Ballistocardiogram artifact removal from EEG signals using the real-time Kalman filter

M. H. In[1], H. C. Kim[1], T. S. Park[1], T-S. Kim[1], M. H. Cho[1], and S. Y. Lee[1]

[1]Dept. of Biomedical Engineering, Kyung Hee University, Yongin, Kyungki, Korea, Republic of

Introduction

The combinational information of the EEG evoked potential (EP) with fMRI is believed to have great potential to improve spatio-temporal performance in functional brain studies. As an attempt to remove BCG artifacts in real time from the EEG signals recorded inside the MRI magnet, the scalp motion information detected by a piezoelectric sensor has been used in estimating the BCG components in the EEG signals [1]. In this study, we apply the adaptive Kalman filter to the electrooculogram (EOG) signals recorded simultaneously with the EEG signals without any extra motion sensors and remove the BCG artifacts from the EEG signals using the real-time Kalman filtering program.

Methods

We have observed that the BCG components in the EOG signals measured beneath the subject's eyes resemble the ones in the EEG signals. It is thought that the resemblance comes from the fact that the EOG measuring points are near the EEG measuring points. Based on the observation, we applied the Kalman filter to the EOG signals to estimate the BCG components in the EEG signals. The Kalman filter output is, then, subtracted from the EEG signals to remove the BCG artifacts from the EEG signals. It has been observed that the Kalman filtering of a single channel EOG signal suffices to remove the BCG components from all the EEG signal channels.

For the real-time BCG artifact removal, we have programmed the Kalman filtering program using C^{++} language and validated the efficacy with the real-time extracting PRVEPs (pattern reversal visual evoked potentials) from the EEG signals of eight healthy subjects recorded inside a 3.0 T MRI magnet. For the validation, the PRVEPs have been extracted from the EEG signals recorded inside and outside the 3.0 T MRI magnet applying the same visual stimulation paradigms and the results are compared with each other. In order to remove the BCG artifacts, we used the proposed method and the Allen's template subtraction method [2]. The performance of the BCG artifact removal has been evaluated with improvement in terms of normalized power spectrum ratio (INPS) [3].

Results

We developed the real-time Kalman filtering PC program as shown in Figure 1 and acquired VEPs from 32-channel EEG signals of eight healthy subjects both inside and outside the 3.0 T MRI magnet with a pattern reversal visual stimulation paradigm. Figure 2 shows three types of VEPs of a subject. One extracted from the EEG signals recorded outside the magnet, and the others extracted from the EEG signals recorded inside the magnet with the BCG artifacts removed by the Kalman filtering in real time and template subtraction of post-processing. The three different types of VEPs have no significant discrepancies among them, and the latencies and the shapes of VEPs are quite similar to each other indicating the efficacy of the proposed method in real-time recording VEPs inside the MRI magnet. The average INPSs of the Kalman filtering have been observed to be greater than those of the Allen's method.

Discusions and Conclusions

The BCG artifact removal with the Kalman filter has been claimed to have some advantages over the template subtraction method. The Kalman filter of this work is capable of adapting to time-varying changes of the BCG artifacts in real-time mode. Since EOG channels are mostly available in typical EEG recording systems, it is more convenient to use EOG signals in the combinatory fMRI/EEG experiments rather than piezoelectric signals with extra circuitries. Also, it is expected that the proposed technique can be greatly utilized in simultaneous fMRI/EEG studies as the Kalman filtering program was developed in the real-time mode.

References

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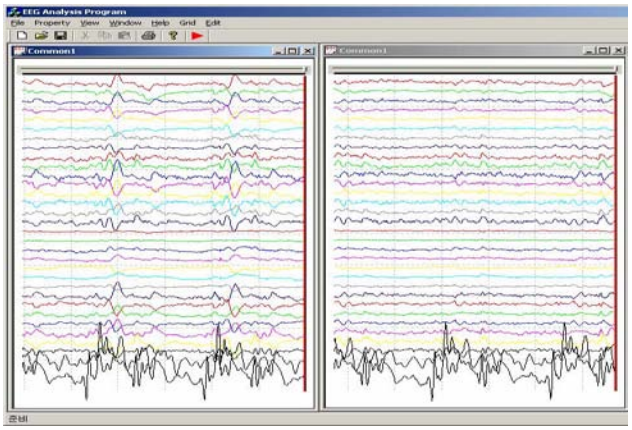

Figure 1. The raw data (left) and Kalman-filtered data (right) with the real-time processing.

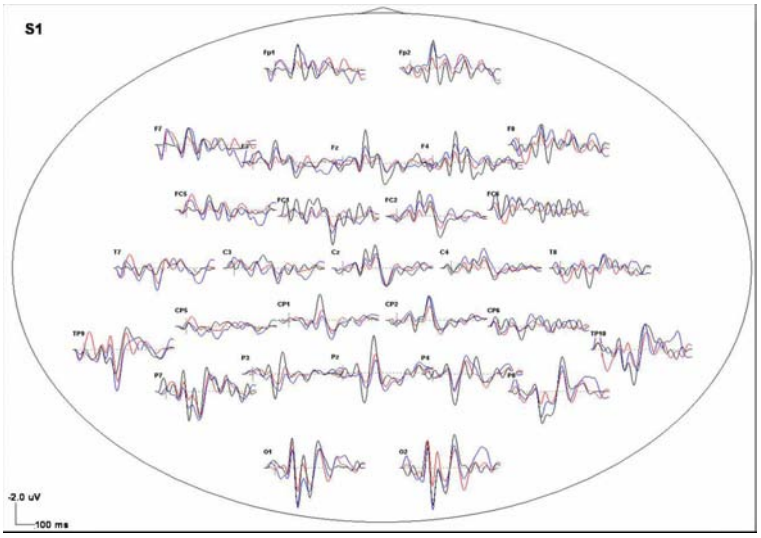

Figure 2. The three types of VEPs extracted from the EEG signals recorded inside (black) and outside the magnet. The blue and red lines are extracted from the EEG signals from which the BCG artifacts have been removed by the proposed and Allen's method, respectively.