in the graph; in all cases, the maximum position error is $+4$ mm for skull thicknesses 11.5 and 1.5 mm. Results for one and three anisotropic layers indicate a dipole deeper than its true position, with error increasing

with eccentricity (Fig. 12). For the three-layer isotropic skull, dipoles are fitted $+4$ mm closer to the scalp. For the model with an open hole in the skull, we find that the dipole position error is about $+15$ mm for deep dipoles and only a few millimeters for cortical dipoles. In fact, *Besa* integrates an optimal amplitude algorithm, which permits fitting on the shape of potential distribution rather than on absolute potential values. In Figure 11b, the curve "isotropic $\times 11.5$ " indicates that, despite a huge potential difference, the shape of "isotropic" and "with hole" are in fact very similar. That is why *Besa* reconstructs the dipole with little position error. In contrast, the curves in Figure 11a have different shapes in the range 30 – 70 degrees. With the hole, the shape is sharper, and logically *Besa* finds the dipole 1.5 cm higher. Values of the dipole moment are reported in Figure 13 and show that the major part of the amplitude difference is taken by the

Figure 12.

Position error of inverse solution using *Besa*. Input data are simulated surface potentials taken at nodes corresponding to a 61-electrode cap (10/20 system). With the three-layer isotropic model, the result at eccentricity 0.81 has not been plotted because the dipole would have been localized in bone, which is impossible.

Figure 13.

Dipole moment of inverse solution using Besa. Input data are the simulated surface potentials taken at nodes corresponding to a 61-electrode cap (10/20 system). The correct dipolar moment to find is 10 nA.m (one-layer anisotropic is hidden by one-layer isotropic).

dipolar moment when curve shapes are comparable. This proves that inverse methods are mostly sensitive to patterns. In addition, the dipolar moment is equal to the initial value multiplied by the MAG factor; thus, the position error depends only on the RDM value.

DISCUSSION

Our resistor mesh model has been validated in comparison to the three-sphere model analytic solution, for different source eccentricities and bone thicknesses. In all cases, the MAG and RDM were in the ranges of 0.997–1.045 and 0.016–0.06, respectively.

The model being thus validated, we studied the effect of bone thickness on surface potential values and patterns. We found that for high eccentricity (0.81), the maximum surface voltage varies by a factor of two when bone thickness varies from 1.5–11.5 mm. For deeper dipoles (eccentricity of 0.24) this factor is lower (around 1.5). These variations are important for all depths and can lead to dipole fitting errors in the inverse problem. The error is minimized for a bone thickness of approximately 7 mm. Patterns do not differ very much when bone thickness varies, suggesting that the main error in the inverse solution affects the dipolar moment to a greater extent than it affects the dipole position. In addition, we have shown that different uniform skull thicknesses can be associated with identical potential distributions. If those effects are not taken into account, non-negligible errors can follow when using inverse methods based on the three-sphere head model for dipole localization. The problem will be even more serious in the real head, where bone thickness may vary from place to place. In such cases, unforeseeable errors can be made.

The effect of anisotropy in a skull modeled with a single layer translates mainly into patterns that are smoother. In

the inverse solution, errors are in both position (2–6 mm deeper due to difference in patterns) and dipolar moment (9.5 nA.m instead of 10 due to different potentials at maximum).

In the next step of the study, we considered the skull as a three-layer compartment. We found that both pattern and amplitude were altered when changing from one to three layers. Dipoles were localized at more superficial positions with larger dipolar moment (13 nA.m).

Radial dipoles pointing to a hole in the skull produced very important variations on the scalp potentials. Some authors reported up to 450% variation [Oostenveld and Oostendorp, 2002]. The variation amounted to 1,150% for our specific dipole at eccentricity 0.81. We also found that effects of the hole on surface potentials were less prominent for deep dipoles than for superficial dipoles, in terms of potential variations, as reported previously [Heasman et al., 2002]. If we consider the solution of the inverse problem, however, the localization error in radial dipole position is larger for deep dipoles (15 mm at 0.21 eccentricity) whereas the error on the dipolar moment is higher for superficial dipoles (90 nA.m at 0.81 eccentricity). This is in agreement with results reported in the literature. Bertrand et al. [1992] examined the influence of a hole in the skull layer on surface potential in a spherical model. They found that for dipoles far from the hole, the orientation was retrieved correctly, but the dipole remained misplaced. In general, dipoles were shifted toward the hole. Van den Broek et al. [1998] reported that in presence of a hole, the error in location obtained from the potential was largest (up to 16 mm) for deeper dipoles. Benar and Gotman [2002] estimated the localization error to be as large as 10 mm for a radial dipole located 30 mm below the hole, with an amplification of the potentials of eight, the recovered dipoles being found closer to the hole than they

really were. In addition, potentials maps were greatly distorted in the presence of a hole in the skull, even for deep sources. Our results agree fully with results reported in these works.

Finally, our resistor mesh model proved to be a good tool, giving very similar results to other studies that used BEM, FEM, or FDM. Its advantages are the simplicity of design and the reasonable calculation time: using a 1.8-GHz Pentium IV personal computer, a forward calculation on the resistor model, containing as many resistors and nodes as was used in this study, lasts for 10 min with a relative error fixed to 10^{-15} . We are currently working to apply our technique to real head modeling, with cubic elements, taking into account local conductivity and anisotropy. For global scalp, bone, and head conductivities, electrical impedance tomography (EIT) [Gonçalves et al., 2000, 2001] can be a powerful tool. To take into account the anisotropy of the brain, head conductivity should be modulated by local coefficients derived from magnetic diffusion tensor imaging [Hauelsen et al., 2002]. Our model proves to be quick, accurate, and easy to implant, and the next challenge is to improve it further by implementing factors related to real conductivity and anisotropy measures in each model element.

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