Dipole Source Analysis for Readiness Potential and Field Using Simultaneously Measured EEG and MEG Signals*

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Abstract— **Various source localization techniques have indicated the generators of each identifiable component of movement-related cortical potentials, since the discovery of the surface negative potential prior to self-paced movement by Kornhuber and Decke. Readiness potentials and fields preceding self-paced finger movements were recorded simultaneously using multichannel electroencephalography (EEG) and magnetoencephalography (MEG) from five healthy subjects. The cortical areas involved in this paradigm are the supplementary motor area (SMA) (bilateral), pre-SMA (bilateral), and contralateral motor area of the moving finger. This hypothesis is tested in this paper using the dipole source analysis independently for only EEG, only MEG, and both combined. To localize the sources, the forward problem is first solved by using the boundary-element method for realistic head models and by using a locally-fitted-sphere approach for spherical head models consisting of a set of connected volumes, typically representing the scalp, skull, and brain. In the source reconstruction it is to be expected that EEG predominantly localizes radially oriented sources while MEG localizes tangential sources at the desired region of the cortex. The effect of MEG on EEG is also observed when analyzing both combined data. When comparing the two head models, the spherical and the realistic head models showed similar results. The significant points for this study are comparing the source analysis between the two modalities (EEG and MEG) so as to assure that EEG is sensitive to mostly radially orientated sources while MEG is only sensitive to only tangential sources, and comparing the spherical and individual head models.**

I. INTRODUCTION

Recordings of cerebral potentials preceding self-paced movement show that the brain is active long before the start of the movement [1]. This pre-movement activity is known as Bereitschaftspotential (BP) or readiness potential which is associated with the planning, preparation and initiation of movement [2]. The corresponding field produced due to the cerebral potentials, known as, Bereitschaftsmagnetfeld (BM) or readiness field have also been reported in [3]. This preparatory movement is a dynamic process involving the activity of multiple cortical areas which makes it difficult to identify sources that are responsible for the generation of BP. Recent advancement uses high resolution EEG and MEG combined with imaging techniques like 3D magnetic resonance imaging (MRI) to derive models of the brain. This further helps in separation of the scalp-recorded potentials and fields to be identified to their underlying source generators.

The readiness potential or field, beginning 2 sec prior to self-paced movement onset, is characterized by two components: a slowly increasing potential at an early stage which shows activity bilaterally in the SMA [4-6] and pre-SMA and a steeper-sloped potential at a later stage beginning approximately 400-500 ms before movement onset with maximal amplitude over the motor cortex contralateral to the moving finger [7]. Synaptic activity within the SMA was proposed to indicate movement planning and preparation while the motor area indicates movement initiation [8].

MEG is dominated by neuronal currents in the brain that are oriented tangentially to the head surface. In contrast, EEG signals predominantly reflect radial cortical activity. Due to this reason there is a latency occurring in MEG making the readiness field to appear on MEG much later than that of EEG. Thus, the bilaterally occurring sources are recorded by EEG but not by MEG because of their radial orientation while the contralateral occurring sources are recorded not only by EEG but also by MEG due to their tangential orientation [9].

This paper examines this claim through the application of dipole source analysis using multichannel simultaneous measurements of both electric potentials, which provide information about the entire activity of the brain, including deep and radially oriented sources, and magnetic fields, which provide the most accurate localization of tangentially oriented sources, to record the readiness potential and field, respectively.

In order to localize the current sources, first the magnetic fields and scalp surface potentials need to be calculated. Determining the electromagnetic potentials/fields from the current sources is known as forward problem [10]. In this study, the most commonly used three-shell spherical and realistic head models are used. The forward problem for the spherical head model is solved analytically, assuming each spherical layer has a homogeneous and isotropic conductivity. The numerical approach used for the realistic head model is the boundary element method (BEM) [11-13]. The approach to

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estimate the location of the current sources in the brain is through the inverse problem using a-priori assumptions on the generation of EEG and MEG signals [14-16]. In our study, a spatio-temporal dipole source-analysis method was used, which assumes that a small number of current sources in the brain can adequately model the surface measurements with at least one point-like dipole whose source positions and orientations are fixed with varying source strength over time.

Thus, this approach is applied on realistic (using the individual MRI and known individual electrode locations from each of the subjects) and spherical head models to perform source analysis for only EEG, only MEG, and both combined signals.

II. Data Acquisition

All measurements presented here were performed using the Elekta Neuromag whole-head measurement system. The system consists of 306 MEG channels and 128 EEG channels all recording simultaneously the electromagnetic distributions of the intracranial ionic currents associated with the information processing. The system is placed in a magnetically shielded room. The 306 MEG channel consists of two orthogonal focally sensitive planar gradiometers and one widespread sensitive magnetometer. The integrated 128 channel EEG-system consists of 124 unipolar channels and 4 bipolar channels, enabling recordings of EEG, EOG and EMG. EMG was recorded from first dorsal interosseous (FDI) muscle.

The experiment was performed by five healthy subjects performing a flexion of the right index finger. Movements were self-paced at irregular intervals of approximately 5 sec, starting from complete relaxation. The recording lasted for 15 minutes for each subject. The experiment was repeated 80 times per subject. The EEG, band-pass filtered between 0.01 and 200Hz, and MEG signals were sampled at 1000Hz.

III. Methods

A. Forward Solution

Source reconstruction for the five subjects was performed on the basis of the individual brain anatomy obtained from MRI using a realistic head model and the averaged head which uses a spherical model. In order to estimate the sources, one must model the sources correctly. A source model often used is the current dipole, which represents a focal area of synchronously active pyramidal cells. The forward problem uses these hypothesized dipoles and computes the electromagnetic field map.

Forward modeling relies on a volume-conduction model (head model) that describes the geometrical and electrical properties of the tissue in the head. The volume conduction often requires a geometrical description of tissue boundaries in the head. The typical head model used in EEG and MEG analysis assumes that the head consists of a set of meshes, triangulated surfaces in 3D-space, typically representing the scalp, skull, and brain. If the conductivities within each of these regions are isotropic and constant, the electric potentials and magnetic fields can be expressed in terms of surface integrals. The forward EEG and MEG problems can then be solved numerically using a boundary-element method (BEM) [17]. BEM calculates the potentials/fields of the non-intersecting homogeneous regions bounded by the scalp, skull, and brain surface boundaries each having a conductivity values of 0.33, 0.0042, and 0.33 S/m. These regions are obtained by segmenting the anatomical images of subjects. Co-registering the coordinate system of the digitized electrodes and landmarks to that of the BEM model was based on the three landmarks (left preauricular point, right preauricular point, and nasion). If the regions of constant conductivity can be modeled as a set of nested concentric spherical shells then analytic solutions exist for EEG and MEG [17].

Since MEG sensor arrays are blind to radial and deep neural current sources, resulting in reduced magnetic-field patterns, there should be an integrated framework during combination of both modalities so as to show radial components and maintain the reconstruction of tangential sources. Basically, EEG depends on absolute conductivities and MEG on relative ones, so MEG can be used to calibrate the EEG conductivities so as to keep the relative conductivities of the scalp, skull, and brain constant. Thus, a common volume conductor model is created by matching the conductivities [18].

The resulting forward model is then used to solve the inverse problem. Dipole source analysis (fixed MUSIC) is used to reconstruct the sources of the readiness potential and field.

B. Inverse Solution

EEG and MEG source analyses have a non-unique solution to the inverse problem, that is, a number of different sources (source locations, orientations and strengths) can generate the same electromagnetic field map at the surface of the head. However, certain a-priori assumptions can be made so as to make the solution unique. In this paper, we used a fixed MUSIC algorithm which assumes source locations and orientations to be fixed with varying strength over time. The inverse problem for dipole analysis seeks the optimal number of dipoles to estimate the sources for a given electromagnetic field distribution. Thus, to estimate the optimal number of dipoles, the spatio-temporal decomposition approach based on principal-component analysis (PCA) is used for defining the source space and estimating the minimum number of dipoles.

MUSIC is a scanning method which is based on estimation of a signal subspace from a set of spatio-temporal data using a singular-value decomposition (SVD). The number of singular values that make up the signal subspace is a parameter for this method. The MUSIC algorithm then scans a single dipole model through the head volume and computes projections onto this subspace until it finds the true source location and orientation.

The complete description of the fixed MUSIC algorithm is explained elsewhere [19]. Source analysis was performed using CURRY software (from Neuroscan).

IV. Results

To closely approximate the entire brain, realistic head shape models for the five healthy subjects was built using BEM. For the averaged head, a 3-shell spherical head model is used. The tissue boundaries represented by triangular meshes with a limited number of nodes (triangle vertices) are shown in Fig. 1 for the individual and spherical head model.

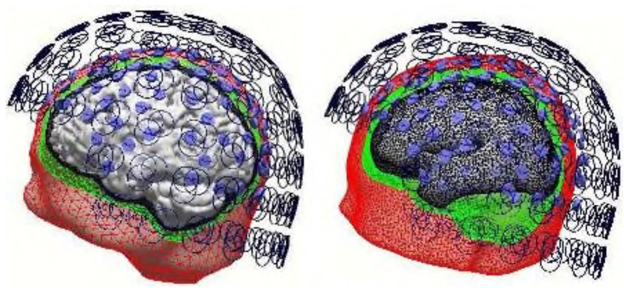

Fig. 1. Standard BEM-model derived from an individual MRI data showing the three brain compartments (BEM scalp: 3248 triangles, BEM skull: 2822 triangles, and BEM brain: 4116 triangles) including the cortex where sources are assumed to be confined (left) and spherical head model derived from averaged MRI data showing the standard scalp, skull, and brain (right). The electrodes overlaid on the scalp and the triple coils over the surface of the scalp are also shown.

The fixed MUSIC algorithm was applied independently for EEG, MEG, and both combined, using the spherical and individual head model of five healthy subjects having the location as an a-priori information. We have analyzed both the early and late stages of BP and BM together, thus, the expected source locations were in the SMA (bilateral), pre-SMA (bilateral) and motor areas (mainly contralateral to the moving finger).

The steps used to localize the sources are as follows:

- Epochs were identified using the first response in relation to the voluntary finger movement as a fiducial point in each movement sequence, spanning 4000 ms before the onset of movement to 500 ms after the onset.
- Pre-processing like notch filtering was used to avoid the 50 Hz power-line artifact and its harmonics.
- The pre-processed detected events were averaged. The noise level was estimated from the first 2 sec (0-2000 ms), which is the region considered as noise for SNR calculation.
- The ground-truth signal interval for the source analysis was defined, that is, from 2000-4000 ms prior to the onset.
- PCA was performed to determine the number of dipoles, depending on the SNR values (S/N $>$ 1), that are used for the dipole-fit algorithm (fixed MUSIC).
- Finally, the dipole-fit algorithm on individual and spherical head models was performed.

The correct source localization was different for the modalities as can be seen from table 1. For only EEG, 3 subjects show sources in the SMA (unilateral), 1 subject in the motor area (contralateral), and 1 subject in the pre-SMA (unilateral) for both head models. For only MEG using the individual head model, 2 subjects show sources in the motor area (contralateral) and 1 subject in the pre-SMA (unilateral). For only MEG using spherical head model, 1 subject shows sources in the motor area and 1 subject in the pre-SMA (unilateral). With EEG and MEG combined and the individual head model, 2 subjects show sources in the SMA (unilateral) and 1 subject in the motor area (contralateral). With EEG and MEG combined and the spherical head model, 1 subject shows sources in the SMA (unilateral) and 1 subject in the motor area (contralateral). Schematically, the results obtained using fixed MUSIC algorithm are shown in Fig. 2 for the realistic (for one of the representative subjects) and spherical head model.

TABLE I

Number of subjects that showed correct estimates of the source for the individual and spherical head model using dipole (Fixed MUSIC) source analysis

	EEG	MEG	EEG+MEG
Dipole-Individual	5	3	3
Dipole-Spherical	5	2	2

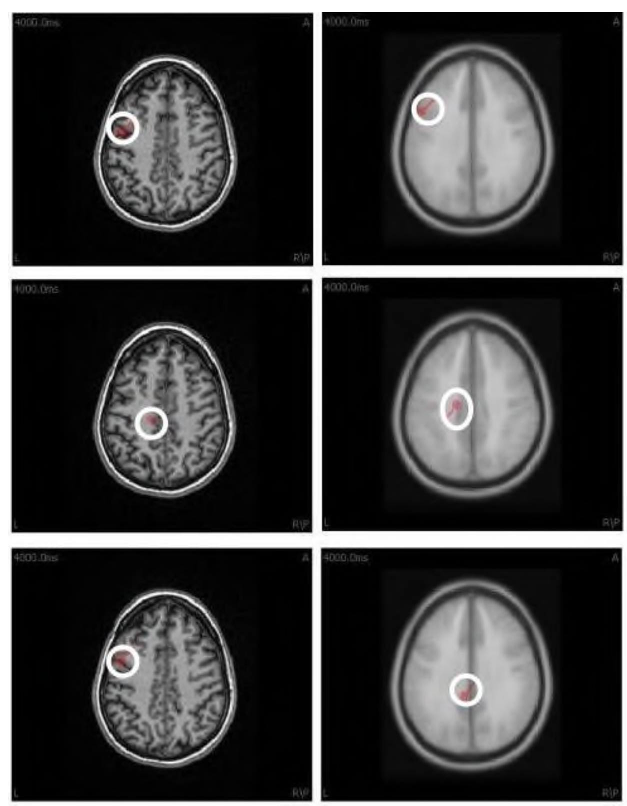

Fig. 2. Single slice plot of a realistic head model for one of the representative subjects in the first column and averaged head plot of the 3-shell spherical head model, in the second column, showing the location of the sources using dipole fit analysis. The first row is the analysis performed independently for only EEG, second row for only MEG, and the third row is for both EEG and MEG combined.

TABLE II

DIPOLE SOURCE ORIENTATIONS OF THE FIVE SUBJECTS EXPRESSED IN DEGREES FOR THE INDIVIDUAL AND SPHERICAL HEAD MODEL. 60-120° ARE CONSIDERED TO BE RADIALLY ORIENTED SOURCES WHEREAS 0-60° AND 120-180° ARE CONSIDERED TO BE TANGENTIALLY ORIENTED SOURCES

Subjects	EEG		MEG	
	Individual	Spherical	Individual	Spherical
1	118.1	128.5	125.5	-
2	102.2	119.4	43.73	130.6
3	93.45	103.9	-	-
4	90	79.61	-	-
5	111.7	117.4	19.51	91.71

From the analysis, both the spherical and the individual head models resulted in the same number of subjects that showed correct estimates of the sources in the expected regions of the cortex. The decrease in number of subjects from five to three in the case of MEG comes from the source orientation where the remaining two subjects have a radial source orientation (60-120°) which can not be detected using MEG as can be seen from table 2. As can also be seen in the case of EEG, all five subjects have a radial orientation for the individual head model, whereas, for the spherical head model only one subject shows tangential orientation. When combining both, the effect of MEG on EEG can be clearly seen.

V. CONCLUSIONS

We have performed source estimation of the readiness potential and field sources relative to the spherical and individual head models, in order to compare the two modalities (EEG and MEG) so as to assure that EEG predominantly localizes radially oriented sources while MEG localizes tangential sources at the desired region of the cortex. In addition, comparison of spherical and individual head models were presented. Thus, the results obtained from the dipole analysis proves this hypothesis by localizing mostly radial sources for EEG and only tangential sources for MEG. Comparison of spherical and individual head models resulted in similar results. As we have analyzed the early and late stages of the potential together, the sources were present on the SMA (unilateral), pre-SMA (unilateral), and motor area on the contralateral side of the moving index finger. During combined analyses, an effect of MEG on EEG is observed, which is related to the large number of sensors that the MEG contains. The conductivity fitting factor used for the combined analyses are also not exact enough as the time interval we used for the source analysis does not have a well-defined tangential source orientation which causes an ambiguity in the source reconstruction for not obtaining an increased information content due to the complementary nature of both modalities. Separate analysis need to be performed, in the future, for both the early and late stages and also other source localization algorithms will be applied further.

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