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# Spatio-temporal Source Localization and Granger Causality in Ictal Source Analysis

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*Abstract*- **We have proposed a new ictal source analysis approach by combining a spatio-temporal source localization approach, and causal interaction estimation technique. The FINE approach is used to identify neural electrical sources from spatio-temporal scalp-EEGs. The Granger causality estimation uses source waveforms estimated by FINE to characterize the causal interaction between the neural electrical sources in order to distinguish primary sources, which initiate ictal events, from secondary sources, which are caused by propagation. In the present study, we applied the proposed analysis approach to an epilepsy patient with symptomatic MRI lesions. It is found that the primary ictal source is within the visible lesion, which gave the consistent presurgical evaluation as MRI for this patient.**

*Keywords*- **spatio-temporal source localization, FINE, Granger causality, subspace, EEG**

## I. Introduction

It is of importance to locate epileptic foci for intractable epilepsy patients who undergo surgical evaluations. The source localization approaches based on EEG or MEG have shown promise for noninvasive localization of epileptic foci using interictal [1] or ictal events [2]. In ictal events, propagation of electric activities is evident [3]. Besides finding intracranial sources responsible for scalp field observations, the task to locate ictal foci by source localization, thus, includes another important component -- that is to distinguish the localized sources into sources which initiate ictal events, defined as primary sources, and sources which are caused by the primary sources due to propagation, defined as second sources.

In the present study, we introduce a new ictal source analysis by combining a spatio-temporal source localization approach, i.e. FINE [4-5], and causal interaction estimation technique, i.e. bivariate Granger causality [6]. The subspace source localization method is used to deal with spatially and temporally measured signals and able to locate multiple dipole sources. The bivariate Granger causality is used to evaluate the quantitative causal interaction between any paired sources, based on their time series modeling. The causal pattern is used to define the primary source and the secondary source accordingly. The feasibility of the proposed approach was tested in an epilepsy patient with visible MRI lesion in localizing ictal sources.

## II. Method

### A. FINE

The spatial correlation matrix of the scalp EEG recordings can be expressed as $R_\Phi = AR_S A^T + \sigma^2 I$ where $R_S$ is the source correlation matrix and $A$ is the gain matrix. The measurement space spanned by $R_\Phi$ consists of signal subspace $E_s$ and noise-only subspace $E_n$ which can be found using eigen-decomposition. In the FINE algorithm, the entire brain can be divided into a number of regions due to its organization, and for a specific region $\Theta$, a small set of vectors in the entire noise-only subspace, denoted by the FINE vectors $F_\Theta$, could be identified based on the concept of principal angles [4,5]. For different brain regions different FINE vectors are used. The FINE estimator can then be expressed as [4,5]

$$J_{FINE}(\underline{r}) = \lambda_{\min}[U_{A(\underline{r})}{}^T F_\Theta F_\Theta{}^T U_{A(\underline{r})}] \quad (1)$$

where $J_{FINE}(\underline{r})$ is the FINE estimator at possible source location $\underline{r}$, $U_{A(\underline{r})}$ contains left singular vectors of the gain vector $A(\underline{r})$. $\lambda_{\min}$ is the smallest eigenvalue of the given bracketed items. In the algorithm implementation, the estimator can be scanned at the entire possible source space and the locations with local extremes (approximate to 0) will thus be regarded as the sources. The amplitudes of the estimated dipoles in the time series can be estimated as

$$S = A^+\Phi; \qquad A^+ = (A^T A)^{-1} A^T \quad (2)$$

where $A$ is the lead field for the identified sources.

### B. Bivariate Granger Causality Estimation

Assume that $S_1(t)$ and $S_2(t)$ denote the two source time series from $S$ in eq. (2). We can use the bivariate autoregressive model [6] to describe their temporal dynamics. Its corresponding formulation in the frequency domain using Fourier transform can be written as:

$$\begin{pmatrix} S_1(f) \\ S_2(f) \end{pmatrix} = \begin{pmatrix} H_{11}(f) & H_{12}(f) \\ H_{21}(f) & H_{22}(f) \end{pmatrix} \begin{pmatrix} E_1(f) \\ E_2(f) \end{pmatrix} \quad (3)$$

where $H(f)$ is defined as the transfer matrix. The Grange causality from source *j* to source *i* in the spectral domain is defined as [7]

$$GC^2_{j\to i} = |H_{ij}(f)|^2 = \frac{|A_{ij}(f)|^2}{|A(f)|^2} \quad (4)$$

## III. Data Collection And Analysis Protocol

A human patient with medically intractable partial epilepsy and symptomatic lesion on MRI was studied using

a protocol approved by the Institutional Review Boards of the University of Minnesota and Mayo Clinic. The patient's EEGs were recorded using 31 electrodes in the modified 10/20 system and were collected continuously at a sampling rate of 200 Hz with a bandpass filter of 1.0 to 35 Hz. The patient had a standardized seizure protocol MRI, which demonstrated a potentially epileptogenic structural abnormality. The scalp EEG and video monitoring was reviewed for the occurrence of ictal rhythms via visual inspection and the time point of ictal onset was determined by experienced epileptologists. The data collection was carried out at Mayo Clinic, Rochester.

The three-sphere concentric inhomogeneous head model was used in the study. The imaged sources of neural activity from FINE were compared with the locations of the patient's lesion on MRI by coregistration (Fig. 1 (b)). Coregistration was achieved by matching the location of 3 fiducial points (nasion and left and right preauricular points). The conductivities for the scalp and brain tissue are 0.33/Ω.m and the conductivity ratio between the brain and skull is 1:1/20.

## IV. Results

Fig. 1 (a) shows the 30-channel waveforms (channel F9 was removed because of artifact) for the selected ictal onset segment from the patient using method described as above. The segment was subject to the spatio-temporal source localization analysis and the identified sources are illustrated using pseudo-colors with MR images as background (Fig. 1 (b)). Two sources were identified by FINE with one within the visible lesion area (top) and another one within the neighbor area of the lesion (bottom). The visible lesion is marked with the red circles in MR images (Fig. 1 (b)) and the coverage of circles is approximately as same as the extent of the visible lesions by visual inspection. The threshold for the FINE estimator values to be a local extreme was selected as 0.02. The source waveforms for each source are also shown in Fig. 1 (b) with green curves. The bivariate Granger causality estimation shows strong directional causal interaction from the one within the lesion (top) to another one in the neighbor of the lesion (bottom).

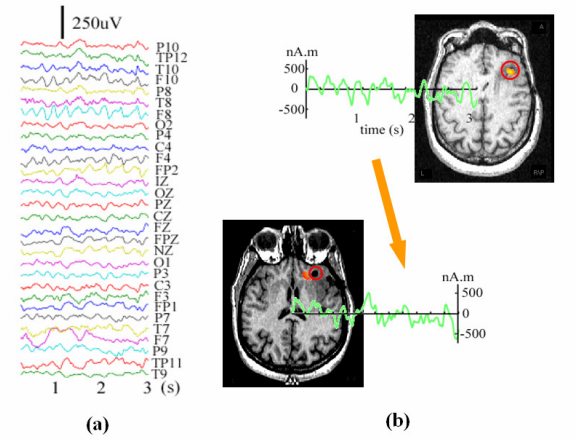


Fig. 1 (a) 30-channel scalp EEG recordings; (b) locations (pseudo-colors) and waveforms (green curves) of the identified sources; the visible lesions from MR images (red circles); and the estimated bivariate Granger causality between sources (yellow arrow)

## V. Discussion

The present study extends the source localization concept in order to identify the epileptic foci using ictal rhythm. The task in such context is not only to find the underlying electrical sources underlying the scalp EEG recordings, but also the need to distinguish sources initiating the ictal event from sources due to the propagation. In the present study, the achievement of such task uses information consisting of source locations, source waveforms, and causal interaction between sources.

The pilot study in an epilepsy patient shows multiple sources appearing within the visible lesion or in its vicinity, which is consistent with other report [8]. If we regard MRI lesion as the "golden" indicator to the focus of epileptogenesis for this specific lesional patient, the FINE-imaged ictal sources well indicate the epileptic foci for the patient. The causal interaction study further indicates the existence of propagation during ictal event, which has also been documented in other study [3]. Specifically, in this patient, we found the primary source is within the visible lesion area while the secondary source is in its vicinity.

In summary, we have proposed a new ictal source analysis approach by combining a spatio-temporal source localization method, i.e. FINE, and causal interaction estimation, i.e. bivariate Granger causality, which shows promise in identifying ictal sources by distinguishing primary source from secondary source. The present promising results suggest this approach merits further investigations.


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