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Real-time EEG artifact correction during fMRI using ICA

Ahmad Mayeli [a,b], Vadim Zotev [a], Hazem Refai [b], Jerzy Bodurka [a,c,d,*]

[a] Laureate Institute for Brain Research, Tulsa, OK, USA
[b] Department of Electrical and Computer Engineering, University of Oklahoma, Tulsa, OK, USA
[c] Stephenson School of Biomedical Engineering, University of Oklahoma, Norman, OK, USA
[d] Biomedical Engineering Center, University of Oklahoma, Norman, OK, USA

HIGHLIGHTS

- A real-time method based on ICA (rtICA) is proposed to remove artifacts from EEG data acquired simultaneously with fMRI.
- The rtICA effectively reduces ocular, motion, BCG, muscle and residual MR artifacts and retrieves EEG signals.
- The rtICA method following the rtAAS outperforms the rtAAS for removing artifacts in real time.
- The rtICA revealed reliable artifact suppression results for further applications of real-time multimodal EEG-fMRI.

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ABSTRACT

Background: Simultaneous acquisition of EEG and fMRI data results in EEG signal contamination by imaging (MR) and ballistocardiogram (BCG) artifacts. Artifact correction of EEG data for real-time applications, such as neurofeedback studies, is the subject of ongoing research. To date, average artifact subtraction (AAS) is the most widespread real-time method used to partially remove BCG and imaging artifacts without requiring extra hardware equipment; no alternative software-only real time methods for removing EEG artifacts are available.

New methods: We introduce a novel, improved approach for real-time EEG artifact correction during fMRI (rtICA). The rtICA is based on real time independent component analysis (ICA) and it is employed following the AAS method. The rtICA was implemented and validated during EEG and fMRI experiments on healthy subjects.

Results: Our results demonstrate that the rtICA employed after the rtAAS can obtain 98.4% success in detection of eye blinks, 4.4 times larger INPS reductions compared to RecView-corrected data, and effectively reduce motion artifacts, as well as imaging and muscle artifacts, in real time on six healthy subjects.

Comparison with existing methods: We compared our real-time artifact reduction results with the rtAAS and various offline methods using multiple evaluation metrics, including power analysis. Importantly, the rtICA does not affect brain neuronal signals as reflected in EEG bands of interest, including the alpha band.

Conclusions: A novel real-time ICA method was proposed for improving the EEG quality signal recorded during fMRI acquisition. The results show substantial reduction of different types of artifacts using real-time ICA method.

1. Introduction

Electroencephalography (EEG) and functional Magnetic Resonance Imaging (fMRI) are widely used, noninvasive, and safe techniques for detecting and characterizing changes in brain states and their relation to brain activity (Ritter and Villringer, 2006). The techniques complement each other well because of high temporal resolution of EEG data and high spatial resolution of fMRI data (Niazy et al., 2005). Furthermore, because EEG is a direct measure of brain activity and fMRI is an indirect measure, simultaneous EEG-fMRI measurements can aid in cross validation. However, recording EEG inside the MRI scanner and during fMRI acquisition suffers from several safety and technical challenges (Kruggel et al., 2000). A major problem is the presence of artifacts in EEG data, such as MR or imaging artifacts and also ballistocardiogram (BCG) artifacts. BCG and imaging artifacts appear in the EEG signal as a result of the sig-

* Corresponding author at: Laureate Institute for Brain Research, Tulsa, OK, USA.
E-mail address: jbodurka@laureateinstitute.org (J. Bodurka).

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nal being recorded inside MRI scanner and during fMRI acquisition respectively (Niazy et al., 2005). Other types of artifacts, such as muscle and ocular artifacts can be present in EEG data regardless if the EEG is recorded inside or outside the MRI scanner (Mantini et al., 2007; McMenamin et al., 2010).

The average artifact subtraction method (AAS) (Allen et al., 1998, 2000) is commonly used to remove BCG and imaging artifacts. To date, it is the most widespread real-time method used to partially remove such artifacts. The AAS method is based on the repetitive pattern of imaging and BCG artifacts, and it generates an artifact template to subtract it from the EEG signal. Even though the AAS can effectively reduce BCG and imaging artifacts, some residual artifacts remain when this algorithm is applied to raw EEG data in both real time and offline (Niazy et al., 2005). High quality, modern MRI scanner gradient controllers together with synchronization of MRI and EEG system clocks enable generation of accurate and reproducible templates of gradient artifacts, and allow for AAS template subtraction that has proven extremely successful (Laufs, 2012). However, temporal variability of BCG artifact makes removal of BCG artifact using the AAS less efficient. While the AAS has proven successful for reducing BCG and, especially, imaging artifacts, the method does not remove ocular, motion, and muscle artifacts. Instead, ICA has been widely used in offline analysis as an alternative for attenuating residual imaging and BCG artifacts, and other artifacts (e.g., Mantini et al., 2007; McMenamin et al., 2010; Srivastava et al., 2005; Wong et al., 2016; Zotev et al., 2016). A variety of ICA-based methods (e.g., FastICA, extended Infomax, Robust ICA, JADE, and SOBI) have been utilized for this purpose. More recently, Hsu et al. (2016) demonstrated that online recursive ICA algorithms are fast enough for real-time EEG source separation. However, they did not suggest any automatic algorithm for identifying artifacts among sources in their study.

Problems associated with EEG artifacts have led to the development of a number of alternative methods for removing fMRI environment and regular physiological artifacts. Niazy et al. (2005) suggested a novel method, namely optimal basis set (OBS), for generating BCG artifact templates. They used principal component analysis (PCA) for capturing temporal variations in artifacts and regressing BCG artifacts from EEG data. The result is superior performance over the AAS for removing BCG artifacts, with fewer residual artifacts remaining. This method has recently been adopted for real-time artifact correction (Wu et al., 2016). Like the rtAAS, this method can only remove BCG and imaging artifacts and the application of this method is obscured when the accuracy of R-peak detection is low due to ECG data distortion. Furthermore, since muscle and especially ocular and motion artifacts often have greater amplitudes compared to neural activity and higher or similar amplitude to BCG artifacts, the interaction of motion, muscle and ocular artifacts on BCG artifact template needs to be investigated further (Wu et al., 2016). Kim et al. (2004) proposed a combination of wavelet-based de-noising with adaptive filtering as post-processing to increase the AAS performance. Likewise, adaptive noise cancellation was suggested as a preprocessing step for the OBS (Niazy et al., 2005). PCA has also been used for removing BCG and imaging artifacts in studies reported in Negishi et al. (2004) and Bénar et al. (2003). Wavelet transform, followed by ICA, has proven to be a useful method for removing artifacts (Akhtar et al., 2012; Zhou and Gotman, 2004).

Several researchers utilized reference signals for removing BCG artifacts (Bonmassar et al., 2002; Dunseath and Alden, 2010; Luo et al., 2014; Masterton et al., 2007; van der Meer et al., 2016). Bonmassar et al. (2002) utilized a piezoelectric motion sensor to estimate motion artifact noise. Correlation between motion sensor and EEG signal was used to design the Kalman filter for removing BCG artifacts. Masterton et al. (2007) introduced a wire-loop-based method for correction of motion and BCG artifacts. Dunseath and Alden (2010) suggested using reference electrodes attached to a conductive reference layer for recording artifacts and further removing noise from EEG data. Although these methods appear beneficial for reducing artifacts, they are not yet widely used. Unfortunately, these methods require hardware modification and additional equipment, which makes them complicated and more expensive to implement (Jorge et al., 2015). Furthermore, some of these methods require complicated and time consuming calculations, which make them less suitable for real-time applications.

Real-time imaging and BCG artifact correction techniques were used in several simultaneous EEG and fMRI studies (Becker et al., 2011; Cavazza et al., 2014; Zich et al., 2015; Zotev et al., 2014). The AAS implemented in real time in the RecView software (Brain Products GmbH, Gilching, Germany) was used in all of these studies for reducing BCG and imaging artifacts. Developing new real-time algorithms for removing EEG artifacts would make real-time analysis of multimodal EEG-fMRI signals more feasible and thus open many new research opportunities to study human brain function.

In this work, a novel real-time EEG artifact correction approach during fMRI (rtICA) is developed. The rtICA is a real-time ICA-based algorithm for reducing BCG and imaging artifacts, in addition to motion, ocular, and muscle EEG artifacts, and to improve EEG data quality acquired during fMRI. Imaging and BCG artifacts are first reduced using the BrainVision RecView software in real time prior to applying the rtICA (rtAAS + rtICA). The following section provides a more detailed description of our proposed rtICA method. Since the EEG activity is changing during time and in different conditions, instead of comparing EEG data recorded during fMRI acquisition and outside MRI scanner, we preferred to compare the performance of the rtAAS + rtICA for removing artifacts with RecView-corrected data and EEG data after applying different offline artifact corrections. Finally, we discuss results and improvement of the EEG data quality. A preliminary report of portions of this work was presented in Mayeli et al. (2015).

2. Methods

2.1. Data acquisition

The study was conducted at the Laureate Institute for Brain Research with research protocol approved by the Western Institutional Review Board (IRB). All participants provided written informed consent and received financial compensation for participation.

The rtAAS + rtICA artifact removal method has been tested on six healthy subjects (mean age: 36 ± 14 years, three females). Four resting EEG-fMRI runs were conducted; each run lasted 8 min 40 s. The participants were instructed to relax and rest with eyes closed for two runs, and then keep their eyes open and fixed on a cross for an additional two runs. Sequence runs with eyes-closed and eyes-open was balanced to eliminate fatigue factor (Yuan et al., 2013).

MR images were acquired via a General Electric Discovery MR750 whole-body 3 T MRI scanner with a standard 8-channel, receive-only head coil array. For fMRI acquisition, a single-shot gradient-recalled EPI sequence with Sensitivity Encoding (SENSE) was employed. The EPI sequence was custom modified to ensure that the repetition time TR was exactly 2000 ms (with 1 μs accuracy) and further enabling accurate correction of MR artifacts in EEG data, recorded simultaneously with fMRI. EPI imaging had the following parameters: FOV = 240 mm, slice thickness = 2.9 mm, slice gap = 0.5 mm, 34 axial slices per volume, 64×64 acquisition matrix, echo time TE = 30 ms, SENSE acceleration factor R = 2, flip angle = 90°, sampling bandwidth = 250 kHz. The fMRI run time was 8 min 40 s. For allowing the fMRI signal to reach