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Stochastic Behavior of Phase Synchronization Mapped with Seizure-Free 256-Channel Scalp EEG

Ceon Ramon[a, b], Mark D. Holmes[c]
Depts. of Electrical Engineering[a] and Neurology, University of Washington, Seattle, WA, USA
[b]Dept. of Bioengineering, Reykjavik University, Reykjavik, Iceland
Correspondence: Ceon Ramon, Dept. of Electrical Engineering, University of Washington, Seattle, WA 98195, USA
E-mail: ceon@uw.edu, phone +1 206 778 0942

Abstract. We examined the spatiotemporal stochastic behavior of the phase synchronization index (SI) derived from seizure-free scalp EEG data of an adult male subject for a three minute period. It was found that in the epileptogenic area the stochastic fluctuations in theta (3-7 Hz) and low gamma (30-50 Hz) bands were higher as compared with the surrounding areas and also exhibited complex spatio-temporal patterns. This has a potential to nonivasively localize the epileptogenic areas from the seizure-free scalp EEG data. The EEG data of three minute duration was filtered in theta or low Gamma band. A detrended fluctuation analysis (DFA) was used to find the averaged stochastic fluctuations in the SI. Contour plots were constructed with 20 sec time-frames using a montage of the layout of 256 electrode positions. The phase synchronization was computed after taking Hilbert transform of the EEG data. The SI between a pair of channel was inferred from a statistical tendency to maintain a nearly constant phase difference over a given period of time even though the analytic phase of each channel may change markedly during that time frame.

Keywords: Noninvasive Epilepsy Localization, Phase Synchronization, High Density EEG

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1. Introduction

Recently [Ramon et al., 2008] we have demonstrated that the stochastic behavior of the phase synchronization derived from the high density (256 channel) scalp EEG data has a potential to localize the epileptic sites in human subjects. This was achieved by use of one minute long seizure free interictal scalp EEG data. The stochastic behavior was higher at the locations of the epileptic sites. In the present work we examine the spatiotemporal behavior over a three minute long period to determine the optimum duration to localize the epileptic sites from seizure-free high density (256 channel) scalp EEG data. Here we report our preliminary results derived from the EEG data of an adult male subject with frontal midline epilepsy. Our results indicate that stable patterns in the stochastic behavior of phase synchronization begin to emerge after 80-100 seconds duration. This will suggest that for this subject, EEG data of 100 seconds duration will be sufficient to localize the epileptic sites in a noninvasive fashion. These results are promising and warrant a larger study with data of many subjects.

2. Material and Methods

Epileptic seizure area in the patient was localized with an 8×8 intracranial grid EEG recordings. Prior to this, high-density 256-channel scalp EEG data was collected with an EEG system developed by Electrical Geodesics, Inc. (Eugene, OR). The EEG data was collected with 250 Hz sampling frequency. A three minute segment of seizure-free data during sleep was selected and imported into MATLAB for further analysis. The selected data set was not in close proximity to seizures. Raw EEG data was filtered using a FIR bandpass filter for theta (3-7 Hz) or low Gamma band (30-50 Hz). One excessively noisy channel was eliminated by replacing it with the averages of its neighbors.

We used detrended fluctuation analysis to compute the stochastic behavior of phase synchronization. The cumulative sum of each channel was calculated. This sum was divided into windows of 10 seconds length, i.e., windows were of 10, 20, 30, ..., 170 and 180 seconds length. Within each window, a linear fit was found and the cumulative sum was detrended. Next, the root-mean-squared (RMS) fluctuation of this detrended sum was calculated. The median fluctuation at each window size was taken. The log of this median fluctuation was plotted against the log of the window size, and a linear fit was found. The slope of this linear fit, denoted alpha, is the result of the detrended fluctuation analysis for each channel. This is what is called long-range temporal correlations (LRTC) [Peng et al., 1995]. As shown by Linkenkaer et al. (2005) and Peng et al. (1995) that detrended fluctuation analysis exposes long range temporal correlations that are characteristic of epileptogenic neocortical networks, the areas where epilepsy begins.

The synchronization between a pair of channel was inferred from a statistical tendency to maintain a nearly constant phase difference over a given period of time even though the analytic phase of each channel may change markedly during that time frame [Freeman Rogers, 2002]. The Hilbert transform was applied on the pairs of EEG traces with a sliding window which is long enough to encompass at least two cycles of the lowest frequency of 30 Hz in the low Gamma band or 3 Hz for the theta band. The analysis was repeated by stepping the window at 8 ms intervals, i.e., two digitized points. The synchronization index (SI) was computed for each pair of EEG traces. A global synchronization index was also computed for each electrode by pairing it with the nearby six electrodes. There were 21 combinations of electrode pairs for each electrode. The SI was averaged over these electrode pairs for each given electrode. After that the LRTC was computed for the SI as explained above. The alphas for the EEGs and the SI were normalized to their common average reference.

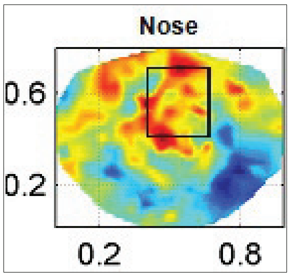

Fig. 1. A layout of spatial plots. Seizure area is marked with a rectangle.

Color intensity plots were constructed using a montage of the layout of 256 electrode positions. The horizontal and vertical axes for plots are in normalized length units. A typical spatial plot is shown in Fig. 1. The nose is on the top, back of neck is at the bottom, left of the subject is on the left side of the plot and right side of the subject is on the right side of the plot. This plot is for the LRTC activity in theta band after 10 sec duration. A rectangle marks the location of the seizure area as mapped with invasive grid recordings. The subsequent plots in Figs. 2 and 3 show the activity in and in the vicinity of the seizure area.

3. Results

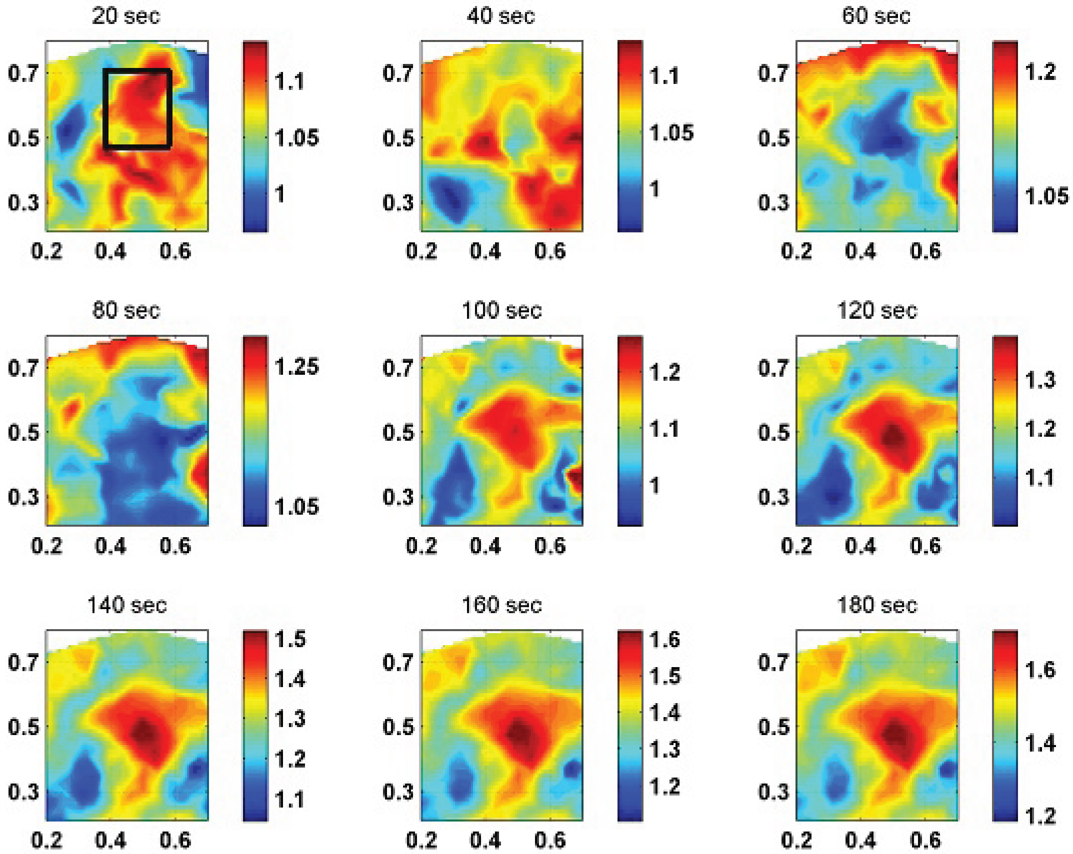

Fig. 2. Spatiotemporal plots of LRTC of phase synchronization index in theta band plotted in 20 sec time-frames. After 100 seconds, the activity becomes stable in the seizure area.

The LRTC of SI in theta band is given in Fig. 2. The plots are with 20 sec interval. The seizure activity as measured with intracranial recordings was in the frontal midline area and it is marked with a rectangle. The spatial patterns of activity between 20 to 80 sec are not stable and exhibit significant variations over time. After

100 sec the patterns in and in the vicinity of the seizure area become stable. After 100 sec, plots also exhibit higher LRTC activity in the seizure area. From these plots, a 100 sec or longer duration of scalp EEG data will be sufficient to localize the seizure area.

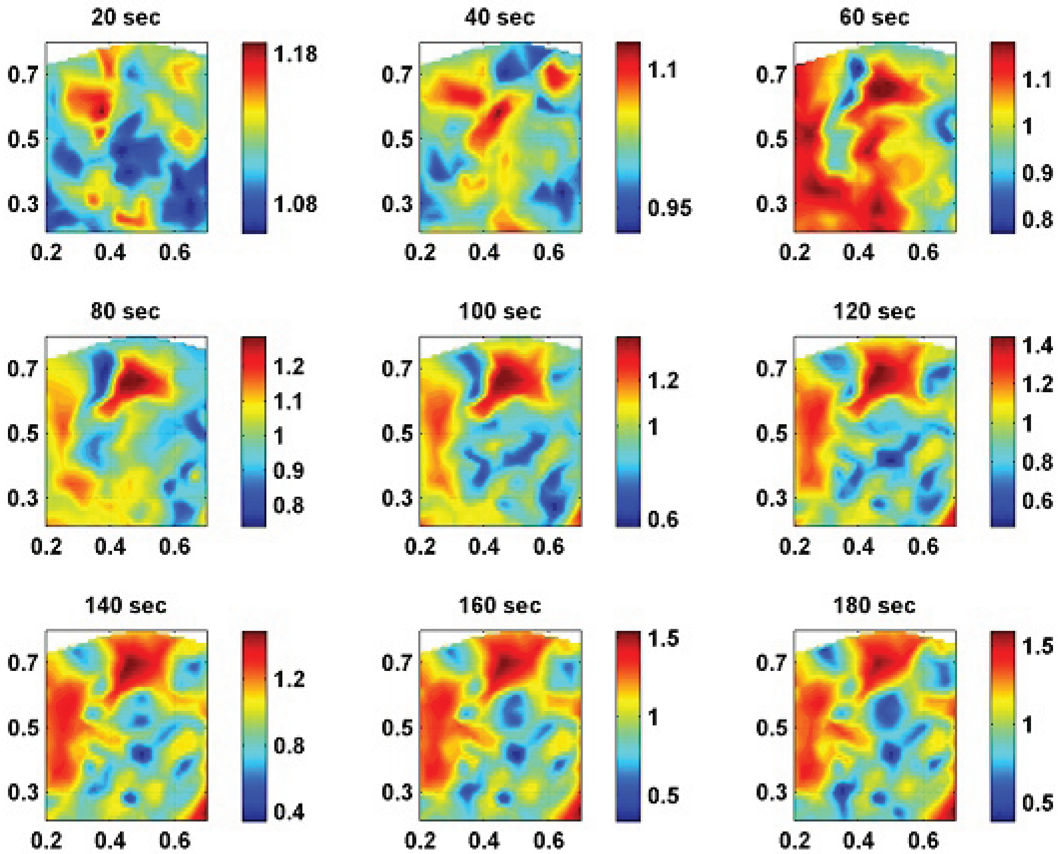

Fig. 3. Spatiotemporal plots of LRTC of phase synchronization index in low gamma band plotted in 20 sec time-frames. After 60 seconds, a stable pattern begins to appear in the seizure area.

The LRTC of SI in the low gamma band is given in Fig. 3. The plots are with 20 sec interval. The seizure area is same as in Figs. 1 and 2. The spatial patterns of activity is very fragmented in the first 60 sec and after that it becomes stable in the upper portion (frontal) of seizure area. From these plots, one can infer that EEG data of 80 sec or longer duration should be sufficient to localize the epileptic site. Combining results from Figs. 2 and 3, a choice of 100 sec will be the best for this particular subject to noninvasively localize the epileptic site from the seizure-free, interictal scalp EEG data.

4. Discussions

These are our preliminary results on the spatiotemporal dynamics of the stochastic behavior of phase synchronization index. These results show that the stochastic behavior of the phase synchronization index changes with time and has a potential to localize the epileptic sites from the seizure-free interictal high density (256 channel) scalp EEG data. For this subject, 100 sec long EEG data will be optimum to localize the epileptic site. However, this duration could be different for other subjects as we previously [Ramon et al., 2008] found that 60 sec duration was enough. Thus, a larger study is needed to further explore the feasability of using short duration seizure-free interictal EEG data to localize epileptic sites. In this study, we examined the stochastic activity only in theta and low gamma bands. Activity in other EEG bands and also cross-frequency couplings should also be examined to find optimum parameters for noninvasive localization of epileptic sites from the seizure-free and epileptiform-free interictal scalp EEG data.

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