Three-Dimensional MEG Measurement

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We have developed a three-dimensional (3-D) second-order gradiometer connected to 39-channel SQUIDs for vector measurement of magnetoencephalogram (MEG) that can simultaneously detect magnetic field components perpendicular and tangential to the scalp. Each coil is orthogonally wound with Nb-Ti wire on a rectangular solid of 3×3×6 cm. To assess discrimination and separation of multiple sources, we carried out both simulation study and 3-D vector measurement of MEG with mixed auditory evoked field (AEF) and somatosensory evoked field (SEF) overlapping in time. The magnetic field distribution perpendicular to the scalp was not helpful for estimating the location and number of sources, owing to the lack of a dipole pattern, but the magnetic field distribution tangential to the scalp can provide information about new constraint conditions by visual inspection. We estimated multiple sources of mixed AEF and SEF from the MEG data of the magnetic field tangential to the scalp, and confirmed the results by comparison with superimposed source locations in MRI of a subject’s head.

Key words: 3-D MEG measurement, constraint condition, multiple sources estimation

1. Introduction

Since 1970, SQUID magnetometers have been used for biomagnetic studies [1]. During the last few years, biomagnetic measurement systems covering the whole head have been developed [2,3]. They are huge and expensive, working in special shielded rooms that have high magnetic field attenuation ratio more than 1,000 [4]. Magnetoencephalogram (MEG) measurement of the magnetic field perpendicular to the scalp is widely used. However, there are problems of separating multiple sources overlapping in time when many distinct areas of the cortex are active [5]-[8]. In these cases, the magnetic field distribution of normal component is not helpful for estimating the location and number of sources, owing to the lack of a dipole pattern. Concerning to overcome the previous problems, new methodology is necessary to develop in both of not only signal processing but also SQUID instrumentation. There are several reports related to a three-dimensional (3-D) vector measurement and system [9]-[16]. We have developed a 3-D second-order gradiometer connected to 39-channel SQUIDs for vector measurement of the MEG that can simultaneously detect magnetic field components perpendicular (Br) and tangential (Bθ,Bφ) to the scalp [13]. Magnetic field distribution tangential to the scalp can provide information about new constraint conditions by visual inspection.

In this paper we focus to the usefulness of 3-D vector measurement for estimating multiple sources in MEG data, which are obtained by a prototype of SQUID system.

2. Characteristic of a 3-D measurement

A 3-D vector measurement of MEG is carried out using a 3-D second-order gradiometer shown in Fig. 1 (a). Coordinate system and measurement positions shown in Fig. 1 (b). The 3-D second-order gradiometer is wound with Nb-Ti wire on a rectangular solid of 3×3×6 cm.

To discuss the magnetic field distribution on the scalp measured with 3-D second-order gradiometer, simulation study of MEG generating by multiple sources in the brain was done. The magnetic field distribution was calculated with a homogeneous spherical conductor model (85 mm radius) as a head.

Fig. 2 (a), (b), and (c) show an example of isofield contour maps of three components (Br, Bθ, Bφ) created by two current sources (each dipole moment : 30nAm) with opposite directions, at D5 and F5, located at a depth of 2 cm from the surface of the head. The distance between two dipoles is 4cm. This source configuration is important for MEG measurement since electric potentials are attenuated at the scalp. As shown in Fig. 2 (a), the map of Br significantly misses the dipole pattern and shows one extreme of -570 fT at ES. However, the map of Bθ shown in Fig. 2(b) clearly shows two extremes of 89 fT at D5 and -89 fT at F5 with opposite polarity. Fig. 2 (d), (e), and (f) show the 3-D magnetic field distribution maps (absolute value) of three components. The number and the
location of the dipoles (sources) are given from tangential magnetic field extremes since the tangential magnetic field shows maximum or minimum fields just above the location of a single dipole [13]. The map of B₀ shown in Fig. 2 (e) clearly shows two extremes at D5 and at F5. Positions of D5 and F5 correspond to the place located each current dipole represented by arrows as shown in Fig. 2 (a).

Fig. 3 shows an example of isofield contour maps created by two current sources with mutually orthogonal directions, as shown in arrows at D4 and F6, separating 4.2 cm apart. In this case, magnetic field distribution of Br component (Fig.3 (a) and (d)) shows a dipole pattern having two extremes of 310 fT at D2 and -310 fT at H6 with opposite polarity due to sum of two current sources. This is an example of miscounting case as a single source to two sources when we calculate the inverse problem by referring only magnetic field distribution obtained from Br component. However, on maps obtained from tangential magnetic fields, B₁ (Fig.3 (b) and (e)) shows one extreme of 65 fT at F6 and B₆ (Fig.3 (c) and (f)) also shows one extreme of 65 fT at D4. Positions of D4 and F6 correspond to the place located each current source.

Fig. 4 shows an example of isofield contour maps created by three current sources located at E3, F5, and E7. Each source is located 3 cm apart from E5. Br (Fig.4 (a) and (d)) shows only one extreme of about 750 fT at E5. However, B₀ (Fig.4 (b) and (e)) shows one extreme of about 115 fT at G5 and B₆ (Fig.4 (c) and (f)) shows two extremes of -110 fT at E3 and 110 fT at E7 with opposite polarity. We can also predict the number and the location of sources by referring magnetic field distribution from B₀ and B₆.

A 3-D MEG measurement we proposed here is very useful for calculating inverse problem with multiple sources in the brain since it gives constraint conditions by referring not only magnetic field distribution of normal component (Br) but also that of tangential component (B₀, B₆).

3. 3-D MEG measurements

In order to make multiple sources in the brain, we carried out 3-D MEG measurement of mixed auditory evoked field (AEF) and somatosensory evoked field (SEF) overlapping in time. The AEF was elicited by 1 kHz tone bursts of 50 ms duration to the right ear. The SEF was elicited by electric pulses of 0.2 ms duration with 6 to 8 mA to the median nerve of the right wrist. The interval of stimulation was 500 ms. Stimulation to the median nerve was delivered 40 ms later than to the ear. There were two evoked fields, namely mixed AEF and SEF, overlapping in time. There were thirty measurement positions on the scalp. All magnetic data were averaged for 400 measurements at each position. The sampling interval was 0.5 ms. Band-pass filter was used in the range of 0.5 to 40 Hz.

We demonstrated a multiple source estimation using the moving dipole inverse solution. Multiple sources are estimated by minimizing the cost function, which are the least-squares fit between the measured magnetic field and calculated magnetic field [14].
In this method, source parameters such as amplitude and orientation were varied, and the minimum cost function was obtained by iterative calculation. The cost function, \( f \), is defined as

\[
f = \frac{\sum_{i=1}^{n} (B_{mi} - B_{ei})^2}{\sum_{i=1}^{n} (B_{mi})^2}
\]

where \( B_{mi} \) is the measured magnetic field at \( i \)-th position, \( B_{ei} \) is the calculated field. The goodness-of-fit, \( G \), is defined as

\[
G = \sqrt{1 - f} \times 100
\]

Fig. 5 (a), (b), and (c) show an example of isofield contour maps at 120 ms latency of AEF and at 80 ms latency of SEF. Solid lines (positive field) of the \( B_{r} \) component show the outflow of magnetic flux from the scalp. These lines (positive field) of \( B_{\theta} \) and \( B_{\phi} \) show magnetic flux directed along latitudes and longitudes. As shown in Fig. 5 (a), the contour map of \( B_{r} \) shows one extreme at measurement position D4. It takes a note that this map is similar to Fig. 2 (a). This map was not helpful in estimating the location and the number of sources. By referring to contour maps of \( B_{\theta} \) and \( B_{\phi} \) shown in Fig. 5 (b) and (c), we can clearly see two extremes with opposite polarity on both contour maps. Namely, these magnetic fields consist of two sources with opposite polarity underlying each extreme [13]. We can obtain initial parameters of the number, the locations and the directions of sources by visual inspection from these contour maps.

We carried out source estimation using these initial parameters. Fig. 5 (d), (e), and (f) show isofield contour maps calculated. The calculated maps \( B_{\theta} \) and \( B_{\phi} \) were estimated from the result of the inverse solution from \( B_{r} \). The goodness-of-fit of \( B_{r} \) is 92.4%, and the goodness-of-fit of \( B_{\theta} \) and \( B_{\phi} \) are 88.7% and 88.6% respectively.

Fig. 6 shows the MRI of a subject’s head. Estimated sources are superimposed on the MRI. The localization of the AEF source (open square) at 120 ms latency on the MRI was estimated at the gyrus of the sylvian sulcus with a depth of 1.8 cm below the scalp, which is in the auditory area. Localization of the SEF source (open circle) at 80 ms latency on the MRI was estimated at the gyrus of the central sulcus with a depth of 1.4 cm from the scalp, which is the somatosensory area. The results of this study, analyzing magnetic fields over the human primary cortices, agree in general terms with the related findings in human studies.

**4. Conclusion**

We have developed a 3-D second-order gradiometer connected to 39-channel SQUIDs for vector measurement of the MEG that can detect magnetic field components perpendicular and tangential to the scalp simultaneously. To assess discrimination and separation of multiple sources,
we carried out 3-D vector measurements of MEG with mixed AEF and SEF overlapping in time. We estimated multiple sources from the MEG data and confirmed source locations are reasonable by comparison with MRI of the subject's head. We conclude that this 3-D vector magnetic field measurement can provide information on new constraint conditions which can be obtained from the tangential magnetic field when we calculate the inverse problem with multiple sources.

Further examples of estimating multiple sources overlapping in time combined SVD method can be seen in papers we reported [15]-[16].

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References


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