SOURCE LOCALIZATION OF EPILEPTIC ACTIVITY FROM INTRACRANIAL EEG BY DIRECTION OF ARRIVAL ESTIMATION METHOD

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Abstract:- Brain activity source localization is an important issue related to origins of neurological epilepsy disorders which reveal oneself by specific EEG activity. Epilepto-surgery treatment is based on complete removing or disconnecting of epilepsy bearing which is responsible for seizure. However precise localization of epileptogenic tissue partly depends on an accurate localization sources of seizure activity or/and inter-ictal specific activity. In this work the DOA (Direction of Arrival) estimation method Multiple Signal Classification (MUSIC) is used to locate distinct sources of specific epileptic activity from intracranial EEG. It is a subspace-based method which allows distinguishing more sources if they are not very close to each other and the Signal to Noise Ratio (SNR) is not low. Due to the fact that the number of active brain activity sources is usually unknown the estimation of DOAs is difficult as well as the MUSIC. It does not allow in some case to achieve an accurate result. We try to overcome these limits by normalizing the MUSIC spectrum with an estimated noise spatial spectrum which does not require the *a priori* knowledge of the number of active sources.

The preliminary results show that used DOA Estimation method is able to identify distinct sources of specific activity as inter-ictal epileptiform discharges in intracranial EEG. We conclude, the method could be useful for revealing the epileptogenic zone boundaries.

Keywords: Intracranial electroencephalography, DOA Estimation, Sources Localization.

1. INTRODUCTION

Epilepsy is a paroxysmal neurological disorder in about 1% population and is characterized by EEG event due to sudden, excessive and rapid discharge of a more or less extensive population of neurons belonging to the gray substance of the brain. Approximately 30% of patients with focal cortical epilepsy remain refractory to pharmacotherapy. In part of these patients (10%), cortical resection/disconnection may be the most effective treatment to achieve seizure freedom. Identification and precise localization of epileptogenic zones (lesion, seizure onset and irritative zone etc.) are the basic presume for successful treatment [1]. For this aim, intracranial electrode implantations are very useful instead of surface scalp EEG [2-3], because they provide information about the potential distribution inside the cortex and depth brain structures. Invasive records are less corrupted by technical artifacts and contain minimum of myographic or eyes potentials [4].

In this sense, advanced techniques of signal processing have been studied to analyze complex activities in order to extract important information as spatial parameters in order to solve a sources localization problem [5]. The studies conducted to formalize the relationship between the electromagnetic activity in the head and the EEG recordings allow divide localization problem in two sub problems [6]. The first one is the forward problem which determines the electric field at the electrode position from known sources [7].The second one is the inverse problem which estimates the location of sources in the brain from recorded EEG signals. The solution requires the definition of a volume conductor and a model for the sources responsible for brain activity.

In this work, the DOA (Direction of Arrival) estimation method using MUSIC [8] is applied on intracranial EEG signals to identify the directions of brain activity sources that contribute to recorded EEG signals and consequently to identify distinct sources of inter-ictal epileptiform discharges. However the detection of these brain sources is not trivial. If there are various independent multifocal sources of epileptiform discharges and the SNR is low, the spatial resolution could be low and not all sources can be distinguished. Moreover the estimation of DOAs is difficult by the fact that the number of active sources is usually unknown thus MUSIC does not allow to achieve an accurate result in some cases. Some sources localization techniques achieve better resolution by calculating a sparse solution for the source localization problem [9]: if the number of sources is small as a result the neural power map vs. location is sparse.

Nevertheless in this work the limits of MUSIC are overcome by normalizing the MUSIC spectrum with an estimated noise spatial spectrum that does not require the *a priori* knowledge of the number of active sources. The noise spatial spectrum is estimated from the noise variance that is
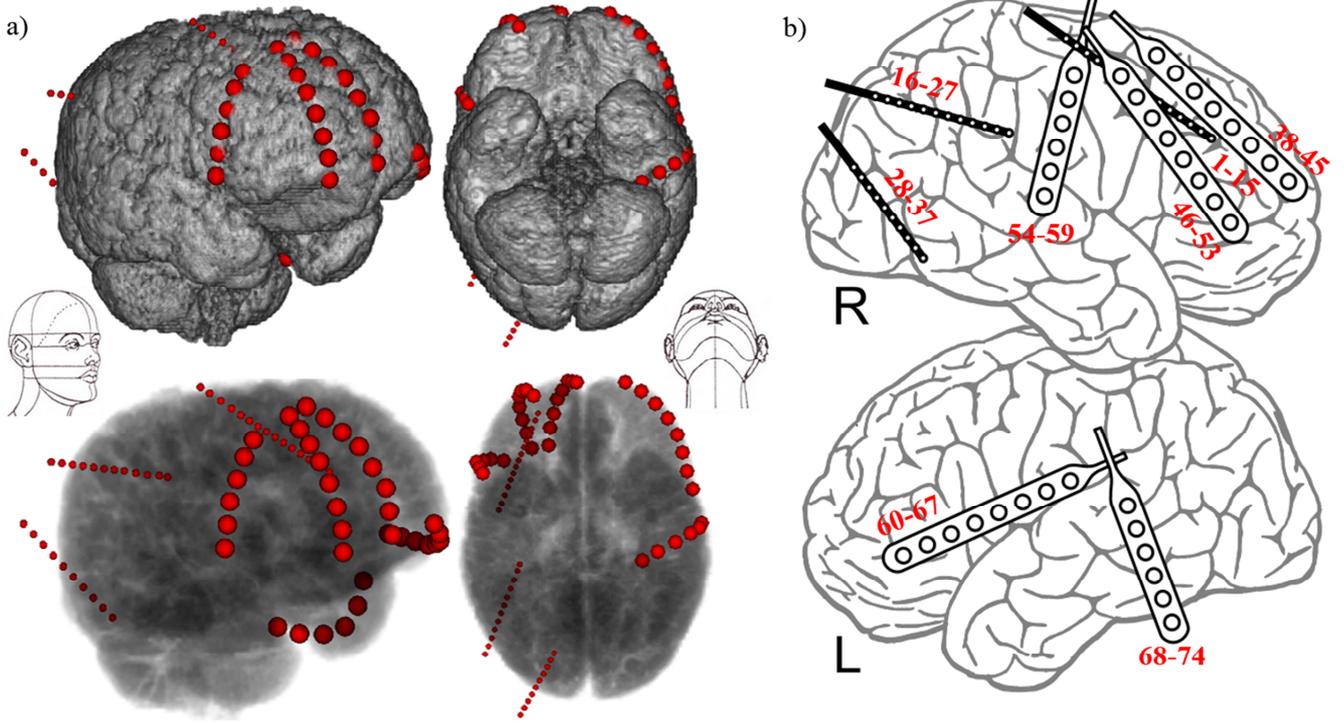
Fig.1:3D-brain model for volume conductor with electrode displacement. a) Isosurface and transparent volume of brain grey matter with red marked electrodes; b) schematic placement of electrodes.

calculated assuming the EEG signals with an additive Gaussian noise.

2. DOA ESTIMATION METHOD

Data were obtained from patient with focal drug-resistant epilepsy based on tuberous sclerosis complex during long-term intracranial EEG monitoring as the standard pre-surgical examination in Motol Epilepsy Center, Motol University Hospital in Prague [10]. Data collection was approved by the institutional ethics committee, and parental informed consent was obtained.

A. *Source and Head Model Assumptions*
The 3D-brain model is obtained by Magnetic Resonance Imaging (MRI), as in Fig.1. Electrode contact positions were extracted from co-registered Computer Tomography (CT) image and marked to the model.

The electrical activity in a limited area of the brain is modeled by a current dipole, which represents a current source within the conductive brain tissue [6]. This model of the brain source has been successively used on scalp EEG data [9]. The current dipole is pictured in Fig.2 as two monopoles of opposite sign, but equal strength I_0, separated by a very small distance p, defined in terms of its location and its orientation.

The dipole moment is defined as

$$\overline{d} = I_0 p \overline{a}_p \tag{1}$$

where $\overline{a}_p$ is a unit vector in the direction of the dipole. It can be decomposed into three dipoles oriented along one direction axis x, y, or z according to the unity vectors a_x, a_y, a_z,

$$\overline{d} = d_x \overline{a}_x + d_y \overline{a}_y + d_z \overline{a}_z \tag{2}$$
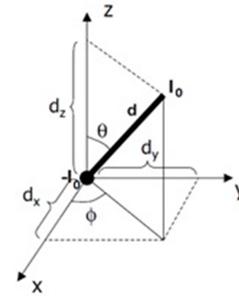

Fig.2: The dipole for a given current source with its component.

Therefore a potential P at an arbitrary point due to a dipole $d=(d_x,d_y,d_z)$ at a position $r_d = (x,y,z)$ can be defined as:

$$P(r,d) = d_x P(r_d,\overline{a}_x) + d_y P(r_d,\overline{a}_y) + d_z P(r_d,\overline{a}_x) \tag{3}$$

By considering a spherical surface in a conductor with conductivity σ, this potential can be expressed as:

$$P(r_f,r_d,d) = \frac{d}{4\pi\sigma(r_f - r_d)^2}\overline{a}_r \tag{4}$$

where $r_f = (x',y',z')$ are the coordinates of the field point in which the potential is measured, and $\overline{a}_r$ is the unit vector in the radial direction.

The distance field point-source is:

$$r = \sqrt{(x-x')^2 + (y-y')^2 + (z-z')^2} \tag{5}$$

Therefore, we consider a source at the center of a sphere of ray *r* and we explore the volume conductor for sources by evaluating the contribution of each them for all recorded signals to each electrode contact. A *lead field* matrix is defined as a function which characterizes sensitivity/energy distributions in the volume conductor by considering the voltage. It is measured at the electrode as a function of the position and orientation of a unit dipole source [6]. Thus the lead sensitivity at a point is the relative lead voltage for a dipole whose direction is adjusted to maximize the response. In this way, each electrode detects the component of the activation of the dipole along its sensitivity direction. Lead field matrix is indicated with $L(r_d)$, and it is determined by dipole position, electrode positions, and properties of the volume conductor.

B. *MUSIC Method*

MUSIC is a subspace-based method which allows distinguishing more sources by evaluating their DOA to electrodes. For this aim a signal subspace and noise subspace are defined [8]. The MUSIC principle uses the fact that the eigenvectors in the noise subspace are orthogonal to those of the signal subspaces. Since the signal subspace contains information about the directions of arrival of each wave related to an active source, the lead field vectors of these directions are also orthogonal to the vectors in noise subspace. MUSIC spectrum is defined as:

$$P_{MUSIC}(r_d) = \frac{1}{L^H(r_d)U_N U_N^H L(r_d)} \qquad (6)$$

where U_N is the noise subspace. MUSIC spectrum will have peaks in correspondence of the direction(ϑ, ϕ) where the lead field vectors in $L(r_d)$ are orthogonal to the noise eigenvectors of U_N. The direction (ϑ, ϕ) are defined according to Fig.3.
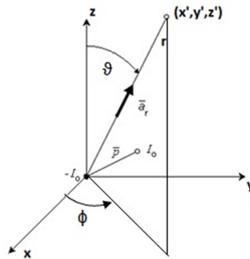

Fig.3: Dipole in reference system

MUSIC allows a larger spatial resolution in comparison with for example Beamforming-based procedures [11]. However if the sources are very close together and the Signal to Noise Ratio (SNR) level is low, the resolution decreases. Moreover it requires the knowledge of active source number.

C. *Spatial Noise Spectrum*

The DOA estimating method is limited by SNR of measured data, because noise is an important component of the calculated spatial spectrum by MUSIC method. The noise could obscure the spatial spectrum. We try to reduce the problem by normalizing the MUSIC spectrum by the estimated noise spatial spectrum. The noise spatial spectrum

can be calculated in function of location within the brain volume as [5]:

$$Tr\left\{L^T(r_d)Q^{-1}L(r_d)\right\} \qquad (7)$$

where $L(r_d)$ is the lead field matrix associated with each source and Q is the covariance matrix of the noise that can be calculated from the data by considering an additive Gaussian noise.

3. RESULTS

MUSIC spectrum is calculated on the EEG signals recorded by 73 electrodes. The signals are divided and analyzed in groups of 20 seconds of duration due to the big amount of available data (three hours of recording). Sections contain specific EEG activity as epileptiform discharges and seizures. Unspecific activity (baseline EEG) has random character and causes background of the MUSIC spectra. Inter-ictal and ictal episodes are analyzed separately. Calculated MUSIC spectrum of section with ictal episodes is shown in Fig.4. The sources identification is difficult due to blurring of the spectrum. The higher peaks are indicated by arrows. The MUSIC method has problem to estimate sources along ϑ=-90° and ϑ=90° directions due to its intrinsic limit [11]. We consider these technical peaks near the instability region for the normalization process. The normalized spectrum in Fig.5 by spatial noise clarifies and reveals more details to sources identification.
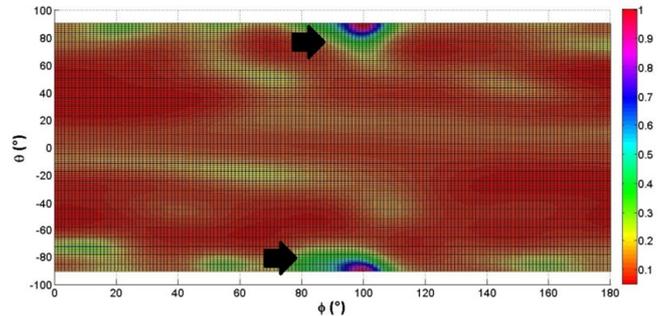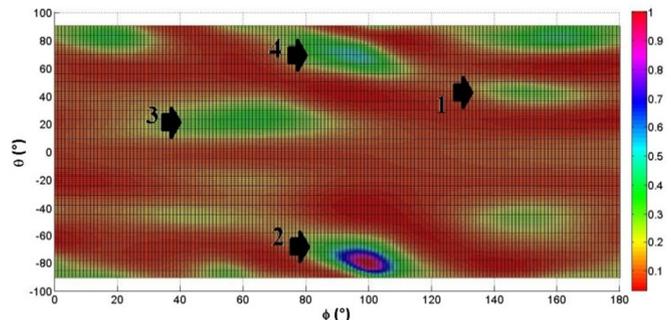

Fig.4: Music spectrum

Fig.5: Normalized MUSIC spectrum by estimated noise spatial spectrum

The four strongest sources location in the figure 5 were compared to electrode placement. Fig.6-8 show 2D projections of localized sources to brain volume corresponding with cortical maps in Fig.1. The rays come out from reference system center and represent directions of specific epileptic activity occurrence. The ray's intersections

with electrodes indicate the suspect area of the source position. The source localizations are compared with known localizations of epileptogenic areas published in [10]. The first source of epileptic activity is localized in surroundings of depth electrodes 1-6 (right frontal) that agree with localization of the seizure onset zone. This area was included within resection. The ray projection of first source is in Fig. 6.
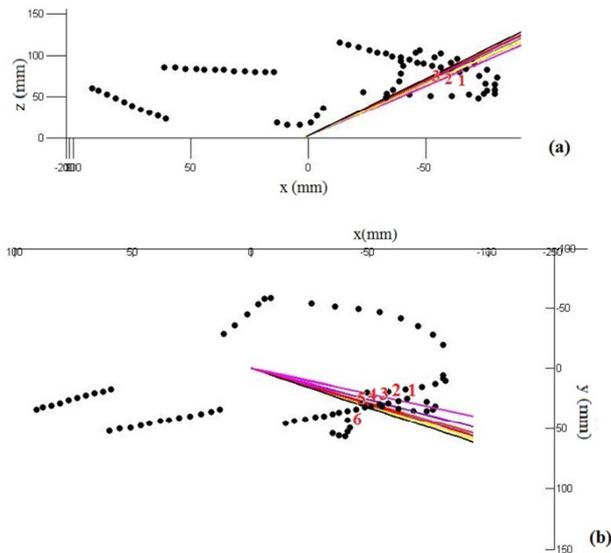
The third source was localized in right occipital lobe close to depth electrodes 17-20. Clinically, the area is affected by tubers and generates abnormal low amplitude EEG activity (mainly interictal discharges and early propagated seizure activity). The ray projection is in Fig.8.

The remained fourth source from Fig.5 is probably a false positive detection. Its localization is near to instability region.

Fig.6: First detected area respect electrode positions: 2D view (x,z) and 2D view (x,y)

The second source is near electrode 69 (Fig.7). Inaccuracy is caused from the dispersion of the rays along coordinate z because MUSIC estimation is inaccuracy for directions close to -90° and 90°[11]. In this case, the area of interest was presumed near to electrodes 69-71 that were localized by neurologist as high-amplitude inter-ictal discharges source. The patient's left temporal lobe also contained macroscopic tuber, which was not primary epileptic area.
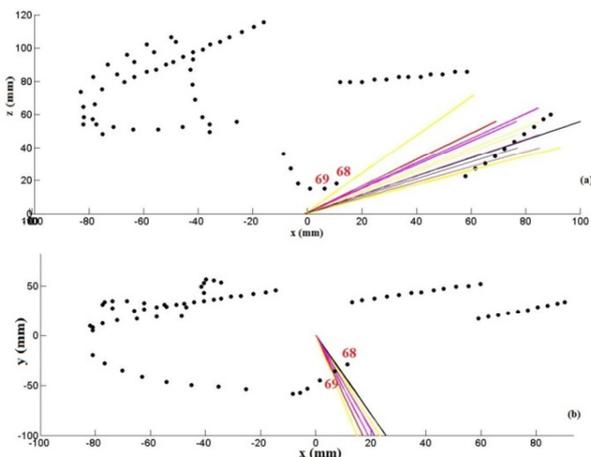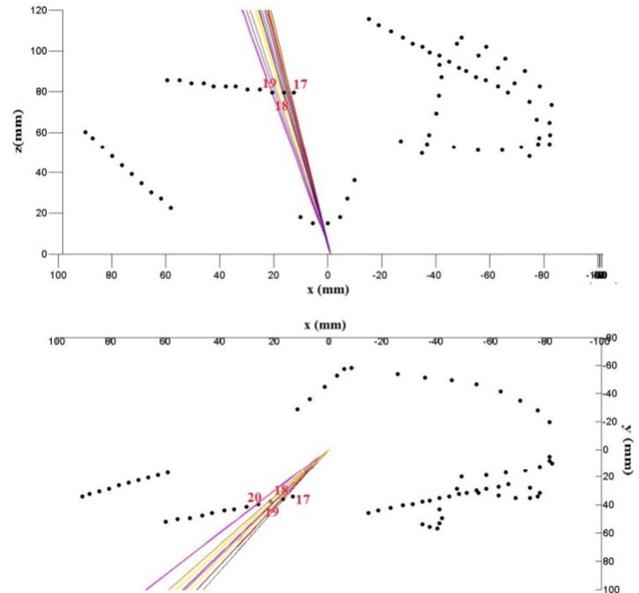

Fig.8: Third detected area respect electrode positions: 2D view (x,y) and 2D view (x,y)

4. DISCUSSIONS

In this work the DOA estimation method using the MUSIC is applied on intracranial EEG of one tuberous sclerosis complex patient to locate his epileptic foci. The MUSIC spectrum is normalized by estimated noise spatial spectrum that significantly improved the results and revealed suspect areas with good agreement with clinical evaluation.

The preliminary results have shown that the used method is able to identify the distinct sources of specific epileptic activity. This approach of invasive EEG analysis can be useful forlocalization of the epileptogenic areas. However further investigations are necessary to define more accurately neural activity and to overcome the limitations of MUSIC. The blind study of large patient database will be the aims of future studies for overviewing the used method.

Fig.7: Second detected area respect electrode positions: 2D view (x,y) and 2D view (x,y)

5. REFERENCES

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