Abstract

Simultaneous recording of electroencephalographic (EEG) and functional Magnetic Resonance Imaging (fMRI) has been a new modality in brain imaging very recently. Blood oxygen level-dependent (BOLD) in fMRI provides sufficient information about the hemodynamics of the brain during changes in the brain metabolism such as in the event of seizure. However, the major drawback of these joint recordings is the destructive effect of the fMRI scanner artifact. Without removal of such artifact the EEG signals cannot be processed. In this paper, an effective method for removal of the scanner artifact has been established by applying blind source extraction (BSE) algorithm followed by the averaging-and-subtraction method. The results have shown that the scanner artifacts have been effectively mitigated.

1. Introduction

With the development of the advanced medical diagnostic techniques, more data recording modalities, such as EEG and fMRI, have been utilized to monitor the small physiological changes in human brain. Although EEG remains as the most commonly used tool in diagnosis of the brain functional abnormalities, the study of simultaneous EEG-fMRI has attracted more attention from both scientific and clinical communities [1] [2] [3]. fMRI provides information about the brain metabolism with a high spatial resolution as reflected by the BOLD effect. It can reveal regional hemodynamic changes with task and stimuli and offers an alternative means of obtaining spatial information. Therefore, fusion of EEG and fMRI will be very beneficial for the localization of the neural sources in some special neuroscience applications. Here the scanner artifact removal is meant to pave the way for our seizure prediction approach from the scalp EEGs [4].

The technical problems of simultaneous EEG-fMRI include the mutual effects on both EEG and fMRI data. Different interferences are induced during the EEG-fMRI acquisition, one of them is the scanner artifact which is caused by the switching magnetic filed gradient used in the scanning process. Various methods to remove these scanner artifacts had been investigated previously, such as in [5] and [6], the methods focused on the eliminations of artifact-specific power spectrum by utilizing fast Fourier transform (FFT) and inverse of it. Some methods tried to improve the recording methods to minimize the scanner effect, such as carefully choosing the image sequence and blank EEG segments during the scan by using a scanner-generated trigger pulse, or modify the timing of the individual gradient switching and RF pulse in the MR acquisition sequence [1] [7]. The conventional artifact removal method, namely averaging-and-subtraction, proposed by Allen [8], which combined the averaging and subtraction followed by noise cancelling. This method could remove the scanner artifact greatly and became the most widely applied method.

An effective approach based on an iterative BSE algorithm has been applied here to highly mitigate the scanner artifact. BSE has been widely used in biomedical signal analysis and processing. The BSE algorithm is based on higher order statistics (HOS) and assumes that the sources are mutually statistically independent. The aim of the algorithm is to find a vector that maximizes the non-Gaussianity of the output signal [9]. The difference between BSE and blind source separation (BSS) is that the BSE algorithm can extract a desired single source from the mixture signals rather than separate all the independent sources at the same time. If more than one source is wanted, the BSE can be repeated to extract those sources one by one. The deflation process after extraction will exclude the sources from the rest of EEGs. In our approach, the artifacts are the sources that we aim to extract from the EEGs. The remaining signals after performing a number of extraction and deflation would be those without scanner artifacts.

In the following sections, the theoretical derivation of the BSE algorithm is introduced firstly. Then we will see how
to select the iteration numbers for the BSE. The method of averaging-and-subtraction is given afterwards. The experimental results of the proposed methods are presented in the final section.

2. Methods

2.1. BSE algorithm

The BSE algorithm proposed here is based on the fact that the scanner artifacts are spike-type signals that always have higher kurtosis than the normal EEGs. Therefore, by maximization of non-Gaussianity of the output signals, the BSE can extract these high kurtosis artifacts.

The problem of BSE algorithm can be mathematically described as in [9], given the \( m \) channel observed data \( x(t) = [x_1(t), x_2(t), ..., x_m(t)]^T \) as a linear and instantaneous mixture of \( n \) underlying sources \( s(t) = [s_1(t), s_2(t), ..., s_n(t)]^T \), mixed by the mixing system \( H \):

\[
x(t) = Hs(t) + n(t)
\]

Then the source \( y \) is estimated by using

\[
y = w^T x
\]

where \( w \) is the unmixing vector needed to be found in a way that maximizes the non-Gaussianity of the output signal \( y \). In our algorithm, \( w \) is initialized as a vector of all one. The cost function to be minimized can be represented as:

\[
J(w) = -\frac{1}{4}|k_s(y)| = -\frac{\beta}{4}k_s(y)
\]

where \( k_s(y) \) is the kurtosis, which measures the flatness (for sub-Gaussian) or peakedness (for super-Gaussian) of a distribution of signals. \( \beta \) is the parameter that determines the sign of the kurtosis of the extracted signal, \( \beta \) will be \(-1\) or \(+1\) when the extracted source has negative or positive kurtosis.

Applying the standard gradient descent approach to minimize the cost function (3) one can obtain:

\[
\frac{dw}{dt} = -\mu \frac{\partial J(w)}{\partial w} = \mu(t) \varphi(y(t))x(t)
\]

where \( \mu(t) > 0 \) is a learning rate, and

\[
\varphi(y) = \beta \frac{\hat{m}_4(y) - \hat{m}_2(y)}{m_2^2} y^3 - y
\]

where the moments \( m_q(y) = E[y^q] \), and \( E\{\} \) is the expectation operator. And \( w \) can be obtained by applying the simple local type LMS learning rule:

\[
w(k + 1) = w(k) + \mu(t) \varphi(y(t))x(t)
\]

Since the BSE extracts the sources one by one, in order to avoid the previous source to be extracted again, the deflation process follows the extraction process. Assuming \( x_j \) and \( y_j \) to be the \( j \)th mixture and the \( j \)th extracted component respectively, the deflation process finds a new mixture \( x_{j+1} \) iteratively based on the following update equation,

\[
x_{j+1} = x_j - \tilde{w}_j y_j, (j = 1, 2, ...)
\]

where \( \tilde{w}_j \) is estimated by minimizing of the following cost function:

\[
J(\tilde{w}_j) = \frac{1}{2} E\{\sum_{p=1}^{m} x_{j+1,p}^2\}
\]

To understand the above cost function, one can consider it as an energy function whose minimum is achieved when the extracted source is eliminated from the mixture of source.

2.2. Application of BSE

In BSE algorithm, the extraction process first extracts the artifact as one source, then deflation process removes this source from the EEGs. In our approach, the EEGs are considered as the mixtures of different sources, which include the scanner artifacts. Therefore, it is needed to run the BSE for a certain number of times in order to remove all of these artifacts. The number of iterations is decided by the prior information from the fMRI recording and measuring the kurtosis iteratively during the BSE process.

Theoretically, once all of the scanner artifacts are removed, the higher kurtosis introduced by the scanner would be decreased greatly. Therefore, kurtosis measurement can be a good criterion to decide about the number of iterations of BSE. This is done by comparing the measured normalized kurtosis with a empirically predefined threshold value. In order to avoid removal of any clinical informative sources, we just set this threshold value to a higher value, which is 1 in this case. The BSE algorithm will stop once the normalized kurtosis decreases to less than 1. The rest of artifacts will be removed by the averaging-and-subtraction method.

2.3. Averaging-and-subtraction

One of the solutions to remove the scanner artifact proposed by Allen et al [8] combines the averaging-and-subtraction and adaptive noise cancellation technique together. This provides a significant improvement to the EEG quality. Theoretically, since the scanner effects are periodic signals, by averaging-and-subtraction we can remove this kind of artifact (if the EEGs we are interested are not periodic). But practically, this technique may cause distortion because of misalignment of the actual and averaged data, which may eliminate some information within the signals.
In Allen’s method, the artifacts averaged over the epochs are synchronized by a scanner-generated "slice trigger pulse", which requires a dedicated connection between the scanner and the EEG system. In our method, the signals used for averaging are aligned by correlation measurement. Because of periodicity of the scanner artifact, by measuring the cross correlation between the selected epochs, a proper alignment of the signals can be made. Since the scanner artifact effects at different channels are slightly different in both shape and latency, the subtraction has to be performed at each channel separately.

3. Experimental Results

The experimental steps can be described as follows: (a) preprocessing, such as baseline removal and lowpass filtering to remove the high frequency components also 50Hz interference; (b) correlation measurement and alignment of the selected segments of EEGs; (c) BSE process for the selected segments to extract the high kurtosis scanner artifacts iteratively; (d) averaging of a substantial number of segments processed by the BSE; (e) subtract the averaged signals from the result of (c) to get the restored signals.

3.1. Application to the simulated signals

Since BSE is based on maximization of non-Gaussianity of the outputs, in the simulation, the source signals were generated with different kurtosis, as 1.5, 3.0 and 4.15, respectively, as in Figure.1. Then the sources were mixed using a matrix with randomly chosen elements as in Figure.2. The final results are given in Figure.3, it can be seen that the mixed source signals have been extracted one by one.

3.2. Application to real EEGs

In our experiments, EEGs are recorded with a sampling frequency of 1000Hz and contain the 50Hz interference. Since the brain activities have relatively low frequency band, the high frequency noises intensively obscure the real EEG information. The EEGs that are contaminated by the scanner artifact are given in Figure.4. A Butterworth lowpass filter with a cut frequency of 45Hz was applied to remove the 50Hz interference. The scanner artifacts still can be seen although after the lowpass filtering (Figure.5).

The BSE algorithm was applied to the filtered EEGs to remove the high kurtosis components corresponding to the scanner artifacts. The number of iterations is estimated from the normalized kurtosis. Figure.6 gives the measured kurtosis which is obtained by averaging the kurtosis from 28
The EEGs after lowpass filtering. 

Figure 5. The EEGs with scanner artifacts after lowpass filtering.

The graph shows how the kurtosis decreases with the number of iterations. The iteration stops when the kurtosis decreases to less than 1. After the BSE process, the averaging-and-subtraction method was performed. Fig.7 gives the final result obtained by the proposed method, from which it can be observed that the scanner artifacts have been effectively removed.

Figure 6. Averaged normalized kurtosis of 28 EEG channels after being processed by BSE.

4. Conclusion

An effective method for removal of the scanner artifacts has been presented in this paper. BSE was firstly applied to extract the high kurtosis scanner artifacts. Then the averaging-and-subtraction was used to remove the rest artifacts, mainly those with low kurtosis such as ballistocardiogram. The final results show that the scanner artifacts have been highly mitigated from the contaminated EEGs. The results of this study pave the way for development of a fusion modality in functional analysis of brain for many applications such as prediction of epileptic seizure from the scalp EEGs.

References