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# Influence of White Matter Anisotropy on EEG Source Localization: An Experimental Study

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*Abstract*—**The goal of this study was to experimentally investigate the influence of the white matter (WM) anisotropy on the EEG source localization. We acquired both visual evoked potential (VEP) and functional MRI (fMRI) data from three human subjects presented with identical visual stimuli. A finite element method (FEM) head model with or without incorporating the WM anisotropy was built to solve the EEG forward problems, and single-dipole source localization was subsequently performed based on the N75 VEP component. The localized dipole positions were quantitatively compared with the locations of the fMRI activations within the primary visual cortex (V1). The results show that the distance between the localized N75 dipole position and the fMRI V1 activation center was slightly smaller when using an anisotropic model than when using an isotropic model. This experimental study suggests that compared to the conventional isotropic model, the anisotropic models incorporating realistic WM anisotropic conductivity distributions do not significantly improve the accuracy of the EEG dipole localization within V1.**

## I. Introduction

THE source localization or imaging based on EEG may serve as an important tool to investigate sensory and cognitive brain functions [1]. To determine the location of cerebral current sources generating the scalp EEG signals, numerous approaches have been proposed to solve an ill-posed inverse problem [1], [2]. The accuracy of localizing the electrical sources inside the brain depends in part on the accuracy of the anatomic description of volume conductor and knowledge of tissue electrical properties.

Previous studies for EEG source analysis are often based on the assumption that the tissues have isotropic conductivity values. However, the white matter (WM) tissues may have an anisotropic conductivity with about 1:10 ratio, ten times larger conductivity parallel to the fibers than the normal to the fibers [3]. To study the effects of the tissue anisotropy on the EEG forward or inverse solutions, various investigations have been carried out including phantom or animal experimental study [4], [5] and realistic simulation studies using the finite element (FE) head models [6]-[9] or the finite difference method based models [10], [11]. These simulation studies tend to suggest that the WM tissues have a non-negligible effect on EEG source analysis, thus suggesting modeling WM conductivity anisotropy should be taken into account for accurate source reconstruction.

To the best of our knowledge, there appears no previous report on experimental results with regard to the influence of the WM anisotropy on the EEG source localization. In this study, we acquired both visual evoked potential (VEP) and functional MRI (fMRI) data elicited by visual stimuli. The accuracy of EEG source localization was assessed through comparison with the fMRI activation maps, and retinotopic relationship [12]. It is well known that the activation of an early VEP component (N75) arises from the primary visual cortex (V1) [13]. This correspondence has also been used to assess the localization error of EEG source imaging [14].

In this paper, both VEP and fMRI data were recorded from three human subjects presented with identical visual stimuli. The FE head models with or without incorporating the WM anisotropy measured through diffusion tensor MRI (DT-MRI) were generated to solve the EEG forward problems, and single-dipole source localization was subsequently performed based on the early VEP component. The localized N75 dipole positions were quantitatively compared with the locations of the fMRI activation within the primary visual cortex. The distance between the N75 dipole locations and fMRI activations was used to assess the goodness of the forward model and thereby the influence of the WM conductivity anisotropy on the EEG source localization.

## II. Materials and Methods

### A. Visual Stimuli

Three healthy human volunteer subjects (males, mean age 29.3) participated in this study according to a protocol approved by the institutional review board at the University of Minnesota. Fig. 1 shows the visual stimuli used for EEG and fMRI experiments. The visual stimuli with varied visual fields consisted of circular black-white checkerboards within the lower left and right quadrant of the visual fields on a homogenous gray background. The stimuli were named with respect to the stimulus size and locations (see Fig. 1). In the EEG experiment, the pattern-reversal checkerboards were reversed at 2 Hz. The visual stimulus was presented in one quadrant at a time. In the fMRI experiment, the same visual stimuli were delivered in six 30-second blocks to one quadrant

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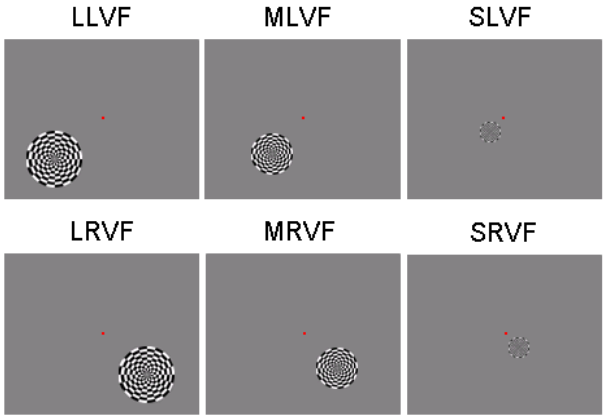

Fig. 1. Visual stimuli used for both EEG and fMRI experiments. The stimuli were named with respect to the stimulus size and locations (LLVF: large left visual field, LRVF: large right visual field, MLVF: middle left visual field, MRVF: middle right visual field, SLVF: small left visual field, and SRVF: small right visual field)

a time separated by seven 30-second resting blocks with only a fixation point on a neural gray screen. Subjects were instructed to gaze at the central fixation point during the EEG recording and fMRI experiments.

### B. FE Volume Conductor Modeling

For FE head modeling, we segmented anatomical MR images into five sub-regions: namely, WM, gray matter, CSF, skull, and scalp. The FE mesh generation was performed using regular tetrahedral elements with inner-node spacing of 2 mm. To generate the isotropic FE head models, the following isotropic electrical conductivities in accordance with each tissue type: WM=0.14 S/m, gray matter=0.33 S/m, CSF=1.79 S/m, skull=0.0132 S/m, and scalp=0.35 S/m [6], [8].

To obtain the anisotropic conductivity tensors on the WM tissues, we first assumed that the conductivity tensors share the eigenvectors with measured diffusion tensors [15]. Then, we adopted three existing techniques of estimating the WM anisotropic conductivities derived from the measured DTs: 1) a linear conductivity-to-diffusivity relationship based on an effective medium approach (EMA) [16], 2) a fixed anisotropic ratio in each WM voxel [8], and 3) a linear conductivity-to-diffusivity relationship in combination with a volume constraint equation [10]. Due to complex, a fourth approach reported in literature [17] was not implemented in the present study. Three different approaches of modeling WM conductivity anisotropy are summarized as follows.

The EMA relates a linear relationship between the eigenvalues of the conductivity tensor $\sigma$ and eigenvalues of the DT $D$ in the following way:

$$\sigma = \frac{\sigma_e}{d_e} D \tag{1}$$

where $\sigma_e$ and $d_e$ denote the extracellular conductivity and diffusivity respectively [16]. For the first anisotropic model, an empirically determined value of 0.736 S·s/mm$^3$ was used [7], [16]. In the following, this model will be referred to as *AnisoLin*. For the second anisotropic model, we used the volume constraint algorithm to compute the fixed anisotropic ratio of 1:10 (i.e., $\sigma_1$=10·$\sigma_2$, $\sigma_2$=$\sigma_3$) [8].

$$\frac{4}{3}\pi\sigma_{iso}^3 = \frac{4}{3}\pi\sigma_1\sigma_2\sigma_3 \tag{2}$$

where $\sigma_1$ is the eigenvalues to the largest eigenvector. $\sigma_2$ and $\sigma_3$ represent the eigenvalues to the perpendicular eigenvectors, respectively. This model will be referred as *AnisoFix*. The third approach was based on a linear scaling of the diffusion tensor ellipsoids using (1) in combination with the volume constraint equation as in (2) [10]. This model will be referred as *AnisoVar*.

### C. EEG Source Reconstruction

To reconstruct the EEG source within the brain, a single equivalent dipole model was utilized to approximate brain electrical sources induced by visual stimuli. The equivalent dipole analysis is to estimate the dipole parameters (i.e., location and moment) that best account for the measured potentials in the least squares sense, thus minimizing the residual errors.

$$\Delta^2 = \left\| Lj - \tilde{M} \right\|^2 \tag{3}$$

where $L$ is the lead field matrix, $j$ the dipole moment, and $\tilde{M}$ the processed VEP data. The location of the single focal source was reconstructed by scanning through a grid of dipole with a spacing of 2 mm defined in the brain volume. At each grid location, the least squares fit was performed to find the best-fitting dipole to the VEP data.

### D. fMRI Data Analysis

The fMRI were analyzed using BrainVoyager (Brain Innovation, Netherlands). The echo-planar imaging (EPI) volumes were motion corrected by aligning all functional volumes to the first collected EPI volume. Slice scan time correction and linear trend removal were also performed. After preprocessing, the functional volumes were aligned to the subjects' anatomical images for co-registration and visualization. The fMRI activation map from the individual subject was obtained by statistical analysis using a general linear model. For the group analysis, fMRI images were transformed into a common Talairach space to compute statistical maps in a group level.

## III. Results

We evaluated the localization errors between the centers of the group-averaged fMRI activation maps and the averaged EEG source locations. Fig. 2 illustrates the centers of the group-averaged fMRI activations and the N75 dipole positions co-registered in the cortical surface. It is clearly visible that the fMRI centers and N75 dipoles are localized in close proximity to the contralateral calcarine fissure or near V1. In Table I, the quantitative comparison results show that the distance between them was slightly smaller when using the anisotropic models (range: 2.45 to 15.39 mm) than when using the isotropic model (3.46 to 15.78 mm).

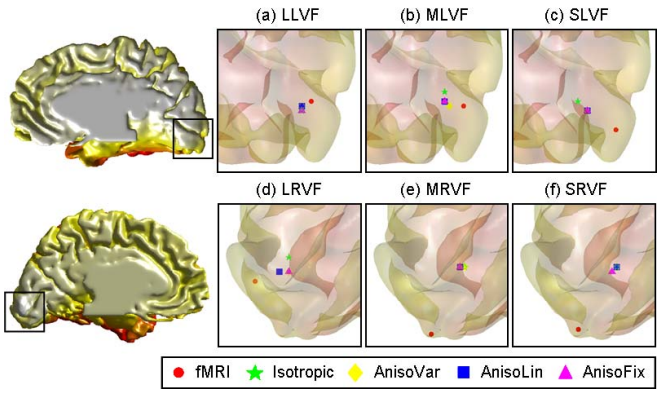


Fig. 2. Spatial locations of the group-averaged fMRI centers and N75 dipoles co-registered in the cortical surface. The enlarged images around V1 from the left in (a)-(c) and right visual fields in (d)-(f) are visualized respectively.

TABLE I
LOCALIZATION ERRORS IN MILLIMETERS BETWEEN THE GROUP-AVERAGED FMRI CENTERS AND AVERAGED N75 DIPOLE LOCATIONS

| Models | LLVF | LRVF | MLVF | MRVF | SLVF | SRVF |
|---|---|---|---|---|---|---|
| Isotropic | 3.46 | 8.60 | 5.39 | 15.78 | 10.00 | 15.56 |
| AnisoLin | 2.45 | 5.48 | 4.24 | 15.36 | 7.21 | 15.39 |
| AnisoFix | 3.30 | 7.35 | 4.24 | 15.36 | 7.21 | 15.13 |
| AnisoVar | 2.45 | 7.55 | 3.16 | 15.78 | 7.21 | 15.39 |

## IV. DISCUSSION AND CONCLUSION

We investigated the influence of the WM anisotropic conductivity on the EEG source localization by means of the human experiments using EEG recorded during sensory stimulation and fMRI as an independent estimate for true activity location. To the best of our knowledge, this is the first experimental study in humans to examine the effects of the WM anisotropy on the EEG source localization by examining the distance between the EEG dipole locations based on the early VEP component and the fMRI-determined activation centers in V1. Our quantitative comparison study described that in V1, the localized N75 dipole locations obtained by the anisotropic models are slightly closer to the centers of the fMRI V1 activations in comparison to the conventional isotropic models. However, no significant improvement is found between the inverse solution using the anisotropic head model vs. that using the isotropic head model. This experimental study suggests that the anisotropic models incorporating realistic WM anisotropic conductivity distributions do not significantly improve the accuracy of the EEG dipole localization in the human primary visual cortex. The inclusion of the WM anisotropy would be less considered in localizing the EEG source within the human primary visual cortex. The present study suggests that the effects of tissue anisotropy on the EEG source analysis should be investigated with more accurate and elaborate experimental scenarios.

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