MAGNETIC DIPOLE LOCALIZATION STUDIES FOR MAGNETOENCEPHALOGRAPHY USING MULTIPLE PHASE INVERSE ANALYSIS AND EXPERIMENTAL VERIFICATION

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INTRODUCTION

Present day Magnetoencephalography (MEG) is a new well-known technique for noninvasively monitoring brain function and expected to stereo-graphically localize active brain regions where neuronal activities occur [1]-[7]. Our objective is to develop a technique localizing active brain regions in three dimensions from MEG data.

We have developed a novel technique for estimating the location and magnitude of dipoles which are used to describe neuronal activities. This technique is independent of mathematical model for an inverse analysis, which is a current based or a magnetic dipole based model [8], [9]. This technique applies methods including truncated singular value decomposition (TSVD) [10], Akaike's information criterion for small sample sizes (AICC) [11], data clustering [12] and downhill simplex computation [13], [14].

We have also created an electronic waveform generating unit to simulate a magnetic field emitted by neurons in a human brain as a magnetic dipole. Measurements using this unit were performed to demonstrate the validity of the proposed technique.

METHOD

<u>Multiple phase inverse analysis</u>

The proposed technique consists of two stages, namely extracting and grouping phases. Figure 1 outlines the procedure.

Extracting phase

When locations of dipoles are known, the relationship between magnitudes of dipoles and magnetic flux density by MEG measurement is linear. In the extracting phase, the locations of dipoles are pre-selected and magnitudes of the dipoles are estimated by TSVD. The order of the truncated singular value is determined with AICC.

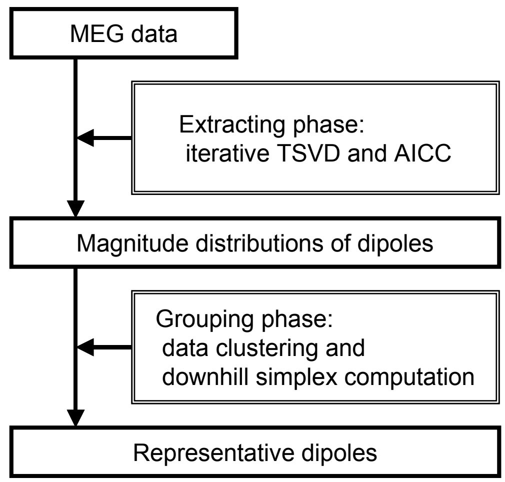

Figure 1: The estimation procedure

Now the cutoff magnitude can be predetermined. Dipoles with the estimated magnitude less than the cutoff magnitude are discarded. Using the remaining dipoles, TSVD and AICC are applied iteratively to eliminate the invalid dipoles. The remaining dipoles are the active units for our analysis. Depending on the required resolution these iterative steps have to be continued until the final threshold value.

Grouping phase

The estimated distributions of dipoles by the extracting phase are grouped into different sets of dipoles by data clustering. Using these sets as initial values, the optimal locations and magnitudes of the dipoles which minimize the residual error between the measured MEG data and the data predicted using the mathematical model are calculated by downhill simplex computation.

<u>Brain magnetic field simulating device</u>

Implementation

Brain neuronal activity waveform can be simulated by generating magnetic field using coils. The magnitude of magnetic field generated by each coil is dependent on the amount of current flowing through it. An electronic circuit for controlling the instantaneous current flowing in the dipole was designed and constructed. This forms our first generation brain phantom.

Functionality

Figure 2 shows the phantom unit. The device consists of a voltage waveform generating unit and a coil as a magnetic dipole generating unit. This serves as a brain magnetic-dipole generating phantom.

The phantom is designed to produce waveforms such as sinusoidal, rectangular and triangular waves. This signal is fed to the dipole-coil. For the ease of using the coil in a MEG machine, the coil is attached to a base made out of a plastic cylinder. The MEG manufacturer supplied head coils were attached to the base to pre-define the head coordinates, as shown in figure 2. The location of the coil as a magnetic dipole is expressed in terms of its relative position to the pre-defined head coordinates.

The magnetic field generated by the dipole is collected by the MEG machine and documented. This experiment is conducted in a magnetic-noise free environment.

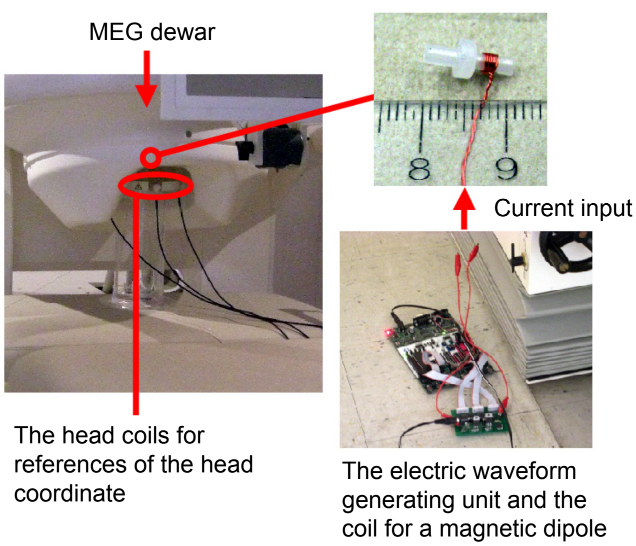

Figure 2: The configuration of the experimental setup

RESULTS

<u>MEG measurement results with the device</u>

A typical MEG measurement result with the phantom is illustrated in figure 3. This pattern represents the output for a rectangular waveform signal to the coil. It can also be seen that the magnetic flux density emitted from the coil replicates the signal waveform. The proposed dipole localization technique is applied on this MEG data at 0.1s. The resulting image map is shown in figure 4.

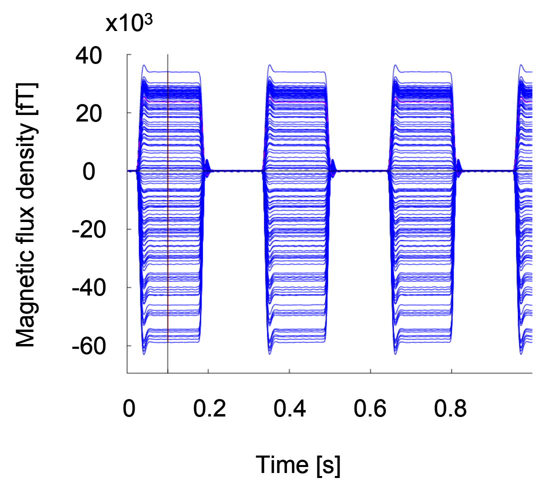

Figure 3: The time-line MEG data

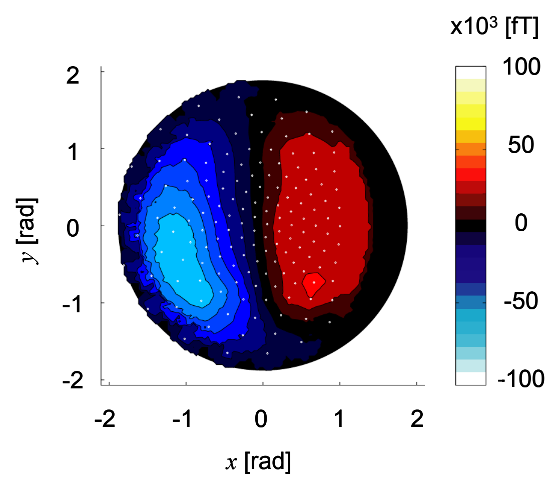

Figure 4: Spatial distribution map of MEG data at 0.1s

Inverse analysis with a magnetic dipole model

The equation of the magnetic dipole model is as follows.

$$\boldsymbol{B}(\boldsymbol{r}) = \frac{\mu}{4\pi}\frac{3\boldsymbol{e}_r(\boldsymbol{e}_r\cdot\boldsymbol{M})-\boldsymbol{M}}{|\boldsymbol{r}|^3} \quad (1)$$

where $\boldsymbol{r}$, $\boldsymbol{B}(\boldsymbol{r})$, μ, $\boldsymbol{e}_r$ and $\boldsymbol{M}$ are the position vector from the magnetic dipole to the measurement location, the magnetic flux density at the measurement location, permeability, the unit vector in the direction of $\boldsymbol{r}$ and the magnitude vector of the magnetic dipole, respectively. If there are more than one dipole, the resulting magnetic flux density will be calculated using superposition.

Figure 5a shows the estimated result of TSVD, AICC and the cutoff process applied on the measured MEG data (fig 4) iteratively. The cutoff magnitude is 10% of the maximum magnitude of the estimated dipoles. The hypothetical dipoles near the actual position eventually remain after the extracting process. Figure 5b shows the estimation result of data clustering and downhill simplex computation using the data from figure 5a. The position and magnitude of the estimated dipole are in good agreement with the actual values.

Inverse analysis with a current dipole model

Current dipole models directly describe neuronal activities unlike magnetic dipole models. Sarvas formula, the simplest current dipole model, is as follows [9].

$$\boldsymbol{B}(\boldsymbol{r}) = \frac{\mu}{4\pi F^2}\left(F\boldsymbol{Q}\times\boldsymbol{r}_q - \boldsymbol{Q}\times\boldsymbol{r}_q\cdot\boldsymbol{r}\nabla_r F\right) \quad (2)$$

where

$$F = |\boldsymbol{r}|\left(|\boldsymbol{r}||\boldsymbol{r}_s| + |\boldsymbol{r}_s|^2 - \boldsymbol{r}_q\cdot\boldsymbol{r}_s\right) \quad (3)$$

Then $\boldsymbol{Q}$, $\boldsymbol{r}_q$ and $\boldsymbol{r}_s$ are the magnitude vector of the current dipole, the position vector of the current dipole and the position vector of the measurement location, respectively. The origin of these position vectors is the center of the spherical conductor.

Figure 5c shows the final estimation result using the current dipole model. If the magnetic flux density from volume currents can be ignored, the relationships between the magnetic dipole and the current dipole are as follows.

$$\boldsymbol{M} \approx \frac{\boldsymbol{r}_q\times\boldsymbol{Q}}{2} \quad \text{and} \quad \boldsymbol{r}_m \approx \frac{2}{3}\boldsymbol{r}_q \quad (4)$$

where $\boldsymbol{r}_m$ is the position vector from the center of the

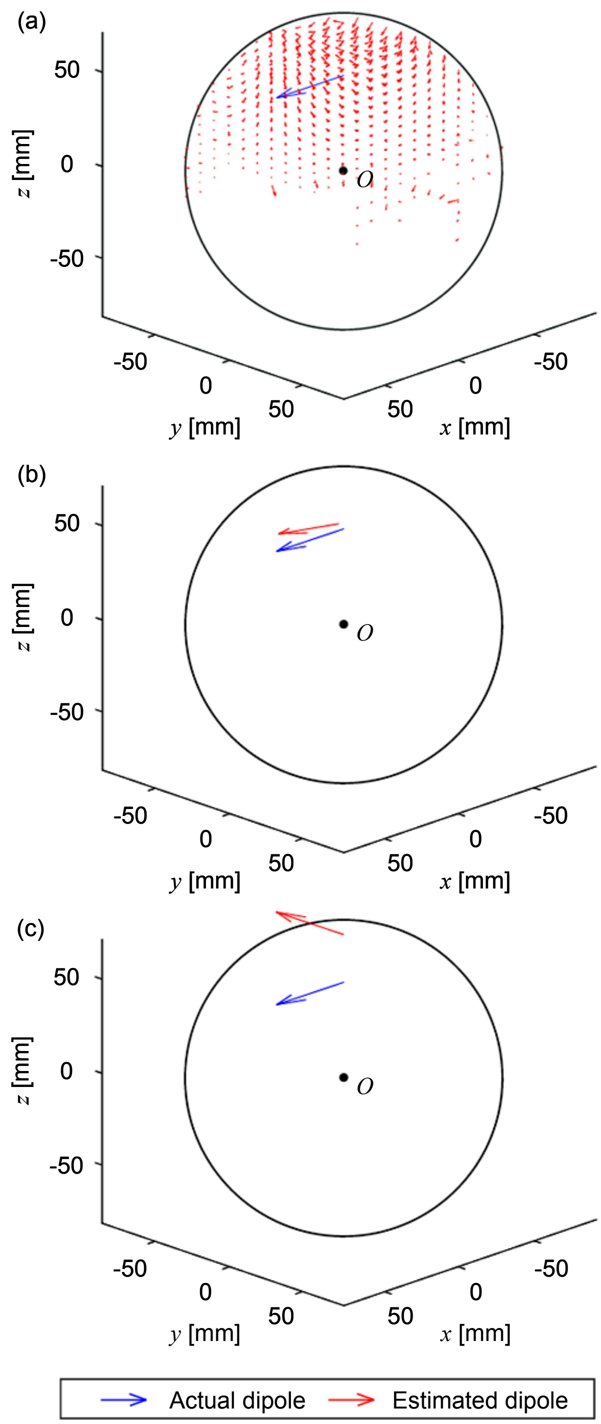

Figure 5: The estimation results

(a) After the extracting phase with the magnetic dipole model

(b) With the magnetic dipole model: $\boldsymbol{M}$ = (549,89,106) nAm^2, $\boldsymbol{r}_m$ = (0,-3,52) mm

(c) With the current dipole model: $\boldsymbol{Q}$ = (3,-15,-1) x10^3 nAm, $\boldsymbol{r}_q$ = (0,-5,72) mm spherical conductor to the magnetic dipole. The position and magnitude of the estimated current dipole are in good agreement with equation (4).

CONCLUSIONS

We have demonstrated a novel method of estimating dipoles to localize active brain regions using MEG data. We have also successfully built a brain phantom and verified the results experimentally. These results show that this method can be applied to real MEG data obtained from patients to localize as well as study the brain neuronal activity. We propose to develop multi-coil phantom using micromachining technology and produce a phantom simulating a closer to real brain section activity and refine the estimation technique to be useful for diagnosis and clinical applications.

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