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The influence of volume conduction effects on the EEG/MEG reconstruction of the sources of the Early Left Anterior Negativity

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Abstract—**To achieve a deeper understanding of language processing in the human brain, scientists and clinicians use Electroencephalography (EEG) and Magnetoencephalography (MEG) inverse methods to reconstruct sources of Event Related Potentials. There exists a persistent uncertainty regarding the influence of volume conduction effects such as the anisotropy of tissue conductivity of the skull and the white matter layers on the inverse results. In this paper, we will study the sensitivity to anisotropy of the source reconstruction of the Early Left Anterior Negativity (ELAN) component in language processing. For EEG, the presence of tissue anisotropy substantially compromises the restoration ability of an L1-norm current density approach. The centers of activity are strongly shifted along the Sylvian fissure in the anterior direction. In contrast, MEG in combination with the L1 norm approach is able to reconstruct the main features of the ELAN source distribution even in the presence of anisotropic conductivity.**

Keywords—**EEG/MEG source reconstruction, influence of skull and white matter anisotropy, finite element method, L1 norm current density reconstruction, ELAN**

I. Introduction

Reconstructing sources of brain activity and their dynamic interplay is an important part of the study of how language processing occurs. Previous findings suggest the existence of three Event Related Potential (ERP) components that correlate with language comprehension processes [1]. The first ERP, the so-called Early Left Anterior Negativity (ELAN) was observed and interpreted to reflect a processing phase during the input is parsed into an initial syntactic structure. The reconstruction of the ELAN sources is of substantial interest and Friederici et al. have suggested a dipole fit approach with seedpoints from functional Magnetic Resonance Imaging (MRI) [1]. The study provided a clear indication that both temporal and fronto-lateral cortical regions in both hemispheres support early syntactic processing with a dominance in the left hemisphere.

A critical component of source reconstruction, an inverse problem, is the numerical approximation method used to reach an accurate solution of the associated forward problem, i.e., the simulation of fields for known dipolar sources in the brain. The forward problem requires a geometric model of the volume conductor (the head and brain), often in the form of spherical shell- or Boundary Element (BE) models [1,2]. The BE method is adequate for piecewise homogeneous isotropic compartments skin, skull and brain, but it does not allow a realistic representation of the anisotropy of conductivity of the skull and white matter. In contrast, the Finite Element (FE) method is able to treat both realistic geometries and inhomogeneous and anisotropic material parameters. First studies show that the inclusion of anisotropy is crucial for an accurate reconstruction of the sources [3,4,5,6,7,8]. Furthermore, newest developments for the FE method in EEG/MEG inverse problems [9,10] dramatically reduce the complexity of the computations, so that the main disadvantage of FE modeling no longer exists.

In this study, we focused on the influence of anisotropy on the reconstruction of the ELAN sources. We constructed a high resolution model of the head, simulated electrical and magnetic fields from given sources, and compared the influence of anisotropy on the accuracy of source reconstruction using an L1-norm current density approach. Our results suggest that including anisotropic conduction is essential for EEG-based source localization but that MEG-based reconstructions suffer less from the omission of anisotropy.

II. Methodology

The first step in the construction of a realistic anisotropic volume conductor model is the segmentation of head tissues with different conductivity properties. For this study, we used T1- and PD-weighted MRI as the input to the segmentation process (Fig.1). The first step was to align the two image sets, for which we used a voxel-similarity based affine registration without pre-segmentation using a cost function based on mutual information. The main components in our nearly automatic segmentation program are a 3D implementation of an Adaptive Fuzzy C-Means classification algorithm which compensates for image intensity inhomogeneities, followed by an algorithm that uses a deformable model to smooth the inner and outer skull surfaces [8]. The result is a 5-tissue segmentation, an

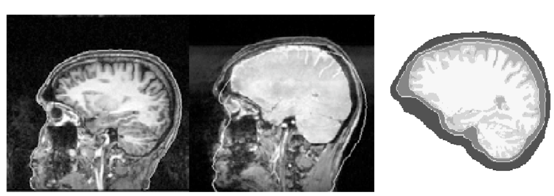

Fig. 1. The segmented head model (right) was generated from a pair of T1- (left) and PD- (middle) MRI with a special focus on an improved segmentation of the skull layer.

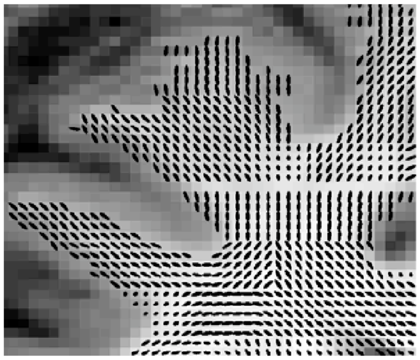

Fig. 2. Detail of the projection of the conductivity tensor ellipsoids onto a coronal cut of the T1-MRI through the Commissura anterior.

example of which is presented in Fig.1 (right).

From the segmented images, we then generated FE models, the first of which included a surface-based tetrahedral tessellation of the relevant 5 compartments, resulting in 147,287 nodes and 892,115 elements. A node-shifted cube approach [8] led to a second, hexahedral FE mesh with 385,901 nodes and 366,043 elements. The following isotropic conductivity values were assigned to skin (0.33 S/m), skull (0.0042 S/m), cerebrospinal fluid (1.79 S/m), brain gray (0.33 S/m) and white matter (0.14 S/m) and ventricular system (1.79 S/m).

Diffusion Tensor MRI (DT-MRI) measurements formed the basis for a realistic modeling of white matter anisotropy [5,6,8]. Following the proposition of [11], we assumed that the conductivity tensors share the eigenvectors with the diffusion tensors. For the determination of skull conductivity tensor eigenvectors, we used a deformable model to generate a smooth surface model of the spongiosa, i.e., a strongly smoothed triangular mesh, which was shrunken from the outer skull mask onto the outer spongiosa surface. The tensor eigenvectors could then be determined from the normal vectors of the triangular mesh [5].

We computed the eigenvalues for both skull and white matter conductivity tensors using a volume constraint that retains the geometric mean of the eigenvalues [5], i.e., the volume of each tensor remains constant. For the anisotropic case, we used a relation of 1:10 for the eigenvalues of skull (radially:tangentially) [3,4,5] and white matter

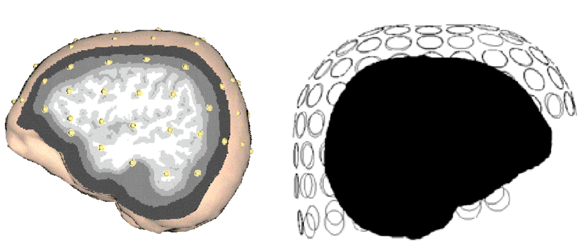

Fig. 3. The 71 EEG sensors and the 148 MEG magnetometer coils.

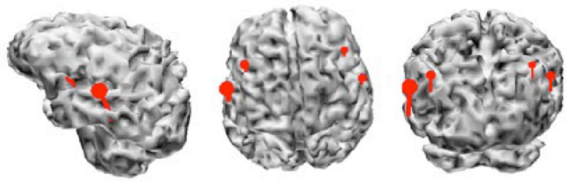

Fig. 4. The four reference ELAN sources.

(longitudinally:transversally) [5,8]. Fig.2 contains a sample projection of the conductivity tensor ellipsoids.

The sensors of the EEG and MEG systems are shown in Fig.3. For the EEG, 71 electrodes were placed on the head surface according to the international 10/20 system [8]. For the MEG, we modeled each magnetometer flux transformer of the BTI (4-D Neuroimaging, San Diego, USA) 148 channel whole-head system with 8 isoparametric quadratic finite row elements.

A cortical influence space surface was generated by means of a dilation of the white matter mask by 1 mm, while taking care that the dilated mask was topologically equivalent to a sphere. In a subsequent step, the surface of the resulting mask was triangulated with 5 mm resolution into 6742 regularly shaped triangles and 3373 vertices. This mesh is a rough representation of the neocortical surface, neglecting deeper gray matter structures such as the basal ganglia. Because such a representation neglects detailed neocortical curvatures, we did not apply a normal-constraint, i.e., sources in all Cartesian directions were allowed for each mesh vertex during source reconstruction. An EEG/MEG lead field matrix **L** was computed for the isotropic tetrahedra model, using the fast FE solver methods described in [8,9,10]. Each of the 3*3373 columns of this matrix stores the simulated 71 EEG potentials and the 148 MEG flux values.

Fig.4 shows the four ELAN reference dipoles we simulated on vertices of the influence space mesh, a source with 33 nAm strength in the vicinity of the left auditory cortex, a left fronto-lateral source with 20 nAm strength and their right hemisphere homologue dipoles with 18 nAm and 16 nAm, respectively.

For the inverse reconstruction, we define the data term

$$Data(\mathbf{j}) := \left\| \mathbf{D}^{-1}(\mathbf{L}\mathbf{j} - \mathbf{u}^{m}) \right\|_2^2 \qquad (1)$$

with **D** a diagonal channel weighting matrix, **j** the current density vector on the influence space mesh, and $\mathbf{u}^{m}$ the EEG/MEG data and an L1 norm model term as

$$Model(\mathbf{j}) := \left\| \mathbf{W}\mathbf{j} \right\|_1 \qquad (2)$$

with a diagonal source location weighting matrix **W**. The goal of the L1 norm current density reconstruction is the minimization of the functional

$$F_{\lambda}(\mathbf{j}) := Data(\mathbf{j}) + \lambda \cdot Model(\mathbf{j}) \quad (3)$$

with respect to $\mathbf{j}$. λ is the so-called regularization parameter. We chose an L1 norm model term, because this method is well-known to be favorable for the reconstruction of focal sources when compared to L2 norm model term definitions [2,12]. We minimized F by means of a nonlinear Polak-Ribiere CG method [8] and for the choice of the regularization parameter λ, we used the L-curve method [2,12] and the X^2-criterion [12]. The diagonal entries of $\mathbf{D}$ were set to the absolute value of the difference between isotropic and anisotropic data $\mathbf{u}^m$. Knowing that we are confronted with superficial reference sources, $\mathbf{W}$ was chosen as the identity operator, i.e., the reconstructed current distribution gives preference to superficial sources.

III. Results

A. *Influence of anisotropy on forward isopotential distribution*

In a first study, we carried out forward computations for the left temporal ELAN source in the nodeshifted hexahedra model. Fig.5 shows the resulting isopotential distributions on a coronal slice through the location of the source for the isotropic case (left) and for the corresponding cases with anisotropy of skull (middle) and WM (right) compartment. Skull anisotropy leads to a slight shift of the ELAN ERP component from lateral to medial directions on the head surface. This can be seen by following the isopotential line marked in black in Fig.5. While for the isotropic case (left panel), this isocontour represented the strongest negative isopotential that reached the surface, in the anisotropic case, the same isopotential line was not able to break through the skull layer. Instead, the a less negative contour was the first to reach the surface and at a more medial location (middle panel). The iso-line marked in brown in Fig.5 shows the effect of white matter anisotropy. It appears that in the anisotropic white matter case (right panel), this isopotential line is forced to follow more strongly a direction perpendicular to the fiber bundles of the corticospinal tract because of an increased volume current flow along the fibers, so that it enters the skull compartment at a different location and, in contrast to the isotropic case, is then able to break through the skull.

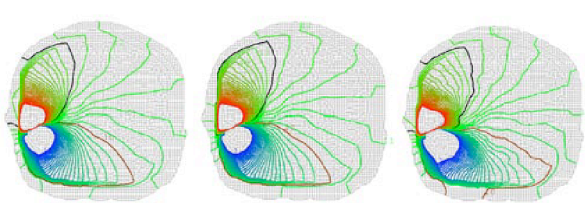

Fig. 5. Isopotential distribution for the left temporal ELAN source: isotropic (left), anisotropic skull (middle), anisotropic white matter (right).

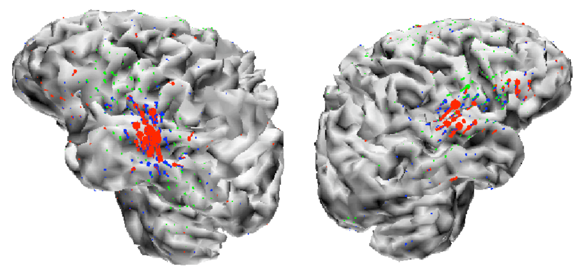

Fig. 6. MEG: L1 norm current density reconstruction results for isotropic (red), and anisotropic (blue, green) reference MEG data using the L-curve method (blue) and the X^2-method (green).

B. *Influence of anisotropy on the L1 norm current density reconstruction*

We carried out L1 norm current density reconstructions using the simulated isotropic or anisotropic (skull and white matter) data $\mathbf{u}^m$. Fig.6 shows the results for isotropic MEG data (red) and anisotropic MEG data using the L-curve-criterion (blue) and the X^2-criterion (green). The solution of the L1 norm for isotropic MEG data shows three centers of activity. This is the error introduced through the choice of the source model (focal reference sources reconstructed by means of a current density method). Surprisingly, the left (which is stronger than the right) fronto-lateral ELAN source could not be reconstructed in contrast to both the temporal and the right fronto-lateral centers. The result of the L1 norm reconstruction (L-curve-criterion) by means of the anisotropic MEG data is only a little more smeared out, but the three activity centers are still distinguishable. This is no longer the case when using the X^2-criterion, where the activity between the fronto-lateral and the temporal reference centers is strongly smeared out on both hemispheres. Fig.7 shows the result for the EEG. In the isotropic case (left), even the focusing L1 norm is not able to distinguish between the temporal and the fronto-lateral centers of activity. Instead of two centers, the activity is smeared out over the whole cortical area between both ELAN sources. The MEG solutions in Fig.6 were much better focused around the reference sources. The reconstructed activity on the left hemisphere dominates over the right hemisphere (not shown). The error is much more

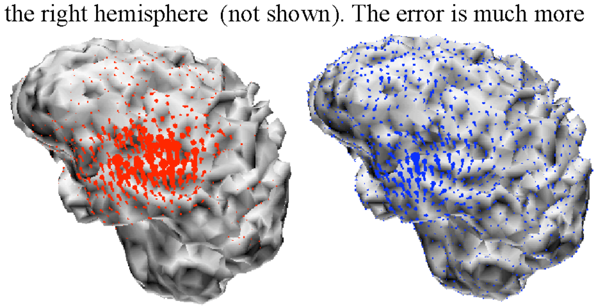

Fig. 7. EEG: L1 norm current density reconstruction results for isotropic (red) and anisotropic (blue) reference EEG data using the L-curve method.

distinct for the anisotropic data (right), where, additionally, the center of activity was strongly shifted in the anterior direction along the Sylvian fissure so that the sources would no longer be expected in the vicinity of the auditory cortex. The results for L2 norm current density reconstruction have comparable properties only that the current density distribution is even more spread out [8] (not shown here).

IV. Discussion

Our results for the influence of anisotropy were mainly in agreement with the literature at least to the extend that such solutions exist. Skull anisotropy had a non-negligible influence on the EEG and nearly no influence on the MEG, as also reported in [3,4,5,8]. We found that the more the source was surrounded by white matter structure, the more important white matter anisotropy modeling became for both EEG and MEG [5,6,7,8]. For MEG, this influence was especially strong for sources with mainly a radial orientation component.

With regard to the reconstruction of the four superficial and tangentially oriented ELAN sources [1], white matter and skull anisotropy were found to have a negligible influence on the MEG reconstruction. In contrast, reconstruction based on the EEG was severely compromised without proper incorporation of anisotropy both for the instantaneous L1 current density reconstruction as well as for regularized multi-dipole fit procedures [8]. The sensitivity of two instantaneous current density reconstruction methods towards skull anisotropy was also studied for EEG in [4]. Marin et al. also studied the sensitivity of current density reconstruction to skull anisotropy. They used the linear L2 norm and a non-linear S-MAP regularization, where the latter, like our L1 norm approach, produces more focalized results than the linear method. In agreement with our results, they reported that skull anisotropy totally compromised the localization ability of the L2 approach and that the restoration of very close active regions was profoundly disabled for both the linear and the non-linear regularization method.

V. Conclusion

With the newest developments in FE modeling for the EEG/MEG inverse problem, the complexity of the computations is now dramatically reduced [9,10], so that the former main disadvantage of FE modeling no longer exists. In localizing EEG ELAN activity, source reconstruction is sensitive to tissue anisotropy and for such cases, FE forward modeling should improve inverse reconstructions. If the sources to be reconstructed are either radially oriented or relatively deep and surrounded by white matter fibers, the MEG based reconstruction will also be sensitive to white matter anisotropy.

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References

[1] A.D. Friederici, Y. Wang, C.S. Herrmann, B. Maess, and U. Oertel, "Localization of Early Syntactic Processes in Frontal and Temporal Cortical Areas: An MEG Study," *Human Brain Map.*, vol. 11, pp. 1-11, 2000.

[2] M. Fuchs, M. Wagner, T.Koehler, and H.A. Wischmann, "Linear and Nonlinear Current Density Reconstructions", *Jour. Clin.Neurophysiol.*, vol. 16, no.3, pp. 267-295, 1999.

[3] S.P. van den Broek, "Volume Conduction Effects in EEG and MEG," Proefschrift Universiteit Twente Enschede, The Netherlands, ISBN: 90-365-0919-x, 1997.

[4] G.Marin, C. Guerin, S. Baillet, L. Garnero, and G. Meunier, "Influence of skull anisotropy for the forward and inverse problem in EEG: simulation studies using the FEM on realistic head models," *Human Brain Map.*, vol. 6, pp. 250-269, 1998.

[5] C.H. Wolters et al., "Influence of head tissue conductivity anisotropy on human EEG and MEG using fast high resolution finite element modeling", In:*Forschung und wissenschaftliches Rechnen, Contributions to the Heinz-Billing Award, Gesellschaft fuer wissenschaftliche Datenverarbeitung mbH Goettingen*, T. Plesser, and V. Macho, V., ISSN: 0176-2516, http://www.billingpreis.mpg.de, no. 58, pp. 111–157, 2001.

[6] J. Haueisen et al., "The Influence of Brain Tissue Anisotropy on Human EEG and MEG," *NeuroImage*, vol. 15, pp. 159-166, 2002.

[7] A. Anwander, C.H. Wolters, M. Duempelmann and T.R. Knoesche, "Influence of realistic skull and white matter anisotropy on the inverse problem in EEG/MEG-source localization," In:*Proc. of the 13th Int. Conf. on Biomagnetism*, H. Nowak, J. Haueisen, F. Giessler, and R. Huonker, VDE Verlag GmbH, Berlin, Offenbach, http://biomag2002.uni-jena.de, pp. 679-681, 2002.

[8] C.H. Wolters, "Influence of Tissue Conductivity Inhomogeneity and Anisotropy on EEG/MEG based Source Localization in the Human Brain", In:*MPI Series in Cognitive Neuroscience*, MPI of Cognitive Neuroscience Leipzig, ISBN 3-936816-11-5 (also: Leipzig, Univ., Diss, http://dol.uni-leipzig.de/pub/2003-33, 2003.

[9] C.H. Wolters, L. Grasedyck and W. Hackbusch, "Efficient Computation of Lead Field Bases and Influence Matrix for the FEM-based EEG and MEG Inverse Problem", *Inverse Problems*, in press.

[10] C.H. Wolters, M. Kuhn, A. Anwander and S. Reitzinger, "A parallel algebraic multigrid solver for finite element method based source localization in the human brain," *Comp. Vis. Sci.*, vol. 5, no.3, pp. 165-177, 2002.

[11] P.J. Basser, J. Mattiello, and D. LeBihan, "MR Diffusion Tensor Spectroscopy and Imaging", *Biophys.*, vol. 66, pp. 259-267, 1994.

[12] A. Rienaecker, A., H. Buchner, H. and G. Knoll, "Comparison of Regularized Inverse EEG Analyses in Finite Element Models of the Individual Anatomy", In:*Quant. and Top. EEG/MEG Anal., H.Witte, U.Zwiener, B.Schack and A.Doering* , Druckhaus Mayer Verlag GmbH Jena-Erlangen, pp.459-463, 1997.