Comparative Study of Different Pulse Artifact Correction Techniques during Concurrent EEG-FMRI using FMRIB

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Abstract *–In this work, a comparative study of three pulse artifact (PA) correction methods –optimal basis set (OBS), simple mean (AAS) and Gaussian-weighted mean (GWM) – along with standard parameters setting for both gradient artefact (GA) and pulse artefact (PA) correction, using open source Functional MRI of Brain (FMRIB) tool-box, in combined EEG-fMRI, is reported. It has been found that, of these three methods, OBS is better in preserving bio-signal while removing PA successfully.*

Keywords *–Electroencephalography, functional magnetic resonance imaging, gradient artifact, pulse artifact and optimal basis set.*

INTRODUCTION

Simultaneous EEG-fMRI is one of potential and popular non-invasive tools for exploring brain function as well as diseases. However, the most challenging part of this arena is to remove two prominent artifacts namely - gradient artifact (GA), caused by switching of waveforms applied to the gradient coils used in MR acquisition, and pulse artifact (PA), due to pulsate motion of blood circulation [1]. GA must be minimized before PA correction, as its magnitude is much greater (~ several mV) than EEG signal (microvolt). The most efficient method for GA correction is fMRI artifact slice template removal (FASTR) [2], because it offers a feature for removal of residual artifacts based on an optimal basis set using principal component analysis (PCA) and is superior to average artifact subtraction (AAS) method, proposed by Allen *et al.* [3].

The pulse artifact, which varies for subjects to subject [4]as well as in cardiac cycles for an individual subject [5], has a linkage with cardiac cycle. In comparison with GA, it is not easily understood and predictability is significantly little in nature. However, as PA has a periodic nature, thus is susceptible to correction via AAS. However, the efficacy is reduced because of artifact variation across cardiac cycles, which could be obtained in correction of PA via AAS. The number of this cycle is small, and is being averaged to formulate artifact template, thus results in PA variation. In procedure of correction, there may be an attenuation of neuronal signal with significant information, if very few cycles are considered in the process of averaging. Therefore, in correction of PA via AAS, compromising is done by using a template of sliding window and considering cardiac cycle repetitions of around ten repetitions [1]. Methods using separation of blind source are being focused due to the limitations in correction methods of PA via AAS. Independent component analysis (ICA) [6,7]and optimal basis sets (OBS) [2, 5], are examples of such methods. Although some reports ICA for PA correction [6,8], others have shown less positive results using ICA [5]. A probable reason for this inefficacy is the diverse field strengths of the scanner used during scanning.

In summary, the spatial filtering approaches for PA correction developed until to-date such as ICA and PCA may not be as efficient as template methods. However, due to the wide variety of post processing methods for PA artifact corrections whose are being used, the comparison of techniques was not yet studied.

OBJECTIVES OF THE STUDY

In this work, different PA correction methods - optimal basis set (OBS), simple mean (AAS) and Gaussian-weighted mean (GWM) - implemented in FMRIB toolbox [2] were compared to evaluate their performance in artifact correction while retaining the neuronal information. AAS is the most popular software based GA correction approach accepted by EEG-fMRI research community however, there is no benchmark comparative study to identify the best PA correction approach. This study will guide anyone to choose the right PA correction algorithm. Therefore, this work is significantly important to the EEG-fMRI research community whoever using the FMRIB toolbox for correcting and analyzing EEG data.

MATERIALS AND METHODS

System PLUS EEG system and an SD32 MRI amplifier (Micromed S.R.I., TV, Italy) were used in this work to record EEG and electrocardiograph (ECG) data. DC coupling was removed by a 10K current limiting resistor connected to each electrode, and high pass filters of 0.15Hz, 40dB/decade. Moreover, low pass filters of 600 Hz, 20dB/decade, were utilized to protect against radio frequency noise. All EEG components, i.e. amplifiers, sigma delta ADC were placed in the scanner room, and optical fiber was used to transmit data to acquisition computer, separated from scanner room. 21 axial slices per volume for TR = 3s, standard axial multi slice EPI, MR data were collected using a 3-T Varian Inova scanner (Palo Alto, CA).

Experiment was carried out on healthy human subjects with the consent of local ethic committee. 32electrodes attached to a EEG cap was placed over the subject's head, and according to 10/20 system, two electrodes (O1 & O2) were over visual cortex, and the reference channel was FCz. The clock of EEG amplifier and MR scanner were synchronized so that artifact template can be reproducible which is necessary for improved artifact reduction. EEG and ECG data were recorded inside the MR scanner while the subject was asked to open and close his eyes in periods of 10 seconds during the execution of multi-slice EPI sequence. The data were sampled at 2048 Hz, more than twice the highest frequency of GA [3]. Forty fMRI volumes were collected with total scanning period of 2 minutes. In EEG data, each slice was marked by 'slice' marker to be used to segment the data to produce artifact template.

ANALYSIS

EEG data have been analyzed in EEGLAB v.11.0.4.3b [9], a MATLAB (The Math Works, Inc.) based open source software for biomedical data analysis, along with its plug-in 'FMRIB' [2]. The raw EEG data were exported to do further analysis in EEGLAB and MATLAB. GA was visible while scrolling the raw data in EEGLAB. All the analysis was done on 30 channels excluding EoG and ECG channel, which were not carrying brain signals. The EEG data were first cleaned for GA correction using FASTR [2]. The principle of this method is well described in his paper. Here we only mention the parameters setting for best optimization-low pass filtering of cut-off- 100 Hz, interpolation- 10 folds, trade off window size- 30, PCs 4 and adaptive noise cancellation (ANC). Finally, the data have been down sampled to 256 Hz to save memory and notch filtering was carried out at line frequency.

GA corrected EEG data were then PA corrected using the methods available in FMRIB tool. This tool identifies QRS complexes locations of ECG data and then recorded the QRS events as 'qrs' marker on the data set which can be used for making artifact template. PA artifact was removed separately by the previously mentioned three methods. In simple mean and GWM methods, no user-input is required other than the 'qrs' marker; however, the number of PC has to find out in OBS method. In simple mean, averages of successive PA around a contaminated data segment were taken and then subtract the result from the data, which is consequently implementing AAS. However, in GWM the artifacts were averaged after multiplying by a Gaussian window weights to emphasis the current artifact shape and reduce the effect of artifacts further. In OBS, PCA on a matrix of all the pulse artifacts in a channel was calculated, then take the first N PCs to form an optimal basis set describing the variations in the artifact. The OBS was then fitted and subtracted from each artifact. In this work, the default value of PC (4) has been used. Fast Fourier transforms (FFTs) were carried out for raw, GA and PA corrected data to verify the findings in frequency domain. The performance of PA methods was evaluated by comparing both time and frequency domain representation of PA corrected data for both eyes open and eyes close data epochs in the O1 channel, associated with visual sensitivity. This was done by a comparing the PA correction through evaluating power of alpha wave of O1 after PA correction using the three correction methods. For further quantification, the mean root mean square (RMS) values over time for all channels were calculated using MATLAB and artifact attenuation, (20*log10 (correction/raw) dB)of the clean data were also calculated for each methods

RESULTS AND DISCUSSION

Figure 1 shows a segment of the raw and GA corrected EEG data using FASTR method. The signal quality of raw data when there is no artifact correction has been performed is completely obscured by different artifacts and it is not possible to extract any neuronal activity from any of the channels. However, same data shows that after GA correction, magnitude of the EEG signal greatly reduced for each channel making it possible to be used for further processing. The PAs were revealed if checked carefully in some of the channels (i.e. O1, O2 etc.) once the high frequency GA has been removed using FASTR, a popular post-processing method. It is also obvious that the magnitude of PA is small compared to GA at lower frequency ensuring the linked of this artifact to the cardiac cycle. Although alpha oscillation can be found on the above-mentioned channels but in crucial case, still any decision on neuronal signals could be error prone. In Figure 2 reveals a comparison of the EEG data quality that was achieved after both GA, PA correction using FMRIB toolbox. PA was corrected using OBS, AAS & GWM after detecting the QRS complex of ECG trace. It is clear from the figure that the amplitude of the remaining signals is much smaller, and therefore, neuronal signals are no longer obscured. Figure 2 also shows that alpha oscillation starts at 40th second on different channels (e.g., O1, O2, P3, Pz, P4, PO3 and PO4 etc.). Figure 3, FFTs of the raw, GA and PA corrected (OBS), shows GA in the raw data occurs at distinct frequencies which were harmonics of the frequency of slice acquisition in the fMRI sequence, extending the entire frequency range of the recording, whereas the PA has a lower frequency (mainly below 10 Hz) than the GA as it is linked to the cardiac activity. So FMRIB tool effectively removes artifact from the raw data to make it easier to extract biological information (shown in in-set of Figure 3), and the low frequency variability in the EEG data has been greatly reduced after GA correction. To investigate the performance difference between different PA techniques, a time series of 10 sec. segment of EEG data containing eyes open and close for channel O1 and O2 using three methods were plotted in Figure 4. It can be visualized from the figure that all three methods are doing well in preserving alpha signal while the subject has closed his eyes however, OBS preserves the signal shape better than other two methods; i.e., preserves the brain signal more accurately than other two methods. Figure 5A clearly reveals the fact of preserving brain signal in frequency domain (8-13Hz alpha band) while reducing artifacts in channel O1 and Figure 5B shows no trace of alpha while the eyes were opened. However, in both the case OBS was shown to attenuate residual artifacts more than other two methods. To test the effectiveness of the different PA correction methods, a quantitative measurement was also done using MATLAB for the raw, GA and PA corrected data. The mean RMS values over 30 channels were calculated using MATLAB and the corresponding attenuation for three methods with respect to raw RMS were also calculated. Mean attenuation for GA, and AAS, GWM and OBS PA corrected data were 29.56, 29.91, 29.90 and 29.96 dB respectively. This clearly reveals that OBS outperforms over AAS and GWM in correcting PA.

CONCLUSION AND RECOMMENDATION

The comparison of different types of PA correction methods (OBS, AAS and GWM) with standard parameters setting for both GA and PA correction using FMRIB is studied here. Among them, OBS is recommended for PA removal, as it is better in preserving bio-signal while removing PA successfully. The outcomes mentioned here will help to explicate important queries in combined EEG-fMRI research. This study compares the algorithms implemented in the FMRIB toolbox only; however, in this comparison if we could add other popular algorithms like ICA, OBS-ICA and some hardware approaches (e.g., optical tracker or motion sensor and reference layer); it would be a complete reference work the researchers in this field. Comparison of OBS with the other types of algorithm based PA correction techniques and hardware approaches will be studied in future work.

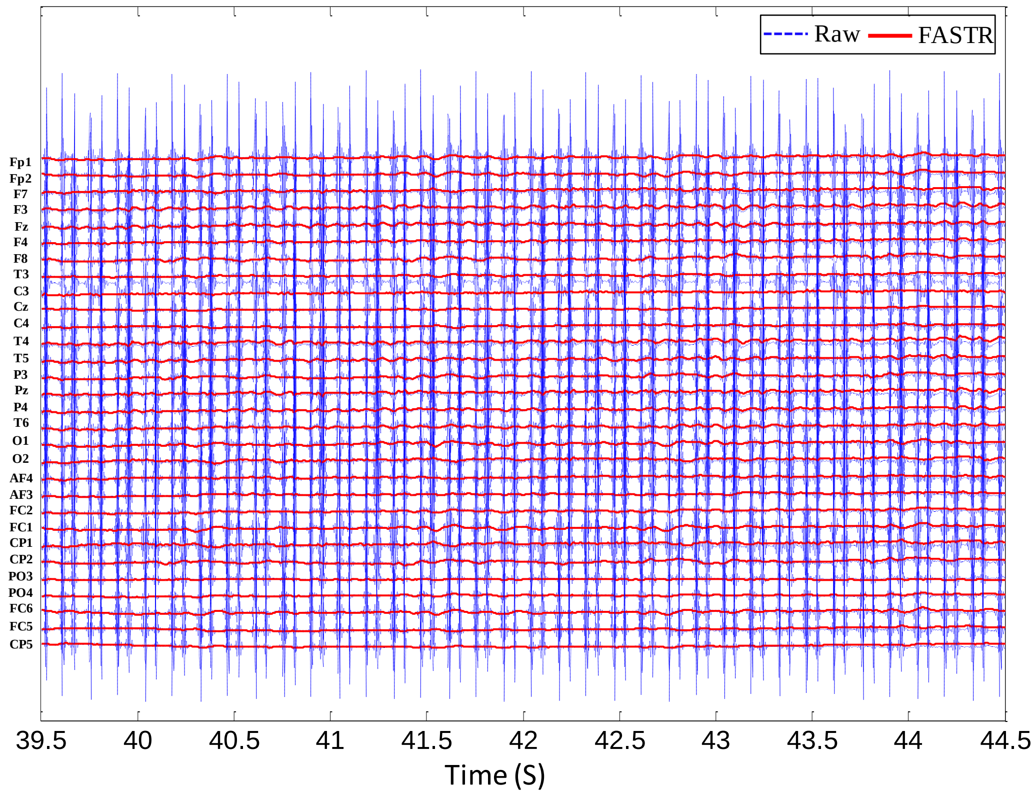

Fig. 1.A five seconds epoch of raw EEG data (dotted blue line) and GA corrected EEG data using FASTR method (red line) were shown which was recorded during concurrent fMRI.

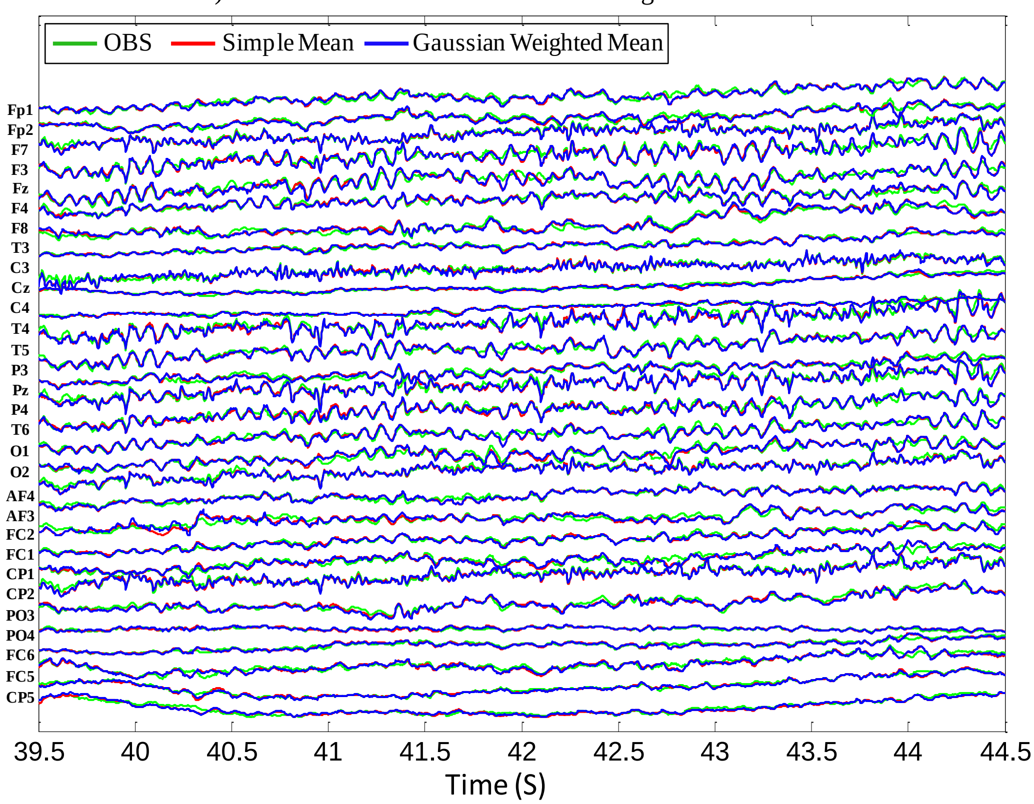

Fig. 2. A five seconds epoch of PA corrected EEG data were shown and PA correction was carried out using OBS (green), Simple Mean (red) and Gaussian-weighted Mean (Blue) respectively.

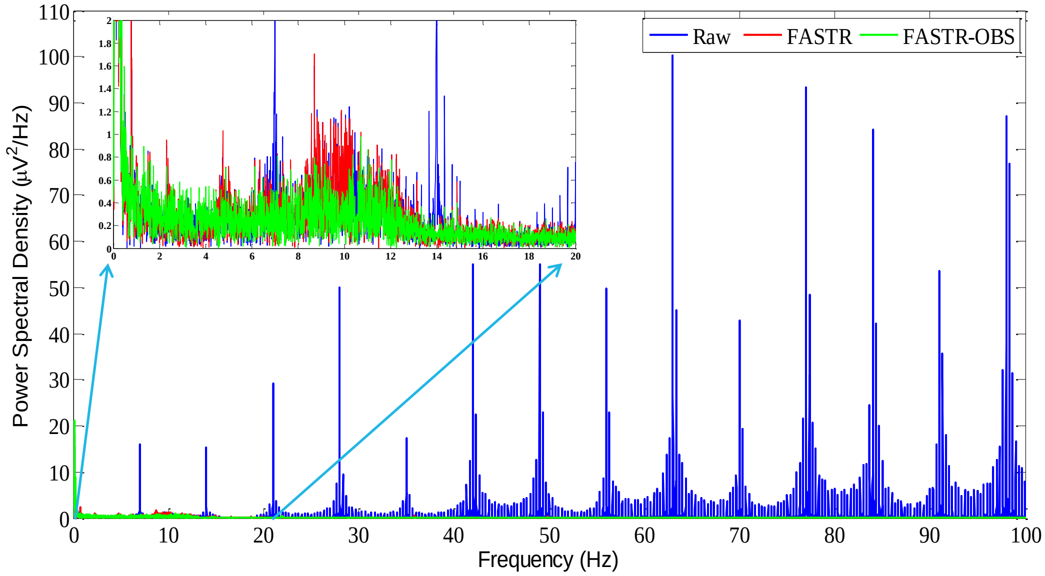

Fig. 3. Power spectral density was shown for raw (blue), GA (red) and PA (green) corrected data for the channel O1. In-set was showing the performance of artifact correction at low frequency.

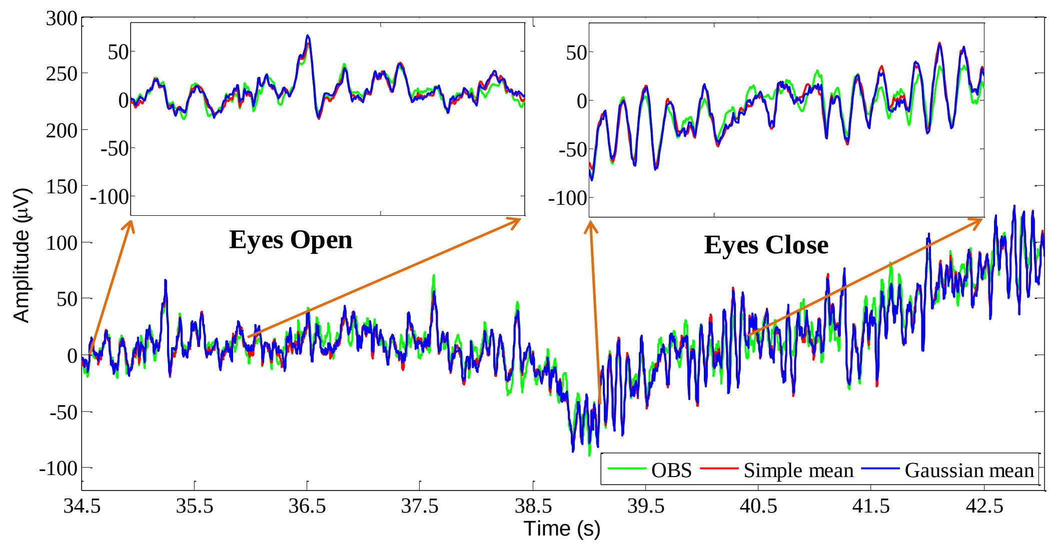

Fig. 4. Performance comparison of three methods in preserving brain signal was shown for channel O1 while data were recorded with subject has opened and closed his eyes

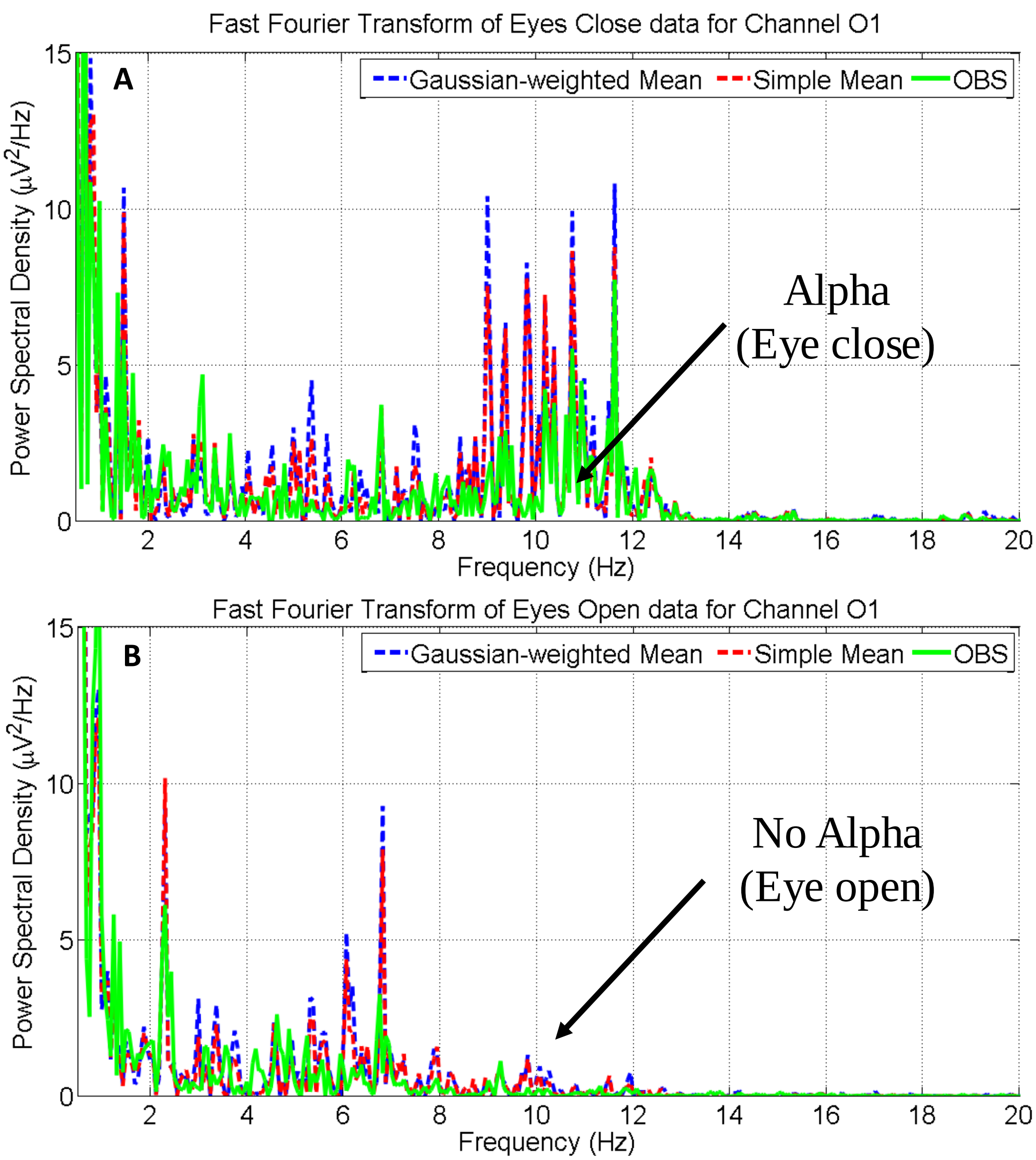

Fig. 5. FFT of the 10 seconds segmented data for eyes close (A) and eyes open (B) for channel O1 to show the comparison between the three correction methods.

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