Biomedical Signal Processing and Control 11 (2014) 114–122

Contents lists available at ScienceDirect

Biomedical Signal Processing and Control

journal homepage: www.elsevier.com/locate/bspc

Technical Note

Study of phase synchronization in multichannel seizure EEG using nonlinear recurrence measure

D. Rangaprakash [a,*], N. Pradhan [b]

[a] Department of Electrical Communication Engineering, Indian Institute of Science, Bangalore 560012, India
[b] Department of Psychopharmacology, National Institute of Mental Health and Neurosciences, Bangalore 560029, India

ARTICLE INFO

Article history:
Received 14 November 2012
Received in revised form
22 November 2013
Accepted 26 February 2014
Available online 4 April 2014

Keywords:
Recurrence plot
Phase synchronization
Correlation between probabilities of recurrence
Multichannel EEG
Linear correlation
Epileptic seizure
Brain headmap

ABSTRACT

Complex biological systems such as the human brain can be expected to be inherently nonlinear and hence difficult to model. Most of the previous studies on investigations of brain function have either used linear models or parametric nonlinear models. In this paper, we propose a novel application of a nonlinear measure of phase synchronization based on recurrences, correlation between probabilities of recurrence (CPR), to study seizures in the brain. The advantage of this nonparametric method is that it makes very few assumptions thus making it possible to investigate brain functioning in a data-driven way. We have demonstrated the utility of CPR measure for the study of phase synchronization in multichannel seizure EEG recorded from patients with global as well as focal epilepsy. For the case of global epilepsy, brain synchronization using thresholded CPR matrix of multichannel EEG signals showed clear differences in results obtained for epileptic seizure and pre-seizure. Brain headmaps obtained for seizure and pre-seizure cases provide meaningful insights about synchronization in the brain in those states. The headmap in the case of focal epilepsy clearly enables us to identify the focus of the epilepsy which provides certain diagnostic value. Comparative studies with linear correlation have shown that the nonlinear measure CPR outperforms the linear correlation measure.

1. Introduction

EEG signals, a record of electrical potentials obtained from the human brain, are complex and random looking signals, which can be analyzed as output of a stochastic process, i.e. system driven by unknown input. Based on this approach, spectral estimation and several other techniques have been developed for analyzing these signals. Several models have also been developed. However, one limitation of this approach is that it bears little or no consideration to the nonlinear process that generates the signal. Another limitation is that the models developed for these sophisticated biological systems do not represent the biological system to any reasonable extent. Hence, there is a need to analyze these signals with a different perceptive. In this work, we are concerned mainly in applying certain nonlinear techniques, which are also nonparametric, for the analysis of EEG signals.

One of the most common neurological disorders is epilepsy which is characterized by sudden and large neuronal discharges in the brain [1]. Epilepsy is an indication of excessive synchronous activity of neurons in the brain [1] and it clinically manifests as seizure. Generalized seizures involve almost entire brain, whereas focal seizures are localized to a particular region of the brain (called epileptic focus). Clinical neurophysiologists have to review the EEG recordings and look for seizures that may have occurred during the monitoring session. However, reviewing a continuous EEG recording for seizures is a time consuming task, which is also prone to human error. Thus a computer based seizure detection system can be of great value for automatic identification of seizure EEG segments. In this paper, we deal with a novel application of a recurrence based synchronization measure for seizure detection and characterization using EEG recordings.

It has been observed that biomedical signals could be generated by a nonlinear dynamical system [2]. In our work EEG signals are analyzed as the output of a chaotic system rather than stochastic system particularly in view of new developments in nonlinear dynamics and chaos. Chaos is the unpredictable long time behavior of a deterministic dynamical system which is highly sensitivity to initial conditions. In case of chaotic systems, it is observed that the system's trajectory starting from a specific initial condition in state space is different from another trajectory starting from a slightly different initial condition. In a chaotic system, these two trajectories will soon start to diverge.

* Corresponding author. Present address: Electrical and Computer Engineering Department, Auburn University, Auburn, AL, USA.
Tel.: +91 9535021951/+13342460604
E-mail address: abhi88iisc@gmail.com (D. Rangaprakash).

http://dx.doi.org/10.1016/j.bspc.2014.02.012
1746-8094/

Since EEG signals are generated by complex nonlinear dynamical biomedical systems like brain, the number of state variables required to define these systems are not small and hence the number of data points to be considered becomes very large. In order to overcome this problem, we have used recurrence plot [3] based synchronization measure for analyzing EEG signals which come under the category of nonlinear dynamical techniques. Since we compute a distance matrix between points of the trajectory of given time series in a RP based technique, the measure permits the utilization of any kind of data and hence very useful for applications where the data could be nonstationary, or nonlinear.

EEG signals recorded under various experimental conditions have been analyzed using many nonlinear techniques. In particular, measures such as correlation dimension and Lyapunov exponents [2], which are based on nonlinear dynamical systems and chaos theory, have been used to describe the complex EEG signal. For computing invariants from the reconstructed attractors, chaos based approaches make certain general assumptions. It is assumed that the signal possesses a non-evolving low-dimensional attractor and it is also assumed that the signal is long, stationary and noiseless. To relax these assumptions, the Recurrence Plot (RP) method has been employed in the literature which also helps in visualizing the behavior of trajectories of dynamical systems in phase space [3]. The advantage of this method is that RPs have an apparent simplicity of implementation and interpretation, and do not require an understanding of system's dynamical attractor. In view of these facts, a recurrence based phase synchronization technique, which is both nonlinear and non-parametric, has been employed in this paper.

The technique of RPs for data analysis is not only a useful tool for visualization but also for quantifying even for data sets with short length [4]. Furthermore, a set of quantification measures obtained from what is known as recurrence quantification analysis (RQA) quantify systematically the different structures found in RP [5]. One of the advantages of RQA resides in its elegant independence from constraining assumptions and limitations plaguing other analyses. Since recurrence structures are simply tallied within the signal (or between signals), there is no need to pre-condition the data. Recurrence analysis is not limited by signal non-stationarity and transients. Hence RQA has proven to be ideally suited for the study of numerous real-world systems encompassing a multitude of disciplines. RQA has found numerous applications in diverse fields [6–8] and its use in studying various biological systems [9,10] including brain [11] has been reported in literature. RQA can also deal with signals from nonlinear systems of any nature in quantifying the activity of system and is model-free. Thus, for analysis of physiological signals like EEG which are often nonstationary and depict nonlinearity, this tool is particularly suitable. Hence, RQA is a good choice to reveal changing dynamics of biomedical systems. RQA quantifies the activity of a system independent of its dynamical nature as also deals directly with the signal without the need for system identification. Even though nonlinear dynamical technique has been applied to study epileptic EEG [12], the application of RQA to study EEG signals appears very promising for the reasons mentioned above.

Phase synchronization takes place between two signals when their respective frequencies and phases are locked. We are concerned here with the application of synchronization to seizure analysis. We would like to observe that phase synchrony does not imply seizure. However, during seizure we observe synchrony in the brain and the waveform patterns are characteristics of seizure. Also our interest in phase synchronization is due to the fact that many biological systems exhibits phase synchronization. It is well known that alpha band increases in synchrony in the occipital region of the brain when eyes are closed. It is also observed that many cognitive tasks involve synchronization. Synchronization patterns measured from EEG in many psycho physiological experiments have also been reported in literature [13] Synchronization is a universal phenomenon with global importance with its applications for chaotic oscillators being recognized [14,15] and subsequently studied by many researchers [16,17]. Literature contains several applications of this phenomenon to natural systems like magnetoencephalography [18], neuronal systems [19,20], cardiorespiratory systems [21] and ecological systems [22]. Efforts have been made in the application of nonlinear phase synchronization in seizure analysis. Lachaux et al. [23] have proposed a method for the quantification of synchronization using phase locking statistics to investigate recordings from an epileptic patient who is performing a visual discrimination task. Chavez et al. [24] have discussed about the estimation of phase synchronization from EEG signals recorded from an epileptic patient. Mormann et al. [25] have presented a technique for detection of pre-seizure state using mean phase coherence as a measure of phase synchronization. Le Van Quyen et al. [26] have discussed ways of characterizing neurodynamic changes in preictal state using nonlinear analysis of brain signals. EEG signals three groups viz. control, seizure and mania have been studied by Bhattacharya [27] to investigate the effect of these pathologies on the degree of phase synchronization between cortical areas. Studies have also been made on the multichannel seizure analysis using nonlinear measures. McSharry et al. [28] have introduced a nonlinear measure, multidimensional probability evolution, for multichannel seizure analysis. Gupta et al. [29] have shown that tracking changes in phase synchronization of narrow band activity of multichannel EEG can be useful for seizure onset detection and prediction. Bianchi et al. [30] have studied multichannel EEG synchronization by evaluating the mutual synchronization among several EEG channels using a measure called cross conditional correlated entropy. This paper discusses the application of a measure called Correlation between Probability of Recurrence (CPR) [31] which uses the concept of probability of recurrences in phase space. The definition of CPR has been extended here to study multichannel seizure EEG signals. The utility of nonlinear recurrence measure CPR has been demonstrated for both focal and global epilepsy cases using surface and contour plots of CPR matrix as well as through brain headmaps. The method employed here, being nonparametric, makes very few assumptions, making it suitable for studying brain function in a data driven way.

It is of interest to observe that many of the synchronization studies are based on linear correlation which has rather limited interpretability in the broader biological context. Specifically, it has been recognized that phase synchronization can be studied using distributed information processing in the brain occurring for many higher order brain processes [32]. While linear correlation can be used for detecting zero-lag first order phase synchronization, it cannot detect higher order and lagged synchronization [32,31]. Thus for a massively interconnected nonlinear complex system such as human brain, nonlinear methods seems better suited for synchronization studies in EEG. Hence the use of a nonlinear measure like CPR seems more appropriate for characterizing phase synchronization in the brain. This paper has validated this by showing that the nonlinear correlation measure CPR is superior in performance to the linear correlation measure. Here synchronization analysis of multichannel EEG signals has been made through a novel use of a nonlinear and non-parametric recurrence based phase synchronization measure.

2. Materials and methods

2.1. Data

We give an account of the multichannel EEG data used in this paper. 16 channel EEG was recorded from 16 subjects who had