Ballistocardiogram Artifact Removal with a Reference Layer and Standard EEG Cap

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Introduction

The ballistocardiogram (BCG) artifact[1] can severely contaminate the EEG signal in simultaneous EEG-fMRI. The current BCG artifact removal methods extract the artifact templates directly from the contaminated EEG data. Due to the leakage problem, the EEG signal may potentially be reduced after the artifact removal. Most recently, it has been proposed to measure the artifact templates by placing a group of electrodes (BCG electrodes) on a semi-conductive layer (reference layer) insulated from the scalp[2,3]. However, although quite promising, the previous BCG reference layer (BRL) methods used the customized electrode system and reduced the spatial resolution of EEG recordings[2] by 50%, or required performing an extra model-building experiment prior to each experiment to determine the layout of the BCG electrodes. In addition, as of yet, the performance of BRL has not been systematically compared to the widely used BCG removal methods. These problems may significantly limit the applications of BRL method in EEG-fMRI studies.

The aims of this study are to (i) propose a more practical and efficient BRL method and (ii) compare its performance with the most popular method, the optimal basis sets (OBS) algorithm[4], on spontaneous and sensory-evoked EEG signals. In this study, by designing the reference layer as a reusable cap (BCG cap), a standard EEG cap is directly used for measuring the reference and EEG signals. Also, the number of BCG electrodes can be arbitrarily selected from the EEG cap, and their spatial locations are preset and fixed on the BCG cap. By adopting these strategies, the BRL method can be readily used on the standard EEG systems without additional hardware modifications or experimental procedures.

Methods

During the EEG recording, a BCG cap was worn by the subject between the scalp and EEG cap (Fig. 1A). The BCG cap was composed of a vinyl and a satin layer (Fig. 1B), which served as the insulating and reference layer, respectively. The standard electrolyte saline was dipped into the satin layer to make it semi-conductive. 32 grommets were built in the BCG cap, and the electrodes in the grommets (scalp electrodes) contacted the scalp for recording the EEG signal, and the other electrodes (BCG electrodes) were placed on the reference layer.

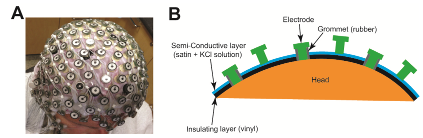

Fig.1 Experimental setup and BCG cap

EEG data were acquired on five healthy volunteers using a 256-EEG system inside a 3 T MRI scanner. An eyes open/closed task, brief full-field checkerboard and tones were used to elicit the spontaneous oscillations (alpha-wave), and visual and auditory evoked potentials (VEPs and AEPs) in the brain. EEG data were acquired both with and without fMRI scan. All the data analysis was performed with the EEGLab and Matlab software. The gradient artifact in the EEG data with fMRI scan was removed first, and then all the EEG data was band-pass filtered at 0.5-50 Hz. The OBS and BRL methods were separately applied to remove the BCG artifacts. In the OBS, the number of principal components was set to the optimal value (= 3)[5]. When using the BRL, the BCG artifact in a scalp electrode was estimated from the signals in the BCG electrodes with the linear regression, and then subtracted from the EEG data. Since the performance of BRL depends on the number of BCG electrodes (N_B), different N_B settings were used in the BRL to examine their relationship. In each N_B setting, the BCG electrodes were uniformly selected from the EEG cap.

The performance of BRL was compared to OBS by assessing the signal qualities after the BCG removal. To evaluate the signal quality of the alpha-wave, the power spectra were calculated from the data epochs during eyes open and closed. The alpha peak power was obtained by integrating the spectral power within the alpha peak frequency +/- 1 Hz, and then the alpha peak power ratio (pPR) of eyes closed to open was used to represent the signal quality of the alpha-wave. In the AEP and VEP data, the peak contrast-to-noise ratio (pCNR) was used as the criterion to evaluate the signal quality. To calculate the pCNR, the CNR curves were obtained by calculating the ratios of the average VEP/AEP signal to its standard deviation at baseline. The response peaks were identified from the CNR curves and the pCNRs were obtained by averaging the CNR values in their FWHM windows.

Results

Figure 2 shows the power spectra and pPR curves from the eyes open/closed experiment in a typical subject. The alpha oscillations at about 10.4 Hz was observed during eyes closed in the data acquired without (Fig. 2A) and with (Fig. 2C) fMRI scan. The pPR values when using BRL with N_B = 80 (BRL-80) and 160 (BRL-160) were substantially higher than with the OBS, both in the case without (Fig. 2B) or with (Fig. 2D) scan. The pPR of BRL-80/-160 averaged over the subjects were larger than the OBS by approximately 65%/82% in the data without scan and 98%/101% with scan.

In the VEP data without (Fig. 3A) and with (Fig. 3B) scan, two strong peaks (P1 and N1) appeared in the CNR curves. The results averaged over the subjects showed that the BRL at N_b = 160 improved the pCNR of primary responses by 43%/38% over the OBS without/with MRI scan. In the AEP experiment, one strong negative peak (N1) was detected without (Fig. 3C) and with (Fig. 3D) scan. The pCNR of AEP when using the BRL is larger than the OBS by 101%/190% in the data without/with scan. In addition, it was found that the performance of BRL increased with increasing N_B (Fig. 4). In the data recorded without/with scan, the performance of BRL at N_B = 20 was higher than the OBS by 57%/74%, 32%/5%, and 37%/87% on the alpha-wave, VEP, and AEP signals, respectively. When N_b =160, these numbers increased to 82%/101%, 44%/38%, and 101%/190%.

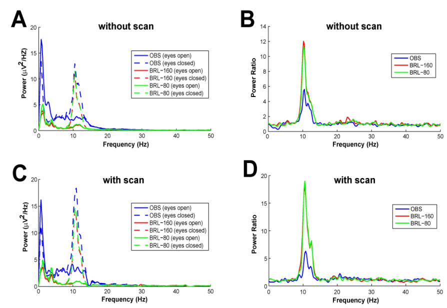

Fig.2 Power spectra and peak power ratios

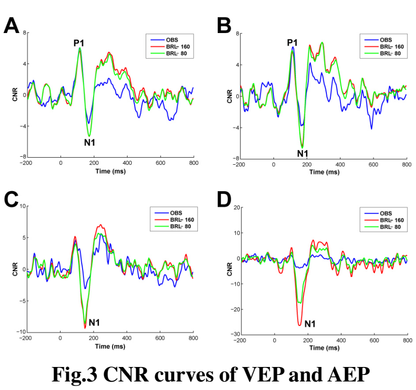

Fig.3 CNR curves of VEP and AEP

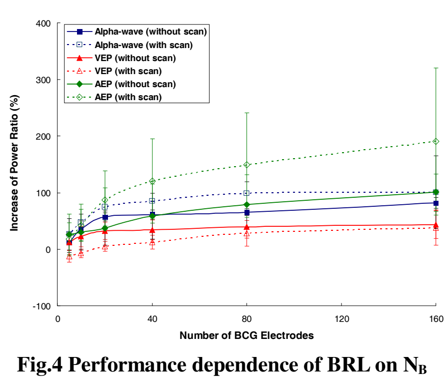

Fig.4 Performance dependence of BRL on N_B

Discussion and conclusion

The results demonstrated that this practical and efficient BRL method can effectively suppress the BCG noise. Moreover, on the alpha-wave, VEP and AEP EEG signals, BRL consistently outperforms OBS when $N_B \geq 20$. It was also found that the performance improves with a larger N_B. Since the maximum allowed N_B increases with the number of EEG channels, using the BRL on dense array EEG systems would provide higher signal quality than with conventional systems. If 20 BCG electrodes are used on a 256-channel system, approximately 92% of electrodes can be used for the normal EEG recording. Thus, superior EEG signal quality can be achieved with negligible loss in the spatial resolution. In conclusion, compared to the traditional method, the BRL method showed better and more robust performance in detecting spontaneous and sensory evoked EEG signals.

References

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