A Hybrid Method to Improve the Reduction of Ballistocardiogram Artifact from EEG Data

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Abstract. Simultaneous recordings of functional magnetic resonance imaging (fMRI) and electroencephalography (EEG) allow acquisition of brain data with high spatial and temporal resolution. However, the EEG data get contaminated by additional artifacts such as Gradient artifact and Ballistocardiogram (BCG) artifact. The BCG artifact's dynamics appear to be more challenging and it hinders in the assessment of the neuronal activities. In this paper, a reference-free method is implemented in which Empirical Mode Decomposition (EMD) and Principal Component Analysis (PCA) has been combined to reduce the BCG artifact while preserving the neuronal activities. The qualitative analysis of the proposed method along with three existing methods demonstrates that the proposed method has improved the quality of the reconstructed data. Moreover, it does not require any reference signal to extract BCG artifact.

Keywords: Ballistocardiogram artifact, Simultaneous EEG & fMRI, Principal Component Analysis, Empirical Mode Decomposition.

1 Introduction

Simultaneous non-invasive Electroencephalography (EEG) and functional Magnetic Resonance Imaging (fMRI) has been used to acquire neuronal activities. Such acquisitions provide further insight to the functions of the brain due to high temporal and spatial resolution [1]. The neuronal activities measured directly with EEG have a good temporal resolution as it acquires neural function on the order of milliseconds [2]. On the other hand, fMRI acquires the neuronal activity indirectly by using the Blood Oxygenation Level Dependent (BOLD) response with spatial resolution of few millimeters. Combining both modalities, brain activities with high temporal and spatial resolution can be analyzed at the same time. In real-time environment, the combination means the concurrent acquisition of EEG and fMRI but such acquisitions also

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get contaminated by additional artifacts compared to the EEG recording alone [3]. The additional artifacts are because of magnetic field inside the scanner. The magnetic field related artifacts which contaminate EEG data are indicated as Equation (1).

$$EEG_{raw} = EEG + Artifact_{GA} + Artifact_{BCG} \tag{1}$$

The $Artifact_{GA}$ represents the gradient artifact also known as imaging artifact. It arises due to the gradient magnetic fields used for spatial encryption of fMRI data [4]. It is periodic in nature and has amplitude of 10 to 100 times compared to the EEG amplitude and can be easily removed using subtraction methods [5]. The artifact that has dynamic impact on the EEG data that can hinder the correct assessment is the Ballistocardiogram (BCG) artifact indicated as $Artifact_{BCG}$. In the first publication on concurrent EEG-MRI acquisition by [6], the BCG artifact was already reported. Its influence on the amplitudes of EEG is up to 200μV at 3T and on the range of 0.5-13 Hz in frequency domain [7]. The periodic occurrence of the BCG artifact after every heart-beat is considered as its key characteristic.

Several methods have been proposed in the literature to remove the BCG artifacts: subtraction method [8], blind source separation (BSS) such as principal component analysis (PCA) [9] and independent component analysis (ICA) [10] and others like [11,12]. Despite several existing methods, the residuals of the BCG artifact are left behind [13]. The main limitations of above mentioned methods are: dependency over a reference (ECG) signal, stability assumption in temporal BCG waveforms, and selecting the number of components that represents the BCG artifact in BSS methods. Finding a suitable method that can reduce the BCG artifact from all types of dataset of EEG is still an ongoing issue [7]. The aim of this paper is to present a reference-free reduction method to extract the BCG artifact and to qualitatively assess the reconstructed artifact-free EEG data.

The structure of the paper is as it follows. Section II provides insight to the datasets used as well as the working phenomenon of proposed algorithm along with mathematical illustration. The results are presented in the section III and their discussion is in section IV. Section V concludes the work done in this study.

2 Data and Methods

2.1 EEG and fMRI Acquisition

The compatible EEG cap with the magnetic field (128-channel HydroCel Geodesic Sensor Net [14]) was used to acquire the EEG data. Two normal subjects participated in this study. They had no history of brain diseases and are normal or corrected to normal vision. The informed consent form was given prior to the experimentation and was signed. The study was approved by local ethics committee of Universiti Teknologi Petronas (UTP), Malaysia and was conducted according to the given guidelines. Two types of datasets were recorded. In the first, the subjects were instructed to stay relaxed and keep their eyes closed, while in the second, an oddball paradigm of two stimuli was presented on a magnetic-compatible projector [15]. Stimuli were divided into target stimuli (10% of the content) and standard stimuli (40% of the content). For the remaining 50% of the content, a fixation symbol appeared between every stimulus. The subjects were instructed to press a button when they saw the target stimulus and do nothing when they saw a standard stimulus. The fMRI scanner used for simultaneous EEG-fMRI acquisition has the magnetic field of 3.0 T. T2*-weighted echo planar imaging (EPI) sequence was used for the acquisitions. In addition, the same tasks have been repeated outside the fMRI scanner and were considered as EEG datasets at 0 T.

2.2 Pre-Processing and Data Analysis

The contaminations of gradient artifact and ocular artifacts (when eyes were not closed) were removed in the pre-processing. To remove the gradient artifact, EGI's Net Station 4.5 EEG software was used with default settings in which Average Artifact Subtraction (AAS) is implemented. Then, the data was filtered using bandpass filter of 0.3-40 Hz and exported to Matlab. The scalp regions used in this study for analysis are: Frontal (F): (19, 4, 24, 124, 27, 123, 33, 122, 32, 1 and 11), Central (C): (30, 105, 36, 104, 41 and 103), Temporal (T): (45, 108, 44, 114, 108, 34, 116, 38 and 121), Occipital (O): (70, 83 and 75), and Parieto-Occipital (PO): (67, 77, 65 and 90). The division of electrodes into the regions was based on 10/10 international system of electrode placement.

2.3 Methods

A reference-free hybrid method EMD-PCA is presented in this paper. In this method, Empirical Mode Decomposition (EMD) is used to decompose the BCG contaminated signal into set of components named Intrinsic Mode Functions (IMFs). The IMFs have different frequency with varying amplitudes [16]. The process to compute the IMFs is known as sifting process. The advantages of using the EMD are: it is adaptive to temporal changes in the original signal, and unlike other decomposition methods, it does not require prior information about the sources mixed in the signal [16]. The PCA is applied then to decompose the correlated set of signals into linearly uncorrelated components i.e. Principal components (PCs) [9]. The components are generally arranged in descending order with respect to the computed variances. The procedure of extracting BCG artifact using the proposed method is as follows:

1. Extract the first four frequency bands using band pass filter (the range 0.3-25 Hz is the typical BCG frequency range [10]).
2. Select first frequency band
3. Decompose the contaminated signal into different components of variable frequency and amplitude called as IMF.
4. Compute the PCs by implementing the PCA over set of IMFs.
5. Calculate the similarity index of each PC with the contaminated signal.
6. From all PCs, select the PC which has maximum similarity index (computed in step 5) as the BCG related component.
7. Repeat the steps 3 to 6 for all bands.

8. Add all the extracted BCG related components to get the BCG template.
9. Subtract the extracted template from the contaminated data to get the artifact free EEG.

The mathematical illustration of proposed method is as follows:

Let E_j, j $= 1, 2, 3, \dots, $n be the band of the contaminated EEG data of sample n. $I = [I_{i,j}]$ of dimension N × n is the decomposed matrix of IMFs, where N is the total number of IMFs. The residual left behind after the EMD decomposition, symbolized by r is a row vector i.e.

$$r = [r_1, r_2, r_3, \dots, r_n]$$

The decomposed contaminated data into IMFs and the residue can be recovered using following equation

$$E_i = \left(\sum_{i=1}^{N} I_{i,j}\right) + r_j, j = 1, 2, 3, \dots, n \quad (2)$$

For further analysis, the set of IMFs and residual were arranged in a matrix form

$$C = \begin{bmatrix} I \\ r \end{bmatrix}$$

where C has $M = N+1$ rows and n columns. The PCA method is then implemented on the matrix C, in which Eigen decomposition is used to compute the eigenvalues and eigenvectors of the covariance matrix of C. Then C can be denoted as

$$C = [V^T][PC]$$

where V^T is the transpose of the matrix of eigenvalues; PC is the matrix containing the eigenvectors. The uncorrelated components or projected signals can be obtained by matrix multiplication of PC with C i.e.

$$S = [PC][C]$$

From the set of uncorrelated components S, one component is selected as a BCG related component i.e. the component that has the maximum similarity index with the contaminated data. Hence, from four bands, a total of four such components were extracted and summed to get the BCG artifact template. Then the extracted BCG template was subtracted from the contaminated data to get the artifact-free EEG data.

$$EEG_{artifact-free} = Contaminated\_data - Extracted\ BCG \quad (3)$$

In addition to the proposed method, three existing methods; Average Artifact Subtraction (AAS) [8], Optimal Basis Set (OBS) [9] and Statistical Feature Extraction for artifact removal (SFE) [17], have been implemented. The implementation of AAS and OBS is done using open source *EEGLAB 10.2.2.4b* toolbox plugin named *FMRIB1.21* and SFE using the *MATLAB* code, provided by the authors at *http://www.amri.ninds.nih.gov/software.html*. The comparison with these implemented methods will help in providing the practical significance of the proposed method.

3 Results

The results of the evaluated parameters after reducing the BCG artifact via proposed method, AAS, OBS and SFE have been presented in this section. In this study, the reconstructed EEG datasets (eyes closed and ERP) has been assessed using the qualitative parameters. The qualitative measures help in the evaluation of original brain activities preserved while reducing the BCG artifact. The parameters are: power spectrum, sample entropy and extraction of ERP. Power spectrum and sample entropy are measured using eye closed dataset, while ERP is extracted from dataset of oddball paradigm.

The power spectrum of eyes closed data has been calculated using Fast Fourier Transform (FFT) in which the welch window of 500 samples with an overlap of 50% and 1024 points are used. Since, the alpha power increases in eyes closed data [18], this parameter is used to analyse whether the power of alpha band is preserved while reducing BCG artifact or not. Two scalp regions have been analysed where the alpha waves are dominant than the other scalp regions which are Occipital and Parieto-occipital region. Figure 1 presents the power spectrum of two subjects.

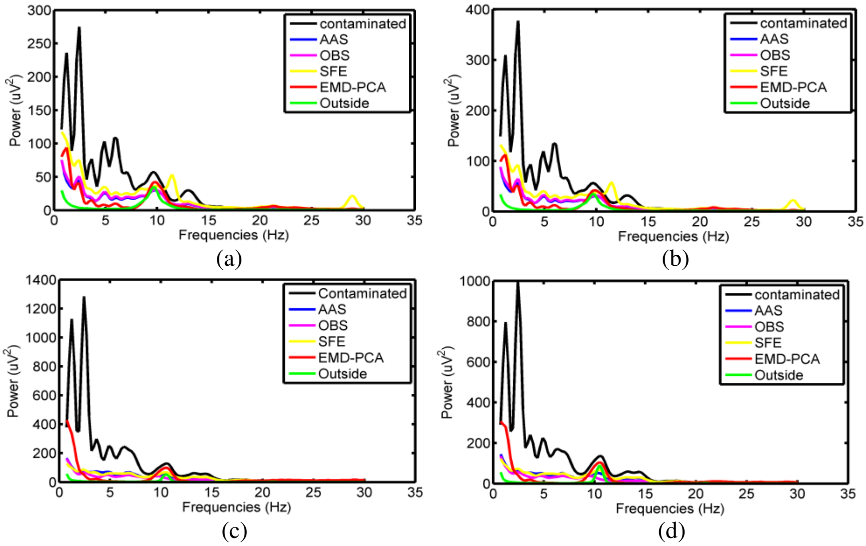

Fig. 1. Power spectrum of two subjects: (a) Occipital region, (b) Parieto-occipital of subject 1 and similarly (b), (d) of subject 2, using contaminated data, reconstructed data via four methods (including proposed method) and dataset recorded outside the scanner

Another way to evaluate the quality of the reconstructed eye closed data i.e. alpha rhythm is to measure the complexity or randomness in the signals [18]. The sample entropy (SE) appears to be a more influential tool to measure the variations in the data and is computed by

$$SE = -\ln\left(\frac{P^{n+1}(r)}{P^{n}(r)}\right) \quad (4)$$

where, n is the number of samples and in this study it is equal to 500 (2 seconds), threshold is denoted by r i.e. 2*σ, where, σ is the standard deviation of the sequence. Pn(r) and Pn+1(r) are the probabilities that m and m+1 sample are same respectively. The SE is calculated using 1 minute data from reconstructed and outside the scanner datasets. The average SE of two subjects has been presented in Fig. 2.

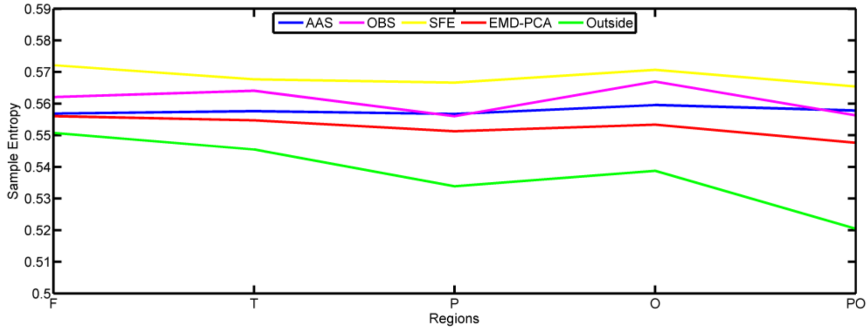

Fig. 2. Sample Entropy of reconstructed datasets via AAS (Blue), OBS (Magenta), SFE (Yellow), EMD-PCA (Red) and outside the scanner data (Green) at five scalp regions

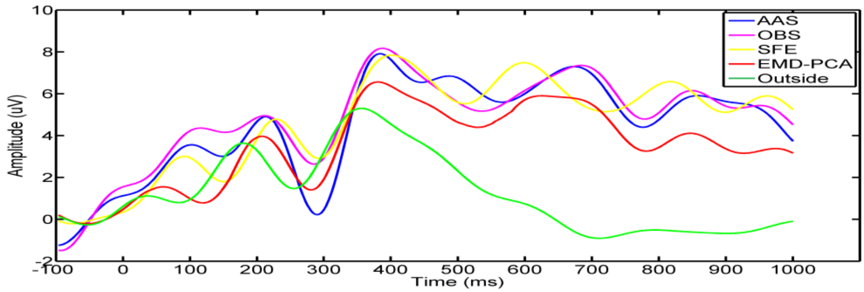

Fig. 3. The ERP waveform extracted from reconstructed datasets (AAS in blue, OBS in magenta, SFE in yellow and EMDPCA in red) and data outside the scanner in green color

The extraction of Event-Related Potential (ERP) is a well-known and widely used parameter in the existing studies to assess the quality of the reconstructed data. The ERP in which P300 has been analyzed at electrode Pz is presented in Fig. 3. The ERP is extracted after averaging 60 trials of target stimuli and then the average of both subjects using reconstructed and outside the scanner datasets. Table 1. describes the parameters (Latency and SNR) to compare the extraction of P300 among the methods.

Table 1. The latency and signal to noise ratio (SNR) of P300

Methods / Parameters	AAS	OBS	SFE	EMDPCA	OS
Latency (ms)	384	388	400	380	356
SNR (dB)	9.67	8.64	16.37	15.14	13.17

4 Discussion

The capability of the proposed method in preserving the brain signal after reduction of the BCG artifact has been evaluated using three qualitative parameters. First, the power spectrum in Fig. 1 shows that the method reduces the BCG influence effectively while alpha waves are not attenuated. The comparison with AAS, OBS and SFE describes that the proposed method is more capable of preserving the alpha rhythm. Secondly, the SE evaluation in Fig. 2 shows that the reconstructed dataset has the closer SE values to the outside the scanner data, compared to the other methods. The pattern of variations in SE values of proposed method is also similar to the outside the scanner data i.e. the complexity in the frontal region is more compared to the Parieto-occipital region.

The ERP database is used to extract the P300 peak from electrode Pz. Fig. 3 shows that ERP can be extracted from all the reconstructed datasets. However, to further investigate the difference between extracted ERP waveforms, latency (the time difference between stimulus onset and P300 peak) and SNR were computed. From Table 1, it can be seen that the latency of ERP extracted from the dataset reconstructed via EMDPCA has less delay compared to others and is closer to the latency of outside the scanner data. However, SFE method has a little high SNR than the proposed method.

5 Conclusion and Future Work

In this research article, the BCG artifact which contaminates EEG data recorded inside the fMRI scanner has been reduced using the proposed reference-free reduction method. The quality of the reconstructed data evaluated in the results shows that the method efficiently reduces the BCG artifact while preserving the brain activities. The method is also compared to the existing studies and the results show that the reduction of BCG has been improved. In addition, the prior information about the data or any reference signal is not required for the extraction of the BCG artifact. The method will be further tested on a large datasets to provide the significant improvement in the utilization of simultaneous EEG and fMRI.

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