# Cortico-Muscular Coherence on artifact corrected EEG-EMG data recorded with a MRI scanner*

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*Abstract*— **Simultaneous recording of electroencephalogram (EEG) and electromyogram (EMG) with magnetic resonance imaging (MRI) provides great potential for studying human brain activity with high temporal and spatial resolution. But, due to the MRI, the recorded signals are contaminated with artifacts. The correction of these artifacts is important to use these signals for further spectral analysis. The coherence can reveal the cortical representation of peripheral muscle signal in particular motor tasks, e.g. finger movements. The artifact correction of these signals was done by two different algorithms the Brain vision analyzer (BVA) and the Matlab FMRIB plug-in for EEGLAB. The Welch periodogram method was used for estimating the cortico-muscular coherence. Our analysis revealed coherence with a frequency of 5Hz in the contralateral side of the brain. The entropy is estimated for the calculated coherence to get the distribution of coherence in the scalp. The significance of the paper is to identify the optimal algorithm to rectify the MR artifacts and as a first step to use both these signals EEG and EMG in conjunction with MRI for further studies.**

## I. Introduction

Several artifact correction algorithms have been developed for data recorded within the MRI scanner. The spectral analysis cannot be directly used on these signals due to their gradient or scanner artifacts introduced by the scanner and the pulse artifacts on the recorded EEG and EMG signals. The correction of these artifacts are essential and at the same time to restrain all the important information of the signals for further spectral analysis. It is well known from previous studies [1-3] in neurophysiology that the movement of the right index finger in a rhythmic way induces coherence in the contralateral side of the brain which was taken as the paradigm in this study. The artifact correction of the EEG and EMG signals were done by two different algorithms. The first is the brain vision analyzer (BVA) [4] and the other is the Matlab FMRIB plug-in for EEGLAB [5] to evaluate which of these algorithms are best suited for signals like EEG and EMG. After the artifact correction of the signals, the well-known Welch periodogram method [6] was used for estimating the cortico-muscular coherence. Thus the cortico-muscular coherence was projected on the scalp for the movement of the right index finger.

In this paper, we compare two artifact correction techniques for further spectral analysis of the signals. First the gradient artifact correction is done for the both the signals separately using both these algorithms. Second, the pulse artifact correction is done and then the power and the coherence spectrum are estimated for all the possible different combinations to conclude which of these algorithms are better in rectifying the artifacts in the recorded EEG and EMG data. It is followed by estimation of the entropy for the distribution of coherence in the scalp and then the results are discussed.

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## II. Methods

### A. Data Acquisition

The EEG data was recorded with a standard 64 channel recording system (Neuroscan, Herndon, VA, USA) using a linked mastoid reference. The forearm was rested comfortably on the MRI sleeping pad. Surface EMG was recorded from the forearm extensors on both hands with two silver-chloride electrodes positioned close to the motor points of the muscle. EMG was full wave rectified and EEG was made reference free by Hjorth transformation [7]. The combination of band pass filtering and rectification is the common demodulation procedure for oscillatory EMG [8]. The data was from 5 normal healthy subjects with the paradigm to move the right index finger up and down in a rhythmical fashion for 1 minute followed by 30 seconds rest which was repeated five times and was done two times once with and once without the MRI scanner in the same lying position to compare the results. The stimulus for the finger tapping was given by presenting them with a visual stimulus on a screen using the E-prime software.

### B. Gradient Artifact Correction

Both the algorithms for the correction of gradient artifacts are based on the same principle, which was proposed in [9]. They divide the original EEG data E in multiple intervals in which the gradient artifacts occur and hence construct an averaged artifact curve $A$ :

$$A_i = \frac{1}{N+1} \sum_{i-N/2}^{i+N/2} E_j \qquad (1)$$

where $i$ is the index of an interval and $N$ determines the number of intervals to calculate the average curve. The template $A$ is afterwards subtracted from the original curve. The index of the summation implies that the averaging is especially performed in terms of a centered moving averaging, in BVA is called sliding average, respectively. The advantage is that the small fluctuations, like temporary head movements, are compensated and not taken into account along the complete data range. The first difference lies in the definition of an interval over which it is averaged. While the BVA [4] performs on intervals made of one complete volume scan with all the slices, the FMRIB plug-in constructs a unique template for each slice. It actually passes through several different stages and introduces an additional step of processing to remove residual artifacts that remain after the average template subtraction. First of all the data is up sampled with an interpolation method to 20 kHz, in order to improve the removal of gradient artifacts and to allow adjustment of slice timing triggers by $\pm 500$ $\mu s$ steps until the correlation with the reference is at maximum. Before the averaging is performed in the second stage, the interpolated data is also high-pass filtered at 1 Hz to remove any slow drifts $\left(E^h\right)$. The artifact template $A$ is then scaled by a constant factor $\alpha$ to minimize the least squares between the template and artifact data and finally subtracted from $E^h$. The result is EEG data with residual artifacts $E^r$.

$$E^r = E^h - \alpha \cdot A \qquad (2)$$

The third step eventually contains the difference to the brain vision analyzer method. The fact that the subtracted data $E^r$ possesses residual artifacts, e.g. from slight variations in the artifact shape among different slices, suggest a subsequent application of principle component analysis, in order to estimate the variations. Dominant components are selected and an optimal basis set $B$ is constructed. The gradient artifact residuals variations $A^r$ will then be described by

$$A^r = \beta \cdot B + \varepsilon \qquad (3)$$

where $\beta$ is a weight vector to fit $B$ to $A^r$ and $\varepsilon$ is an error term. A combination of $\alpha A$ and $A^r$ then yields a complete estimation of the gradient artifacts. Subtraction of both artifact templates from the $E$ finally reveals the clean EEG data $E^c$.

$$E^c = E - \left(\alpha A + A^r\right) \qquad (4)$$

In the end remains the down-sampling of $E^c$ to the initial sampling rate. It is important to notice that the estimated gradient artifacts are subtracted from the original EEG data $E$ and not the high pass filtered version $E^h$ as the low frequency range might be of interest. Moreover the main difference of the FMRIB plug.-in to the brain vision analyzer method lies in the combination of a moving average and an optimal basis set that describes the residual variations. Brain vision analyzer actually operates similar to equation (4) where only the $A^r$ term is set to zero. In Figure 1 (A) one second of EEG raw data is plotted in (B) with only gradient artifact correction using BVA in (C), using FMRIB plug-in respectively.

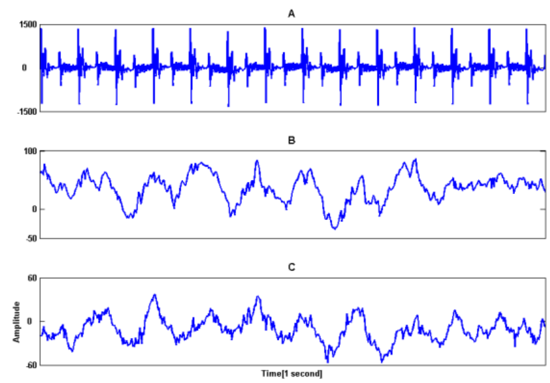


Figure 1. A) One second raw EEG data within the scanner. B) EEG data after Gradient artifact correction using BVA. C) EEG data after Gradient artifact correction using FMRIB plug-in.

## C. Pulse Artifact Correction

The correction of pulse artifacts in the BVA consists of two parts. First of all the occurrence of qrs complexes must be detected. The next step is the correction of these detected pulses in the data. The detection of qrs complexes is done in terms of a coherence method. In this procedure the coherence and mean amplitude correlation of ECG channel (or any other specified channel with significant pulse artifacts) with a template is continuously calculated. In case both values exceed certain thresholds the current position is marked as a qrs complex. Unfortunately BVA does not include a possibility to verify false or missing detections. This has to be done manually and therefore requires more time, especially for long recordings of data.

The removal of pulse artifacts in the EEG is based on an average artifact subtraction [10] and similar to the case of gradient artifacts or equation (1), respectively. First, the positions of each qrs-complex is transferred to the EEG data, where an additional time shift $\left(\approx 210\ ms\right)$ is applied as pulse artifacts always appear in the EEG with a short delay. Second, the EEG is divided into sections that are each centered on the qrs positions with a length of the mean

$R-R$ interval. Analogue to the moving average the ten previous sections are averaged to form the pulse artifact template and finally subtracted to yield the clean EEG data. This is done for each heartbeat and EEG channel separately. The FMRIB plugin works with a modified algorithm from [11] for the detection of qrs complexes. It basically applies a complex transformation to a combined threshold. This method requires an ECG channel that is first of all bandpass filtered from 7 to 40 Hz. Electromyogram noise is afterwards removed by a moving average. In combination with the so-called k-Teager energy operator [12, 13] the following complex transformation $X$ is constructed from the filtered ECG

$$X(i) = \max\left(E^2(i) - E(i-k)\cdot E(i+k), 0\right) \qquad (5)$$

where $i$ is the time index and $k$ is a frequency selection parameter [14] which depends on the sampling rate $f_s$ of the present EEG/ECG data and is emphasized on the $10^{th}$ harmonic frequency of the ECG, i.e., $f_d = 10\,Hz$ [9].

$$k = \frac{f_s}{4\cdot f_d} \qquad (6)$$

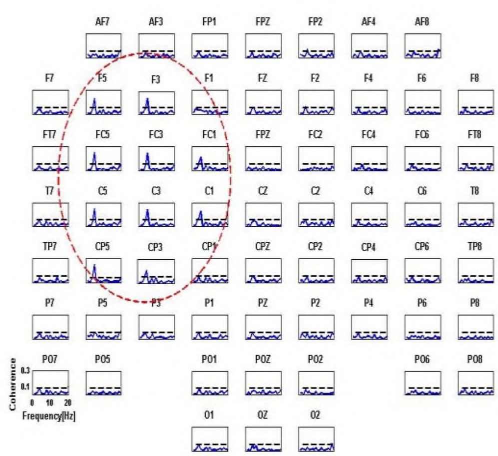


Figure 2. Coherence spectra for all the 64 EEG channels with right flexor EMG channel. Red dash ellipse indicates the contralateral region of coherence for the right hand finger movement.

This complex transformation is then applied to the adaptive threshold $MFR(i)$, which is made of three different thresholds [11]. A qrs peak is marked at the time index $i$ if the condition $X(i) \geq MFR(i)$ is fulfilled. Besides the detection of qrs complexes the FMRIB plugin also provides a method to examine the results for false or missing detections. In this process the position of the qrs complexes are described by a binary vector and it uses the median and standard deviation of all $R-R$ intervals. The first step of this examination removes a qrs peak or verifies it as false, respectively, if its distance to the previous peak is less than the median $R-R$ interval minus three times the standard deviation. During the second step missing peaks are inserted whenever the difference between two consecutive peaks is greater than 1.5 times the median $R-R$ interval, i.e., false negatives are corrected. After each of these two steps the qrs peak positions are adjusted by maximizing the correlation of the ECG data and an averaged heartbeat waveform that has been constructed by transferring the peak positions onto the ECG. In the last phase eventually the removal of the pulse artifacts are carried out. The application of principle component analysis (PCA) is based on the assumption that pulse artifacts are on the one hand time varying but on the other hand also sampled from an unknown set of possible variations [15] and therefore suggests the use of an optimal basis set to estimate those artifacts. Analogue to the BVA module all qrs peaks are transferred with a time shift to the EEG. PCA is then performed on each EEG channel separately where the first 3 principle components are used as an optimal basis set. The optimal basis set is afterwards fitted to and subtracted to yield an EEG cleaned from any pulse artifacts. The power and coherence was estimated using the Welch periodogram method [6] with a confidence limit as defined in [16].

## III. RESULTS

The EEG and EMG data was corrected for artifacts separately using both these algorithms. The coherence was estimated between the EEG and EMG (right forearm extensor) data with the MRI scanner. In Figure 2 the coherence for all the 64 channels in which it is clearly seen that there is significant coherence at 5Hz only in the contralateral side of the brain for the right finger movement as expected. In order to have a quantitative measure of the distribution of coherence over the scalp for all the 48 different combinations of the two algorithms the entropy was estimated for each combination for all the electrodes.

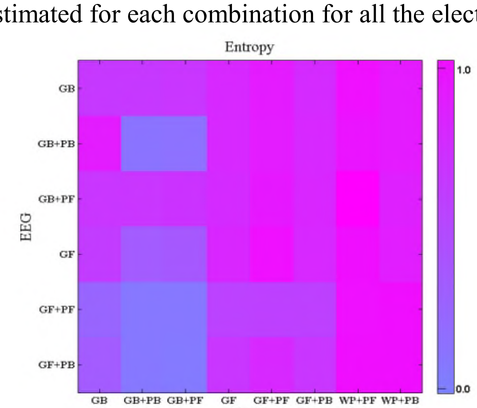


Figure 3. Entropy for all the 48 combinations for the data within the scanner.

In the Figure 3, GB stands for (Gradient artifact correction with BVA), PB (Pulse artifact correction with BVA), GF (Gradient artifact correction with FMRIB-Plug in) and PF (Pulse artifact correction with FMRIB-Plug in). Figure 3 the entropy for all the combinations are given in which the lowest value for the combination GF+PF (for EEG) and GB+PB (for EMG) which indicates that the distribution is more concentrated on the contralateral side for this combination. For comparison the coherence without the scanner was estimated between the EEG and EMG for 4 different combinations of the two algorithms and the estimated entropy for the combination 1-2 gave the lowest value as shown in Figure 4. By evaluating all these combinations for the data within the scanner and without the scanner we can conclude that the FMRIB plug-in was the best for EEG data artifact correction and the brain vision analyzer for the EMG data.

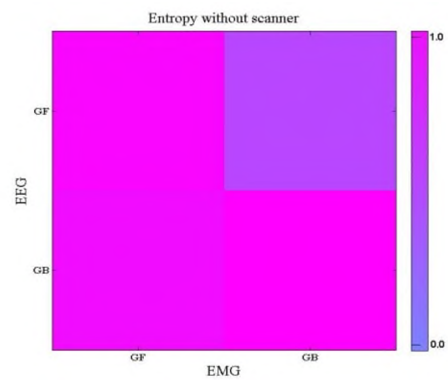


Figure 4. The Entropy for the 4 combinations for the data without the scanner

## IV. DISCUSSION

We have presented a comparison of two analysis techniques for correction of artifact in time series recorded within the MRI scanner. The spectral analysis revealed in some of the combinations the distribution of the coherence on the scalp was spread over all the channels because of the artifacts, so the entropy was estimated to get the exact distribution of coherence on the scalp for the validation of these algorithms. FMRIB plug-in for the correction of EEG and the correction of EMG with the BVA which indicates using both these methods is essential. Both these analysis were able to correct the artifacts in the signals investigated but the best result for coherence was obtained for the correction of EEG with FMRIB plug-in and the correction of EMG with the BVA. FMRIB plug-in was best suited for the broad band EEG signal due to four different steps involved in the correction of the artifacts compared to the EMG signal which has more dynamics in the signal best suited for the template matching algorithm used in BVA. The coherence for the signals recorded outside the scanner also confirmed the result within the scanner after artifact correction. The time series artifact rectification analysis discussed here are powerful tools for getting more information about the signals which can be later compared with the FMRI activation in the brain for the finger movement.

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