DETECTION AND LOCALIZATION OF EPILEPTIC BRAIN ACTIVITY USING AN ARTIFICIAL NEURAL NETWORK FOR DIPOLE SOURCE ANALYSIS

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ABSTRACT
We present a method for the detection of focal epileptic spikes in the EEG (electroencephalogram). The method is based on the dipole source localization technique and provides a source location estimate for each detected spike. An artificial neural network is used for performing dipole source localization, in order to be able to perform the detection method in real-time. The sensitivity and specificity of the method is studied on the basis of real patient EEG. It is observed that the method is able to operate with a sensitivity and specificity of 80% and 60%, respectively. We conclude that the method is suitable for real-time preprocessing of long-term EEG recording, in order to extract the relevant EEG epochs for subsequent source analysis.

1 INTRODUCTION
The electrical activity of neurons within the brain is reflected by the potential distribution measured on the surface of the head. An electroencephalogram (EEG) is a measurement of the time-varying potential differences between electrodes fixed on the skin of the head (scalp). The EEG is used in many applications where the spatial and temporal aspects of electrical brain activity are studied. In patients with epilepsy, spike activity is a frequently encountered feature in the EEG. Localization of the small region in the brain where the spikes originate, provides information used to identify the brain area involved in the onset of epileptic seizures, called the ‘epileptogenic focus’ [1].

When analyzing long-term EEG acquisitions that last several days, the first step is the detection in time of epileptic spikes. Automatic detection methods for epileptic spikes are very desirable, because the visual inspection of the whole EEG measurement is too time-consuming in practice. The second step is to use localization techniques for determining the source region of the epileptic spikes within the brain. A commonly used approach is to model the electrical activity as a current dipole, and to determine (iteratively) the location and orientation of the dipole source that best fits the spatial potential distribution and temporal variation of the measured epileptic spike [2, 3].

In this paper, we present a method, based on dipole source analysis, that combines both the detection and the localization of epileptic spike events in the EEG. In order to make it possible that the method be applied to EEG signals in real-time, we trained an artificial neural network (ANN) to perform the dipole source localization [4]. This approach results in a substantial speed-up compared with the traditional iterative dipole localization procedure.

2 METHODS
2.1 Iterative dipole source localization
The EEG measured at m electrodes at a single time instant can be represented by the vector $\mathbf{v}_{\text{meas}} \in \mathbb{R}^{m \times 1}$. In our experiments, 27 EEG electrodes were used. If the measurement originates from a focal electric source in the brain, the 3 location and 3 component parameters of an equivalent dipole model are determined by minimizing the residual energy (RE), expressed in percent:

$$RE = \frac{||\mathbf{v}_{\text{meas}} - \mathbf{v}_{\text{mod}}||}{||\mathbf{v}_{\text{meas}}||^2},$$

where $\mathbf{v}_{\text{mod}} \in \mathbb{R}^{m \times 1}$ contains the potentials generated by the dipole model. The residual energy indicates the fraction of the energy in $\mathbf{v}_{\text{meas}}$ that is not explained by the dipole model.

The most common approach in dipole localization is to adapt iteratively the dipole location and components, until the optimal dipole parameters are found, using, e.g., the simplex algorithm [5] as a minimization procedure for the $RE$. In each iteration, a so-called forward evaluation is performed, that calculates the electrode potentials corresponding with the dipole parameters. For forward evaluations, either spherical or realistically shaped head geometries can be used to model the
2.2 Dipole localization using an artificial neural network

A multi-layer perceptron is trained for performing dipole source localization. The network has 27 inputs for applying the electrode potentials, two hidden layers each having 45 neurons, and three output neurons yielding the desired dipole locations. Neural network training is performed by applying the error-backpropagation algorithm [6] in the incremental mode. The training examples are artificially generated by choosing at random a dipole location and dipole components, and by calculating the corresponding electrode potentials with a forward evaluation in a (spherical or realistic) head model.

2.3 Focal spike detection using a dipole source model

When an arbitrary epoch of measured EEG is presented, the residual energy measure can be used to investigate whether the signals were produced by a focal electric source. In search for the presence of epileptic spikes with focal origin, the EEG within a sliding time window with a width of \(n\) time samples is analyzed with the dipole source localization technique (either iteratively or using the ANN), resulting in the \(RE\) measure as a function of time. If a focal spike is present in the EEG, the \(RE\) should become zero in the ideal case that no background EEG activity would disturb the spike. In practical situations with background EEG present, a significantly low \(RRE\) can be expected. If the time window is located over an epoch of EEG that contains no focal EEG event, the resulting \(RE\) will have a high value, because at that time instant, the brain activity cannot be modeled by a dipole.

Prior to performing a dipole source localization, the EEG within the considered time window is first preprocessed using a singular value decomposition (SVD) [7]: the EEG \(V_{\text{meas}} \in \mathbb{R}^{m \times n}\) is decomposed into

\[
V_{\text{meas}} = U \cdot S \cdot V^T = \sum_{i=1}^{m} s_{ii} U_{i,1} \cdot V_{i,1}^T, \quad (m < n). \tag{1}
\]

This expression shows that \(V_{\text{meas}}\) can be decomposed into at most \(m\) 'potential distributions', found in the columns of \(U\), with the corresponding amplitude time courses in the columns of \(V\), weighted by the singular values \(s_{ii}\) from the diagonal matrix \(S\). In our method, we will perform a dipole localization for the potential distribution represented by \(U_{i,1}\), the first column of the matrix \(U\), instead of analyzing the complete epoch of \(n\) time samples.

Analyzing only the first component of the SVD of the EEG-datamatrix is based on the assumption that most of the signal energy of an epileptic spike will be comprised in this first component. We define the measure

\[
S = \frac{s_{11}^2}{\sum_{i=1}^{n} s_{ii}^2},
\]

which indicates what fraction of the total energy in the EEG is contained within the first SVD-component. The measure \(S\) will be used to determine the time instants where a single SVD-component is dominant in the EEG.

Two detection criteria are used for the detection of the epileptic spikes:

\[
RE \leq \theta_{RE}, \quad S \geq \theta_S, \tag{2}
\]

with \(\theta_{RE}\) and \(\theta_S\) two threshold values to be chosen.

Figure 1 shows an EEG fragment of 8 sec duration with three epileptic spikes (approximately at \(t=476, 478,\) and 482 sec). Figures 2b and 2c show the time evolution of the \(RE\) and \(S\) measures, respectively, together with two EEG channels in figure 2a. The decision variables \(RE\) and \(S\) were calculated using a window of 250 msec (50 samples at 200 Hz sampling rate) that was gradually slid forward in steps of 25 msec. It can be appreciated that a choice of \(\theta_{RE} = 10\%\) and \(\theta_S = 60\%\) will lead to the detection of the three spikes.

3 RESULTS

3.1 Iterative vs. ANN dipole localization

After training the ANN with 10 millions of training examples, an average dipole localization error of 0.327 cm is achieved for the spherical head model (the iterative approach localizes perfectly in the absence of noise). Figure 3 shows the spatial distribution of dipole localization errors in noiseless conditions for an ANN trained to localize within the spherical head model, and for an
ANN trained for a realistic head model. In the presence of noise (signal-to-noise ratio of 20) in the measured EEG, the average localization error amounts to 0.750 cm and 0.575 cm for the ANN and iterative approaches, respectively. The ANN approach is thus only slightly more sensitive to noise than the iterative localization method. The calculation time needed for an iterative dipole localization is 2.86 sec on a SUN ULTRA60 (360 MHz). The ANN dipole localization, however, only requires 15.4 msec. Therefore, we can conclude that the ANN dipole localization approach provides a strong decrease in calculation time, at the cost of only a slight loss of localization accuracy. The ANN will therefore be used in our method for the detection and localization of focal epileptic activity, as it is capable of performing the analysis in real-time.

3.2 Detection and localization of focal brain activity

The choice of appropriate values for the threshold values $\theta_{RE}$ and $\theta_S$ is determined from the study of a ROC curve (receiver operation characteristic), which displays the specificity vs. the sensitivity of the detection method. The sensitivity is the percentage of epileptic spikes in the EEG that are detected by the method, and the specificity is the percentage of the detections that is in fact a spike in the EEG. In order to be able to estimate the sensitivity and specificity of the detection method, epileptic spikes were first visually retrieved within a twenty minutes EEG registration of a patient. Afterwards, the detections made by the detection method were compared with the visually identified spikes. Figure 4 shows ROC curves for five different values of $\theta_S$. The parameter $\theta_{RE}$ varies along each of these curves. In can be observed that the sensitivity of the method increases while $\theta_{RE}$ is increased, but that at a certain point, the maximal sensitivity is reached and the specificity starts to decrease, due to an increasing number of false detections. The envelope of the different ROC curves (indicated by the dashed line) can be considered to be the general ROC curve of the detection method (for the EEG of this patient). It shows e.g. that by a proper choice of the threshold parameters, a sensitivity of 80% together with a specificity of 60% can be reached. These values are reached when $\theta_{RE} = 7.5\%$ and $\theta_S = 65\%$.

Figure 5 shows the localization results obtained from the analysis of the 20 minutes of EEG. The figure shows a front, top, and side view of the spherical head model. Each dot corresponds to one detection that was made during the 20 minutes. The large ‘cloud’ at the right side corresponds to detections of epileptic spikes. This shows that the dipole sources corresponding with the epileptic spikes are all lying in the same brain region, which confirms the hypothesis that a certain region within the brain is responsible for the generation of the epileptic spikes. A limited number of detections yield dipole lo-
4 DISCUSSION AND CONCLUSIONS

We presented a method for the combined detection and localization of focal epileptic activity. The detection method is based on a dipole source model for focal brain activity and has the advantage that for each detection, an estimation of the source location and orientation is given at once, without further calculations. It is important to note that, apart from the choice of the window size, the method does not assume any prior knowledge about the events to be detected (duration, signal shape), other than the fact that the events originate from brain activity in a focal brain region. The ROC curve based on the analysis of 20 minutes of patient EEG indicates that the method is able to reach an acceptable level of sensitivity and specificity. The use of an ANN for dipole source localization, instead of the iterative localization approach, permits a real-time application of the presented method, which is an interesting feature if the technique is to be applied during long-term EEG acquisitions. The presented method offers the opportunity of performing an automatic real-time ‘scanning’ of the EEG in search of focal brain activity, and to classify the detected events according to location of the source in the brain. Thus it can serve as a preprocessing step that selects relevant EEG epochs for subsequent analysis with more sophisticated source localization approaches.

References


