Multidimensional Filtering of the Electroencephalogram (ECOG) for Epileptic Focus Localization

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Abstract:

In this paper the rationale of a method for the detection and localization of focal epileptic activity from multichannel ECOG recordings is introduced. The proposed method, the “Spatio-Temporal Laplacian”, emphasizes the need to consider both the spatial and the temporal attributes of focal epileptic activity. In its current implementation the method discriminates the events of interest by means of combined measures of spatial and temporal sharpness, yielding a 2-dimensional representation that facilitates the localization of the focus. Some preliminary off-line results are presented.

I. Introduction

The accurate localization of the epileptogenic areas in the cerebral cortex is of great importance during the surgical procedure applied to eligible patients with focal epilepsy. The excision of the foci localized in dispensable cortex has provided significant relief to a group of patients for whom surgical therapy was indicated. Our research is aimed at the development of an automated tool that can help the neurosurgeon in locating the epileptic foci from the electrocorticogram (ECOG) in the operating room. The signals available for the localization of the foci are obtained from a flexible electrode array that is placed directly on the exposed cerebral cortex of the subject [Reid, 1989]. The electrodes are normally connected in longitudinal and/or transversal “bipolar chains” that yield the instantaneous voltage difference sensed by each pair of electrodes (Fig. 1). Ultimately, we would like to provide the neurosurgeon with continuous real-time monitoring of the epileptogenic activity in the area of the cortex covered by the array, by means of a 2-dimensional representation of an instantaneous index of epileptic activity. We would also like to automatically select the data segments that are likely to show the location of the foci when displayed as animated maps that the user steps-through at the desired pace. This paper reports preliminary off-line processing that has been designed to achieve these goals.

Focal epilepsy is characterized by the appearance of sharp spikes in the Electroencephalogram (EEG) or ECOG of the patient. These abrupt transients correspond to the simultaneous discharge of a population of cortical (pyramidal) cells acting in abnormal synchrony [Martin, 1985]. The pyramidal cells are oriented perpendicularly to the surface of the cortex and their collective activation at the epileptic focus results in a perturbation of the electric and magnetic fields similar to that caused by the momentary appearance of a relatively strong electric dipole also oriented perpendicularly to the cortex. Equivalently, this phenomenon has been modeled as a current density source/sink pair that appears and disappears in a sudden fashion. Either source model, when considered within the brain, will introduce a gradient in the potential field measured at the surface of the cortex, around the focus, as well as superficial currents that will diverge from or converge to the focus location.

Figure 1. Electrode Array and Bipolar Derivations. The array is placed directly on the cerebral cortex of the patient.

From the previous considerations, it may be hypothesized that some characteristic features of the focal epileptogenic activity that is represented by a spike in the conventional ECOG records are its large magnitude, its local spatial extent and its sudden character.

The many forms in which computers have been applied to the analysis of EEG records from epileptics have been summarized by Gotman [1987]. The pioneering work in the field of automatic focus localization includes that of Lopes da Silva et al [1977], based on the relative frequency of detections at each electrode and Hjorth’s “Source Derivation” technique [1975]. As the computing power available increases, the automated processing of multichannel EEG data is becoming popular. The most common schemes emphasize the relative energy contents of the different frequency bands (alpha, beta, etc.) and display this information in individual “maps” that usually include the whole head of the patient, as reviewed by Duffy [1986, 1989]. Due to the separation of the information in several frequency bands, however, these approaches are not naturally suited for the detection of a transient event such as an epileptic “spike” which lacks a characteristic frequency spectrum.
II. Conventional approaches to focus localization with the ECoG

The traditional method for focus localization involves sampling the potential field in the surface of the cortex by means of an array of electrodes like the one in Figure 1 and plotting the voltage differences between electrodes (bipolar derivations) as functions of time. When differential voltages sharing a common electrode show sharp transients in opposite directions ("spikes" with "phase reversal"), it is assumed that the potential field responsible for such deflections is the manifestation of an epileptic dipole lying beneath that common electrode. The complete specification of the location of the focus requires the observation of simultaneous "phase reversals" in both the transversal and longitudinal bipolar derivations that include the suspected electrode.

It is worth noting that with this type of display a large portion of the integrative task involved in the interpretation of the ECoG for focus localization is left to the EECee. The traces plotted in the chart are completely dissociated from the spatial attributes of the electrodes that generated them except, maybe, for the adjacency of traces produced by adjacent electrodes. Most of the spatial information has to be mentally reconstructed by the interpreter by referring to some kind of electrode placement diagram. At the same time, he or she needs to analyze the characteristics of the time plots. In addition, the traditional localization technique relies almost exclusively on the presence of evident "phase reversals", being unable of detecting any subtler indications of focal epileptic activity.

III. Spatial enhancement of the potential field recordings

A first step towards enhancing the amount of information about local effects conveyed by the displayed signals was introduced through the use of the "Source Derivations" [Hjorth, 1975]. In this technique, simultaneous readings from surrounding electrodes are also used to determine whether or not an electrode is placed on a significant current sink or source.

Particularly, using the current source/sink model for an active epileptogenic population the following relationship can be established [Nunez and Katzenelson, 1981]:

$$\vec{J} = -\sigma(\text{grad} (V))$$  
\[eq. 1\]

where:

$\vec{J}(x,y)$ is the current density vector at point $x,y$

$\sigma$ is the conductivity of the medium

$V(x,y)$ is the electric potential at point $x,y$.

Thus, the significance of a certain point as a sink or source of current density can be measured through its divergence at that point:

$$\text{div}(\vec{J}) = \text{div}(-\sigma \times \text{grad} (V)) = -\sigma \Delta V$$  
\[eq. 2\]

$$\text{div}(\vec{J}) = -\sigma(\text{Laplacian} (V))$$  
\[eq. 3\]

where:

$$\text{Laplacian} (V) = \frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2}$$  
\[eq. 4\]

According to this, a point on the surface of the cortex right above an active epileptic focus can be expected to have a very large (positive or negative) value of the Laplacian.

Hjorth [1975,1976] noted the usefulness of this notion in improving the spatial sensitivity of multichannel scalp EEG recordings and in locating foci of activity from them. He proposed an approximation to the spatial second derivatives involved in the Laplacian for the case where, as in EEG and ECoG recordings, only the potential values at a few spatial coordinates are known [Hjorth, 1979]. In his approximation all the available electrode potentials are used for the estimation of the Laplacian at a given point, weighting their contribution according to the inverse of their distance to the point under analysis. The result of this pre-processing, the "Source Derivations", can then be plotted with the standard polygraph [Hjorth, 1975,1976] or shown in a topographic map, as it has been done for scalp EEG records [Rodin and Cornellier, 1989; Infantosi and Almeida, 1990].

The source derivation technique indeed makes use of the Laplacian operator as a type of 2-dimensional (spatial) high-pass filter that will attenuate widespread phenomena, while magnifying localized changes, which makes it suitable to detect one of the characteristics of focal epileptic events mentioned above. However, this type of preprocessing does not address the possibility of using the temporal characteristics of the phenomenon for its automated detection. The "search" for the transient character of the suspected epileptic activity is still left to the human observer.

IV. Temporal evolution of the activation of epileptogenic foci and its use for foci localization.

Although the source derivation has proved to be useful in enhancing local effects, it has also been found that, when used to obtain topographic maps of scalp EEG recordings from epileptic patients, the "source derivation produced highly detailed maps with at times considerable complexity and variability, but also containing certain constant features" [Rodin and Cornellier, 1989]. While this rich complexity can be taken advantage of or disregarded (if necessary) by the EEG interpreter during off-line analysis of the data, it might distract the attention of the neurosurgeon trying to locate the epileptic focus in the operating room. Furthermore, if an automatic system is to capture only segments of the data stream that are likely to indicate the location of the focus when displayed as maps, a more stringent selection criterion should be used.

We propose to involve both the spatial and temporal characteristics of focal epileptogenic activity by using a 3-dimensional sample space ($x,y,t$) to perform the processing and attempt to answer simultaneously the questions of the spatial ($x,y$) and temporal ($t$) location of the focal epileptogenic activity within the sample space.

The main assumption involved in this proposition is that an electrode from the array that senses an epileptic "spike" will simultaneously display large absolute values in its two spatial second derivatives ($\partial^2 V/\partial x^2$, $\partial^2 V/\partial y^2$) and also in its temporal second derivative ($\partial^2 V/\partial t^2$). Accordingly, this approach should incorporate the merits of Hjorth's source derivation with those of sharpness measuring techniques ($\partial^2 V/\partial t^2$) used by Walter (1973) and Smith (1974) for epileptic "spike" detection, as reported by Gotman (1987).
Then, for such a 3-dimensional scalar field \( V(x, y, t) \), the Laplacian could be defined as:

\[
\text{Laplacian} \left( V(x, y, t) \right) = \nabla^2 (V)
\]

\[
\nabla^2 (V) = \left( \frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2} + \frac{\partial^2 V}{\partial z^2} \right)
\]

\[
\text{eq. 4}
\]

\[
\nabla^2 (V) = \left( \frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2} \right) + \left( \frac{\partial^2 V}{\partial r^2} \right)
\]

\[
\text{eq. 5}
\]

\[
\text{Laplacian} (V(x, y, t)) = SL + TL
\]

\[
\text{eq. 6}
\]

where SL (the spatial Laplacian) can be computed through Hjorth's method or through alternative algorithms [Infantosi and Almeida, 1990] and TL (the temporal Laplacian) can be estimated by central differences on the time series for the voltage sensed by each electrode.

It is easily noticed that involving the temporal Laplacian adds one more dimension to the filtering or discriminating procedure, since TL acts as a special type of high-pass filter for the voltage sensed by each electrode.

V. The Spatio-Temporal Laplacian as a measure of focal epileptogenic activity in the ECoG

When SL and TL were computed independently for segments of 16-channel ECoG data obtained from the array shown in figure 1 and displayed as animated contour level maps, consistent formations were observed in both maps at the electrode location that would have been identified as the focus using the traditional techniques (Fig. 2). However, significant background fluctuations were still noticeable throughout the array in both maps. Furthermore, when the maximum instantaneous absolute value of each of these indices was plotted versus time for selected 1-second segments, the background levels observed in the absence of paroxysmal epileptic activity were still considerable. Figure 3 shows such plots for the particular 1-second segment that will be used as an example throughout this paper. Composing the Laplacian operator as the sum of SL and TL, as suggested by equation 6 did not show a very significant improvement in the maximum-to-background ratio.

In order to obtain a function with a higher discriminant power the alternative formulation used was:

\[
\text{STL} = \frac{\text{Spatio Temporal Laplacian}}{\text{STL} = SL \times TL}
\]

\[
\text{eq. 7}
\]

With this definition, a certain electrode will be assigned a high value of STL at a certain time only if the instantaneous reading for that electrode is significantly different from the instantaneous readings of its neighbors in all directions (spatial sharpness) and also significantly different from future and past readings from the same electrode (temporal sharpness). This can be thought of as "gating" one of the sharpness measures with the other, in such a way that only local and abrupt changes will be given preference. If TL and SL are viewed as filters this is equivalent to cascading them instead of connecting them in parallel. When the maximum absolute value of STL in the array is plotted versus time and compared with Figure 3, the maximum-to-background ratio is observed to have increased (Fig. 4).

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**Figure 2.** Contour maps of TL and SL during the occurrence of an interictal "spike" (sample 218 in the 1-second segment used as example).

**Figure 3.** Maximum instantaneous values of TL and SL plotted versus time for the selected 1-second segment.
VI. Discussion

In the preliminary tests that have been performed using the STL process on multichannel cortical data this approach has proved successful in assigning large output values to electrode samples during the occurrence of abrupt and local changes of the potential field at that point. Further development of the particular implementation algorithms is necessary to ensure that the temporal Laplacian does not penalize any of the transients with durations within the accepted "spike" duration interval and that the intrinsic non-uniformity of the spatial Laplacian for a bounded array is kept within appropriate limits.

Overall, we consider that the most important points introduced in this approach are the realization that local epileptic activity generates a full spatio-temporal perturbation in the electric and magnetic fields in the brain and the proposition that the two spatial dimensions that are available in ECg recordings, as well as the temporal dimension, should be comprehensively involved in its identification.
VII. References


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