Dynamic Feature Extraction of Epileptic EEG Using Recurrence Quantification Analysis

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Abstract - Detecting the reliable transition point embedded in the electroencephalograms (EEGs) is a challenge in the field of epileptic research. In this research, a recurrence quantification analysis (RQA) is proposed to help medical doctors to reveal dynamical characteristics in EEGs of patients suffering from epilepsy. In contrast with traditional chaos methods, the merits of RQA method is that it can measure the complexity of a short and non-stationary signal without any assumptions such as linear, stationary and noiseless noise. In this study, EEGs with generalized epilepsy were collected in Epilepsy Center of Renji Hospital. The test results show that three RQA measurements, i.e. recurrence rate, determinism and entropy can track the complexity changes of brain electrical activity. RQA variables show a large fluctuation in pre-ictal stage, which reflects a transitional state leading to seizure activity. On the contrary, RQA variables fluctuate in relatively small bounds in ictal stage, which is due to organized and self-sustained rhythmic discharge. Therefore, RQA could be a promising approach in prediction and diagnosis for epileptic seizures.

Index Terms - Epileptic Seizure; EEG; Recurrence quantification analysis (RQA); Dynamic Feature.

I. INTRODUCTION

Nowadays, a hot topic in the field of epilepsy research is the detection of any reliable marker, embedded in the electroencephalograms (EEGs) [1]. This can be exploited to predict the seizure with a sufficient advance notice. EEG monitoring systems have become important clinical tools for evaluation and treatment of epilepsy [2]. So far, many methods have been proposed to analyze EEG data and recognize EEG pattern. In the last decade, much more attention has been paid to the dynamic characteristics of brain electrical activity. In particular, these new measures, i.e. Lyapunov exponents [3] and correlation dimension [4], are based on assumptions of non-linear dynamical systems (chaos). These methods can describe the complexity of EEGs but require a long, stationary and noiseless data to analyze. Actually, EEG data from an epileptic patient is evolving fluctuant which presents non-stationary and noisy characteristic. Therefore, a useful tool which may help medical doctors to detect significant patterns in epileptic EEGs is the recurrence quantification analysis (RQA). The main advantage of RQA is that it can provide useful information even for short and non-stationary data where other methods fail. In this study, RQA is applied to quantify dynamics of EEG data for epileptic patients. The three fundamental RQA measures test the different dynamical characteristics of background, pre-ictal and ictal EEG. The research provides useful analysis tool for medical doctors to detect the reliable transient marker embedded in long-term EEG record.

II. MATERIALS AND DATA ACQUISITION

EEG data were collected from patients with generalized epilepsy in Epilepsy Center of Renji Hospital. EEG were recorded using Ag/AgCl electrodes and were placed in accordance with the international standard 10-20 system at Fp1, Fp2, F3, F4, C3, C4, P3, P4, O1, O2, F7, F8, T3, T4, T5 and T6. The EEG data were sampled at 200Hz and filtered with a high-pass filter at 0.5Hz and a low-pass filter at 70Hz. A 50Hz notch filter was also employed. Fig.1 shows the EEGs of a patient under pre-ictal and ictal stage respectively. Each segment is 2 min long.
III. METHODS

The RQA is a method of nonlinear data analysis for the investigation of dynamical systems. This method, developed by Charles Webber and Joseph Zbilut [5], aims to quantify differently appearing recurrence plots (RPs) [6] based on the small-scale structures. Recurrence plots are graphical tools which visualize the recurrence behaviour of the phase space trajectory of dynamical systems. Recurrence plots are briefly defined in (1).

\[ R_{ij} = \Theta(\epsilon - \|x_i - x_j\|), i, j = 1, \ldots, N \]

where \(\|\cdot\|\) is the norm and \(\Theta(x)\) is the Heaviside function. This means if the distance between \(x_i\) and \(x_j\) is less than \(\epsilon\), then \(R_{ij} = 1\) and a dot is placed at \((i, j)\) in the RP. The scale \(\epsilon\) is a cutoff distance defining a sphere centred at \(x_i\).

Although several measures have been introduced in RQA in the recent past [7], this research mainly focuses on three fundamental measures as originally introduced by Webber and Zbilut [5].

1) Recurrence Rate (\%REC), which is the density of recurrence points in a recurrence plot. The recurrence rate corresponds with the probability that a specific state will recur. \%REC is calculated by (2).

\[ \%REC = \frac{1}{N^2} \sum_{i,j} R(i,j) \]

2) Determinism (\%DET), which is the ratio of recurrence points on the diagonal structures to all recurrence points. Diagonal lines represent epochs with similar time evolution of states. Therefore, \%DET is related with the determinism of the system. \%DET is calculated by (3).

\[ \%DET = \frac{\sum_{l=1}^{N} \sum_{i,j} R_{ij}}{\sum_{l=1}^{N} \sum_{i,j} R_{ij}} \]

3) ENTR refers to the Shannon Entropy of the frequency distribution of the diagonal line lengths, which is a measure of the complexity of the recurrence structure. ENTR is calculated by (4).

\[ ENTR = -\sum_{l=1}^{N} p(l) \ln p(l), \]

where \(p(l) = P(l) / \sum_{l=1}^{N} P(l)\)

These three fundamental recurrence variables quantify the deterministic structure and complexity of the plot.

IV. RESULTS

In this research, RQA is applied to discover hidden dynamics of epileptic EEG data, including the structure and the quantification analysis of the recurrence plots (RPs). The purpose is to reveal the subtle features in human EEG signals. EEG epileptic activity consists of different stages: (1) the ictal stage starts at the seizure onset. It is characterized by high amplitude, organized and self-sustained rhythmic electrical discharges; (2) the pre-ictal stage is the period immediately preceding a seizure; (3) the post-ictal stage is the period following the seizure end and represents a return to normal background activity; (4) the inter-ictal stage is the period between the post-ictal stage of one seizure and the pre-ictal stage of the next seizure. It is characterized by sharp waves and spikes [8].

A. Structure of Recurrence Plots (RPs)

Two typical signals (Fig.2 and Fig.3) are selected to analyze their structure of recurrence plots. Usually, stochastic behaviour causes non or short diagonals and a large amount of isolated recurrence points, whereas deterministic behaviour causes longer diagonals [7]. Sine signal (Fig.2) is one kind of periodic deterministic signals. The RP of sine signal (Fig.2) is characterized by the long diagonal line structures parallel to the main diagonal, which indicates the determinism of the system. EEGs (Fig.3) are non-stationary and evolving fluctuant. The RP of background EEG (Fig.3) is characterized by many isolated recurrence points, which demonstrates the complex characteristics of human brain system.

The measures based on diagonal lines, vertical and horizontal structures make it possible to identify and quantify the dynamic features of the system. In the next section, three quantification measures of RP are considered.

B. Recurrence Quantification Analysis (RQA)

In this section, the EEG recordings obtained in pre-ictal and ictal stage are analysed. Three recordings are shown in the top panels of Fig.4. The onset of seizure can be observed associated to rapid build-up of high amplitude and rhythmic activity of the EEG. The length of each EEG recording is 4 min (containing 48,000 points, divided into 48 segments). Three RQA measures, i.e. \%REC, \%DET and ENTR are calculated for each segment with a dimension of \(m=15\), a delay of \(\tau=11\), a radius of \(\epsilon=1.5\), NORM = min norm, RESCALE = max dist. The change of RQA variables along the EEG is illustrated in the below panels of Fig. 4. In pre-ictal stage, RQA variables often fluctuate in relatively large bounds. Take the results in Fig.4 (a) for example: \%REC changes from 11 to 35, \%DET from 25 to 80, ENTR from 0.8 to 2.4. From the onset of seizure, EEGs begin to show high amplitude and rhythmic waveform. Accompanied by the drastic change of EEG wave, the value of all RQA variables clearly drops and changes in relatively small bounds. Also take the results in Fig.4 (a) for example: \%REC changes from 11 to 17, \%DET from 29 to 50, ENTR from 0.8 to 1.2. Fig. 5 shows the statistical distribution of RQA variables. Here the results obtained in Fig.4 (a) are illustrated. The similar results are observed in other EEG recordings. The total results for five EEG recordings are listed in TABLE I. Both the mean value and the standard deviation of RQA variables in the pre-ictal stage are larger than that in ictal stage. The large fluctuation of RQA variables in pre-ictal stage might be reflective of a transitional state leading to seizure activity. The smaller RQA fluctuation in ictal stage is due to the organized and rhythmic waveform of seizure EEG.
Fig. 2. Recurrence plot of a sine signal epoch. The most striking feature of this plot is the long diagonal line structures parallel to the main diagonal. RQA parameters: a dimension of $m=15$, a delay of $\tau=11$, and a radius of $\varepsilon=0.2$, NORM=min norm.

Fig. 3. Recurrence plot of a human background EEG epoch. This plot has a large number of isolated points. RQA parameters: a dimension of $m=1$, a delay of $\tau=1$, and a radius of $\varepsilon=0.2$, NORM=min norm.

Fig. 4. Epileptic EEGs and their RQA measures. Three EEG recordings containing the seizure onset are illustrated in the top panel and onset of seizure is indicated by arrow. Each EEG recording lasts 4 min and is divided into 48 segments. Each segment contains 1,000 points. Panels represented below show the behaviour of three RQA variables by using a dimension of $m=15$, a delay of $\tau=11$, and a radius of $\varepsilon=1.5$, NORM=min norm, RESCALE=max dist. The onset of seizure was accompanied by the high amplitude and sustained rhythmic electrical discharges. All the RQA variables fluctuate in relatively smaller bounds after the seizure onset. In addition, the value of RQA measures appears smaller after the onset.

Fig. 5. Statistical distribution of three RQA variables in pre-ictal and ical stage. Only the statistical results for Fig.4 (a) are shown. The similar results are obtained for the other EEG recordings. The solid line indicates the value distribution in pre-ictal stage. The dotted line represents the value distribution in ical stage. Not only the mean value but also the standard deviation of all RQA variables is smaller in ical stage.
EEGs visual inspection. The seizure of epileptic and liberate doctors from long-term discharge. Our results verified the application of RQA can reveal the changing dynamics of EEG data at various times. In the future, RQA methods can help medical doctors to predict the seizure of epileptic and liberate doctors from long-term EEGs visual inspection.

V. DISCUSSIONS AND CONCLUSIONS

Nowadays, more attention has been paid to discover the mechanism of phase transition from normal state to ictal state, which helps to predict the epileptic seizure [1]. Traditional methods such as time serials visual inspection and spectral analysis [9] are based on the principle that EEGs are generated from random processes. Therefore, these methods fail to detect the embedded dynamics of EEGs. Recently, some investigators such as chaotic measures regard the brain electrical activity as non-linear behaviour. These methods such as Lyapunov exponents [3] and correlation dimension [4] can provide the information of complexity of EEGs. However, only long, stationary and noiseless EEG signals are suitable for these methods.

To overcome the drawbacks of above methods, this research applied recurrence quantification analysis (RQA) method, which can deal with short, non-stationary and noisy signals. Actually, epileptic EEGs contain transients embedded in background noise, which are of great importance for diagnostic purposes. In this study, the structure of recurrence plot and the quantitative measures of RQA are analysed for the EEGs in inter-ictal, pre-ictal and ictal stages. The test results show different dynamical characteristics in different states. Three fundamental RQA measures, i.e., %REC, %DET, and ENTR succeed tracking the change of complexity of EEGs. Pre-ictal stage demonstrates an unstable transitional state characterized by large value and large standard deviation of RQA variables. After the onset of seizure, RQA variables fluctuate in relatively small bounds and show a relatively smaller mean value. This indicates that epileptic seizure is organized and self-sustained rhythmic discharge. Our results verified the application of RQA can reveal the changing dynamics of EEG data at various times. In the future, RQA methods can help medical doctors to predict the seizure of epileptic and liberate doctors from long-term EEGs visual inspection.

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REFERENCES


<table>
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<th>EEG Recording</th>
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<th>%DET</th>
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Mean value for each EEG recording in pre-ictal and ictal stage respectively. Standard deviation is indicated in parentheses.