The study of spatiotemporal scaling features and correlations in complex biomedical data

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Annotation

In this work, we study the capabilities of the normalized range method (*R*/*S* analysis) in the study of fractal patterns in biomedical data of complex living systems. The capabilities of the proposed algorithms were demonstrated by analyzing the scaling features of the temporal dynamics of the tremor rate in Parkinson's disease, the bioelectrical activity of the brain of patients with epilepsy, including those under external influences. The results can be used in computational biophysics and physics of complex systems to search for diagnostic criteria for neurological and neurodegenerative diseases, as well as to study the processes of biological aging and changes in the "physiological complexity" of the human body.

Introduction

Time signals, including experimental series of biomedical data, produced by complex systems, contain unique, inherent in highly organized composite objects, information about the evolution, organization, structure, as well as the nature and role of the interaction of individual components.

Analysis of the self-similar properties of biomedical data allows establishing diagnostic criteria for various neurodegenerative and neurological diseases, as well as psychiatric disorders [1].

This paper focuses primarily on the optimization of numerical algorithms for calculating the Hurst exponent, considering the features of the spatiotemporal structure in the analyzed biomedical data sets. The next goal is to search for diagnostic criteria for neurological and neurodegenerative diseases.

Normalized range method. Local generalization of the Hurst exponent

The dynamics of an experimentally recorded parameter of a complex system as a discrete time series x_j of some variable X can be represented as:

$$X = \{x(T), x(T+\tau), x(T+2\tau), ..., x(T+(K-1)\tau)\},$$
$$x_j = x(T + j\tau).$$

Here T is the initial moment of time, $(K–1)\tau$ is the total signal registration time, τ is the sampling time step.

To calculate the Hurst exponent, the following relation is used:

$$\frac{R}{S} = (a \cdot N)^H,$$

where a is a constant value, which we further consider equal to 1, N is the number of observations, H is the Hurst exponent, S is the standard deviation, R is the deviation range.

The essence of the localization procedure in calculating the Hurst exponent is to extract information about local persistent and antipersistent features of time signals and study their local structure.

To study the local behavior of the Hurst exponent, two algorithms can be implemented.

In first case, the calculation is carried out by splitting the initial time series into short segments of a certain size $n\tau$ and then finding the value of the Hurst exponent for each segment. Thus, a sequence of values is obtained:

$$H(T, T+n\tau), H(T+n\tau, T+2n\tau), ...,$$
$$H(T+(K-n-1)\tau, T+(K-1)\tau).$$

For the second algorithm, in the initial time series, value of Hurst exponent is calculated for a considered segment of length $n\tau$. The the window $n\tau$ is shifted by one sampling step to the right. The value of Hurst exponent is calculated for this segment as well, and the whole sequence of actions is repeated. As a result, a sequence of values is obtained:

$$H(T, T+n\tau), H(T+\tau, T+(n+1)\tau), ...,$$
$$H(T+(K-n-1)\tau, T+(K-1)\tau).$$

Description of experimental data

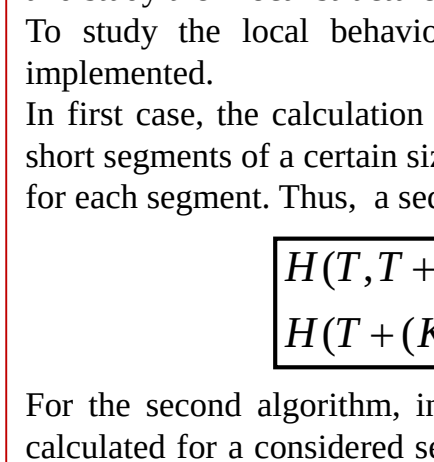

Fig. 1. The location of the electrodes according to the international system "10–20%".

In this study we considered two types of biomedical data:

1) Pathological index finger tremor velocity signals of 16 patients with Parkinson's disease. Registration was performed in the absence of medical interventions, under the influence of deep brain stimulation and drugs (8 conditions in total) [2].
2) Electroencephalograms (EEG) of patients with epilepsy. Recordings included periods before, during and after an epileptic seizure [3].

Analysis of correlations and features of space-time scaling in real biomedical data

Based on the normalized range method, we carried out an analysis of the correlation's dynamics in velocity signals of the pathological tremor of the index finger for a patient with Parkinson's disease.

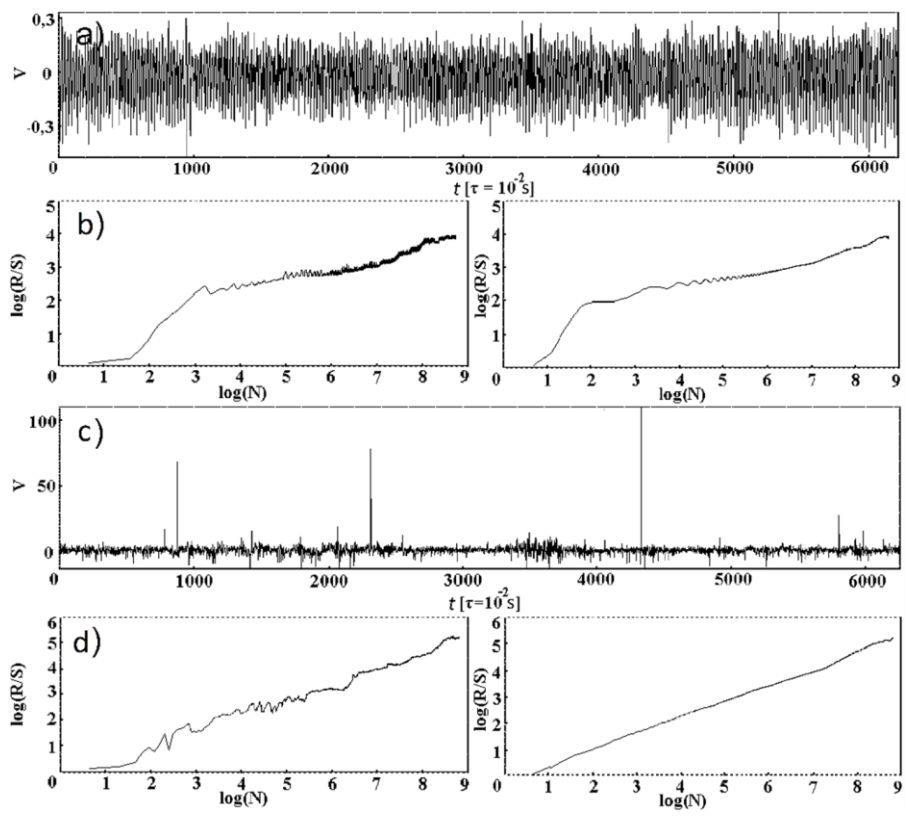

Fig. 2. Dependences of log(*R*/*S*) on log(*N*), obtained for the dynamics of the human pathological tremor velocity in Parkinson's disease. (a) – in the absence of medical intervention, (c) – when using combined treatment tactics (levodopa and deep brain stimulation). (b), (d) – Hurst exponent calculation results using the fast algorithm (on the left) and the slow algorithm (on the right).

The average values of Hurst exponent in the absence of medical intervention are 0.51 and 0.52 for the fast and slow algorithms, respectively. A medical event leads to an increase in the level of correlation and an increase in the trend stability of the analyzed signal, for example, in the case of a combined effect, the values of the parameter H increase to values of 0.6.

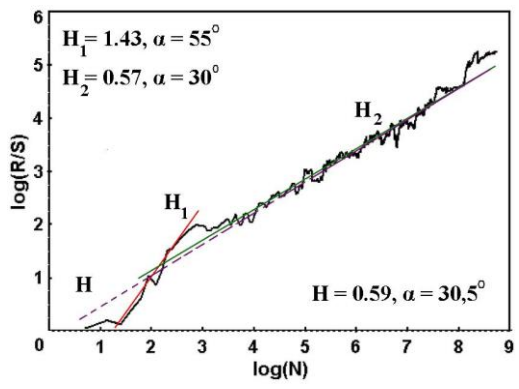

Fig. 3. The dependence of log(*R*/*S*) on log(*N*) calculated using a fast algorithm for a time series of a patient with parkinsonism after treatment. The dotted line denotes the averaged approximating straight line.

Within the framework of the *R*/*S* analysis, we have conducted a study of the correlation's dynamics in human electroencephalogram signals.

EEG area	Fast algorithm	Slow algorithm
Before seizure	0.58	0.59
During seizure	0.39	0.4
After seizure	0.48	0.49

Table 1. The values of Hurst exponent for different areas of bioelectrical activity of a patient with epilepsy during a tonic seizure.

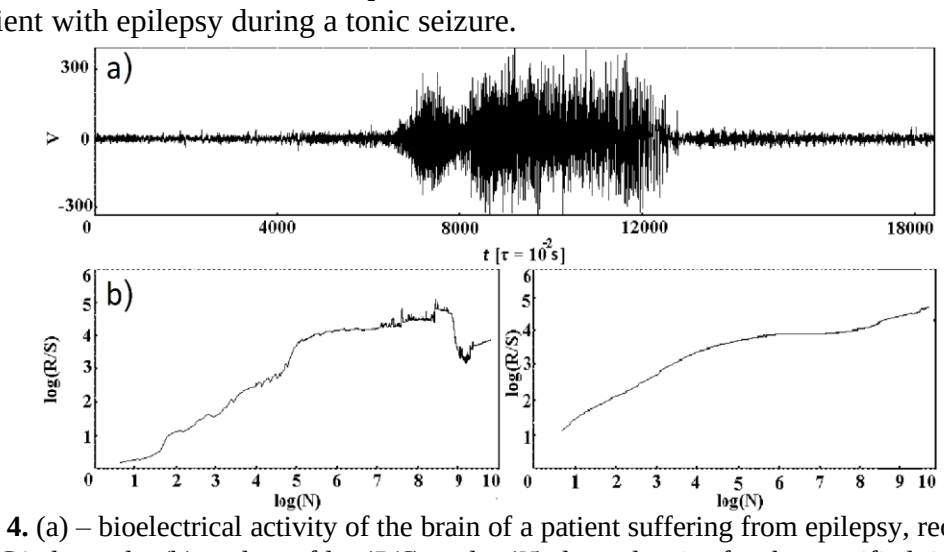

Fig. 4. (a) – bioelectrical activity of the brain of a patient suffering from epilepsy, recorded by the *C*4 electrode, (b) – plots of log(*R*/*S*) on log(*N*) dependencies for the specified time series: fast algorithm on the left, averaging algorithm on the right.

The analysis of the Hurst exponent values indicates the manifestation of different types of correlation in the EEG signal before, during and after an epileptic seizure.

Before, during and after an epileptic seizure, the local behavior of the Hurst exponent changes. Before the seizure, the behavior of the Hurst index is characterized by a persistent character. During an attack, the H values correspond to the area of antipersistent correlations. After an attack, the Hurst index returns to the initial relaxation level.

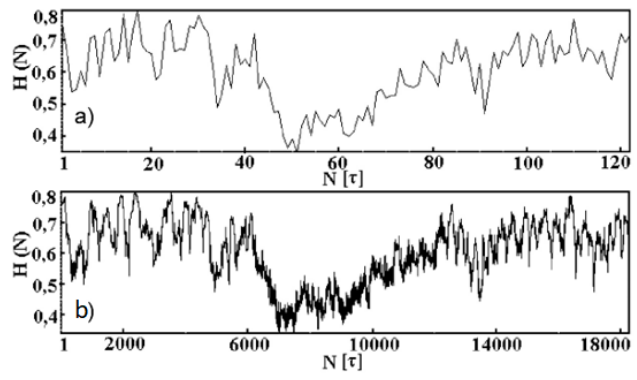

Fig. 5. Typical time behavior of the Hurst exponent for the EEG signal of a person with epilepsy. (a) – construction of time behavior by dividing the original signal into segments of acceptable length; (b) – construction by moving the local window each time by one sampling step.

Conclusions

In the frameworks of the *R*/*S* analysis an increase in the persistent nature of correlations was found in the case of a therapeutic effect on a patient with Parkinson's disease. A reversal (decline-rise) nature of the dynamics of correlations was found during a tonic seizure in a person with epilepsy. An analysis of the local behavior of the Hurst exponent $H(t)$ allowed revealing the alternation of persistent and antipersistent correlations in certain areas of the EEG signal of a person during a tonic seizure.

[1] T. Azizi, "On the fractal geometry of gait dynamics in different neuro-degenerative diseases", Physics in Medicine, vol. 14, p. 100050, 2022.

[2] A. Beuter, M.S. Titcombe, F. Richer, C. Gross and D. Guehl, "Effects of deep brain stimulation on amplitude and frequency characteristics of rest tremor in Parkinson's disease", Thalamus & Related Systems, vol. 1, pp. 203–211, 2001.

[3] O.A. Rosso, A. Figliola, J. Creso and E. Serrano, "Analysis of wavelet-filtered tonic-clonic electroencephalogram recordings", Medical and Biological Engineering and Computing, vol. 42, pp. 516–523, 2004.

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