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Marker-based ballistocardiographic artifact correction improves spike identification in EEG-fMRI of focal epilepsy patients

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HIGHLIGHTS

- Ballistocardiographic motion in the MR scanner is measured by an optical marker.
- The motion information can be used to correct BCG artifacts in EEG-fMRI.
- The correction improves IED identification and the resulting fMRI activations.

ABSTRACT

Objectives: Ballistocardiographic (BCG) artifacts resemble interictal epileptic discharges (IEDs) and can lead to incorrect IED identification in EEG-fMRI. This study investigates IEDs marked in EEGs corrected using information from a moiré phase tracking (MPT) marker.
Methods: EEG-fMRI from 18 patients was processed with conventional methods for BCG removal, while 9 patients used a MPT marker. IEDs were marked first without ECG information. In a second review, suspicious IEDs synchronous with the BCG were discarded. After each review, an event-related fMRI analysis was performed on the marked IEDs.
Results: No difference was found in the proportion of suspicious IEDs in the 2 patient groups. However, the distribution of IED timings was significantly related to the cardiac cycle in 11 of 18 patients recorded without MPT marker, but only 2 of 9 patients with marker. In patients recorded without marker, failing to discard suspicious IEDs led to more inaccurate fMRI maps and more distant activations.
Conclusions: BCG artifact correction based on MPT recordings allowed a more straightforward identification of IEDs that did not require ECG information in the large majority of patients.
Significance: Marker-based ballistocardiographic artifact correction greatly facilitates the study of the generators of interictal discharges with EEG-fMRI.

1. Introduction

Simultaneous recording of electroencephalography (EEG) and functional magnetic resonance imaging (fMRI) in focal epilepsy patients is a non-invasive method with a high temporal resolution attributable to the EEG and a high spatial resolution conditioned by the fMRI (Lemieux et al., 2001; Seeck et al., 1998). The method is based on different magnetic properties and concentrations of oxygenated and deoxygenated hemoglobin (BOLD effect; blood oxygenation level dependency) at the time of interictal epileptic discharges (IEDs) (Gotman and Pittau, 2011; Hamandi et al., 2004; Warach et al., 1996) and can be used to detect epileptogenic networks (Gotman, 2008; Laufs, 2012).

Since the EEG is recorded inside the magnetic field of the MRI scanner, its quality is impaired by technical and movement-related artifacts (Allen et al., 2000, 1998). A high magnetic field strength and rapidly changing gradients in combination with movements of conducting materials such as EEG electrodes and

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electrode wires cause image acquisition artifacts (Bénar et al., 2003; Ives et al., 1993). These technical artifacts are characterized by a magnitude many times higher than the physiological EEG (Allen et al., 2000; Felblinger et al., 1999) and strong deterministic components: relative polarity and amplitude can differ from channel to channel, but the timing and shape remain more or less reproducible, which facilitates artifact correction (Anami et al., 2003). The standard correction is based on average artifact subtraction (AAS), a method that averages artifactual periods in each channel, cancelling out physiological EEG information and leaving only artifact that is subsequently subtracted (Allen et al., 2000). Variations of this method include Fourier transformation (FT) (Hoffmann et al., 2000), online correction methods (Garreffa et al., 2003), principal component analysis (PCA) (Negishi et al., 2004), optimal basis set (OBS) (Niazy et al., 2005) and independent component analysis (ICA), which can further improve image artifact correction (Grouiller et al., 2007).

A particular challenge until now is the correction of the more variable pulse or ballistocardiogram (BCG) artifact caused by barely perceptible, heart-related head movements which can bear a resemblance to IEDs in the EEG and therefore can lead to inaccurate IED markings (Flanagan et al., 2009) as well as plausible but incorrect patterns in the fMRI (Jansen et al., 2012). Already in clinical routine, EEGs recorded outside the MRI scanner EEGs in supine position revealed a heart-beat related artifact in the late eighties and methods for avoiding this artifact were described, such as changing into an upright position or placing a pillow under the patient's head (Niedermeyer and da Silva, 2005). First recordings of simultaneous EEG-fMRI in the mid-nineties (Huang-Hellinger et al., 1995; Ives et al., 1993) also described small heart-beat related artifacts interpreted as pulsatile whole body movements with reference to the heart cycle (Huang-Hellinger et al., 1995). The main components of the BCG artifact originate from a pulsatile movement of conducting EEG electrodes and wires in the magnetic field due to pulsation of bigger blood vessels, especially laterally, and nodding head movements (Allen et al., 1998; Ives et al., 1993; Nakamura et al., 2006). Blood flow contributes a further component as blood functions as a conductor (Debener et al., 2008; Wendt et al., 1998). Yet the precise contributions of each component and the relationship between them are only starting to be understood (Mullinger et al., 2013). In combination with temporal and spatial variability, a complete correction of the BCG artifact in the EEG therefore remains difficult.

For the BCG artifact correction, similar methods are established as for image acquisition artifacts, albeit with certain limitations. A complete elimination of the BCG artifact with AAS presupposes temporal steadiness and a reliable detection of each QRS complex, which cannot be guaranteed. This leads to an incomplete artifact correction that fails to integrate all components of the BCG artifact and results in artifactual residuals after subtraction (Mulert and Lemieux, 2009). Consequently, OBS have also been considered to model temporal variability (Negishi et al., 2004; Niazy et al., 2005). Moreover, topographical characteristics of the BCG artifact (Debener et al., 2008) and its independency with respect to physiological EEG activity can be used in spatial approaches such as PCA and ICA (Srivastava et al., 2005). These methods can avoid the need to measure the exact timing of the QRS complexes (Bénar et al., 2003). Both PCA and ICA are established as correction methods of the BCG artifact, but their use is restricted by training and experience of the operator (Mulert and Lemieux, 2009). ICA for BCG correction has been performed effectively many times in the literature (Leclercq et al., 2009; Mantini et al., 2007; Nakamura et al., 2006). However, impairments of ICA correction methods are described particularly at higher magnetic field strengths (over 1.5 T) that lead to dynamic spatial changes of the BCG artifact (Debener et al., 2007). Therefore a combination of OBS and ICA is proposed for BCG artifact correction at higher magnetic field strengths (Debener et al., 2008, 2007). EEG quality in EEG-fMRI recordings is often good but still not completely artifact-free compared to EEGs recorded outside the MRI scanner. The reviewing of EEGs recorded during continuous EEG-fMRI is therefore a tedious process in which any IED-like waveform must be carefully examined, usually in the context of concurrent ECG information, to determine whether it is a true IED or potentially a residual BCG artifact.

A limitation of the BCG correction methods described above is that they provide only an indirect modeling of the underlying BCG artifact. This allows on the one hand a good subtraction of the BCG artifact, but it is also possible that real EEG activity is affected.

For a more precise correction of the BCG artifact, movement sensors attached to the electrode cap can be used to directly measure head movements (Bonmassar et al., 2002; Masterton et al., 2007). Moving general linear model methods are used to allow for BCG artifacts beyond the duration of the heart cycle (Vincent et al., 2007). Another recently published technique uses direct measurement of BCG signals using standard EEG electrodes that have been insulated from the scalp (Chowdhury et al., 2014; Xia et al., 2014). Applying optical marker systems analogous to those used for MRI motion correction (Gumus et al., 2015; Maclaren et al., 2012) is another approach for directly recording the BCG signal in healthy subjects (LeVan et al., 2013).

In this study it was investigated whether the latter optical tracking system could simplify the EEG review process in epilepsy patients by no longer having to rule out residual BCG artifacts during the identification of IEDs. Comparisons were made between EEGs and resulting fMRI activation images of patient data processed either with standard BCG artifact correction methods or with MPT marker-based BCG correction under the following aspects: (1) relation between IED markings and the BCG within the heart cycle; (2) localisation of BOLD effects and concordance with IED localisation in resulting fMRI activation maps.

2. Materials and methods

The goal of this study was to evaluate a new BCG correction method based on motion information recorded by an optical tracking system applied to EEG-fMRI of focal epilepsy patients.

2.1. Patients

Twenty-seven patients with focal epilepsy were recruited from the Epilepsy Centre and the Department of Neuropediatrics and Muscular Diseases of the University Medical Centre Freiburg. Patients were informed about potential risks by their physician and gave informed consent. The Research Ethics Commitee of the University Medical Center Freiburg authorised the study.

Inclusion criteria for EEG-fMRI data were:

(1) Frequent IEDs (>3 in 20 min) recorded in routine EEG outside the scanner and
(2) lack of contraindication for MRI recording and
(3) ability to lie calmly over a period of time in the MRI scanner.

Depending on the willingness of the patient, the EEG-fMRI scanning time lasted up to 40 min.

2.2. Data acquisition

Scalp EEG was recorded continuously inside a 3-Tesla MRI scanner (Trio Tim, Siemens Healthcare, Erlangen, Germany) with a 64-