Ballistocardiac artifact removal algorithm for simultaneous EEG/fMRI

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Abstract

Ballistocardiac pulse artifact is one of the most significant factors that hinders simultaneous recording of electroencephalogram (EEG) and functional magnetic resonance imaging (fMRI). The purpose of this study was to develop a novel heartbeat artifact removal algorithm that resolves problems of several previous methods [1],[5]. Our method consists of mean waveform subtraction, selective removal of wavelet coefficients, and adaptive filtering. The recursive least square adaptive filtering operates without dedicated sensor for the reference signal, and it is turned on only when the mean subtraction and wavelet-based noise removal is not satisfactory. Performance of the proposed system is demonstrated for experimental EEG recording within 3 T scanner.

Introduction

Simultaneous recording of EEG and fMRI is a promising tool for functional brain mapping, which provides both high spatial and temporal resolution. Any neuroscientific studies utilizing event-related potential and neuroimaging such as positron emission tomography (PET) or fMRI can be benefited from this combined technique [1]. Another advantage from the simultaneous EEG/fMRI is that one modality can provide information that complements the other. EEG-triggered fMRI studies of epilepsy [2] and studies on brain activation according to sleep stages are two typical examples. Limitation of the combined technique comes from the artifacts induced in EEG waveforms: the ballistocardiac artifact and the magnetic field switching for MR imaging are two major sources of artifact. We present a novel signal processing technique that combines advantages of two previous techniques for ballistocardiac artifact removal. Performance assessment and comparison with previous methods are presented using synthetic data based on experimental data, and also using real experimental data of alpha-wave-dominant normal EEG and epileptic EEG.

Methods

Six normal subjects (3 females, 3 males, age: 21.5 ± 1.38) were volunteered for the EEG recording within MR scanner. We used an fMRI-compatible EEG recording system, BrainAmp-MR (BrainProducts GmbH, Munich, Germany), along with a specially-designed electrode cap (BrainCap-MR). The EEG recording was performed inside a 3 Tesla MR scanner at fMRI lab in Korea Advanced Institute of Science and Technology. The lead wires from each EEG electrode are fixed firmly to the cap surface for the immobilization. Fig. 1 shows the block diagram of our heartbeat artifact removal algorithm. Basically it consists of two branches; one is based on mean pulse waveform subtraction along with residual noise reduction using selective elimination of wavelet coefficients, and the other is based on RLS adaptive filtering. Our system is operated on 10 s segment of the input signal. The mean subtraction branch performs the role of heartbeat artifact removal that is essentially similar to the method of Allen et al. [1], with an important addition of wavelet-based denoising. The mean-subtracted signal is decomposed into eight dyadic scales by discrete wavelet transform (WT) using Coiflet-5 basis function, and then the coefficients of scales d1 and d2 are thresholded by the method of Donoho [3] in order to reduce high frequency random noise. Subsequently, the coefficients of the scales d6 and d7 are eliminated if they are within 1 s interval centered at the heartbeat peak or if their absolute values are larger than 1/10 of the amplitude of heartbeat peak amplitude. Then, the denoised waveform is obtained from the inverse wavelet transform (IWT). Since the wavelet denoising may remove a large portion of background EEG when the power is concentrated on theta or delta bands, our system utilize adaptive filter instead of the mean subtraction combined with wavelet denoising. Another case when the adaptive filter is activated is when the result of artifact removal is not sufficient, which is determined by calculating correlation coefficient between the Teager energy operator [4] output of the input signal and the processed signal.

Results

Fig. 2 (a) and (b) show performances of our system and conventional mean subtraction algorithm applied to the EEG contaminated by ballistocardiac artifact when the alpha wave (Fig. 2 (a)) and the theta wave (Fig. 2 (b)) is dominant, respectively. The second panel is the case when the mean subtraction is applied, and the first panel is the result obtained from the proposed system shown in Fig. 1. It is also tested for the beta- and delta-dominant EEGs, and for the epileptic EEG. To quantify the performance, the correlation coefficients between the output of the artifact removal algorithms and the underlying EEGs were calculated. The results shows that the proposed system is superior over the mean subtraction for all the EEGs considered.

Discussion

The ballistocardiac pulse artifact removal algorithm proposed in this paper utilizes relative advantages of previous methods and improves their drawbacks so that the possibility of faster and more exact processing of a large amount EEG data recorded simultaneously with fMRI. Compared to the method of Bonmassar et al. [5], our system does not require a separate sensor for the acquisition of the pulse-dominant reference signal. We showed that a useful reference signal for heartbeat artifact removal by RLS adaptive filter can be obtained from two EOG channels. The operation of adaptive filter is performed only when the performance of the mean subtraction/wavelet denoisng branch is not satisfactory, so that the required computation time is much shorter than the method of Bonmassar et al. [5] which updates filter coefficients for all the time samples of input signal.

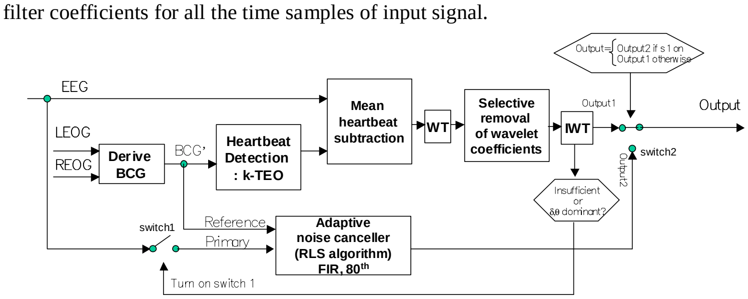

Fig. 1: (a) Block diagram of the proposed ballistocardiac artifact removal system.

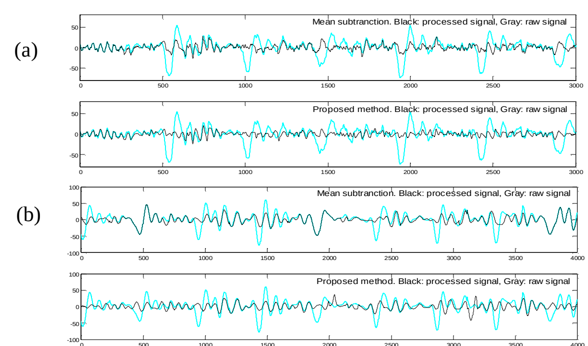

Fig.2: Performance of the proposed method (a) alpha-dominant signal (b) theta-dominant signal

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