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EEG Current Source Imaging using VEP Data Recorded inside a 3.0T MRI Magnet

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Abstract: We have performed EEG current source imaging on the cortical surface using visual evoked potentials (VEPs) recorded inside a 3.0 T MRI magnet. In order to remove ballistocardiogram (BCG) artifacts in the VEPs, an improved BCG template subtraction technique is devised. Using the cortically constrained current source imaging technique and pattern-reversal visual stimulations, we have obtained current source maps from 10 subjects. To validate the EEG current source imaging inside the magnet, we have compared the current source maps to the ones obtained outside the magnet. The experimental results demonstrate that there is a strong correspondence between the current source maps, proving that current source imaging is feasible with the evoked potentials recorded inside a 3.0 T MRI magnet.

Key words: Ballistocardiogram, Visual evoked potential, MRI, Template-based artifact removal, EEG current source imaging

INTRODUCTION

Complementary information of EEG evoked potentials (EPs) and functional magnetic resonance imaging (fMRI) has been utilized in functional brain studies to improve the spatial and temporal resolution since one of them lacks if only one technique is used[1, 2]. In practice, most of combinatory EEG/fMRI experiments are performed in two separate settings, thus differing in space and time. However, simultaneous or interleaved acquisition of EEG/fMRI data in the same setting is more ideal to maintain identical experimental conditions and to measure the brain functions with the cognitive status of the subject unchanged[3]. In the combinatory studies of EEG/fMRI, it is critical to obtain high-quality EEG signals in the main magnetic field of MRI. However, the strong main magnetic field of MRI induces ballistocardiogram (BCG) artifacts (BAs) in the EEG signals, preventing proper EEG/EP signal analysis and current source imaging. Several techniques have been proposed to remove the BAs from the EEG signals[4, 5, 6]. With the aids of the BA removal algorithms, visual and audio EP signals have been obtained from the EEG signals acquired inside the magnet without significant differences in their waveforms as compared with the EP signals recorded outside the magnet [6, 7]. However, it has not been attempted to reconstruct neuronal current source maps from the BA removed EP data yet. A recent simultaneous EP/fMRI study with the low resolution electromagnetic tomography (LORETA) technique for the current source imaging showed improved spatiotemporal dynamics of the brain activity for target detection even though BAs had been removed with the simple threshold-and-rejection based technique[3].

In this work, we have devised an improved BA removal technique by extending the template subtraction technique[4, 5] for the EEG current source imaging in combinatory EEG/fMRI studies. After removing the BAs from the visual EP (VEP) data recorded inside a 3.0 T MRI magnet, we have reconstructed the current source maps using the cortically constrained current source imaging approach[8, 9]. For validation, we have compared the current source maps for the BA-removed VEPs (i.e., inside the magnet) with the ones for the BA-free VEPs (i.e., outside the magnet).

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MATERIALS AND METHODS

VEP Measurements

VEP signals were recorded from ten healthy volunteers inside and outside the 3.0 T magnet of the whole body MRI scanner (Magnum 3.0, Medinus, Korea). The volunteers (10 men, mean age: 26.5) with no history of neurological or psychiatric disorder were recruited from an academic institution. The study was approved by the institutional ethics review board of Kyung Hee University, Korea, and written informed consent was obtained from each subject.

We used an MRI-compatible 32-channel EEG recording system (BrainAmp MR, Brain Products GmbH, Germany) for EEG data acquisition. The EEG data acquisition system has a 16 bit depth with the voltage resolution of 100 nV and the dynamic range of ±3.2mV. The sampling rate was 1 kHz and the bandwidth of the bandpass filter was 1-60 Hz. All the EEG recordings were performed with the standard 10-20 uni-polar system referenced to Cz. Electrode skin impedance was kept below 2kΩ To minimize motion artifacts caused by the EEG lead wires between the EEG cap and the EEG amplifier, we fixed the lead wires to a supportive structure using plastic ties. The horizontal eye channels were modified to record electrocardiogram (ECG) between the standard V1 ECG lead and the left outer canthus.

For visual stimulation, the checkerboard patterns were presented to the subject. Each stimulation block consisting of two pattern reversals at 8Hz was repeated. The stimulation patterns were generated with the non-commercial S/W (Psychophysics Toolbox, USA) running on a Macintosh computer. To make the stimulation conditions as identical as possible inside and outside the magnet, we projected the visual stimulations through an LCD projector to a 40 inch semi-transparent screen, that were visible to the subject lying supine both inside and outside the magnet without applying any imaging gradients. For precise synchronization of the stimulation onset timing, TTL-level trigger signals were generated with a photo-diode placed on the right-bottom side of the monitor screen, which converted a contrast change from black to white into an electrical signal.

BA Removal

Based on the observation that BCG waveforms exhibit time-varying nature depending on the heart-beat pattern and interval of the subject, we extended the BA template subtraction method[4] to have multiple correlative templates. To achieve this, first we obtained the BCG timing information from the location of QRS complexes of the ECG signals using the QRS detection algorithm[10]. After the ECG peak detection, we assigned template timing windows to every heart beat in a given EEG channel to extract BCG waveforms. Each window contains a BCG waveform and the window segments are denoted as $\{BCG_i\}$, $i=1 \sim N$ (N is the total number of heart beats). The width of the timing window was about 730ms. The width of the timing window is depending on the subjects. From the $\{BCG_i\}$ set, we made BA subtraction templates for every timing window in a given EEG channel as follows:

Step I: For the i-th BCG segment, compute correlation coefficients with the rest of BCG segments. Collecting the BCG segments that have greater correlation coefficient than the given threshold, create the correlative BCG set, $\{CBCG_j\}$ where $j=1, \ldots, M$ and $M<N$.

Step II: Obtain the i-th BA subtraction template from the set $\{CBCG_j\}$ by computing the median of all the correlative BCG waveforms.

Step III: Subtract the i-th template from BCG_i to remove the BA.

Step IV: Repeat Step I~ III until $i=N$.

The main concept of the correlative template subtraction technique is illustrated in Fig. 1.

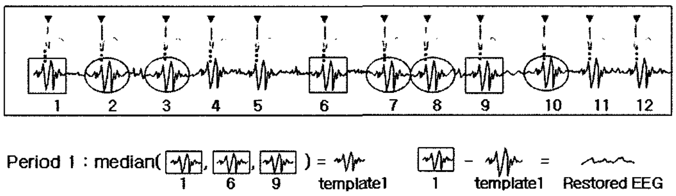

Fig. 1. A schematic diagram of the correlative BA template subtraction technique.

EEG Source Imaging

In computing the EEG forward solution, we used the boundary element method (BEM) with a realistic brain surface model derived from the 3D magnetic resonance images[11]. The boundary surface meshes for the head were generated by fitting the standard boundary element model of the commercial source analysis software (ASA Version 2.1, ANT Software, Netherlands) to the 3D magnetic resonance images of a subject. We assumed three layers, brain, skull and scalp, with the conductivity ratio of 1:0.0125:1. Each boundary was composed of 1016 triangular elements and 510 nodes. To reconstruct current sources in the brain, we applied the cortically constrained distributed source approaches[8, 9] which constrain the current source locations on the interface between the white and gray matters and along the orientations perpendicular to the cortical surface. The interfacing surface between the white and gray matter was extracted from T_1-weightd MR images (256×256×200, voxel size: 1mm × 1mm × 1mm) of the subject and tessellated into about 300,000 triangular elements including about 150,000 vertices. To extract and tessellate the cortical surface, we used the software called 'BrainSuite' developed by Shattuck and Leahy at the University of Southern California, USA[12]. The BEM mesh model and the tessellated cortical surface model calculated from the MR images of a subject were used for the current source imaging of all the subjects. For the EEG electrode positioning, we identified the electrode coordinates from the 3D magnetic resonance images of the subject obtained with the gel-filled capsules attached on top of the EEG electrodes. We used the linear inverse estimation with the inverse operator, $\mathbf{W}=\mathbf{R}\mathbf{A}^{T}(\mathbf{A}\mathbf{R}\mathbf{A}^{T} + \mathbf{C})^{-1}$, to reconstruct the distributed current sources, in which $\mathbf{A}$ is the lead field matrix that relates point sources to the electrodes, $\mathbf{R}$ the source covariance matrix, and $\mathbf{C}$ the noise covariance matrix[13]. The current source distributions were estimated by multiplying $\mathbf{W}$ by the BA removed EP data at the given time point.

RESULTS

We first observed that the BCG waveform patterns of all the subjects are different and even the BCG waveform patterns of a single subject also vary depending on the heart beat pattern. Figure 2 shows a set of representative BCG templates at the O1 and T7 electrodes of Subject A. As can be noticed from the figures, the BCG template waveforms are quite different even in the same EEG channel. In both experiments performed inside and outside the magnet, we acquired the VEP data for about 300 s with each epoch period of 280 ms. In the calculation of VEPs, epochs containing signals greater than 50 μV were rejected and the BAs were removed with the proposed technique.

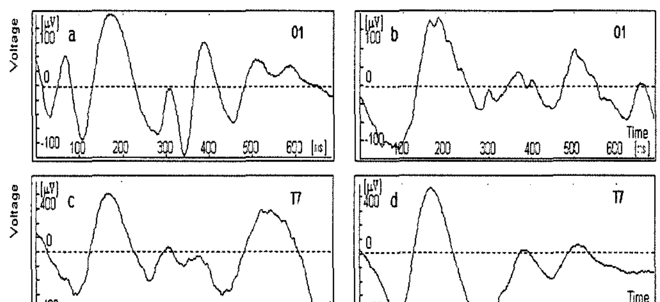

Fig. 2. (a),(b) Two representative BCG template waveforms at O1 channel. (c),(d) Two representative BCG template waveforms at T7 channel.

In Fig. 3, we compare typical VEPs at the O2 electrode obtained outside and inside the magnet. The solid and dotted lines represent VEPs of Subject A measured outside and inside the magnet, respectively. For a reference, we also show the VEP measured inside the magnet without applying the BA removal technique (the dashed line). We took the average of the EEG/EP signals in 120 epochs to obtain the VEPs. The peak of the VEPs appears 130 ms after the stimulation onset. The correlation coefficient between the solid and dotted lines was found to be 0.915.

From the VEPs obtained outside the magnet and inside the magnet with the BA removal, we reconstructed two kinds of current source maps on the cortical surface for each subject. Out of 10 subjects, two subjects (Subject F and J) showed barely noticeable current sources in the visual cortex both inside and outside the magnet, hence we classified them as failures. In order to validate the EEG current source imaging inside the magnet, we identified the locations of the maximum current density in the visual cortex region in the two kinds of current source maps and calculated the distance between the two locations. To account the area change of the EEG current sources, the source areas, which had current densities greater than 20% of the peak density in the visual cortex region, were computed in the two kinds of current source maps. The relative source area change was computed by dividing the source area outside the magnet by the one inside the magnet. Table 1 summarized the results for all 10 subjects. Subject H showed more than 3cm deviation in the source location. Excluding the three cases (Subject F, H, and J), the rest of subjects showed the source location changes of less than 23 mm and the source area changes of less than ±40%.

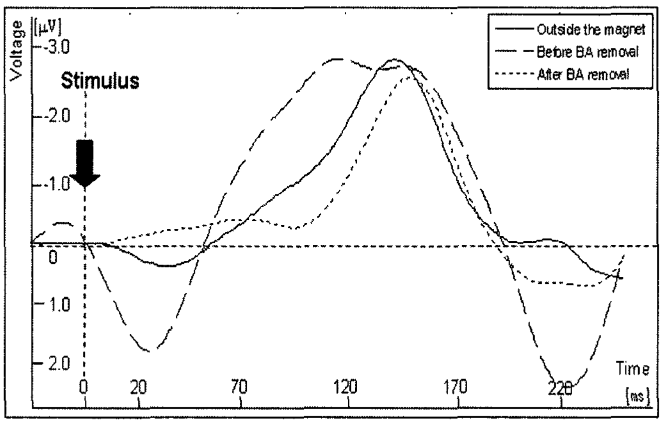

Fig. 3. A BA-free VEP at O2 channel of Subject A obtained outside the magnet (solid line) and a BA-removed VEP at the same electrode of the same subject obtained inside the magnet (dotted line). For a reference, a BA-contaminated VEP is also shown (dashed line).

Table 1. Source location difference and relative source area change in the two types of EEG source imaging performed outside and inside the magnet.

Subject	Source location difference [mm]	Relative source area change [%]
A	2	101
B	6	100
C	21	86
D	13	140
E	4	100
F*	6	196
G	20	81
H	32	94
I	23	79
J*	14	21

* Failure case

In Fig. 4, we show the EEG current source maps of Subject A and B as representative examples of the successful cases. The current source maps were calculated at the time of maximum VEP peaks. The colored regions in the figures represent the area on which current densities are greater than 20% of the peak current density. The figures clearly demonstrate strong similarity between the current source maps obtained inside and outside the magnet.

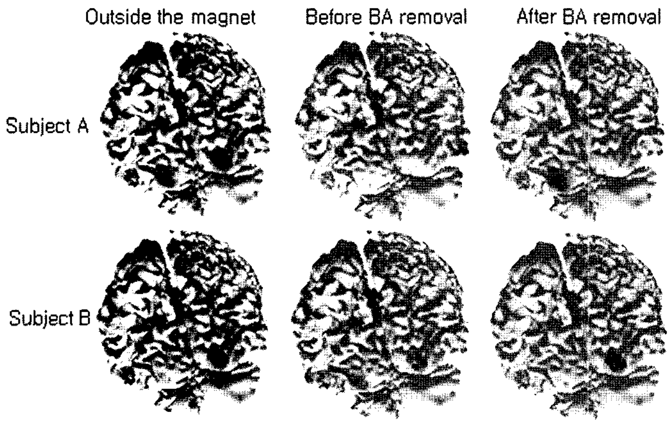

Fig. 4. Representative examples of the current source map.

DISCUSSIONS

It has been reported that the evoked potentials recorded inside an MRI magnet are inevitably different from the ones recorded outside the magnet due to the arousal or vigilance of the subject caused by being inside a small and closed space of the magnet, aside from the BCG or gradient pulse effects [7]. Since the EP data have been recorded inside the magnet without applying any imaging gradient pulses in our study, it is believed that the difference is due to the residual BAs and/or the effect of arousal or vigilance of the subject. Despite the difference in experiment conditions between the two types of EP measurements, our results suggest that EEG current source imaging for combinatory EEG/fMRI studies looks feasible with the proposed BA removal technique and the cortically constrained approach. However, further investigations are needed to make the EEG current source imaging inside an MRI magnet a routine practice. Firstly, the technique needs to be validated with more complex experimental paradigms for EP measurements. That is, the accuracy of EEG current source imaging should be checked with smaller EP signals than the VEPs used in this study. Secondly, the effect of BAs should be further investigated in the case of EEG electrode configuration with bigger number of electrodes (64 or 128). Finally, we need to have EEG/EP measurements using simultaneous or interleaved EEG/fMRI schemes. In such EEG/fMRI experiments, EEG signals are further contaminated by gradient pulse artifacts if sufficient intervals between the EPI sequences are not permitted.

CONCLUSIONS

Using the extended BA removal technique and the cortically constrained current source imaging technique, we obtained current source maps on the cortical surface from the visually evoked potential data recorded inside a 3.0 T MRI magnet. The experimental results of 10 volunteer studies suggest that EEG current source imaging on the cortical surface is feasible inside a 3.0 T MRI magnet.

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