IN VIVO MEASUREMENT OF SKULL AND BRAIN RESISTIVITIES WITH EIT BASED METHOD AND ANALYSIS OF SEF/SEP DATA

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Abstract- **In this paper we present results of the equivalent brain and skull resistivities (ρ_{brain} and ρ_{skull}) for 6 different subjects using 2 different and independent procedures: an EIT based method and the combined analysis of SEF/SEP data. With the EIT based method known currents are injected into the head and the resulting potential distributions are recorded from scalp electrodes. The conductivities are estimated by fitting the conductivity parameters of a 3-sphere head model onto the measured potentials. With the combined SEP/SEF method, a current source is activated inside the brain using a nervous medianus stimulation. The MEG data is used to determine dipole position and tangential orientation, whereas the simultaneously recorded EEG data is used to find the dipole radial component and the electrical conductivities of the brain and the skull.**

The results show a large variability in the ratio of skull and brain conductivities $\rho_{skull}/\rho_{brain}$ over subjects. However, a strong agreement was found between the results of EIT and SEF/SEP methods even though they are quite different, both in theoretical and technical terms.

These results indicate that generic conductivity values will result in large systematic errors of EEG inverse modelling. However, the good agreement between the EIT and the SEP/SEF method indicates that the individual's $\rho_{skull}/\rho_{brain}$ ratio can reliably be determined using the EIT method.

***Keywords* – resistivity, brain, skull, EIT, SEF, SEP.**

I. INTRODUCTION

The Inverse Problem (IP) [1] of EEG aims to determine the sources inside the brain that best explain the electrical potentials measured on the surface of the scalp. The determination of the sources is made through the use of mathematical models, which describe the head as an electrical conductor. In this way, the knowledge of the electrical conductivities of the tissues of the head must be known a priori and it is known that the solution to the EEG IP is highly dependent on the values taken for these parameters [2],[3],[4]. The first attempts to measure the electrical conductivities of the tissues were made “in vitro” and often using animal tissue sample. These measurement procedures suffer from large systematic errors. As a consequence, the values presented in literature for the electrical conductivities show a wide range of variation and there might be a factor of 7 between the minimum and maximum conductivity values reported for a certain tissue [5]. Recently, several studies have been performed to try to estimate “in vivo” the electrical conductivities of several head structures. Some approaches like the one in [6] use the Boundary Element Method (BEM) and realistic head models to estimate the equivalent electrical resistivities of brain, skull and skin. Other approaches like in [7] use of the combined analysis of MEG and EEG data to estimate the electrical conductivities as well as the source parameters. In this paper it was chosen to use spherical models to avoid obtaining biased estimations of the resisitivities since the accuracy of the BEM depends on the values of $\rho_{skull}/\rho_{brain}$ as well as on the node distribution among the head compartments. The SEF/SEP analysis presented here differs from the one in [7] in that MEG and EEG data are analysed using separate mathematical models, decreasing the complexity of the computations.

II. METHODOLOGY

A. Head Models

The spherical model is defined in two different ways. In the *default model*, a sphere is fitted to the grid of electrodes used in each subject and taken as the description of the skin. The radii of the two spheres describing the skull and the brain are respectively equal to 0.92 R_{skin} and 0.87 R_{skin}, where R_{skin} is the radius of the sphere describing the skin. The same relative skull thickness (r.s.t), equal to 0.05, is taken for all subjects.

In the *individual model* instead of taking the factors 0.92 and 0.87 for all subjects, these parameters are adjusted for each subject by fitting a set of concentric spheres to their realistic model, therefore adjusting the r.s.t. for each subject.

The approximation $\rho_{brain}=\rho_{skin}$ is made.

B. Methods

The theoretical basis for the EIT method, using the spherical models for the head has already been described in [8].

In the SEF/SEP method the analysis is performed in 2 steps:

1. The sources, which best explain the recorded magnetic N20 data in the time samples around the latency of the response are computed with the single dipole model. Therefore both the positions and the tangential components become known parameters;
2. EEG data is used to compute the radial components of the dipoles as well as the brain electrical conductivity and the brain to skull conductivity ratio. Since both the dipole's positions and tangential components are already known the parameters aforementioned remain the only unknowns to be determined.

The potential Ψ_i measured on a sensor **i** located at $\vec{\mathbf{r}}_i$ at time instant **j** can be written as:

$$\Psi_{ij} = M_j^R \rho_{brain} \Theta_{ij}^R\left(\vec{\mathbf{r}}_{\mathbf{i}}, \vec{\mathbf{r}}_{\mathbf{d},j}, \frac{\sigma_{skull}}{\sigma_{brain}}\right) + M_j^{T1} \rho_{brain} \Theta_{ij}^{T1}\left(\vec{\mathbf{r}}_{\mathbf{i}}, \vec{\mathbf{r}}_{\mathbf{d},j}, \frac{\sigma_{skull}}{\sigma_{brain}}\right)$$
$$+ M_j^{T2} \rho_{brain} \Theta_{ij}^{T2}\left(\vec{\mathbf{r}}_{\mathbf{i}}, \vec{\mathbf{r}}_{\mathbf{d},j}, \frac{\sigma_{skull}}{\sigma_{brain}}\right) \quad (1)$$

where

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$\vec{\mathbf{r}}_{\mathbf{d,j}}$ is the dipole position at time instant **j**;

$\sigma_{\text{brain}} = \dfrac{1}{\rho_{\text{brain}}}$ is the conductivity of the brain;

$\sigma_{\text{skull}} = \dfrac{1}{\rho_{\text{skull}}}$ is the conductivity of the skull;

M_j^R is the radial component of the dipole moment at time instant **j**;

M_j^T contains the tangential components of the dipole at time instant **j**: M_j^{T1}, M_j^{T2};

Θ_{ij}^R and Θ_{ij}^T are respectively the potential generated on sensor **i** at time instant **j** by the radial and tangential components of the dipole on a sphere of normalised conductivities: $\left(1, \dfrac{\sigma_{\text{skull}}}{\sigma_{\text{brain}}}, 1\right)$.

The IP is defined as the computation of the parameters M_j^R, ρ_{brain} and $\sigma_{\text{skull}}/\sigma_{\text{brain}}$ that best explain the electrical potentials measured on the scalp. If the potential measured on a certain sensor **i** at time instant **j** is considered, then the difference between measured (Ψ_{ij}) and predicted ($\tilde{\Psi}_{ij}$) potential is expressed as:

$$\cos t = \frac{\sum_{ii'j} \left(\tilde{\Psi}_{ij} - \Psi_{ij}\right) C_{ii'}^{-1} \left(\tilde{\Psi}_{i'j} - \Psi_{i'j}\right)}{\sum_{ii'j} \Psi_{ij} C_{ii'}^{-1} \Psi_{i'j}} \qquad (2)$$

where **i** and **i'** run over the total number of measuring sensors, **j** runs over the number of time samples analysed and $C_{ii'}$ is the spatial covariance [9] between EEG channels **i** and **i'**. Although $\sigma_{\text{skull}}/\sigma_{\text{brain}}$ must be estimated using non-linear minimisation procedures, M_j^R and ρ_{brain} are in principle determined by exact expressions because they are linear parameters.

C. Data Acquisition

Data from 6 normal subjects was acquired using the Omega MEG/EEG system (CTF Systems Inc.). Data for the SEF/SEP analysis was obtained from the stimulation of the median nerve using an electrical current. The frequency of the stimulus was set at 2 Hz and its duration was 0.2 ms. Current intensity ranged from 2.5 to 12 mA. After the onset of the stimulus, MEG and EEG data were recorded simultaneously at a rate of 1250 Hz, using 151 MEG channels and 64 EEG channels, with the electrodes positioned according to the extended 10-20 system. Data was filtered on-line with an anti-aliasing low-pass filter at 400 Hz and off-line using a low-pass filter at 300 Hz and a high-pass filter at 5 Hz. In order to improve the signal-ratio 500 to 700 artifact-free epochs of 0.4 seconds had to be averaged.

The acquisition of data for EIT analysis was made using the aforementioned EEG system with the electrodes positioned according to the extended 10-20 system. Current was injected on a pair of electrodes measuring the potential distribution on the remaining sensors, this procedure being repeated for several injection pairs. The injection electrodes were positioned with a maximum separation between them, and the reference electrode located approximately halfway between injection and extracting electrodes to decrease the effects of local variations of the skull conductivity on the results. The injection-extraction electrode pairs were chosen to cover the whole perimeter of the head.

The current generator produced a 60 Hz sinusoidal electrical current of 10 μA rms. Data was acquired at a rate of 1250 Hz, using on-line high and low-pass filters at 0.16 Hz and 300 Hz respectively. For each injection pair, epochs of 105 seconds were recorded.

III. RESULTS

The results obtained with the spherical model, both with default and fitted head model are represented in Tables I and II.

TABLE I

Results obtained with EIT and SEF/SEP, default r.s.t. (ratio=$\rho_{\text{skull}}/\rho_{\text{brain}}$)

EIT method				**SEF/SEP Method**			
Sub	ρ_{brain} (Ω.cm)	ρ_{skull} (Ω.cm)	ratio	ρ_{brain} (Ω.cm)	ρ_{skull} (Ω.cm)	ratio	r.s.t.
1	440	13300	30	175	7441	43	0.05
2	245	30800	127	–	–	–	0.05
3	280	26900	96	280	24000	86	0.05
4	295	20000	68	250	16300	65	0.05
5	245	16100	66	250	18600	74	0.05
6	330	15200	46	210	13900	66	0.05

TABLE II

Results obtained with EIT and SEF/SEP, individual r.s.t. (ratio=$\rho_{\text{skull}}/\rho_{\text{brain}}$)

EIT method (individual r.s.t.)				**SEF/SEP Method** (individual r.s.t.)			
Sub	ρ_{brain} (Ω.cm)	ρ_{skull} (Ω.cm)	ratio	ρ_{brain} (Ω.cm)	ρ_{skull} (Ω.cm)	ratio	r.s.t.
1	400	5400	14	169	4497	27	0.12
2	216	10180	47	–	–	–	0.13
3	210	14000	67	278	18394	66	0.10
4	264	7300	28	265	11515	43	0.13
5	215	10300	48	248	14478	58	0.08
6	250	6000	24	209	9461	45	0.12

The observation of the tables above shows that in general the results given by both methods are in agreement (Fig. 1), in particular with respect to the values of $\rho_{\text{skull}}/\rho_{\text{brain}}$. The results using the SEF/SEP method are not presented for subject 2 since in this case no useful EEG response was recorded. For subjects 1 and 6, the agreement between the absolute values of the resisitivities is not as good as for the other subjects. However for these two subjects, the values of $\rho_{\text{skull}}/\rho_{\text{brain}}$ given by EIT and SEF/SEP are not as similar as for the other subjects and therefore larger differences in the absolute values of the resistivities are more likely to appear. In both methods, and particularly for the EIT model, the difference between the results obtained using the default and individual r.s.t. lies mainly in the estimations for the skull resistivity. In fact the values of ρ_{skull} obtained using the fitted r.s.t. come afected by a factor which is approximately equal to (individual r.s.t)/(default r.s.t.), meaning that both methods have the ability to compensate for changes in the geometry.

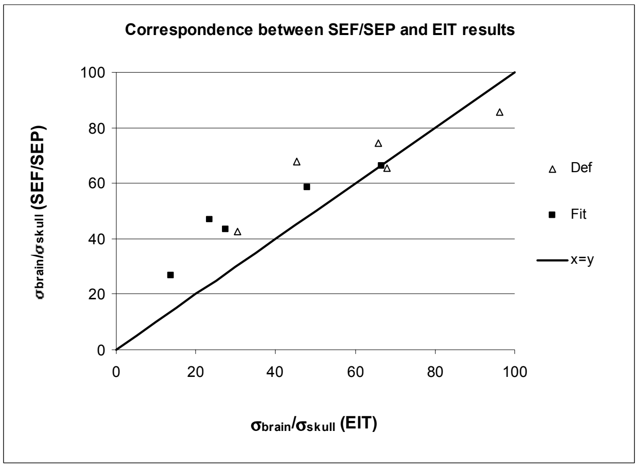

Fig. 1. Comparison between the values of $\sigma_{brain}/\sigma_{skull}$, given by EIT and SEF/SEP using both the default (*Def*) and individual (*Fit*) r.s.t.. For comparison, the identity line (*x*=*y*) is also represented.

IV. DISCUSSION

The results obtained with the present work show the ability of the described methods to compute "in vivo" the equivalent resistivities of brain, skull and skin. Furthermore, both methods show the ability to compensate for geometrical variations of the head model, particularly the skull thickness, by adjusting the estimation of the skull resistivity accordingly. In this way, the computed electrical parameters may not necessarily be coincident with the true values but they are the ones which best compensate for errors being committed in the geometry of the head, being this what is desirable to have when dealing with EEG modelling.

The variability of $\rho_{skull}/\rho_{brain}$ was clearly confirmed by two different and independent methods. Although part of this variability might be explained by the systematic errors of the head model, it is also true that especially the skull structure is very complex [10] and variations in its characteristics from subject to subject are very likely to occur. The use of realistic models in future studies will clarify the source of variation since the geometrical errors will be corrected.

V. CONCLUSION

The results obtained in this study clearly show that there is indeed a source of variation in the equivalent electrical properties of the head compartments to be accounted for. In this sense, a method should be used to compute the equivalent electrical properties "in vivo" for each subject. We think that in particular the presented EIT method not only has the ability to fulfil this goal but also requires technical conditions usually available in any EEG laboratory.

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