EEG preprocessing for synchronization estimation and epilepsy lateralization

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Abstract

The global framework of this paper is the synchronization analysis in EEG recordings. Two main objectives are pursued: the evaluation of the synchronization estimation for lateralization purposes in epileptic EEGs and the evaluation of the effect of the preprocessing (artifact and noise cancelling by blind source separation, wavelet denoising and classification) on the synchronization analysis. We propose a new global synchronization index, based on the classical cross power spectrum, estimated for each cerebral hemisphere. After preprocessing, the proposed index is able to correctly lateralize the epileptic zone in over 90% of the cases.

1 INTRODUCTION

The presurgical evaluation in patients suffering a drug-resistant partial epilepsy is a process involving several steps, the final goal being the localization of the epileptogenic zone (EZ) and the possible analysis of its connections to other cerebral areas. The first step towards localization of the EZ is its lateralization (finding the hemisphere generating the initial epileptic activity). A second step is the analysis of the spread of the ictal activity to other areas. A possible approach to both objectives is the synchronization analysis: a method of lateralization based on synchronization estimation can reinforce clinical reasoning and, next, the patterns of synchronization by hemisphere might indicate the dynamics of the ictal progression. This paper concerns the first step: our first aim is to investigate the lateralization ability of the synchronization estimators.

Literature concerning seizure lateralization is not so frequent. This lateralization is commonly made by visual inspection of interictal EEG [1, 2], ictal [3, 4] or using semi-automatic or automatic lateralization [5, 6]. In the framework of quantification methods for seizure lateralization two types of methods are presented in the literature: methods based on the temporal dynamics of EEG [7, 5] and those based on frequency domain

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[8, 9]. The main drawback in automatic lateralization using scalp EEG recordings is the presence of artifacts (eye blinking, muscular artifact, movement, chewing, etc.) and noise. The implementation of a methodology for automatic seizure lateralization could be an important tool for neurologists.

A second objective of this paper is to evaluate the effects of preprocessing of raw scalp EEG recordings and its impact on the study of automatic methods of synchronization, like the cross power spectrum (CPS). For this purpose, we briefly remind in section 2 some theoretical bases. The preprocessing methodology is also presented in this section. In order to quantify the information obtained by the interchannel relationship estimator an new index was introduced in this study. The results obtained on a database are presented and discussed in third section. Finally, in last section we conclude and we note some perspectives of this work.

2 METHODOLOGY

2.1 Synchronization in frequency domain

A multichannel autoregressive (AR) model writes as:

$$\mathbf{x}(t) = \sum_{k=1}^{p} \mathbf{A}(k)\mathbf{x}(t-k) + \mathbf{e}(t) \tag{1}$$

with $\mathbf{A}(k)$ as the AR coefficients matrix, n the number of channels, $\mathbf{x}(t-k)$ the time-delayed values vector, p the model order and $\mathbf{e}(t)$ the error vector. In frequency domain (1) becomes: $\mathbf{x}(f) = \bar{\mathbf{A}}(f)^{-1}\mathbf{e}(f) = \mathbf{H}(f)\mathbf{e}(f)$, where $\bar{\mathbf{A}}(f) = \mathbf{I} - \mathbf{A}(f)$ and $\mathbf{I}$ the identity matrix. $\mathbf{H}(f)$ is called the transfer function matrix. The power spectral matrix $\mathbf{S}(f)$ is obtained as: $\mathbf{S}(f) = \mathbf{H}(f)\mathbf{V}\mathbf{H}^{*}(f)$, where * denotes the Hermitian and $\mathbf{V}$ is the noise covariance matrix. The element $S_{ij}(f)$ of $\mathbf{S}(f)$ gives the cross power spectrum (CPS) and describes the common power distribution between 2 signals x_i and x_j in terms of frequency:

$$S_{ij}(f) = |\mathbf{S}_{ij}(f)| \tag{2}$$

In this work, we estimated the AR model using the Yule-Walker method (for the coefficients $\mathbf{A}(k)$) and the AIC (Akaike's Information Criterion) for the order p.

2.2 Preprocessing

Scalp EEG recordings are always disturbed by artifacts and noise. Artifact synchronization leads to errors in medical interpretation. That is why a preprocessing step should be considered. In scalp EEG signal processing framework, the model generally used considers a mixture of independent cerebral and non cerebral sources (artifacts) and noise.

The most frequently used method for identifying sources is the blind source separation (BSS) [10]. Most of the methods proposed in the literature for the identification and elimination of artifacts are a combination of two techniques: BSS and classification methods [11, 12, 13]. In order to take into account the additive measurement noise, we have applied in this work the complete prepocessing method proposed in [14, 15]. This method combines in an optimal manner BSS, classification and wavelet denoising (Figure 1).

Figure 1: Preprocessing chain

2.3 Global synchronization

In order to quantify the information provided by the synchronization method on the study, we propose an index. The matrix $\mathbf{M}_w = \{\sigma_{ij}\}$ is defined as proportional to the sum of the CPS in an interval of frequencies: $\sigma_{ij} = \sum_f S_{ij}(f)$, where i and j are two signals and f the frequency. In this work, we focus on electrophysiological (EP) frequencies band (0.5-32 Hz). This index quantifies the global synchronization by averaging all the off-diagonal elements of $\mathbf{M}_w$:

$$I = 2\frac{\sum_{i=1}^{N}\sum_{j=i+1}^{N}\sigma_{ij}}{N(N-1)} \tag{3}$$

The index indicated above is calculated for 4 windows: interictal/ictal period, right/left hemisphere. To compare the I values for the different EEG recordings, a normalization index is required. Thus, each value is normalized with respect to the sum of all 4 estimated indices [1]:

$$I_{ln} = \frac{I_l}{I_{ic,l} + I_{ic,r} + I_{i,l} + I_{i,r}} \tag{4}$$

3 RESULTS AND DISCUSSION

3.1 Database

The 51 recordings of our database were recorded in 28 adult patients with epilepsy: 23 patients with 2 recordings and 5 patients with a single recording. All patients, aged between 16 and 56 years old, were diagnosed with temporal lobe epilepsy (31 left and 20 right). Recordings were acquired using 24 electrodes placed on the scalp (EEG surface) according to the International 10-20 system.

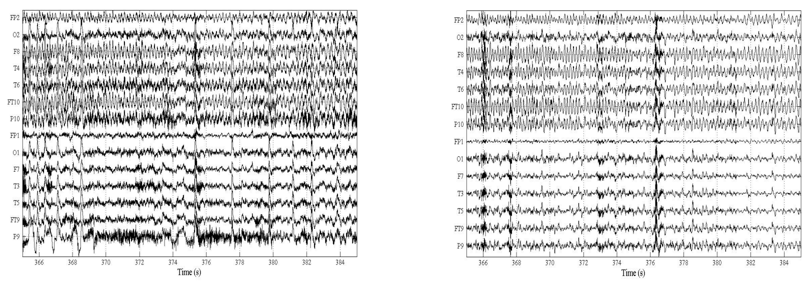
3.2 Preprocessing and synchronization

This section focuses on the benefits of applying this preprocessing methodology on EEG recordings in order to improve the results of automatic analysis methods. We present here the results of the synchronization estimation on raw and preprocessed EEG. The window size was fixed at 20 s and two kind of windows were used: one

[1] l and r symbolize the left/right hemisphere and ic and i the interictal/ictal windows respectively.

interictal, containing normal brain activity, and one ictal window, taken 5 s after the seizure onset indicated by the clinician.

To illustrate this application, we take first the ictal EEG window, acquired using the International 10-20 system. The Figure 2(a) shows only 14 channels (Fp1, O1, F7, T3, T5, FT9 and P9 and the corresponding opposite hemisphere electrodes) selected by the neurologists as the most representative electrodes for our application. The recording is highly disturbed by ocular and high frequency artifacts. The Figure 2(b) presents the same interval after preprocessing.



(a) raw (b) preprocessed

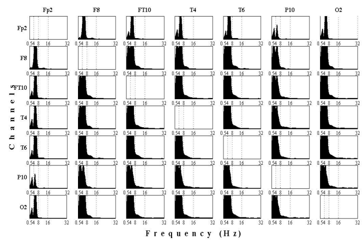
Figure 2: Ictal EEG example

We observe that ocular artifacts were reduced, while epileptic activity is more evident in some channels. The high frequency activity was not completely eliminated, but it decreases remarkably. This is a clear example of the importance of preprocessing in artifact-contaminated and noisy scalp EEG recordings, improving firstly their visual inspection. Figures 3(a) and 3(b) illustrate the CPS corresponding respectively to the 7 right and left channels without preprocessing, while Figures 3(c) and 3(d) show the CPS after preprocessing. Since we are interested here only in the interchannel synchronization, the diagonal elements (power spectra) were set to 0.

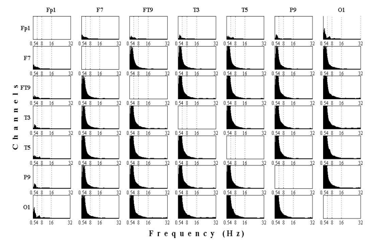
A visual analysis of Figures 2(a) and 2(b) confirms that epileptic activity is present in channels corresponding to the right hemisphere (also indicated by clinicians). This observation is confirmed by the synchronization analysis. For raw EEG, synchronizations in θ (4-8 Hz), band mainly associated with epileptic activity, appear much more on the CPS of the Figure 3(a) than on the CPS of the opposite side. We can also notice that the δ activity, unrelated to seizures is present in both hemispheres. The analysis of the preprocessed CPS (Figures 3(c) and 3(d)) shows that δ activity decreases as a result of preprocessing, while the information corresponding to seizure is not perturbed. Synchronizations associated with ocular artifact were reduced. We also notice that the CPS energy is higher on the hemisphere containing the origin of seizure than on the opposite side.

The second example corresponds to the interictal signals (not presented). As previously, Figure 4 show the CPS of the 7 channels in study before and after preprocessing.

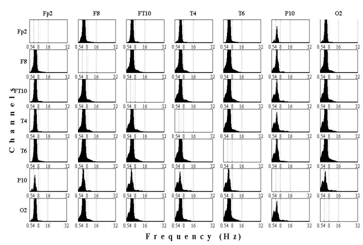
In Figures 4(a) and 4(b), we observe the existence of a δ (0.5-4 Hz) activity, most notably in the right hemisphere than in the left one. This activity is normally associated to ocular artifact. The reduction of δ and β (13-30 Hz) activities in original recordings



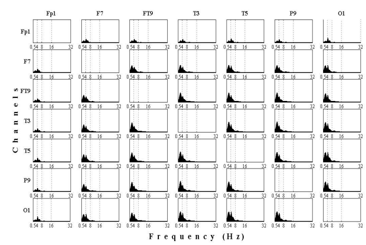
(a) right hemisphere, raw



(b) left hemisphere, raw

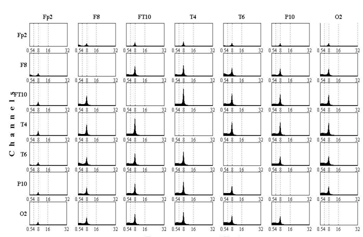


(c) right hemisphere, preprocessed

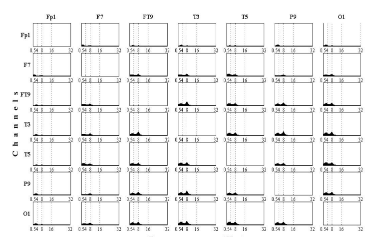


(d) left hemisphere, preprocessed

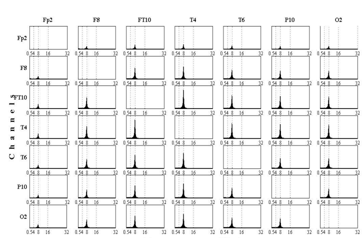
Figure 3: Cross power spectrum of an ictal EEG



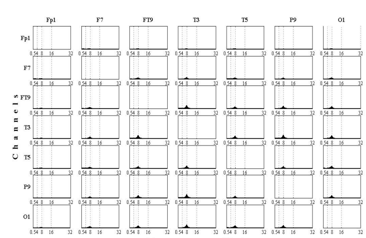
(a) right hemisphere, raw



(b) left hemisphere, raw



(c) right hemisphere, preprocessed



(d) left hemisphere, preprocessed

Figure 4: Cross power spectrum of an interictal EEG

by preprocessing improves the CPS, as shown in Figures 4(c) and 4(d). In general, we can notice that in the interictal period, signals contain less energy than during seizure.

3.3 Lateralization

As said previously, the normalized indices I_n (4) are calculated for each hemisphere, before and during the ictal period, before and after preprocessing. Thus, 16 normalized values of I are obtained for each recording. Table 1 shows the 16 mean values and standard deviations obtained for the complete database.

Table 1: Mean values and standard deviations of I_n.

Right seizures (20 patients)				
Period	**Interictal**		**Ictal**	
Hemisphere	Left	Right	Left	Right
Raw	0.081 (0.081)	0.081 (0.079)	0.354 (0.119)	0.485 (0.126)
Preproc.	0.051 (0.054)	0.059 (0.063)	0.319 (0.129)	0.569 (0.169)
Left seizures (31 patients)				
Raw	0.058 (0.061)	0.052 (0.057)	0.513 (0.096)	0.376 (0.085)
Preproc.	0.069 (0.064)	0.065 (0.062)	0.578 (0.135)	0.288 (0.080)

A first global analysis shows that the highest means of the computed index correspond to the channels on the seizure side, both for raw and preprocessed data. In other words, for patients with a right epileptic focus, the highest means are obtained in right channels. This remark is similar for the opposite side. A more detailed analysis highlights the role of the preprocessing: for patients having a right seizure, the index of the opposite hemisphere (left) decreases with preprocessing; however, the index in the hemisphere containing the epileptic focus (right) increases with preprocessing.

In interictal period, the mean values in both hemispheres are small and close between them. A small decrease, probably due to the elimination of non-informative activities by preprocessing, of this mean values is observed.

In order to illustrate Table 1, a left vs. right indices graphic can be obtained, as the Figure 5 shows. A bisector was drawn to distinguish between left/right seizures.

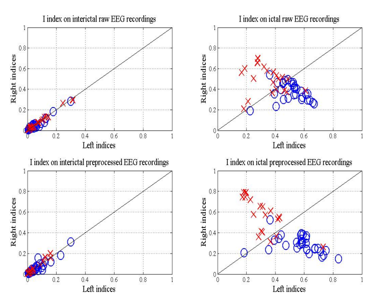


Figure 5: Results of I_n on the database in EP band ("$\circ$" represents patients with left seizures and "$*$" denotes patients with right seizures).

In Figure 5, indices of interictal raw EEG are close and it is difficult to distinguish between left and right seizures. However, for ictal indices, the difference of seizures is clearer. Nevertheless, some seizures are close to the bisector, making difficult their possible lateralization. The interictal conditions are similar for raw and preprocessed indices. However, in the graphic during ictal period after preprocessing a better seizure separation is appreciated. Despite this improvement, some seizures were estimated on the wrong side. According to this evidence (quantitative and visual), it seems that we can distinguish more easily between the two hemispheres during ictal interval and that this discrimination is improved by applying a preprocessing step.

4 CONCLUSIONS AND FUTURE WORKS

The importance of preprocessing in scalp EEG recordings was highlighted in this work. The preprocessing showed, in a first time, a significant improvement in visual inspection of EEG recordings and, in a second time, in the study of synchronizations. This study could lead to a possible application: the seizure characterization. This characterization could be from 3 perspectives: temporal (which synchronizations are present), in frequency (which bands are involved in synchronizations) and spatial (which channels are involved). A future study suggests the application of preprocessed EEG to studies of direct and indirect causality, using methods as the DTF or the PDC, which have demonstrated a good performance as relationship estimators in previous works [16], in order to reduce false connections due to non-existent synchronizations.

The proposed index aimed to quantify the global synchronization of the channels under study. After the discussion presented in the previous section, it seems that this index could allow both the lateralization and the detection of epileptic seizures. For example, if we consider a simple lateralization criterion as the ratio between left and right indices ($L = I_l/I_r$), we could say that if L>1, we are in the presence of a left seizure, whereas if L<1 we have a right seizure. If we apply this criterion to our database, we have for raw EEG a 78.43% (40) of good lateralizations, whereas for preprocessing recordings we get a 90.20% (46) of seizures well lateralized.

As mentioned previously, in this work we focused the EP band (0.5-32 Hz). Future investigations aim to use EP sub bands (δ, θ, α, β). It is also possible to propose a similar analysis using a different window size. Another kind of indices could be proposed, for example indices to quantify the maximum or the spatial synchronization, or a combination between them. We only used 7 channels, but a study using different or more electrodes is also possible. Finally this study was made using static windows. An improvement could be using sliding windows with the objective to obtain a dynamic study.

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