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A Method to remove MRI Artifact from Continuous EEG based on the combination of FASTR and ARX

ZhenYu Wang, Peng Xu*, TieJun Liu, Xu Lei, Dezhong Yao*

Key Laboratory for NeuroInformation of Ministry of Education, School of Life Science and Technology, University of Electronic Science and Technology of China(UESTC), Chengdu, 610054, CHINA

E-mail: xupeng@uestc.edu.cn; dyao@uestc.edu.cn

Abstract: When electroencephalographic (EEG) and functional Magnetic Resonance Imaging (fMRI) are simultaneously recorded, the gradient artifacts coming from the MRI scanner will seriously distort the EEG data. It is necessary to recover EEG from the gradient artifacts contaminated recordings. FMRI Artifact Slice Template Removal (FASTR) has been proved to be an effective method to correct the gradient artifacts. However, the main limitation of the FASTR based approach is it may less or over remove the useful EEG information. To deal with this limitation of FASTR based approach, a new approach combining FASTR and Auto-Regressive eXogenous (ARX) is proposed for a more robust correction of the kind of artifact. In the proposed procedure, for each channel, the ARX is used to build the multi-models based on the preliminary FASTR results, and an optimal model is selected from those multi-models for further artifact removal. The application of the proposed approach to an EEG dataset contaminated by strong gradient artifacts proved its effectiveness for MRI artifacts removal.

***Keywords**:* Simultaneous EEG/fMRI; Gradient artifacts; FASTR; ARX

1. Introduction

Simultaneous use of electroencephalographic (EEG) and functional Magnetic Resonance Imaging (fMRI) has been actively developed over the last years. Recording EEG during fMRI (EEG/ fMRI) holds great promise for examining the spatial and temporal dynamics of brain processes [Gotman et al. , 2004; Hamandi et al. , 2004; Salek-Haddadi et al. , 2003]. However, when these two signals are simultaneously recorded, EEG will be seriously contaminated by the gradient artifacts of MRI scanner, where the amplitude of gradient artifacts is usually of a larger order compared to EEG. Without any correction, it is usually not possible to use EEG recordings for further analysis.

Several approaches have been proposed to remove this kind of artifact. The Average Artifact Subtraction (AAS) proposed in [Allen et al. , 2000] is the most widely used method for the removal of the gradient artifacts. The process can be viewed as taking the projection of each epoch onto the space spanned by the average artifact template and subtracting this component from the raw EEG data. An Adaptive Noise Cancellation (ANC) procedure is then used to remove any further residual artifacts. While the method was shown to be adequate in lower frequency, and the average artifact template alone may not account for temporal variations in the gradient artifacts. Independent Component Analysis (ICA) [Grouiller et al. , 2007; Srivastava et al. , 2005] is also used to remove EEG artifacts in simultaneous EEG/fMRI recordings. This appears a prior as a valid approach to separate EEG and gradient artifacts because these signals are generated by different processes. The limitations of ICA for EEG data acquired in the MRI scanner are that, one is its intrinsic difficulty in processing recordings containing high-power disturbance, and the other is the neural signals are highly non-stationary.

In this paper, a new approach combining FMRI Artifact Slice Template Removal (FASTR) [Negishi et al. , 2004; Niazy et al. , 2005] and Auto-Regressive eXogenous (ARX) [Ljung, 1999] is proposed for robust removal of gradient artifacts. In essence, FASTR is a variation of AAS. In FASTR, a unique artifact template for each slice artifact in each EEG channel is constructed and then subtracted. Each slice template is constructed as the local moving average plus a linear combination of basis functions that describe the variation of residuals. The basis functions are derived by performing temporal Principal Component Analysis (PCA) on the artifact residuals and selecting the dominant components to serve as a basis set. However, the main limitation of FMRI is that not only artifacts but some useful EEG activity may be subtracted, and vise verse. In order to lower this limitation of FASTR, a more robust correction of the kind of artifact is necessary to be implemented. In this paper, the ARX is selected for further artifact removal based on the FASTR results. In the proposed approach, for each channel, the ARX builds the multi-models based on the dynamic relationships between the other channels, and then an optimal model is selected to correct the possible bias introduced by FASTR.

2. Material and Methods

2.1 FMRI Artifact Slice Template Removal (FASTR)

FMRI Artifact Slice Template Removal (FASTR) algorithm was proposed in [Niazy et al. , 2005]. FASTR decomposes the spatio-temporal EEG recordings into orthogonal temporal components, whose number is equal to the EEG channels. Since the gradient artifacts are uncorrelated with neuronal activity and of much higher amplitude, they are usually captured in the very first PCA components.

The FASTR algorithm can be implemented with the below four steps: (i) the realignment following interpolation and slice-timing; (ii) subtraction of local artifact templates; (iii) gradient residual artifacts removal using optimal basis sets; (iv) adaptive noise cancellation.

2.2 Auto-Regressive eXogenous (ARX)

However, for the FASTR based approach, the performance to remove gradient artifacts is largely dependent on how much degree of the average artifact templates contributes to the artifacts and signals, which may lead to lose useful EEG information or remove the gradient artifacts incompletely. If there exists a period before the simultaneous EEG and fMRI recording that only EEG is recorded, the EEG recordings in this period could be used as the reference to correct the FASTR results for a more reliable EEG recover. This protocol is feasible and easy to be implemented in the simultaneous EEG and fMRI recording experiment. Derived from this point, we proposed to use the Auto-Regressive eXogenous (ARX) to perform the correction operation.

ARX [Ljung, 1999] utilizes input-output data to determinate the model structure and parameters by the Least Squares (LS). ARX model uses the previous inputs and predicted outputs as the new inputs, and then the predicted outputs can have an filtering effect on the input signals because of it considers the previous inputs. The ARX model can be represented by the following equation,

$$y(t) + a_1 y(t-1) + \cdots + a_{n_a} y(t-n_a) = b_1 u(t-1) + \cdots + b_{n_b} u(t-n_b) + e(t) \tag{1}$$

where $y(t)$ is the Output at time t, and $u(t)$ is the input at time t, and n_a is the number of poles, and n_b is the number of zeroes plus 1, and $e(t)$ demonstrates the white-noise disturbance value. The parameters $a_k (1 \le k \le n)$ and $b_k (1 \le k \le n)$ are the parameters to be estimated. The detail for solving equation (1) could refer to [Ljung, 1999].

As mentioned above, the artifacts always may be less or over subtracted in FASTR procedure, and we will use the following procedure to further correct the FASTR results for a more reliable EEG recover. To perform the correction, we assume that the dataset is recorded as the protocol that EEG is solely recorded before the simultaneous recording of EEG and fMRI. The pure EEG is used as the reference for ARX based correction. During the correction procedure, for each channel, after the multi-models based on the dynamic relationships between the other EEG channels and current channel are built using the FASTR results as input and the corresponding reference as output, the optimal model is selected according to the maximal correlation coefficients (CC) between the reference signal of current channel and the ARX output. Finally, based on the selected optimal ARX model, the preliminary FASTR results is fed into the model for EEG correction.

2.3 EEG/fMRI dataset and pre-processing

We use the EEG/fMRI dataset in EEGLAB (http://www.sccn.ucsd.edu./eeglab/ , Salk Institute, La Jolla, CA) provided by the University of Oxford Centre for Function MRI of the Brain FMRIB for evaluation. EEG data were recorded using the SystemPLUS EEG system and an SD32 MRI amplifier, and fMRI was performed using a 3-T Varian Inova scanner. Excitation (slice-timing) triggers from the MRI machine were recorded in the EEG data. In recording, EEG was approximately recorded for 29 seconds before EEG and fMRI were simultaneously recorded, and the interval of EEG recordings was used as the reference for EEG correction. In the recording time, the first 30 common reference EEG channels were used for EEG and two bipolar channels were used to record electromyogram (EMG) and electrocardiograph (ECG). In this paper, the last two channels were rejected for further analysis. The details about the data acquisition could refer to [Niazy et al. , 2005]. After the FASTR, a low-pass filter with cut-off frequency 70 Hz was used to filter Gaussian distribution, and recordings were down sampled to 256 Hz for the efficiency of data storage, memory usage and ARX-based correction.

3. Results

We used the FASTR procedure in EEGLAB (http://www.sccn.ucsd.edu./eeglab/ , Salk Institute, La Jolla, CA) provided by the University of Oxford Centre for FMRIB with the following parameters: low-pass filter cut-off frequency = 70 Hz, averaging window length = 30, up-sampling frequency = 10 kHz and a notch filter ranges from 45 to 55 Hz to remove the any line noise.

As shown in Fig. 1 (a), the effect of fMRI on EEG recordings is very obvious, where EEG is totally contaminated by MRI artifacts. After the application of FASTR, Fig. 1 (b) shows that the gradient artifacts were removed effectively. Fig. 1(c) shows the results when ARX based approach is used for the further artifacts removal. Visually, both FASTR and ARX based approach could effectively eliminate the MRI artifacts.

Fig. 2 reveals the details of one channel when ARX correction is used. The zoom window shows that the ARX correction could actually improve the quality of recovered EEG data, where ARX correction achieves the more consistent result with a smaller relative error (RE) 0.04 compared to the preliminary FASTR result with RE 0.15.

After MRI artifacts are removed for the 30 EEG channels, the 1001-datapoint interval from 19.5-sec to 23.5-sec were selected to calculate the relative error (RE) using the pure EEG as references for both FMRIB and ARX based approaches, respectively. The average and standard deviation (STD) of RE for these two approaches are listed in Table 1. The paired t-test is performed with the null hypothesis that the REs of these two approaches are same. The statistical test results in $p<0.01$ indicating that ARX correction has significant effect on the artifact removal.

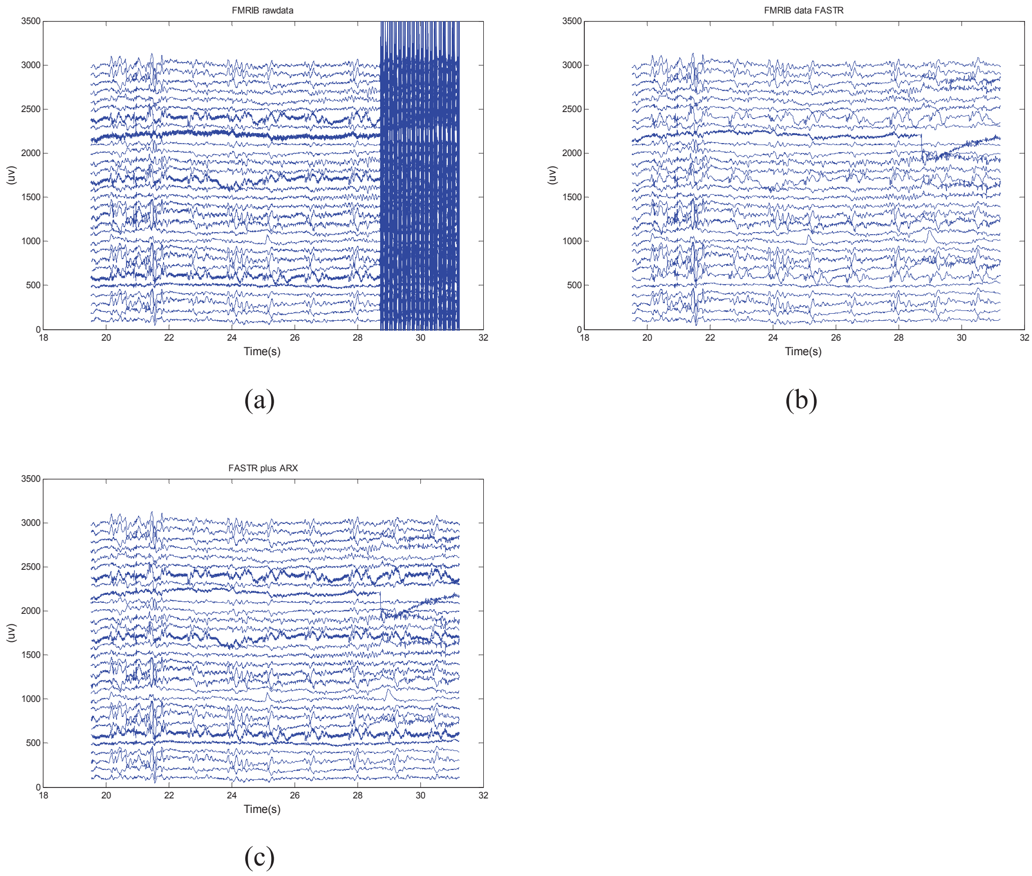

Figure. 1 *The procedure for MRI gradient artifact removal. (a) Gradient artifact in EEG data. The effect of fMRI on EEG data. Noting the high amplitude noise at approximately 29-sec after scanning begins; (b) FASTR results. (c) ARX correction results.*

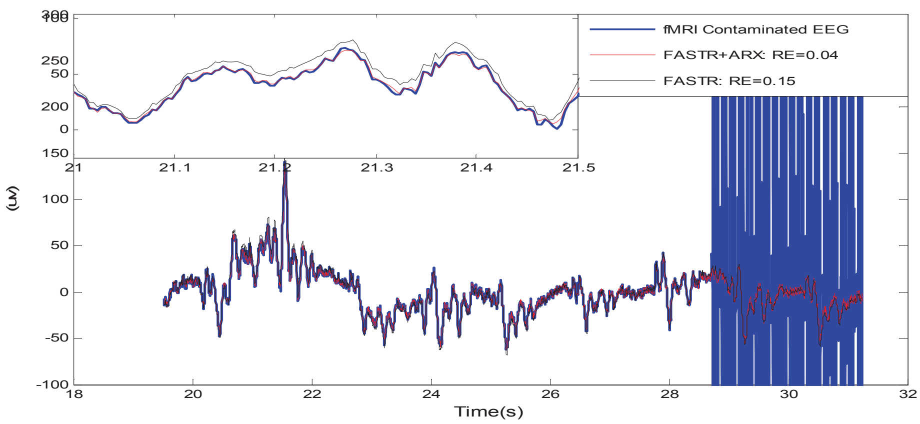

Figure. 2 *The details of one channel when ARX correction is performed. The blue solid line is the gradient artifact contaminated EEG; the red one is the result of ARX correction; and the black one is the FASTR result. The high amplitude noise occurs at approximately 29-sec after scanning commenced. The magnifying box on the upper left-hand corner is the interval from21-sec to 21.5-sec.*

Table 1. *The relative error (RE) of FASTR and ARX based approach*

	ARX	*FASTR*
RE (mean± std)	*0.0799 ± 0.0194***	*0.1784 ± 0.0618*

*** indicates $p<0.01$*

4. Discussion and Conclusions

The present paper proposed a new approach to the EEG/fMRI gradient artifacts correction by combining ARX and FASTR. In essence, FASTR is based on Image Artifact Reduction (IAR) [Allen et al. , 2000] with addition of a PCA decomposition for gradient artifacts removal. However, the performance of FASTR based approach is largely dependent on how much the artifact and signals can be represented in the artifact templates and the PCs, i.e., the useful EEG information may be less or over removed. Using the pure EEGs recorded before the simultaneous EEG and fMRI, ARX could be used to reduce the bias induced by FASTR.

As shown in Fig. 1, both FASTR and ARX based approach can effectively remove the MRI artifacts. The details revealed in Fig. 2 visually proves the effectiveness of ARX correction, and the values in Table 1 further confirm that the ARX correction could improve the MRI artifacts removal in statistical sense with $p<0.01$.

The results reported in this paper are only based on one dataset, and more datasets are needed to evaluate the ARX approach. Compared to other approaches, the ARX correction needs to perform a short period recording of EEG before MRI scanners works, and we think this protocol is easy to be implemented in the simultaneous EEG and fMRI studies.

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