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Muscle and eye movement artifact removal prior to EEG source localization

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Abstract— **Muscle and eye movement artifacts are very prominent in the ictal EEG of patients suffering from epilepsy, thus making the dipole localization of ictal activity very unreliable. Recently, two techniques (BSS-CCA and pSVD) were developed to remove those artifacts. The purpose of this study is to assess whether the removal of muscle and eye movement artifacts improves the EEG dipole source localization. We used a total of 8 EEG fragments, each from another patient, first unfiltered, then filtered by the BSS-CCA and pSVD. In both the filtered and unfiltered EEG fragments we estimated multiple dipoles using RAP-MUSIC. The resulting dipoles were subjected to a K-means clustering algorithm, to extract the most prominent cluster. We found that the removal of muscle and eye artifact results to tighter and more clear dipole clusters. Furthermore, we found that localization of the filtered EEG corresponded with the localization derived from the ictal SPECT in 7 of the 8 patients. Therefore, we can conclude that the BSS-CCA and pSVD improve localization of ictal activity, thus making the localization more reliable for the presurgical evaluation of the patient.**

I. INTRODUCTION

Epilepsy is a chronic disorder affecting the daily life of people suffering from this kind of disorder. An epileptic seizure is the clinical manifestation of epilepsy and goes together with abnormal electrical activity in the human brain. The activity results from clusters of neurons which depolarize and repolarize synchronously. An electro-encephalogram (EEG) records this activity in function of time and remains a very valuable tool in the diagnosis of patients suffering from epilepsy. In presurgical evaluation the patients are considered for a surgical removal of the epileptogenic focus. Therefore, a correct localization of the focus is of crucial importance. A way to mathematically estimate this focus is by EEG dipole source localization.

The EEG dipole localization problem consists of two problems. First, the forward problem calculates the potential values at the scalp electrodes for a given electrical source in a specified geometry by solving Poisson's equation [1]. Second, the inverse problem searches the source parameters for given scalp potentials. However, a given set of scalp potentials can be caused by an infinite set of source parameters. To impose unicity, we use the dipole model as a source. A number of methods has been developed to estimate the multiple dipoles [2]. In this study we used RAP-MUSIC to solve the inverse problem [3].

Unfortunately, the EEG also captures electrical sources originating from outside the brain, such as muscle or eye activity. These sources distort the EEG and thus make the localization of the dipole source more difficult. Moreover, the low signal to noise ratio of the signal makes the localization very diffuse.

Recently two techniques were developed to remove those artifacts. One technique tackles the removal of muscle artifacts based on the autocorrelation of the signal. Another technique based on SVD eliminates eye artifacts. The aim of this study is to investigate whether the source localization of the pre-ictal and ictal seizure onset can be improved by artifact removal.

II. METHODS AND MATERIALS

A. Muscle artifact removal by BSS-CCA

BSS-CCA is a blind source separation technique (BSS) based on canonical correlation analysis (CCA), which assumes mutually uncorrelated sources which are maximally autocorrelated. In general, the BSS techniques recover a set of K unknown source signals $\mathbf{S}(n) = [\mathbf{s}_1(n), ..., \mathbf{s}_K(n)]^T$ which are linearly mixed. The signals at the sensors $\mathbf{X}(n) = [\mathbf{x}_1(n), ..., \mathbf{x}_K(n)]^T, n \in \mathbb{N}$ can be written as:

$$\mathbf{X}(n) = \mathbf{A} \cdot \mathbf{S}(n), \quad (1)$$

with $\mathbf{A}$ the unknown mixing matrix. The unknown source signals in $\mathbf{S}(t)$ are approximated, by a scaling factor, as

$$\mathbf{Z}(n) = \mathbf{W} \cdot \mathbf{X}(n) \quad (2)$$

with de-mixing matrix $\mathbf{W}$. Unless there are extra constraints imposed, it is in general impossible to solve this problem.

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BSS-CCA impose the previously mentioned constraints by using CCA with input $\mathbf{X}(n)$, the observed time courses and input $\mathbf{Y}(n)$, a temporally delayed version of the original data matrix ($\mathbf{Y}(n) = \mathbf{X}(n-1)$). Consider the linear combinations of the mean corrected components in $\mathbf{X}$ and $\mathbf{Y}$:

$$\begin{aligned} \mathbf{u} &= w_{x_1}\mathbf{x}_1 + ... + w_{x_K}\mathbf{x}_K = \mathbf{w_x}^T\mathbf{X}, \\ \mathbf{v} &= w_{y_1}\mathbf{y}_1 + ... + w_{y_K}\mathbf{y}_K = \mathbf{w_y}^T\mathbf{Y}, \end{aligned} \quad (3)$$

CCA finds the weight vectors $\mathbf{w_x} = [w_{x_1}, ..., w_{x_K}]^T$ and $\mathbf{w_y} = [w_{y_1}, ..., w_{y_K}]^T$ that maximize the correlation ρ between the variates $\mathbf{u}$ and $\mathbf{v}$ [4], [5]. When CCA is used for blind source separation, as presented here, the variates $\mathbf{u}$ correspond to the sources and ρ to their autocorrelation [5]. Due to the broad frequency spectrum of EMG contamination in scalp EEG recordings, muscle artifacts tend to have more properties of temporally white noise, thus having a low autocorrelation. By consequence, the muscle artifact sources, or components, are always those with the lowest autocorrelation. Muscle artifact can then be removed by setting the columns representing the activations of the artifactual sources equal to zero in the reconstruction

$$x_{clean}(t) = A_{clean} z(t), \quad (4)$$

with $z(t)$ the sources obtained by BSS-CCA, and A_{clean} the mixing matrix with the columns representing activations of the muscle artifactual sources, set to zero [5].

B. Eye artifact removal by pSVD

Piecewise Singular Value Decomposition (pSVD) is a recent technique that is suited to remove large amplitude artifacts from multichannel measurements [6]. In contrast with basic SVD, pSVD uses 4 consecutive windows and averages them. The result is then compared to a template. The template has scalp potentials maps that corresponds to eye blinking and movement artifacts. By eliminating sources that matches with the template, the EEG is purified from those artifacts.

Since the technique is based on template matching it can only be used if there is sufficient prior knowledge about the spatial activation pattern of the artifacts. It has been shown to be an excellent means to clean up EEG recordings from artifacts introduced by eye blinks and saccades [7].

C. Multiple dipolar source estimation by RAP-MUSIC

The RAP-MUSIC algorithm uses the separation of the M-dimensional measurement space $\mathbf{V}$ into a signal Φ_{sig} and noise Φ_n subspace [3]. Assume the spatio-temporal model for the measurement data with additive white noise, $\mathbf{V} = \mathbf{AS} + \mathbf{N}$. The spatial autocorrelation matrix and it's Singular Value Decomposition (SVD) can be written as follows:

$$\begin{aligned} \mathbf{R}_v &= E\left\{\mathbf{V}(t)\mathbf{V}(t)^T\right\}, \\ &= [\mathbf{\Phi}_{sig}\mathbf{\Phi}_n] \begin{bmatrix} \mathbf{\Lambda}_{sig} & 0 \\ 0 & \mathbf{\Lambda}_n \end{bmatrix} [\mathbf{\Phi}_{sig}\mathbf{\Phi_n}]^T \end{aligned} \quad (5)$$

where $\mathbf{\Lambda}_{sig}$ and $\mathbf{\Lambda}_n$ are diagonal matrices with the singular values of $\mathbf{V}$ associated with the signal and noise subspace, resp.

The RAP-MUSIC consists of a search of p sources, through all possible dipole configuration, where the scalp potentials have the highest subspace correlation with the signal subspace. The search algorithm scans through possible source configuration looking for p peaks in the subspace correlation with the signal subspace. Errors in the estimation of Φ_{sig} reduce subspace correlation in a single global maximum and at $p-1$ local maxima. RAP-MUSIC avoids the problem of peak-picking by removing the component of the signal subspace that is spanned by the first source, which is found by simply taking the maximum subspace correlation. In this way the problem of finding 1 global maximum and $p-1$ local maxima is transformed into searching for p global maxima.

The relative residual energy is then defined as the relative amount of energy that cannot explain the EEG by the p dipoles, found by the RAP-MUSIC:

$$RRE = \frac{\|(\sum_i^p \mathbf{G}(\mathbf{r}_i, \mathbf{d_i})) - \mathbf{V}\|}{\|\mathbf{V}\|} \quad (6)$$

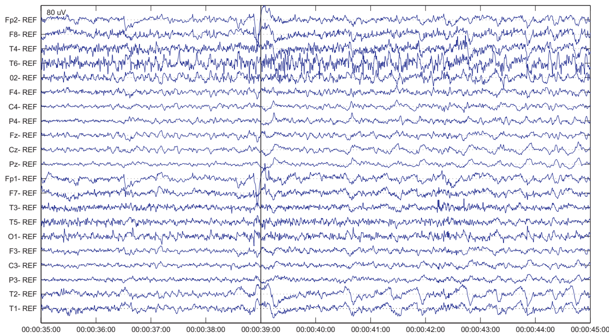
where $\mathbf{G}(\mathbf{r}_i, \mathbf{d}_i)$ is the scalp potentials caused by the $i'th$ dipole, calculated by solving the forward problem.

D. Data sets and algorithm parameters

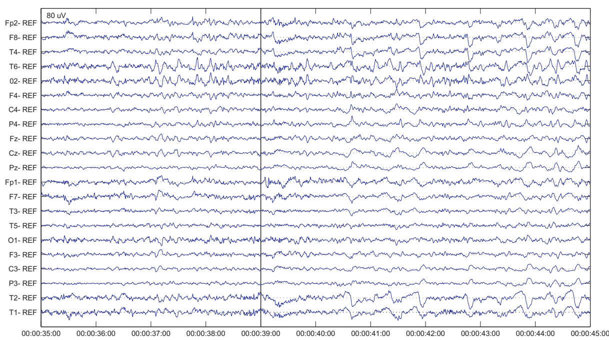
A total of 8 EEG-fragments of on average 1.5 minutes, including seizure onset, were analyzed. The EEGs were measured in a standard 10-20 system, with 2 extra temporal electrodes. The epochs were subjected to the BSS-CCA algorithm and to the pSVD algorithm, resulting in two data sets for each patient: a filtered one and an unfiltered one. In both data sets we applied RAP-MUSIC to estimate the dipolar focus of the seizure. The signal subspace was chosen to be spanned by the six vectors associated with the six highest singular values. In that signal subspace 3 dipolar sources were estimated by the scanning method. We applied a K-means clustering on the dipoles that had a RRE less than 25%. The K-means clustering searched of 6 clusters. The most prominent cluster is the cluster containing the most dipoles. The ictal SPECT of the 8 patients was used for a validation of the localization of the ictal focus. The ictal SPECT and the EEG was examined by an expert, who pointed the region where the seizure onset originated. Table I shows a summary of the data sets used. In the first column the patient is shown; in the second column is the localization according to ictal SPECT.

TABLE I
SUMMARY OF THE DATA SETS.

Patient	ictal SPECT
P1	Left Temporal
P2	Right Parietotemporal
P3	Left Temporal
P4	Left Temporal
P5	Left Frontal
P6	Right Temporal
P7	Left Frontotemporal
P8	Occipital

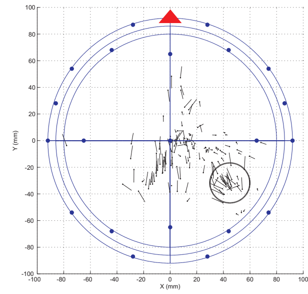


(a) Unfiltered EEG

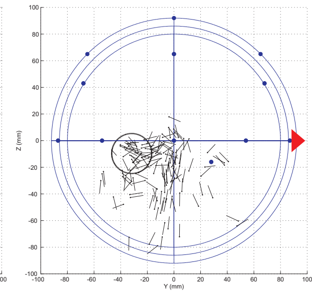


(b) BSS-CCA and pSVD filtered EEG

Fig. 1. Excerpt of the (a) unfiltered EEG and (b) filtered EEG. The seizure starts around 39 seconds as indicated by the black line.

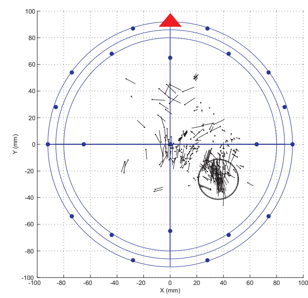


(a) View at top

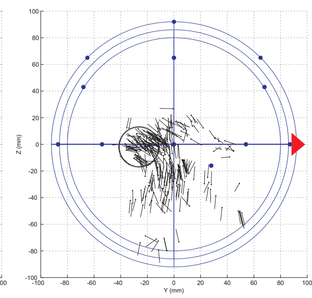


(b) View at right side

Fig. 2. A plot of the dipoles in a 3D spherical headmodel using the unfiltered EEG. Figures a and b represent the dipoles found after the seizure start. Figure a is in the XY-plane, while b is in the YZ-plane. The big triangle indicates the nose. A sphere indicates the most prominent cluster.



(a) View at top



(b) View at right side

Fig. 3. A plot of the dipoles in a 3D spherical headmodel using the BSS-CCA and pSVD filtered EEG. Figures a and b represent the dipoles found after the seizure start. Figure a is in the XY-plane, while b is in the YZ-plane. The big triangle indicates the nose. A sphere indicates the most prominent cluster.

III. RESULTS

The results of two cases are extensively described, followed by a summary of the results on all patients.

A. Patient P2

A first patient had seizures, originating from the right parietotemporal region, as was shown from the ictal SPECT. A 10 seconds window of the unfiltered EEG is shown in figure 1(a). A black line is drawn at the beginning of the seizure, which is around 39 seconds. We can see that the EEG is heavely distorted by muscle activity on channels T4, T6 and O2. Also an eye movement artifact is present at 39 seconds at channels Fp1 and Fp2. After the BSS-CCA and pSVD processing the same excerpt is shown in figure 1(b).

Figure 2 shows a plot of the estimated dipoles using the unfiltered EEG. Only the dipoles that were estimated after the black line, thus in the ictal period, are shown. A sphere shows the most prominent cluster (i.e. the cluster containing the most dipoles). This indicates that the localization is very diffuse. In a similar setting, a dipole plot of the filtered EEG by BSS-CCA and pSVD is shown in figure 3. Here we can see a more tight clustering of the dipoles, which is indicated by the sphere, in the right parietotemporal region at the time the seizure occurs. This corresponds with the ictal SPECT and the physician's opinion.

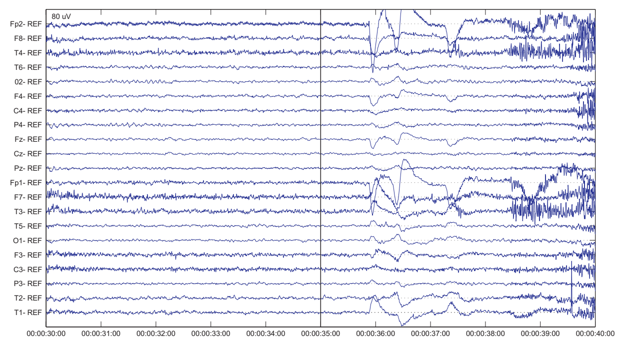
B. Patient P3

A second patient had left parietotemporal seizures, which was indicated by the ictal SPECT. The unfiltered EEG and the BSS-CCA and pSVD processed EEG are shown in figures 4(a) and 4(b). Again, a black line was drawn at the time the seizure started, which was at around 35 seconds.

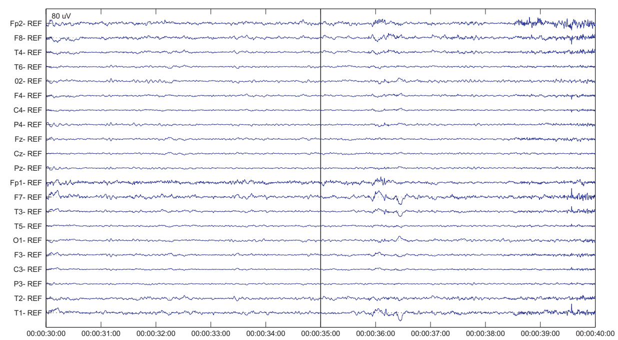
Figure 5 shows a plot of the estimated dipoles using the unfiltered EEG. Dipoles that occur in the ictal period is displayed in 5. The circle indicates the best clustering that was obtained by the k-means clustering. The centroid of the cluster is the center of the circle. We can see that the most prominent cluster is situated at the front of the head. This is due to a lot of eye artifacts, which can also be seen from the EEG in figure 4(a). The same setting was used for displaying the dipoles of the filtered EEG by BSS-CCA and pSVD is shown in figure 6. The most prominent cluster is shown in the circle, the centroid of the cluster corresponds to the center of the circle. Dipoles with the best subspace correlation form a cluster in the upper hemisphere in hte left frontotemporal region, which corresponds to the ictal SPECT. The cluster corresponds with the expert's opinion from the ictal SPECT.

C. Summary of the results

The results of the most prominent cluster obtained by the K-means clustering are shown in figure 7. For each patient we can see that the centroid of most prominent cluster of the unfiltered EEG moves to a new location in the BSS-CCA and pSVD filtered EEG. By visual inspection we can see that the new location of the centroid of the most prominent cluster is more in correspondance with the localization of the ictal

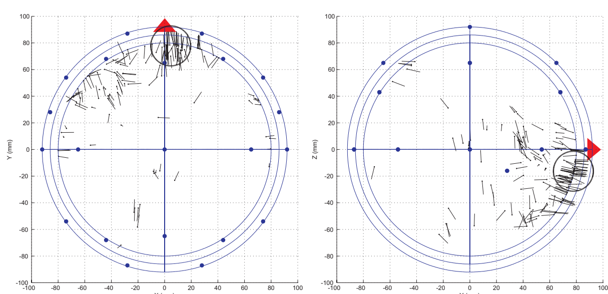


(a) Unfiltered EEG



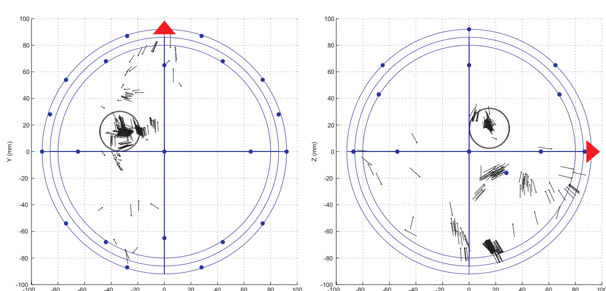
(b) BSS-CCA and pSVD filtered EEG

Fig. 4. Excerpt of the (a) unfiltered EEG and (b) filtered EEG. The seizure starts around 35 seconds as indicated by the black line.



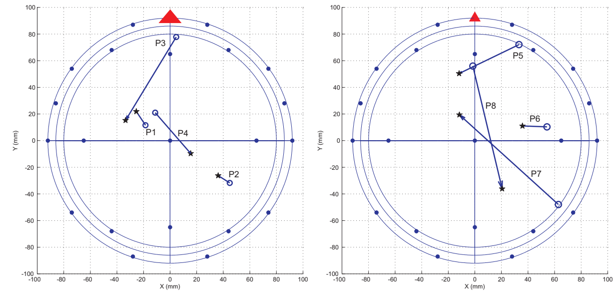
(a) View from top (b) View from right side

Fig. 5. A plot of the dipoles in a 3D spherical headmodel using the unfiltered EEG. Figures a and b represent the dipoles found after the seizure start. Figure a is in the XY-plane, while b is in the YZ-plane. The big triangle indicates the nose. A sphere indicates the most prominent cluster.



(a) View from top (b) View from right side

Fig. 6. A plot of the dipoles in a 3D spherical headmodel using the BSS-CCA and pSVD filtered EEG. Figures a and b represent the dipoles found after the seizure start. Figure a is in the XY-plane, while b is in the YZ-plane. The big triangle indicates the nose. A sphere indicates the most prominent cluster.



(a) (b)

Fig. 7. A plot of the clustercentroids of the most prominent cluster that is changed by the BSS-CCA and pSVD. For each patient an arrow is drawn from a circle shape to a star shape. The circle shape is the centroid of the most prominent cluster of the dipoles of the unfiltered EEG, while the star shape is the centroid of the dipoles of the BSS-CCA and pSVD filtered EEG. For the sake of visualization the figure is split up in two with the first 4 patients (P1-P4) in (a) and the last 4 patients (P5-P8) in (b).

focus, based on the expert's opinion of the ictal SPECT and shown in table I.

IV. Discussion and Conclusions

Removing muscle artifact removal and eye movement artifacts in the EEG improves the source localization of the ictal onset of the seizure. For 7 of the 8 patients we examined, the artifact removal resulted in better and tighter clusters. On top of that, the localization of the clusters corresponded with the ictal SPECT the physician's diagnosis. In the presurgical evaluation of patients with refractory epilepsy, the artifact removal techniques can greatly improve the localization the ictal onset zone based on the EEG.

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