Reconstruction of quasi-radial dipolar activity using three-component magnetic field measurements

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HIGHLIGHTS

- Novel vector-biomagnetometers enable reconstruction of quasi-radial brain activity.
- We demonstrate this reconstruction of radial brain activity for Brodmann area 1 in the somatosensory system.
- Vector-biomagnetometers provide greater insight into brain activity than does standard magnetoencephalography.

A B S T R A C T

Objective: While standard magnetoencephalographic systems record only one component of the biomagnetic field, novel vector-biomagnetometers enable measurement of all three components of the field at each sensing point. Because information content in standard one-component magnetoencephalography (MEG) is often not adequate to reconstruct quasi-radial dipolar activity, we tested the hypothesis that quasi-radial activity can be estimated using three-component MEG.

Methods: We stimulated the right median nerve in 11 healthy volunteers and recorded the somatosensory evoked fields over the contralateral hemisphere using a novel vector-biomagnetometer system comprised of SQUID-based magnetometer triplets. Source reconstruction for the early cortical components N20m and P25m was subsequently performed.

Results: Both tangential and quasi-radial dipolar activity could be reconstructed in 10 of the 11 participants. Dipole locations were found in the vicinity of the central sulcus, and dipole orientations were predominantly tangential for N20m and quasi-radial for P25m. The mean location difference between the tangential and quasi-radial dipoles was 11.9 mm and the mean orientation difference was 97.5°.

Conclusions: Quasi-radial dipolar activity can be reconstructed from three-component magnetoencephalographic measurements.

Significance: Three-component MEG provides higher information content than does standard MEG.

1. Introduction

Electroencephalography (EEG) and magnetoencephalography (MEG) are non-invasive modalities for recording brain activity at high temporal resolutions. Source reconstruction based on EEG and MEG is a widely used technique in the neurosciences that allows for spatio-temporal disentanglement of overlapping brain activity. Dipolar source models are commonly employed to describe the electrical activity in a certain brain area. Although EEG and MEG signals are generated by the same underlying bioelectric sources, they have different sensitivities with respect to superficial and deep sources, and also with respect to radial and tangential sources (Goldenholz et al., 2009). Therefore, the two modalities are used in combination to distinguish these sources (Jaros et al., 2008; Wood et al., 1985).

Distinction between radially and tangentially oriented sources is based on the local inner skull curvature; however, it has its cor-
respondence in the cortical anatomy, too. Tangential brain activity originates mainly from the walls of the sulci, while radial brain activity originates mainly from the crown of the gyri or the bottom of the sulci.

Baule and McFee (1965) showed that a radial electric dipole in a spherical volume conductor does not produce a magnetic field outside the sphere. However, in a realistic volume conductor, radial dipoles also produce magnetic fields outside the volume conductor (Cohen and Cuffin, 1991; Cohen et al., 1990; Melcher and Cohen, 1988). In additional, strictly radial dipoles would occur in only a few real cases, as the dipoles are commonly slightly tilted relative to the radial direction because of the anatomical structure of the cortex and the extent of most activities (Murakami and Okada, 2006), or because of non-spherical local skull curvature. Throughout this study, we use the term quasi-radial dipole to describe the radial dipole in a realistic volume conductor.

One specific property of MEG is its lower sensitivity to quasi-radial sources than tangential sources (Cohen and Cuffin, 1983). It has been shown both experimentally (Melcher and Cohen, 1988) and in simulation studies (Haueisen et al., 1995) that quasi-radially oriented dipoles produce magnetic fields that are 4–10 times weaker outside the head than those from tangentially oriented dipoles in the same position; thus, MEG is considered inappropriate for localization of quasi-radial sources due to low SNR. However, only one component of the vectorial biomagnetic field has been used in previous studies. Whole head biomagnetometer typically measure the component of the magnetic field approximately normal to the head surface ($B_z$). Flat bottom biomagnetometer typically measure the component of the magnetic field normal to the bottom of the cryostat ($B_z$). Recently developed vector-biomagnetometers (Burghoff et al., 1999; Kobayashi and Uchikawa, 2001; Liehr and Haueisen, 2008; Schnabel et al., 2004) enable recording of all three vectorial components of the biomagnetic field. Measurements (Kobayashi and Uchikawa, 2001) and simulations (Artur et al., 2004) showed a higher information content for data from vector-biomagnetometers than for those with standard biomagnetometers.

The aim of this study is to investigate experimentally the feasibility of reconstructing quasi-radially oriented dipoles based on vectorial measurements of biomagnetic fields. We chose the somatosensory system for investigation because of its well-known capability of reconstructing quasi-radially oriented dipoles that overlap in time.

2. Methods

2.1. Participants and measurements

Eleven healthy volunteers (6 males, 5 females; age, 27.4 ± 5.2 years), 10 right-handed and one left-handed, underwent examination with the ARGOS 200 vector-biomagnetometer (AtB Srl, Pescara, Italy) positioned over the somatosensory cortex. The median nerve was stimulated contralateral to the magnetic recording site. The current was randomized between 0.7 and 1.4 ms. A total of 512 epochs was obtained. Data were sampled at 1025 Hz with a hardware low-pass filter of 256.25 Hz. ECG, and horizontal and vertical EOG were recorded to detect artifacts.

Isotropic T1-weighted magnetic resonance (MR) images of the brain with resolution of 1 mm were obtained from each participant to provide realistic head modeling for the source localization procedure. Co-registration between MR and MEG coordinate systems was obtained by digitizing and rigidly transforming anatomical landmarks (nasion, left and right pre-auricular points).

2.2. Vector-biomagnetometer

The vector-biomagnetometer used included 195 superconducting quantum interference devices (SQUIDs). Sensors were fully integrated planar SQUID magnetometers produced using Nb technology with integrated pick-up loops. The sensing area for each of the 195 sensors was a square of 8 mm side length. The intrinsic noise level of the SQUIDs was below 5 fT Hz-1/2 at 10 Hz.

Triaxial vector magnetometers were formed by grouping three basic sensor elements into a triplet. The three square sensor elements in each triplet were arranged perpendicular to each other on the three adjacent planes of one corner of a cube (Fig. 1 inset), enabling measurement of the magnetic field vector. There are two identical but rotated versions of the triplets, in order to realize a dense arrangement of the triplets (Fig. 1). Thus, six components of the magnetic field were measured [$B_{a1}$, $B_{a2}$, $B_{a3}$] and [$B_{b1}$, $B_{b2}$, $B_{b3}$], where the indices 1 and 2 indicate the two rotated triplets (Moraru et al., 2011). To ensure that all three SQUIDs were located a similar distance from the bottom of the measurement system, this corner of the cube was placed closest to the bottom of the cryostat (with the cube standing on this corner). An additional advantage of this arrangement is that the commonly measured $B_z$ component (i.e., perpendicular to the cryostat bottom) of the magnetic field can be obtained simply by adding the magnetic flux vectors measured by the three SQUIDs and projecting the sum vector onto the common device axis. Fig. 1 shows the schematics of the sensor setup.

The SQUID electronics have a dynamic range of 22 bits, with a lowest resolution of 2.05 fT and range of ±4.31 nT. The system was installed in a magnetically shielded room with three layers of highly permeable material and one layer of aluminum (AtB Srl, Pescara, Italy). The shielding performance was 38 dB at 1 Hz and 80 dB at 20 Hz.
For visualization purposes and to allow for better comparison with the literature, local $[B_{a1}, B_{b1}, B_{c1}]$ and $[B_{a2}, B_{b2}, B_{c2}]$ at each triplet were transformed to global $[B_x, B_y, B_z]$ values for each triplet.

### 2.3. Source localization

A realistic one-compartment boundary element model was derived for each volunteer, to serve as a forward model. The inner skull boundary was segmented out of the MR imaging data sets and triangulated. The triangle side length was set to 7 mm (Haueisen et al., 1997).

MEG data preprocessing consisted of artifact rejection, common mode rejection, band pass filtering (3rd-order Butterworth 20–170 Hz), and baseline correction (−100 to 0 ms). The noise estimate was computed separately for each channel as the variance of the 20% samples with the lowest amplitude. A two-step spatio-temporal dipole localization procedure was performed with the Nelder–Mead Simplex method (Nelder and Mead, 1965).

For the sake of comparison, the entire source localization procedure was repeated using the $B_y$ only. As indicated above, $B_y$ was obtained simply by adding the magnetic flux vectors measured by the three SQUIDs and projecting the sum vector onto the common device axis.

Source localization was performed with Curry version 4.6 (Compumedics NeuroScan, Charlotte, NC). All other computations were done in Matlab (The Mathworks, Natick, MA).

### 3. Results

Fig. 2 shows the butterfly plots of the magnetic signals over time for the three components $B_x$, $B_y$, and $B_z$ for one volunteer. The N20m latency, as derived from these plots for all volunteers, was $20.3 ± 1.4$ ms. The signal-to-noise ratio for all volunteers was $12.8 ± 4.1$, $12.7 ± 4.3$, and $14.5 ± 5.6$ ($B_x$, $B_y$, and $B_z$).

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Fig. 3 shows an example of the measured magnetic field distributions. The $B_y$ field pattern is similar to the field pattern measured with standard biomagnetometers and shows a typical dipolar arrangement for the tangential N20m and a monopolar arrangement for the quasi-radial P25m. For the N20m, the $B_y$ field pattern shows a slightly quadrupolar arrangement (two negative maxima in the center of the field pattern) and the $B_y$ field pattern shows a tri-polar arrangement. Regarding the P25m, both $B_x$ and $B_y$ show dipolar arrangements. This is in agreement with simulated field patterns (Haueisen et al., 1995). The central points of the field patterns of the N20m and P25m are slightly different, and indicate the different origins of the two underlying sources. As expected, P25m quasi-radial activity generally produces lower field amplitudes (difference in line increment in Fig. 3), which are, however, clearly above the noise level for all volunteers. Regarding P25m quasi-radial activity in Fig. 3, both $B_x$ and $B_y$ show higher amplitudes (and thus higher SNR) than does $B_z$. Higher SNR generally yields more stable source localization results.

We also performed a principal component analysis (PCA) for the interval of the first cortical components N20m and P25m. Because the two activities are oriented perpendicular to each other, PCA clearly distinguished the quasi-radial and tangential field patterns. We calculated the ratio of the eigenvalues as $3.92 ± 0.97$ (tangential/quasi-radial), which also corresponds well to the example amplitude ratio of the measured tangential/quasi-radial field patterns in Fig. 3 (approximately 3.6). Note that the absolute eigenvalues of tangential and quasi-radial field patterns depend on amplitudes, which cannot be compared across participants because of varying sensor positions.

For 10 of the 11 participants, we found the expected source locations for both dipoles (N20m and P25m) in the vicinity of the central sulcus. Fig. 4 shows the results of the source localization procedure for one volunteer. No reliable localization was obtained for one participant, which was likely caused by a problem in the co-registration between MR and MEG coordinate systems. The mean distance between the quasi-radial and tangential dipoles was $11.9 ± 5.4$ mm, which is within the expected range for the dis-
We found the angle between the two dipoles to be $97.5 \pm 28.5^\circ$, which is also in accordance with the expected range.

We additionally performed single component source localization using only the $B_z$ component. As expected, the localization results were generally the same for the N20m. However, only in three volunteers the single component approach yielded source locations in the vicinity of the somatosensory system. For the other seven volunteers, the source locations were in other parts of the brain. For source localization using only $B_z$, the mean distance between the quasi-radial and tangential dipoles was $25.6 \pm 14.8$ mm, where even the smallest distance was larger than 14 mm.

**4. Discussion**

In the present experimental study, we demonstrated that it is possible to localize quasi-radial dipolar activity in the human somatosensory system using a three-component MEG. The first cortical activities in Brodmann areas 3b and 1, which can be represented by a tangential and a quasi-radial dipole (Allison et al., 1991; Buchner et al., 1994; Wood et al., 1985) and which overlap in time, were clearly distinguished in principal component analysis, dipole location, and dipole orientation.

The findings of the present study are in line with those of previous studies that demonstrated that magnetic field distribution measured tangentially to the scalp can provide additional information for the solution of inverse problems with multiple sources in the primary and secondary somatosensory cortex overlapping in time, after median nerve stimulation (Kim et al., 2003) or finger stimulation (Kim et al., 2006). Similarly, the usefulness of vectorial magnetic field measurements was previously shown for discriminating multiple sources of magnetic alpha waves overlapping in time (Kim and Uchikawa, 2002). In a different field of application, Bradshaw et al. (1999) suggested that gastric and intestinal activity can be distinguished based on vectorial magnetic field measurements and that in general, vectorial measurements increase the ability to separate different physiological signal components, as well as non-physiological components.

In the non-invasive diagnosis of spinal cord function for orthopedic and neurologic applications, SQUID vector gradiometers provide more information on the evoked magnetic field distribution in the spatially limited area of the neck (Adachi et al., 2009). It was reported that in magnetocardiography, localization of the accessory conduction pathway in a patient with Wolff–Parkinson–White syndrome was improved when using vector data compared with one-component field data (De Mehlis et al., 2010). Similarly, in simulation studies, improved localization accuracy was shown for single dipoles when using vector data compared with one-component field data (Arturi et al., 2004; Nara et al., 2007). The improvement can be partly attributed to the higher SNR obtained by a greater number of sensors. Consequently, with vectorial data, fewer trials are required in the averaging process in order to achieve the same localization accuracy (Arturi et al., 2004). A similar result was obtained for distributed sources and minimum norm solutions (Di Rienzo et al., 2005). On more theoretical grounds, using a projection method, Di Rienzo and Haueisen (2007) showed that independent from noise level considerations,
vectorial field data provided more information in the inverse problem compared with that obtained from one-component data.

With regard to the human head, it has been argued that volume currents have a stronger effect on the tangential components of the magnetic field \((B_h, B_o)\) than on the radial component \((B_r)\); accordingly, MEG systems that measure only \(B_r\) have been suggested. However, the wide availability of realistic volume conductor models enables volume currents to be taken into account. Moreover, Kwon et al. (2002), using an auditory stimulation paradigm, indicated that accurate source locations in the auditory cortex could also be obtained by using only the tangential components of the magnetic field.

The present study has several limitations. Our forward computation model included anatomically realistic individual 1-compartment boundary element models. Although boundary element models provide a more realistic description of conductivity distribution in the human head compared with simple spherical models, they have the intrinsic disadvantage of homogeneous and isotropic conductivity compartments. Finite Element Method models enable detailed modeling of inhomogeneous and anisotropic conductivity distributions (Güllmar et al., 2010; Haueisen et al., 2002). We chose the boundary element approach for the present study for two reasons: these models are currently in more common use, and model construction is easier to achieve for compartmental models. Consequently, the influence of inhomogeneous and anisotropic conductivity distributions on the different field components remains to be investigated.

A further limitation of our experimental study is that it uses a measurement system designed for magnetocardiography. The flat bottom cryostat is not optimal for MEG because there is a larger distance between the sensors and the head at the periphery of the sensor array. In addition, the patient position unit in this system consists of a fixed array of coils, which is mechanically more difficult to fix on the head than on the torso.

5. Conclusion

To the best of our knowledge, this is the first study to reconstruct quasi-radially oriented dipoles based on vectorial biomagnetic measurements. We conclude that quasi-radial dipolar activity can be estimated from such measurements and that greater insight into brain activity may be obtained using three-component magnetoecephalographic measurements compared with those from standard magnetoencephalography. Vectorial biomagnetic measurements further improve the signal-to-noise ratio and thus allow for better localization of weaker components such as the P25m.

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References


