A New Method for Detection and Source Analysis of EEG Spikes

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Abstract—**In the past our research group has developed a method for the detection of focal epileptic EEG (electro-encephalogram) spikes that is based on the dipole source localization technique and provides a source localization for each detected spike. In this paper we revisit this method and propose a more accurate explanation of its behavior. Based on this we (i) propose a new method for the detection of epileptic EEG spikes in which the eccentricity of the fitted dipole serves as a new decision variable (ii) conclude that for EEG spike detection one has to make a distinction between EEGs acquired during sleep and during wake.**

Keywords—**Detection, dipole eccentricity, EEG, source analysis, spikes**

I. Introduction

The electroencephalogram (EEG) reflects the electrical activity of the neurons within the brain. It is an important clinical aid for the diagnosis of epilepsy, since the EEG of patients with epilepsy can reveal typical epileptiform activity, during seizures (ictal EEG) and in between seizures (interictal EEG). The most prominent example of interictal epileptiform activity is the epileptic spike. Using electrical source localization techniques, it is possible to identify the so-called irritative zone, i.e., the area in the brain where the interictal spikes originate. The localization of this area also provides important information about the brain area involved in the onset of the epileptic seizures, called the ictal onset core. The most commonly used source model for a focal brain source is the current dipole model.

In order to successfully apply these EEG source localization techniques, one first has to identify the present interictal spikes in the (possibly long-term) EEG recording. Since the visual identification of this epileptiform activity is a very time consuming and intensive operation, a method for the automatic detection of these spikes would be highly appreciated. Furthermore, such a method would, at least, allow a semi-automatic identification of the irritative zone and/or epileptogenic focus.

In the past, our research group has developed a method for the detection of focal epileptic EEG spikes that is based on the dipole source localization technique and that combines a spike detection and localization in a single method [1,2]. In this paper we revisit this method, and propose a more accurate explanation of its behavior than the ones that have been proposed so far. Based on this, we introduce a new method for the combined detection and source analysis of epileptic EEG spikes.

II. Methods

A. Dipole modeling: fixed dipole

The EEG measured by m electrodes at a single time instance can be represented by the vector $\mathbf{v}_{meas} \in \mathbf{R}^{mx1}$. If we can assume that these measured potential differences are caused by a focal electrical source in the brain, then a current dipole can be used to model the measured EEG and localize the electrical active area in the brain. A current dipole is characterized by its position $\mathbf{r}_d$, orientation $\mathbf{e}_d$ and intensity parameter d, and the relation between the generated potential differences and the dipole parameters can be written as: $\mathbf{v}_{mod} = \mathbf{L}(\mathbf{r}_d)\bullet\mathbf{d}$, with $\mathbf{d} = d\mathbf{e}_d$. The matrix $\mathbf{L}$ is called the lead field matrix, and is determined by the dipole position, electrode positions, and the head geometry.

The dipole parameters for the dipole that best (in the least-square sense) describes a given measured potential topography $\mathbf{v}_{meas}$ can be found by iteratively minimizing the relative residual energy [4] (*RRE*): $RRE = \|\mathbf{v}_{meas} - \mathbf{L}(\mathbf{r}_d)\bullet\mathbf{d}\|^2 / \|\mathbf{v}_{meas}\|^2$, with $\|.\|$ the Euclidian norm.

B. Focal spike detection using a dipole source model

In search for interictal spikes with a focal origin, the EEG within a sliding window, with a width of n time samples, is investigated using a fixed dipole model. Since we assume that these spikes are caused by a small area in the brain, this means that we search for EEG epochs (i) where only one source is electrically active and (ii) that can adequately be modeled by a current dipole source. Here, we would also like to remark that these are only necessary conditions for the presence of a spike in the EEG epoch under investigation, not sufficient conditions: certain scalp potential distributions can be caused by extended electrical activity, but can still quite accurately be modeled by a single dipolar source. Also note that these requirements impose no constraint on the precise shape of the spikes.

The method proceeds as follows. First, the EEG epoch within a sliding window $\mathbf{V}_{meas} \in \mathbf{R}^{mxn}$ is decomposed using a Singular Value Decomposition (SVD) [3]: $\mathbf{V}_{meas} = \mathbf{U}\bullet\mathbf{\Sigma}\bullet\mathbf{V}^T = \Sigma_i\ \sigma_i\ \mathbf{U}(:,i)\bullet\mathbf{V}(:,i)^T$. This expression can be interpreted as a weighted sum of the outer product of m potential topographies (columns of matrix $\mathbf{U}$) and the corresponding time series (columns of matrix $\mathbf{V}$), with the singular values as the weighting factors. Since we search for EEG epochs where only one source is active, it is meaningful to define the following measure: $S = (\sigma_1)^2 / \Sigma_i\ (\sigma_i)^2$, which indicates what fraction of the total energy in the EEG epoch is contained within the first SVD component. For these epochs where an interictal spike is present, S should have a large value, indicating that a single SVD component is dominant in the EEG epoch.

Next, the first SVD component of the EEG epoch under investigation is analyzed using a fixed dipole model. In the presence of an interictal spike, we should obtain a good dipole fit, and hence a low value of the $RRE = \|\mathbf{U}(:,1) - \mathbf{L}(\mathbf{r}_d)\bullet\mathbf{d}\|^2$.

To summarize, an EEG epoch is labeled as containing an epileptic EEG spike, if the fraction of the energy in the first SVD component S is above a certain threshold θ_S, and the relative residual energy RRE of the dipole model for this first component drops below another threshold θ_{RRE}.

C. Detection variants

In order to gain an insight into the proper functioning of the presented method, we investigated the performance of the following detection variants:

(0) detection iff $S > \theta_S$ & $RRE < \theta_{RRE}$
(1) detection iff $S > \theta_S$
(2) detection iff $RRE < \theta_{RRE}$
(3) detection iff $(\sigma_1)^2 > \theta_\sigma$
(4) detection iff $E_V = \Sigma_i (\sigma_i)^2 > \theta_E$
(5) detection iff $S > \theta_S$ & $\|\mathbf{r}_d\| < 7.9$ cm
(6) detection iff $(\sigma_1)^2 > \theta_\sigma$ & $\|\mathbf{r}_d\| < 7.9$ cm

Detection variant (0) is the original detection method we discussed in section II.B. In variants (1) and (2), the detection is accomplished with only one of the derived detection parameters: this allows us to study the behavior of each parameter separately. In detection variant (3), we use the un-normalized version of the detection parameter S. In variant (4) the detection is based on the total energy in the EEG epoch under study. Variants (5) and (6) use the same detection criterion of, respectively, variants (1) and (3), however with an additional restriction on the fitted dipole position: the eccentricity of the dipole should be smaller then 7.9 cm, i.e., only EEG epochs for which the fitted dipole is within the brain compartment are retained.

TABLE I
EEG FRAGMENTS USED AND THE EER OF DETECTION METHOD

n°	n° of spikes	wake / sleep	type of epilepsy	n° of eye blinks	EER detection method
1	246	wake	CPS ± SG	132	72[5]
2	239	wake	CPS ± SG	61	72
3	80	sleep	CPS ± SG	0	40
4	129	sleep	CPS ± SG	0	40

legend: CPS = complex partial seizure; SG = secondary generalization

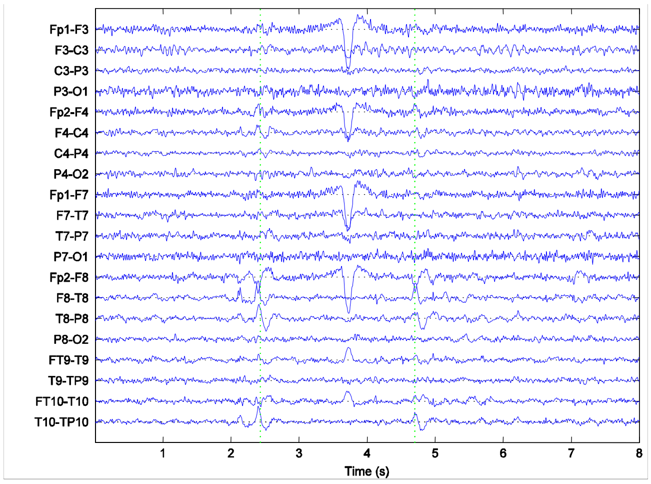

Fig. 1. EEG fragment of 8 s duration of patient 1.

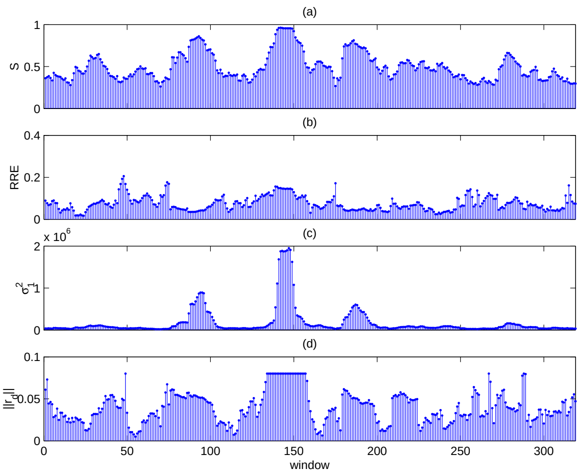

Fig. 2. Parameters S (a), RRE (b), $(\sigma_1)^2$ (c) and $\|\mathbf{r}_d\|$ (d) as a function of time.

III. MATERIALS

The EEGs we used for revisiting and improving our detection method, were recorded with a 32-channel Telefactor Beehive system for long-term EEG monitoring, using a sample rate of 200 Hz. Twenty-one electrodes were placed according to the international 10-20 system, with six additional lateral electrodes to cover the temporal regions.

The detection method was investigated using four EEG epochs of 20 minutes, from four different patients with refractory complex partial seizures with a suspected seizure onset in the temporal lobe; two of these EEG recordings were acquired during sleep (see table 1). The interictal epileptic spikes in these EEG fragments were visually identified by an experienced neurophysiologist in order to validate the detection method. Also, the eye blinks present in the recordings were manually labeled.

A time window of 250 ms (n = 50 samples) was used, and the analysis window was moved in steps of 25 ms. For the dipole calculations, a three-shell spherical head model was used. The boundaries between the spherical brain compartment and the spherical shells for skull and scalp had a radius of 8.0, 8.5 and 9.2 cm, respectively. The conductivity ratio between the soft tissue and the skull was set to 80.

IV. Results

Fig. 1 shows an EEG fragment of 8 s duration of patient 1, with two epileptic spikes (approximately at 2.5 and 4.5 s), and one eye blink (approximately at 3.5 s). In fig. 2, the evolution in time for this EEG fragment of the parameters S, RRE, $(\sigma_1)^2$ and $\|\mathbf{r}_d\|$, respectively, is plotted. Fig.3 displays the Receiver Operating Characteristic (ROC) curves of the original detection method that are obtained for the whole EEG fragment of patient 1. Each curve corresponds to a particular choice of the threshold θ_S; the parameter θ_{RRE} varies along each of these curves. The envelope of the different ROC curves can be considered to be the general ROC curve of the detection method. Table 1 lists, for all four EEG fragments, the Equal Error Rate (EER) that was achieved for this method. The EER is the point of the ROC curve for which the sensitivity is equal to the specificity. Fig. 4 shows the ROC curves that are obtained for the variants discussed in section II.C, again for the EEG fragment of patient 1. Finally, the windows used in the detection method were labeled into two categories according to the visual scoring of the neurophysiologist: windows containing a spike (‘spikes’) and windows containing an eye blink (‘eye blinks’); the remaining windows were classified as ‘rest’. Fig. 5 displays the value distribution of the parameters S, RRE, $(\sigma_1)^2$ and $\|\mathbf{r}_d\|$, respectively, for the EEG fragment of patient 1 according to these categories.

V. Discussion

From table 1, it is striking to observe the large difference in performance of the detection method that can be obtained with EEG fragments obtained during wake and sleep: during wake, an acceptable level of performance could be achieved by a proper choice of the threshold parameters, whereas during sleep the maximum sensitivity and specificity that can be achieved are quite inadequate for practical application. An inspection of the EEG during sleep, along with the calculated parameters S and RRE, showed that although at the time instances where a spike was present the parameter S had large values (confirming our assumption that the spike is generated by one source), there were numerous other time instances where the

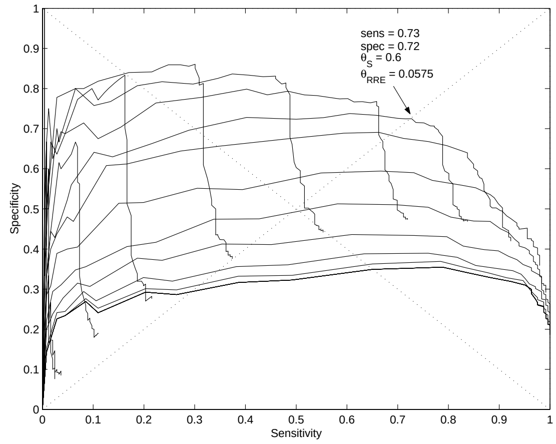

Fig. 3. ROC curve of the detection method (0), for the EEG fragment of patient 1.

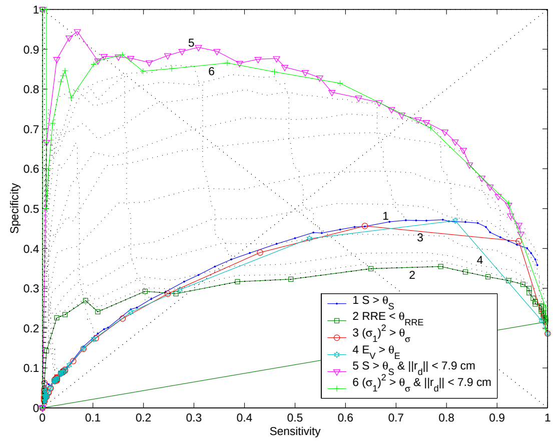

Fig. 4. ROC curves for the detection variants (1) – (6), for the EEG fragment of patient 1. The ROC curves from the detection variant (0) are over plotted with a dotted line.

parameter S had large values as well. The parameter RRE did not provide useful information to make the discrimination between the present epileptic spikes, and the other time instances where S had a large value.

The poor performance of the method during sleep probably has to be attributed to the presence of different generators of the EEG during sleep and the fact that during sleep, a number of other phenomena occur in the EEG that can be well described with one dipolar source, although the underlying source can be spatially extended. Also interesting to observe is the fact that during sleep a lot of electrical activity originates from the irritative zone. The waveforms associated with the underlying source, however, do not show a typical epileptic spike pattern. It is tempting to assume that the detection method picks up this activity, since the method searches for focal activity, without focusing on a specific waveform. In the following, we will focus on the EEG of patient 1 and 2 (EEG acquired during wake).

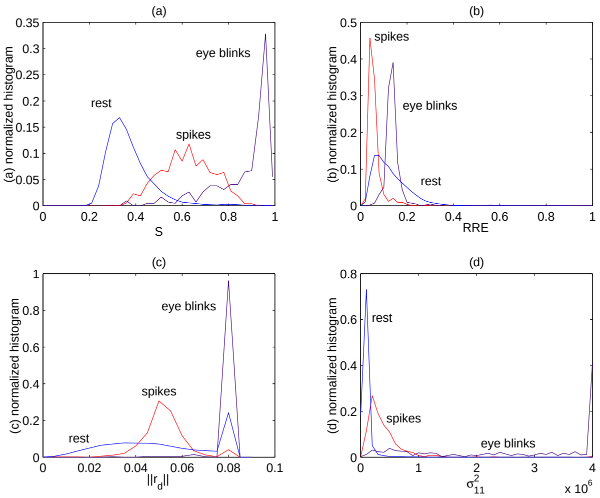

Fig. 5. Value distribution of the parameters S (a), RRE (b), $\|\mathbf{r}_d\|$ (c) and $(\sigma_1)^2$ (d).

The good performance of the method during wake can be appreciated in fig. 3: for a proper choice of the threshold values, a sensitivity and specificity of more then 70 % can be reached.

In fig. 2 (a) and (b), it can be observed that at the time instances where a spike is present, S has a large value, and RRE has a small value, as could be expected. We further note that at the time instance were an eye blink occurs, S also has a large value, but the RRE at that time instance is larger than the RRE values obtained for the present epileptic spikes. This larger value can be understood, because, as is intuitively clear, an eye blink can be better modeled with two dipoles [5], instead of one. Therefore, although both spikes and eye blinks have a high value for the S parameter, the discrimination between the epileptic spikes and the eye blinks can be made based on the value of the parameter RRE, as can also be clearly seen from fig. 5 (b).

In fig. 4 it is observed that the variants (1), (3) and (4) have a comparable performance for the EEG of patient 1. For patient 2, however, we found that the variants (3) and (4) outperformed the detection variant (1). The better performance of variant (4), where a detection is performed based on the total energy in the sliding EEG window, indicates that the amplitude of a spike is a very important characteristic; a characteristic that is lost by using the parameter S. It can be understood that variant (3) performs almost identical to variant (4), since for a spike almost all the energy will be concentrated in the first SVD component (based on the assumption that a spike is generated by one source – an assumption that was confirmed by the observation that the parameter S had large values for the spikes). It even slightly outperforms variant (4), since the use of only one SVD component implies some form of noise reduction.

In fig. 2 (d), it can be observed that at the time instance where the eye blink occurs, the eccentricity of the fitted dipole reaches the value 8.0 cm, i.e., the border of the brain compartment. This observation led to the formulation of the detection variants (5) and (6). In fig. 4 we can see that the variants (5) and (6) have the same or even a better performance than the original detection method. This can be understood as follows: previously we have shown that the parameter RRE chiefly makes the discrimination between spikes and eye blinks. This role is now fulfilled by the parameter $\|\mathbf{r}_d\|$. The better performance has to be attributed to the fact that this criterion on the dipole eccentricity at the same time removes electrode artefacts. A big advantage of these variants is that there remains only one threshold value to be selected (for the parameter S or $(\sigma_1)^2$), since the border of the brain compartment is known a priori. For patient 2 we also found the same or better performance of variants (5) and (6); variant (6) had the best performance.

VI. Conclusion

We conclude that: (i) the parameter S is capable of identifying those EEG epochs where only one source is active (focal spike), but that an important characteristic of a spike, namely its higher amplitude, is lost; therefore the use of the parameter $(\sigma_1)^2$ has to be considered, (ii) the role of the parameter RRE chiefly lies in making the discrimination between spikes and eye blinks. We showed that this discrimination can better be fulfilled by observing the eccentricity of the fitted dipole, (iii) one has to make a distinction between EEG's acquired during sleep and during wake: during wake, an approach based on variant (5) or (6) could be followed in order to search for typical EEG spikes. During sleep, the original detection variant could be further explored for its capabilities to identify the irritative zone.

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