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Ballistocardiogram artifacts in simultaneous EEG-fMRI acquisitions

Katrien Vanderperren[a], Jennifer Ramautar[bc], Nikolai Novitski[bc], Maarten De Vos[a], Maarten Mennes[bc], Bart Vanrumste[af], Peter Stiers[e], Bea Van den Bergh[c], Johan Wagemans[c], Lieven Lagae[b], Stefan Sunaert[d], Sabine Van Huffel[a]

[a]Department of Electrical Engineering, [b]Department of Paediatric Neurology, [c]Department of Psychology, [d]Department of Radiology, Katholieke Universiteit Leuven, Leuven, Belgium
[e]Faculty of Psychology, Universiteit Maastricht, Maastricht, The Netherlands
[f]Biosciences and Technology Department, Katholieke Hogeschool Kempen, Geel, Belgium

Correspondence: Katrien Vanderperren, Department of Electrical Engineering, Research Division SCD, Kasteelpark Arenberg 10, 3001 Leuven, Belgium. E-mail: katrien.vanderperren@esat.kuleuven.be, phone +32 16 321799

Abstract. The simultaneous acquisition of electroencephalograpy (EEG) and functional magnetic resonance imaging (fMRI) data is very promising for the study of cognitive processes and disorders but causes severe artifacts in the EEG. In this study the aim is to remove the ballistocardiogram artifact, caused by cardiac pulse-related movements of the electrodes in the magnetic field. For this purpose a method based on blind source separation with Second Order Blind Identification (SOBI) was used and compared with Optimal Basis Set (OBS), a method based on channel-wise template subtraction. To validate the accuracy of the removal, an experiment that evokes visually evoked potentials was performed, inside and outside the scanner. Both methods were valuable but the same quality as in measurements without magnetic field could not be achieved.

Keywords: Visually Evoked Potentials (VEPs), EEG, fMRI, ballistocardiogram artifacts, SOBI

1. Introduction

Simultaneous acquisition of electroencephalography (EEG) and functional magnetic resonance imaging (fMRI) is a promising method in the study of cerebral dynamics. The complementarities between the high temporal resolution of EEG and the high spatial resolution of fMRI can provide a better understanding of brain function and dysfunction. However, when acquired in the MR scanner, EEG data are highly contaminated with two major artifacts. Firstly, gradient artifacts occur because of the switching of the magnetic fields during fMRI acquisition. These artifacts can have amplitudes 10 to 100 times larger than those of EEG signals. In addition to this, ballistocardiogram (BCG) artifacts appear, caused by the cardiac pulse-related movement of the scalp electrodes inside the magnetic field. This study will focus on the characteristics of the BCG artifact and on its removal. The quality of the removal will be validated with visually evoked potentials (VEPs).

2. Material and Methods

2.1. Data acquisition

Because the focus in this study is on BCG artifacts, the measurements were restricted to EEG data without acquiring fMRI. For validation purposes the EEG data were not only acquired inside the static magnetic field of the scanner, but also outside the scanner room. The EEG data were collected from 62 standard scalp sites using the BrainAmps MR plus (BrainProducts, Munich, Germany). Two additional electrodes were placed below the left eye and on the right lower back to monitor eye blinks and electrocardiograms, respectively. All 64 channels were recorded with Cz as a reference and POz as a ground. Electrode impedances were kept below 10 kΩ. For the measurements inside the scanner a Siemens 3T was used.

A visual detection task was performed with segments of circular black-and-white checkerboard stimuli presented one at a time in randomized sequences to one of the four quadrants of the visual field. In addition, a large circular black-and-white checkerboard is presented as a central stimulus on the central part of the screen. This task was selected as it evokes a robust P1 component useful for validating the artifact removal. The P1 component is a positive deflection in the VEP around 100 ms after the stimulus onset. After this P1, a negative (N1) and a positive deflection (P3) are expected.

2.2. Characteristics of the BCG artifact

In a first part of the study the aim was to learn about temporal, spatial and spectral behavior of the BCG artifact. To study the temporal characteristics the data was epoched on the QRS peaks (detected on the ECG channel with an algorithm from [Niazy et al., 2005]) and averaged over these epochs per channel. The obtained signals are shown for two subjects and channels FC3, AFz, F4, C6, F1, AF4, FC6 and CP4 in Fig. 1 with an average reference. From this figure, it is clear that the artifact's shape and amplitude can differ between different channels. The amplitude can even change slightly over time. Fig. 1 also shows that between different subjects the artifact pattern can be completely different (see full and dashed lines).

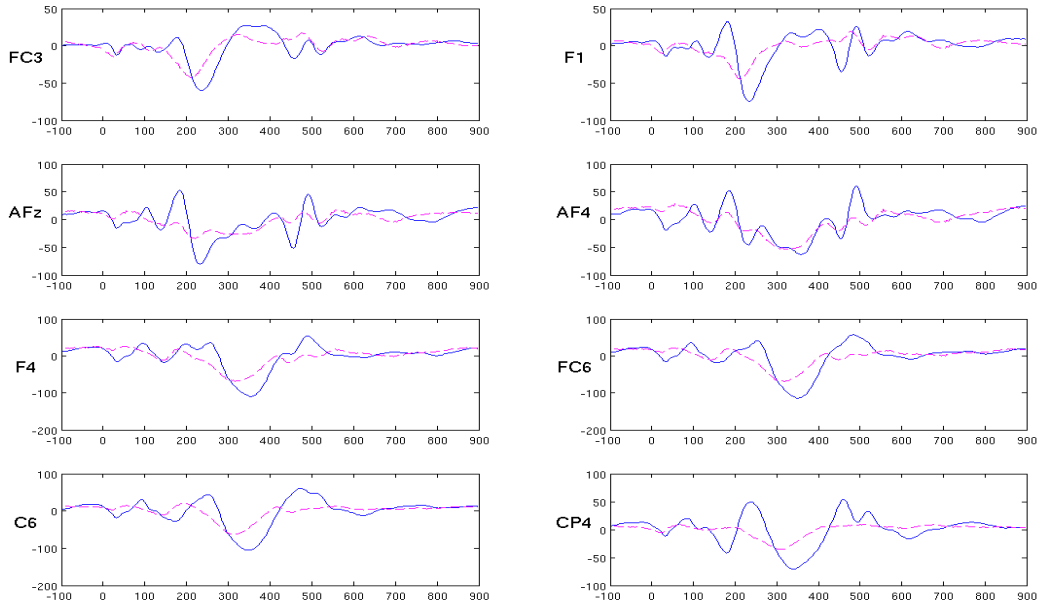

Figure 1. *Temporal BCG artifact representation by epoching on QRS peaks and averaging. The temporal pattern of the artifact clearly differs between different channels (see different panels) and different subjects (see full and dashed lines).*

The localization of the BCG artifact is represented by the spatial distribution of the intensity of the BCG related epochs at specific latencies. As above these epochs are created by epoching on QRS peaks and averaging. In Fig. 2a and Fig. 2b one can see the potential distribution of the values in the BCG epochs at latencies of respectively 100 and 400 ms. In Fig. 2c the potential distribution of another measure, namely the peak-to-peak value is shown. This peak-to-peak value is computed by subtracting the minimum of the maximum value in an averaged epoch. The first two figures clearly indicate that the BCG artifact has an opposite polarity at the two sides of the head. These findings are in correspondence to [Debener et al., 2007]. The influence of the artifact is more pronounced in lateral channels, as can be seen from Fig. 2c.

In the frequency spectrum, the artifact causes a peak at the heart rate frequency and at several harmonics. In Fig. 3 the normalized power spectral density on channel F8 is shown for a subject with a heart rate frequency of around 0.85 Hz. The peaks at this frequency and at four higher harmonics are clearly visible.

2.3. Artifact removal

Blind source separation is a signal processing technique that can be used to recover independent sources from a set of simultaneously recorded signals that results from a linear mixing of the source signals. In [Mantini et al., 2007] the fastICA algorithm was already successfully used to remove BCG artifacts for clinical studies based on EEG/fMRI integration. In [Niazy et al., 2005] the Optimal Basis Set (OBS) method is proposed for the same purpose. OBS is based on the channel-wise subtraction of a

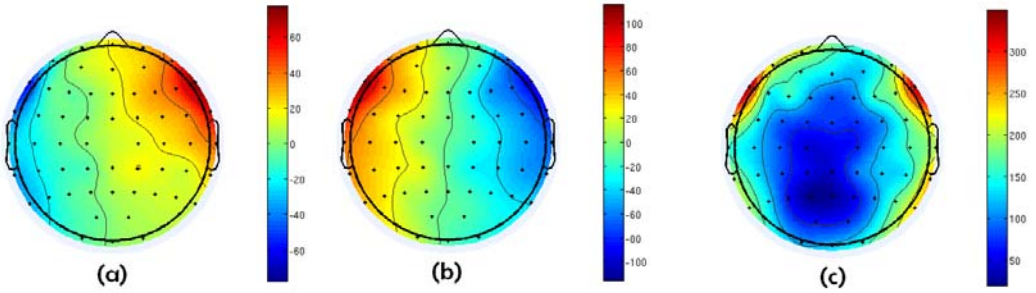

Figure 2. *Spatial BCG artifact representation with spatial distribution of specific values out of averaged BCG related epochs. (a) value at latency of 100 ms; (b) value at latency of 400 ms; (c) peak-to-peak-value. The BCG artifact has an opposite polarity at the two sides of the head and is more pronounced in lateral channels.*

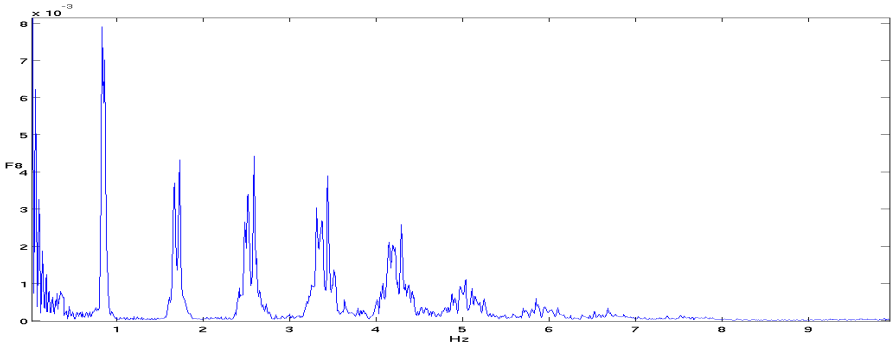

Figure 3. *Spectral BCG artifact representation with normalized power spectral density on channel F8. There is a clear peak at the heart rate frequency of 0.85 Hz and at several of its harmonics.*

BCG template, computed by means of principal component analysis on all QRS epochs of each channel. The number of principal components used for this template, is the most important parameter to optimize in OBS.

In the present study, Second Order Blind Identification (SOBI) [Belouchrani et al., 1997] is used to separate BCG artifacts from VEPs. After applying SOBI the artifact-related components need to be selected and the EEG data are reconstructed without these components. The selection procedure is based on computing the correlation between the sources and a certain template. Next, an appropriate threshold on this correlation must be chosen to discriminate between BCG and VEP related components. As a template, both the ECG channel and an averaged BCG signal were used. This BCG signal was created by concatenating the averaged QRS epochs (such as the ones shown in Fig. 1) and averaging the resulting signals over all channels.

The results of SOBI are validated on three subjects and compared with the best results of the OBS method. A first criterion is the residual artifact after removal. This is characterized with the peak-to-peak amplitude of the signals created by epoching on the QRS peaks. Also the presence of peaks at harmonics of the heart rate frequency is verified. The recovery of the VEPs of interest can be validated by comparing the results from measurements with and without magnetic field.

3. Results

Before the artifact removal is applied, bad channels (because of bad impedances or broken electrodes) are removed from the data. For OBS the default value of 3 for the number of principal components gives the best results with respect to the measures defined above, so this value is chosen for further comparisons. For SOBI the choice of the number of sources and the threshold on the correlation is not straightforward because both parameters seem to be subject-dependent. Nevertheless, it can be concluded that the number of sources has to be chosen between 15 and 30 and that the threshold has to be rather low, between 0.10 and 0.20. Using the BCG signal as a template for correlation does not differ much from correlating with the ECG signal.

Both the OBS and the SOBI method result in a significant reduction of the peak-to-peak amplitude of the averaged QRS epochs. The minimum peak-to-peak amplitude of the residual BCG is 4 % of the original BCG amplitude for both methods. In the frequency spectrum, the peaks at the harmonics of the

heart rate frequency are reduced with the SOBI method and completely removed with the OBS method. The presence of the peaks for SOBI might indicate that some residual BCG artifact is still present. However, the peak-to-peak value and the presence of heart rate related frequency peaks are only measures of the presence of the artifact. It is also necessary to verify whether the activity of interest is not affected by the artifact removal.

For this purpose, VEPs are extracted from the data cleaned with OBS or SOBI. These VEPs were pooled over all conditions. In Fig. 4a the VEP from outside the magnetic field is shown, while in Fig. 4c and Fig. 4e the VEPs from respectively the SOBI and the OBS method are presented. Fig. 4b, Fig. 4d and Fig. 4f show the potential distributions of the peak identified as the P1 component. The VEPs are for both methods of a much lower quality than in the situation without magnetic field. Nevertheless, some small P1 components are visible in both cases, but their incorrect potential distributions might indicate that some residual BCG artifact is present. In the results from SOBI and OBS the positive P3 is recognized, while the N1 is distorted in both cases. It is clear that the amplitudes of the components of interest are heavily reduced due to the artifact removal.

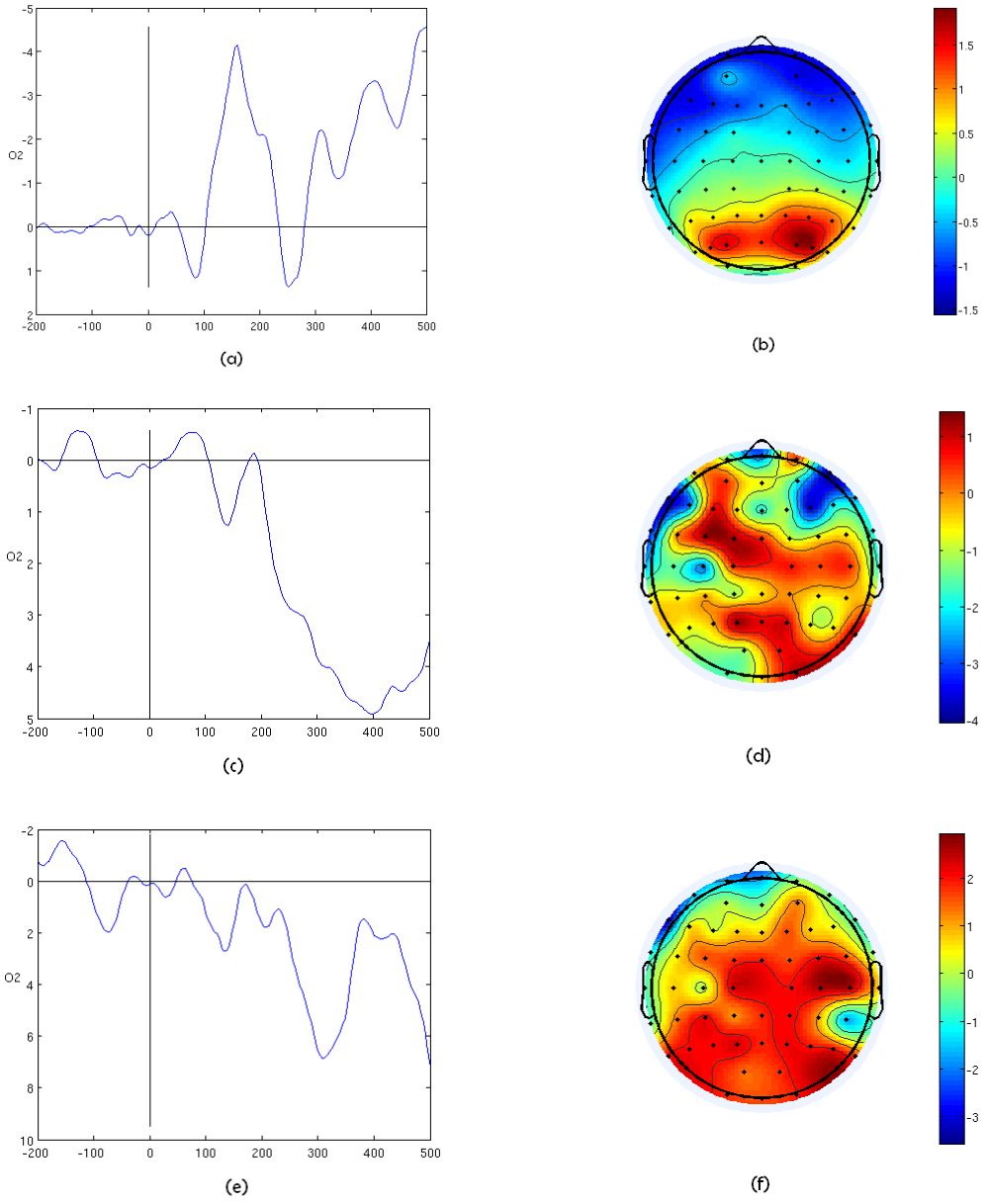

Figure 4. *VEP on channel O2 of visual detection task and potential distribution of the peak identified as the P1 component. (a-b) Results without magnetic field. (c-d) Results on data cleaned with SOBI. (e-f) Results on data cleaned with OBS.*

4. Discussion

The removal of the BCG artifact is a complex problem because the artifact pattern depends on the particular electrodes and on the measured subject. To assure an accurate validation, an experiment that elicits VEP components was used. These are rather small components, which require a very precise artifact removal. The use of SOBI in this application is useful but needs further improvements to achieve VEP components with sufficient quality in every situation. The automatic selection of the number of components and an appropriate threshold for the correlation would be an improvement to adapt the method to every subject. Since correlating with the BCG template gives as good results as correlating with the ECG signal, the SOBI method is less dependent of the quality of the ECG measurement. The quality of the OBS results on the other hand, is strongly dependent on the accuracy of the QRS peak detection, for which a qualitative ECG measurement is needed. Hence, this might be a drawback of the OBS method.

However, since both methods did not reveal satisfactory results, the question rises if VEPs with the same quality as outside the magnetic field can ever be obtained inside the MR scanner.

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