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Multifractal parameters as an indication of different physiological and pathological states of the human brain

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HIGHLIGHTS

- We analyze EEG pattern of normal humans and patients with epilepsy.
- Different physiological states (eyes open and closed) were analyzed for a normal set.
- Data from different sections of the brain and seizure activity was analyzed.
- Different values of width for different physiological and pathological states.
- MFDFA can be employed for diagnosis of the epileptogenic zone.

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ABSTRACT

This paper presents a study on multifractal parameters of EEG patterns on the human brain. Multifractal detrended fluctuation analysis was applied to human EEG for normal and epileptic patients in different states. The results show that the degree of multifractality of EEG for patients in an epileptic seizure are much higher compared to normal healthy people. The degree of multifractality for normal humans with eyes open and closed was also significantly different. Thus the multifractal parameters can be used to distinguish between different physiological and pathological states of the human brain. The results are discussed in detail.

1. Introduction

Many complex dynamical systems are found in nature which can be characterized by a set of nonlinear differential equations. The reason for chaotic behavior of such complex systems is attributed to nonlinearity. The human brain is such a complex system made up of billions of nerve cells, called neurons, which transmit signals inside the brain and from the brain to the rest of the body. Epilepsy is a neurological condition which affects the nervous system. It is a general term used for a group of disorders in which nerve cells of the brain discharge anomalous electrical impulses from time to time, causing a temporary malfunction of the other nerve cells of the brain. This results in an alteration of perception, strange sensations, emotions, or sometimes convulsions, muscle spasms, and in some cases complete loss of consciousness. In normal functioning of the brain, information is conducted in the form of an electrical signal from one neuron to the other.

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All functioning of the brain depends on electrical signals being conducted from one neuron to a subsequent one, the message being modified as required. A normal brain constantly generates electrical rhythms in an orderly way. In epilepsy this order is disrupted by some neurons discharging signals inappropriately.

Epilepsy is the tendency to have repeated seizures that begin in the brain, due to clusters of neurons communicating abnormally [1]. Epilepsy can begin in all ages and it causes social problems. Biomedical sciences looks to predict the clinical onset of epileptic seizures so that a patient could have surgery. Electroencephalograms (EEGs) and brain scans are common diagnostic tests for epilepsy. Epilepsy is a serious disorder and it affects from 1% to 2% of the global population.

Fractal geometry is an approach that has been important to study epilepsy. It is used to analyze, describe, and model complex forms or curves found in nature, through fractal dimension, that serves as a quantifier of complexity. Fractal geometry mathematically characterizes systems that are basically irregular at all scales. Fractals can be classified into two categories: monofractals and multifractals. Multifractals are more complicated self-similar objects that consist of differently weighted fractals with different non-integer dimensions. Thus the fundamental characteristic of multifractality is that the scaling properties may be different in different regions of the systems. Monofractals are those whose scaling properties are the same in different regions of the system. Fractal geometry can be used to analyze electroencephalograms (EEG) from epileptic patients to determine where the epileptogenic region is located, so the epileptic patient can undergo surgery [1].

Electroencephalography is the neurophysiologic measurement of the electrical activity of the brain by recording from electrodes placed on the scalp or, in special cases, on the cortex. It has been mentioned earlier that the brain is a complex nonlinear system consisting of thousand of neurons. Hence the EEG data taken is a result of an ensemble of neurons interacting with each other as well as remote neurons whose potentials are not included in measurement. So the question arises of how far EEG time series can reveal information of the dynamical properties of the brain. A lot of experiments in the past have shown that EEGs are capable of providing information about states of the brain [2,3].

In this paper a multifractal detrended fluctuation analysis of the EEG pattern of normal and epileptic patients is done. C.K Peng et al. were the pioneers in this field and they introduced the detrended fluctuation analysis (DFA) methodology to study the properties of DNA sequences [4]. It has been extensively applied to different fields e.g. geology, DNA sequences, neuron spiking, heart rate dynamics economic time series and also to weather related and earthquake signals [4–12]. In spite of their wide range of applications it is however found that many geophysical signals as well as medical patterns do not represent simple monofractal behavior which can be accounted for by a single scaling exponent [13,14] e.g. if the signal consists of random spikes or a crossover timescale which separates regimes with different local behavior. In the later case, different scaling exponents are required for different parts of the series indicating a time variation of the scaling behavior [15]. Different scaling exponents can be also revealed for many interwoven fractal subsets of the time series [16]. So a multifractal analysis of the data would be more appropriate. The multifractals are fundamentally more complex and inhomogeneous than monofractals [17] and describe time series featured by very irregular dynamics, with sudden and intense bursts of high-frequency fluctuations [18]. The simplest type of multifractal analysis is given by the standard partition function multifractal formalism designed to describe multifractality in stationary measures [19,20]. However this method does not correctly estimate the multifractal behavior of signals which are affected by certain trends or non-stationarities. Another method called the wavelet transform modulus maxima (WTMM) method [21–23] was proposed, based on the wavelet analysis and it was able to characterize the multifractality of non-stationary signals. Ivanov et al. [24] have studied the multifractality of human heart rate dynamics using the WTMM methodology. The multifractal detrended fluctuation analysis was first conceived by Kantelhardt et al. [25] as a generalization of the standard DFA. MFDFA is capable of determining multifractal scaling behavior of non-stationary time series. It has been applied successfully to study various non-stationary time series [25–39]. MFDFA allows a global detection of multifractal behavior, while the WTMM method is suited for the local characterization of the scaling properties of signals. Moreover the MFDFA does not require a big effort in programming but provides reliable results.

MFDFA has been successfully applied in the past to study EEG patterns in humans as well as in different animals [40–42]. Multifractal analysis of EEG using other methods is also not uncommon [43–49]. The present study also reveals very interesting results and is discussed in detail.

2. Description of the data

The data of this paper is extracted from the experiments carried out by Andrzejak et al. [2]. The details of the data and data selection procedure can be obtained from the reference. The data consists of five sets A–E. The plot of one signal from each set is shown in Fig. 1. Each set contains 100 single channel EEG segments each of 23.6 s duration. A part of one data (1 s) for each of the sets A–E is shown in Fig. 1. The brief description of sets is given below:

(i) Set A: Extra cranial recording of healthy subject with eyes open
(ii) Set B: Extra cranial recording of healthy subject with eyes closed
(iii) Set C: Intracranial recordings from the hippocampal formation of the opposite hemisphere of the brain of patients in seizure free interval
(iv) Set D: Intracranial from within epileptogenic zone of patients in seizure free interval
(v) Set E: Seizure activity of patients.