Validating the effect of muscle artifact suppression in localizing focal epilepsy*

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Abstract— **Source localization of an epileptic seizure is becoming an important diagnostic tool in pre-surgical evaluation of epileptic patients. However, for localizing the epileptogenic zone precisely, the epileptic activity needs to be isolated from other activities that are not related to the epileptic source. In this study, we aim at an investigation of the effect of muscle artifact suppression by using a low-pass filter (LPF), independent component analysis (ICA), and a combination of ICA-LPF prior to source localization in focal epilepsy. These techniques were applied on the EEG data obtained from a left-temporal lobe epileptic patient by artificially contaminating the isolated spike interval, present in the four left-temporal electrodes, with a muscle artifact. The results show that the muscle artifact was fully suppressed. Applying the dipole and current-density reconstruction (CDR) source-analysis algorithms on the filtered data, we were able to identify the location of the epileptogenic zone similar to that of the original undistorted data.**

I. INTRODUCTION

Electroencephalographic (EEG) recordings are used to measure the electric fields of the brain by placing electrodes on the scalp according to the 10-20 system. Many neural diseases can be diagnosed using those recordings [1]. However, a main problem that can be encountered in the EEG measurements is the presence of different kinds of artifacts, such as physiological (eye movements, heartbeat, muscle activities, etc.) or technical (electrode popping, power-line) artifacts. In the case of epileptic brain-activity recordings, the most common artifacts correspond to muscle artifacts, which hide the physiological information such as the epileptic spikes.

As a straightforward solution to remove those distortions, a low-pass filter (LPF) is applied to all channels, assuming that the physiological information lies below a certain cut-off frequency; otherwise, the LPF is no longer a suitable technique.

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A very common technique used to decompose the signals into components and extract some of the artifacts is independent-component analysis (ICA). The artifactual components are removed prior to signal reconstruction [2]. In [3], ICA has been applied to remove muscle artifacts from patients with temporal-lobe epilepsy. However, it was observed that the muscle artifacts appeared in nearly all the components, and they were mixed with relevant brain activity. Therefore, it was then suggested in [3] to combine ICA with digital filters to remove muscle artifacts more efficiently. In [4], this suggestion was applied to ictal recordings (recordings during a seizure) and it was demonstrated that by using this combination, the identification of the ictal pattern was improved. For that reason, in this study, ICA is combined with a LPF in order to suppress the artifacts in a more efficient manner.

Source-reconstruction methods have been widely used as a non-invasive imaging technique during the diagnosis of pre-surgical evaluation of patients with focal epilepsy. Dipole and current-density reconstruction (CDR) methods serve as an effective tool. Dipole methods assume that active brain regions can be approximated by a few dipolar sources, whereas CDR methods assume that active brain regions are generated by a large number of dipolar sources distributed across the cortical surface [5]. In this work, we have used the fixed MUSIC dipole method and a CDR-based exact low-resolution electromagnetic tomography (eLORETA).

The aim of this work is to suppress the muscle artifact, that artificially contaminates the temporal-lobe epileptic spike, using LPF, ICA, and a combination of ICA-LPF before localizing the ictal activity using the dipole and CDR methods so as to validate that the original source location is similar to that of the source estimated after filtering.

II. METHODS

In order to perform the source analysis in signals that are artificially contaminated with muscle artifacts and locate the epileptogenic zone after suppression of the distortions, scalp EEG recordings were performed on a left-temporal lobe epileptic patient using 39 EEG electrodes. EEG was continuously recorded for 20 sec at a sampling rate of 500 Hz. The offline analysis started with the visual selection of a spike from a segment of 7.5 sec EEG data, so as to analyze the beginning of the spike. The isolated spike was present in the four left-temporal electrodes (T7, FT9, T9, and TP9). These electrodes have a spike pattern with onset, peak, and polarity reversal. To create the muscle

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artifact, a band-pass filter from 40-160 Hz was applied to real muscle artifacts from a different epileptic patient. The generated muscle artifact was added to the time interval of the spike present in those left-temporal electrodes to contaminate them. LPF, ICA, and a combination of ICA-LPF were employed thereafter to suppress the muscle artifact.

The method used to perform the source analysis integrated the use of a dipole method (fixed MUSIC) and CDR method (eLORETA) using the three-shell spherical head model as a model for the volume conduction. The estimated source location was superimposed on the standard brain template. The source analysis was applied separately on the signals before and after filtering for the time interval of the 50% rising phase of the spike (start of the spike deflection to the peak - 71 ms) and for the time interval of the spike (starting from the onset to the end of polarity reversal - 142 ms). The peak in both cases was marked at the time point of maximal negativity with the highest amplitude. The source analysis has been performed using CURRY software (from Neuroscan).

A. Muscle Artifact Suppression Techniques

1) Low-Pass Filter (LPF): As stated above, a straightforward solution to suppress the muscle artifact is by using a LPF. In this study, a Butterworth LPF is employed because it provides a maximally flat passband and presents a smaller phase distortion than other recursive filters, such as elliptic or Chevyschev types. The order of the employed filter is 10 and the cut-off frequency is set to 45 Hz. The contaminated data are passed through the LPF.

2) Independent-Component Analysis (ICA): ICA separates the signals into components by making two assumptions: The sources are supposed to be non-Gaussian (at most one Gaussian component is allowed) and they are assumed to be independent. The ICA model is described in [6].

$$\mathbf{y}(k) = \sum_{l=1}^{m} \mathbf{c}_l s_l(k) = \mathbf{C}\mathbf{s}(k), \tag{1}$$

where $\mathbf{y}(k) = [y_1(k), ..., y_n(k)]^T$ is the mixed-signal vector, k is the time instant, and n denotes the number of EEG electrodes. $\mathbf{s}(k) = [s_1(k), ..., s_m(k)]^T$ denotes the independent source signals. $\mathbf{C} = [\mathbf{c}_1, ..., \mathbf{c}_m]$ is an $n \times m$ mixing matrix of full rank, with $n \geq m$, i.e. the number of mixture signals is greater than or equal to the number of the independent sources. In this study, we deal with the case when $n = m$, i.e., no dimensionality reduction is applied.

Among all available ICA algorithms to estimate the independent components (ICs), we have used FastICA [7] (a MATLAB package freely available [8]) due to its fast convergence. The FastICA algorithm is used with the "deflation" approach and stabilization "on". This algorithm is applied to the contaminated data and the ICs are computed.

The ICs that are contaminated with artifact are selected by visual inspection of the time signals, since it was clear enough to see which components contain the muscle artifact (high amplitude and high frequency). The artifactual components were removed and the filtered data were reconstructed.

3) ICA-LPF: To have a more efficient suppression of the artifacts and keep the physiological information, ICA is combined with a LPF. The FastICA algorithm is applied to the contaminated data, and the components contaminated with muscle artifact, selected by visual inspection of the time signals, are passed through a Butterworth LPF with the same characteristics as described above. The filtered components that still contain residual muscle artifacts are removed completely.

B. Head Model

A classical spherical model with 3 shells is used in this study. These are concentric spherical shells, the first sphere representing the skin and the other two representing the skull and brain, respectively, having conductivity values of 0.33, 0.0042, and 0.33 S/m, respectively. Using the electrode positions provided in the EEG data, the best-fitting sphere is constructed with a radius of R for the outer-shell of the skin. The remaining shells of the skull and brain sharing the same center will have radii of 0.93 R and 0.85 R. The potentials measured at the scalp electrodes are then calculated using the closed-form analytical solution of Poisson's equation [9].

C. Source Localization

1) Fixed MUSIC: This is one of the dipole-source-reconstruction methods. Dipole models use an a-priori assumption about the number of dipoles. In this study, a single dipole was sufficient to accurately represent the source that best explains the measured scalp potential data with focal origin. The fixed MUSIC algorithm assumes source locations and orientations to be fixed with varying strength over time. It is a subspace-source-localization approach, based on the singular-value decomposition (SVD), to solve the spatio-temporal inverse problem using a scanning strategy. It scans a single-dipole model through the entire source space and computes projections on to the signal subspace.

The complete description of the fixed MUSIC algorithm is given elsewhere [10].

2) eLORETA: CDRs compute simultaneous activity at a large number of possible source locations and provide extra information, such as the extent of the neuronal activation. Moreover, CDRs do not require prior knowledge of the number of dipoles. eLORETA is one of the CDR methods which is a discrete, 3D-distributed, linear, weighted minimum-norm inverse solution. It assumes sources to be small and confined in a given cortical area, in this case the standard brain. The linear inverse solution shown in (2) with weights given by (3) estimates the source location with zero localization error for point sources [11]:

$$\hat{\mathbf{J}} = \mathbf{W}^{-1}\mathbf{L}^T(\mathbf{L}\mathbf{W}^{-1}\mathbf{L}^T + \alpha\mathbf{M})^{+}\mathbf{\Phi}, \tag{2}$$

where $\hat{\mathbf{J}}$ denotes the source to be estimated, $\mathbf{W}$ is a symmetric weight matrix, $\mathbf{L}$ is the lead-field matrix determined by the geometry and conductivity profile of the head, α is the regularization parameter, $\mathbf{M}$ is the centering matrix which subtracts the average value, making the inverse solution to be

reference independent, '+' denotes the pseudo-inverse, and $\mathbf{\Phi}$ denotes the potentials at scalp electrodes.

$$w_i = \left[\mathbf{L}_i^T(\mathbf{L}\mathbf{W}^{-1}\mathbf{L}^T + \alpha\mathbf{M})^{+}\mathbf{L}_i\right]^{1/2}, \quad (3)$$

where w_i are the diagonal elements of the weight matrix $\mathbf{W}$ and $\mathbf{L}_i$ is the i-th column of the lead-field matrix $\mathbf{L}$.

III. RESULTS

In Fig. 1, a segment of two 7.5 sec EEG signals are shown, recorded from the two left-temporal electrodes (TP9 and T9), before and after contaminating them with muscle artifact as well as after applying the three filtering techniques.

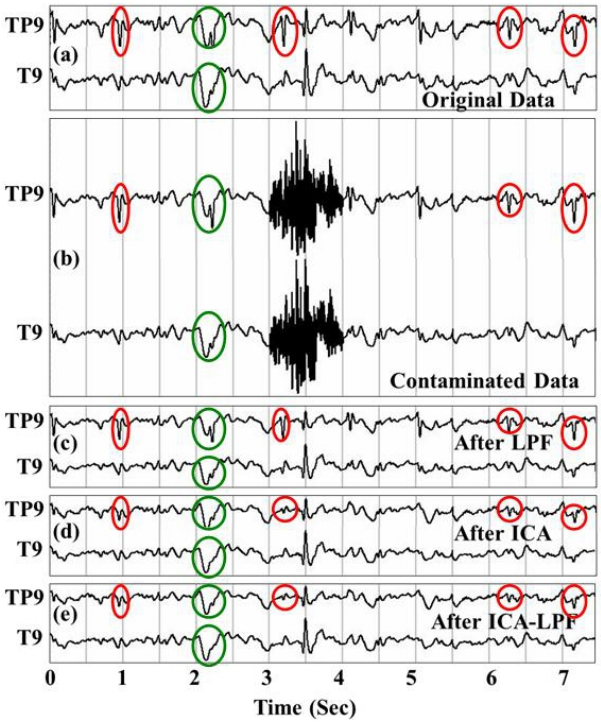

Fig. 1. (a) Original data before adding the muscle artifact, a segment of 7.5 sec out of 20 sec; (b) contaminated data, after adding a muscle artifact where a spike is present; (c) after using a LPF; (d) after using ICA; (e) after using ICA-LPF. The encircled signal represents the heart-beat artifacts and eye-blink artifact, indicated in red and green, respectively.

In Fig. 1a, the original undistorted signals from TP9 and T9 are plotted. A muscle artifact is then added to the interval where a spike is present. The distorted signals are plotted in Fig. 1b. As seen in this figure, the physiological spikes are hidden. After using a LPF, the muscle artifact is suppressed as observed in Fig. 1c. By using ICA, not only the muscle artifact is removed, but also the heart-beat artifacts, which is clearly seen in TP9, (see Fig. 1d). The same occurs when ICA is combined with a LPF, as observed in Fig. 1e, having less distortions in the latter case.

To quantify how well the filtering techniques suppressed the muscle artifact, we have divided the segment of 7.5 sec EEG data into 10 time intervals, each interval containing a data of 0.75 sec, and calculated the variance (average of the 4 left-temporal electrodes) for each interval separately before and after filtering. It can be seen from Fig. 2 that there is a significant difference of variance in the fifth interval where the artifact is added and after filtering the variance decreases indicating that the artifact is fully suppressed. In other intervals a clear difference between the original undistorted data and the filtered one's is observed which is due to the removal of heart-beat artifacts in addition to the muscle artifact. The increase in variance in the third time interval is due to the eye-blink artifact which is not removed by any of the filtering techniques. Hence, it can be seen in the original, contaminated, and filtered bar plots.

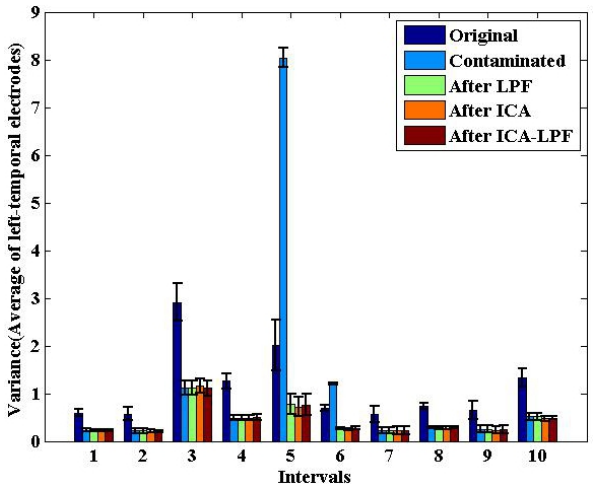

Fig. 2. Average variance comparison of the 4 left-temporal electrodes, between the original undistorted, contaminated and filtered data using LPF, ICA, and ICA-LPF, for each time interval obtained by dividing the segment of 7.5 sec EEG data into equal 0.75 sec EEG data. The error bars indicate the standard deviation of the estimated variances.

In Fig. 3, the source analysis results, using fixed MUSIC and eLORETA, for the time interval of the 50% rising phase and the whole spike pattern (starting from the onset to the end of polarity reversal) are shown for the original undistorted and the contaminated data as well as for the data after applying the three filtering techniques. It is expected that, after filtering, the source should be in the left-temporal lobe as found from the original undistorted data.

The fixed MUSIC localizes the source of the rising phase in the left superior-temporal lobe, whereas eLORETA shows the extent of the sources with the highest activity being in the left-temporal lobe as can be seen in Fig. 3a. The location of the source for the whole spike pattern, localized by the fixed MUSIC algorithm, moved to the left front-temporal lobe (brodmann area 44), whereas eLORETA maintains more or less a similar location to that of the rising phase, as can be seen in Fig. 3b. There is no significant difference in the current density of the highest source for the original and filtered signals, whereas for the contaminated data there is a significant increase of power which is due to the additional muscle artifact and not to the actual scalp EEG recording.

The result confirms that the location of the source after filtering is similar to that found from the original undistorted data, and the effect of the artificially added muscle artifact on the source localization can also be seen yielding a different

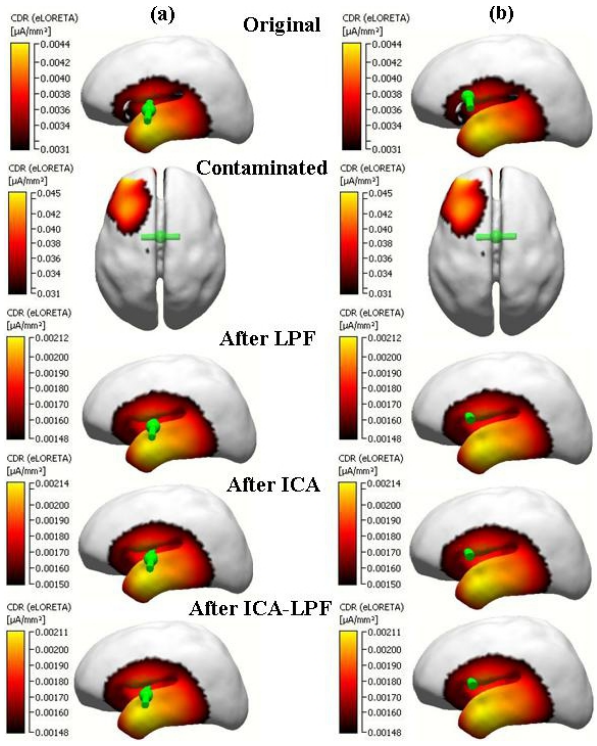

Fig. 3. Integrated-dipole (fixed MUSIC) and CDR (eLORETA) source localization, applied on the original undistorted, contaminated, and filtered data using LPF, ICA, and ICA-LPF, respectively, to localize: (a) the rising phase interval (3432-3503 ms); (b) the whole spike pattern (3432-3503-3574 ms). The peak of the spike is present at a time point of 3503 ms. The color bar indicates the intensity level of the current density from the lowest to the highest level.

location other than the region of interest. This result was supported by calculating the euclidean distance between the reference, i.e., the location of the source at the time point of maximal negativity from the original undistorted data (for the rising phase: -66.7,23.3,49.8 mm (for fixed MUSIC) and -60.9,15.2,32.6 mm (for eLORETA); for the spike pattern: -53.1,39.3,59.4 mm (for fixed MUSIC) and -59.2,18.1,33.1 mm (for eLORETA)) to that of the source at the same time point obtained from the three filtering techniques as shown in table 1. It can be clearly seen that the significant increase of the euclidean distance for the contaminated data has considerably been reduced after filtering and that all the three filtering techniques (LPF, ICA, and ICA-LPF) showed a closer distance indicating that the location of the source is almost similar to that found from the original undistorted data.

IV. CONCLUSIONS

In this study, we have performed muscle-artifact suppression by means of LPF, ICA, and ICA-LPF prior to localizing the cortical generators of the ictal activity in focal epileptic patient by means of dipole and CDR analyses. The results validated that a muscle artifact influences the source localization accuracy in identifying the accurate epileptogenic region responsible for the epileptic activity. The dipole (fixed MUSIC) and CDR (eLORETA) methods showed that estimated source of the filtered data, using the three techniques, were located in the left-temporal lobe as expected similar to that found from the original undistorted data. The two interval analyses of the rising phase and the whole spike pattern helped in understanding the epileptic focus. It was observed that, using the eLORETA, which has a zero localization error, the location of the strongest source for both time intervals was less variable than that of the fixed MUSIC method. The comparison between fixed MUSIC and eLORETA can be extended in future work by studying more patients with confirmed epileptic focus. Moreover, generating a pure muscle artifact using blind source separation techniques and application of canonical correlation analysis (CCA) method to remove the muscle artifact is of future interest.

TABLE I

EUCLIDEAN DISTANCE COMPARISON OF THE LOCATION OF THE SOURCE BEFORE AND AFTER FILTERING IN MM

Methods	Fixed MUSIC		eLORETA	
	Rising phase	Spike	Rising phase	Spike
Distorted	68.21	55.00	79.62	74.69
LPF	5.21	17.23	1.12	1.88
ICA	7.53	15.48	2.17	2.38
ICA-LPF	8.29	16.10	3.61	1.83

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