

Analysis of Epileptic Seizures Stages through Attractor Dynamics

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Abstract: *By employing mathematical procedures specific to non-linear dynamics, we devised a method for analyzing all the stages of an epileptic crisis. It can be seen that a specific attractor (reconstructed in the states space by time delay method) can be associated with each stage of the brain dynamics: normal functioning and epileptic crisis (pre-crisis, epileptic seizure, post-crisis). Moreover, since for each attractor a Hurst coefficient can be determined, we can state that each stage of an epileptic seizure can be characterized either by calculating the specific Hurst coefficient, or by calculating its fractal dimension.*

Keywords: EEG; epileptic seizure; attractors; nonlinear dynamics.

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Introduction

According to the World Health Organization (WHO), around 50 million people worldwide have epilepsy, making it one of the most common neurological diseases globally (World Health Organization, 2019). Approximately 75% of epilepsy begins during childhood, researchers stating that the developing brain could have a heightened susceptibility to seizures (Stafstrom & Carmant, 2015).

Epilepsy is a chronic neurological disorder, characterized by convulsive seizures, always followed by loss of conscience. Convulsions manifest through member contractions, followed by their stretching and back arching. Often, general members shaking follows. In most cases, the skin of the affected person turns blue, due to interrupted respiration. The time it takes for one to regain a normal state after such a seizure can be between 10 to 30 minutes, but the recovering period can even extend to several hours. During this period fatigue, headache, speaking impairment and abnormal behavior can occur.

An International League Against Epilepsy (ILAE) classification of epileptic seizures and epilepsies, published in 2010, divides them into three categories: generalized, focal, and epileptic spasms (Berkovic, 2015; Berg et al., 2010). The origin of focal seizures can be found in neuronal networks limited to part of one cerebral hemisphere. Generalized seizures start in bilateral distributed neuronal networks. Also, this classification states that seizures can originate in the cortex or in subcortical structures. By employing different diagnostic tools, physicians can identify the seizure/epilepsy type, and thus a correct diagnostic evaluation and treatment plan can be formulated.

Epileptic seizures occur due to distortions of the normal balance between excitation and inhibition in the brain (Rho et al., 2010). The imbalance can be a result from an alteration at several levels of brain function. There are various physiological reasons for the developing brain to be particularly prone to seizures (Berkovic, 2015). Even in the case of a normal developing brain, excitatory synaptic function develops before inhibitory synaptic function, favoring enhanced excitation and seizure generation. Moreover, early in life, the neurotransmitter GABA causes excitation rather than inhibition (Pitkänen et al., 2015). These facts can explain why the very young brain is susceptible to seizures.

Epilepsy can be evaluated through different means, electroencephalography, which will be discussed later on, being the widely used one.

Patient's history and neurologic examination (supported by clinical laboratory evaluations) form the basis of diagnosing seizures and epilepsy. Several important historical features are the clinical context in which the seizure occurred (including premonitory signs), details of the seizure (such as phenomenology, responsiveness, focal features), and the postictal state (Stafstrom & Carmant, 2015).

Neurological examinations assess the focal signs that might implicate or localize cerebral pathology. Moreover, the general physical examination can also determine if the patient has an underlying condition.

Computed tomography (CT) and magnetic resonance imaging (MRI) scans are important adjuncts to the clinical examination and EEG in the evaluation of a person with seizures. Neuroimaging techniques are especially sensitive for central nervous system structural lesions. Focal neurologic findings on examination (e.g., unilateral weakness, asymmetric reflexes) impose neuroimaging techniques. CT is valuable in the acute setting to detect hemorrhage, calcification, or tumors.

MRI is more likely to show an abnormality in a patient with focal seizures, abnormal neurologic findings, or focal discharges on EEG. MRI is preferred because of its increased sensitivity compared to the CT scan, especially for the detection of cortical malformation, dysgenesis, or hippocampal sclerosis. Quantitative, computer-assisted volume analysis of the temporal lobes may detect asymmetries that are not readily apparent on visual analysis of the scan.

Moreover, several new imaging techniques are available to aid in the assessment of epilepsy (Rho et al., 2010). MRI abnormalities can be correlated directly with EEG activity. Functional MRI (fMRI) takes advantage of blood oxygen level dependence (BOLD) to image neuronal activation and map interictal or ictal epileptiform activity and localize language and memory. Magnetic resonance (MR) spectroscopy measures the concentrations of a variety of neurochemicals in different brain regions and can sometimes assist in localizing a seizure focus. Positron emission tomography (PET) images the brain's regional use of glucose with asymmetries suggesting areas of interictal or ictal abnormality. Single-photon emission-computed tomography (SPECT) compares local blood flow discrepancies, information that is most useful when recorded during a seizure. Magnetoencephalography (MEG) assesses the brain's dynamic electromagnetic fields and can better localize epileptic dipoles, including those tangential to the scalp, which can be missed by conventional EEG (Caruso et al., 2013). These advanced modalities are used mainly in epilepsy centers for presurgical evaluations (Kay & Szaflarski, 2014).

Electroencephalography (EEG) is the basic method for diagnosis and monitoring epilepsy. EEG is a non-invasive electrophysiology procedure of exploring the central nervous system by recording the electrical activity of the brain. It involves placing electrodes on the surface of the head, thus recording electrical potential fluctuations caused by ionic biological currents circulating at the neuronal level. The recorded signals are transmitted to a computer through a dedicated acquisition board, where they are analyzed and, eventually, printed. The temporal resolution is high, allowing for the characterization of rapid changes in currents, but the spatial resolution is low, it being limited by the number and placement of electrodes.

EEG recording can be done in a non-invasive way, on the scalp, or in an invasive way, intracranial, during surgical procedures. Each method has its advantages and disadvantages (Lehnertz et al., 2003).

In the case of scalp EEG, the signal must propagate through several layers of non-neuronal tissue (cerebrospinal fluid, skull, scalp), each of these layers affecting the signal in a different way. The signal is thus attenuated and, for this reason, in order to record it, it is necessary for bigger regions of the brain to be simultaneously active. This procedure is an easy and affordable one. In some cases, it can provide sufficient information, in other it is just a preliminary step, followed by a detailed intracranial investigation. Electrical potentials are registered by a helmet, in which electrodes are placed in standard positions in order to be able to compare readings for the same patient, or for different patients. In Figure 1 the international 10-20 system for placing scalp EEG electrodes is presented (Varsavsky et al., 2011). On the left (a) the positions and labels for each electrode are presented, while on the right – (b) and (c) – two standard methods for signal measurement are shown.

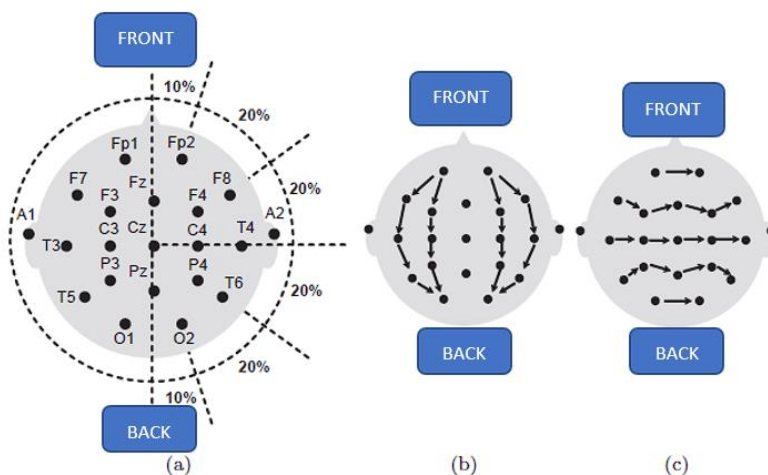


Fig. 1. The international 10-20 system for placing scalp EEG electrodes

In the case of intracranial EEG, the recordings are done with cortex placed or depth electrodes, which penetrate towards subcortical systems (like the hypothalamus) (Schomer & Da Silva, 2012).). This technique is usually employed before a surgery, in order to determine as accurate as possible the region of the brain for resection. It is a quite rare procedure and a standard placement of electrodes is difficult to establish due to patient particularity.

The analog signals generated by the brain and registered by the electrodes are transmitted to an interface responsible with amplifying, filtering and digitizing signals, before they are being sent to the computer for analysis and storage.

Interpreting and EEG can be a very difficult task which requires experience, because there are no standards for these readings. No two identical EEGs can be found – modifications can occur depending on the conscience level (awake, or in different sleep stages), the status of the sense organs (open or closed eyes, covered or uncovered ears etc.), age etc. However, there are several repeating patterns for the majority of people and they can be recognized by an EEG.

The main alterations that occur in the case of an epileptic patient are:

- i. synchronization – signals registered from different channels are alike, because the neuronal activity is similar on an extended region of the cortex. Synchronization can be observed either in several channels, or in their majority;
- ii. high signal amplitude – after the onset of the epileptic seizure, the amplitude of recorded signals is far higher than before the seizure. This

is caused on one hand by the cortex hyperexcitability, and on the other hand because channels synchronization occurs;

iii. oscillations – they manifest once the epileptic activity has sufficiently expanded.

EEG is very useful in the study of epilepsy because it quantitatively highlights the changes in time of the brain's electrical activity. In this way, transitions from seizure to between seizures interval can be distinguished, and, more important, the pre-crisis stage can be identified, which can lead to predicting the onset of the actual epileptic seizure. However, decades of research have shown us that identifying a set of characteristics for distinguishing between pre-crisis, crisis, and inter-crisis can be a very difficult task. A range of defining traits must be extracted from the EEG by processing signals, which are frequently affected by noise and extremely complex, apparently chaotic. In recent years important progress has been made in interpreting EEGs by using nonlinear dynamics that allow obtaining additional information. This type of dynamics can provide powerful methods and algorithms for signal processing that can lead to valuable quantitative information, which can be related to the qualitative information obtained through clinical observation of epileptic patients. Moreover, the obtained data has been used for developing new brain dynamics model or optimizing the current ones.

Materials and methods

In the present paper we analyzed 19 EEG's recorded from epileptic patients using various mathematical procedures from nonlinear dynamics (for example, Fast Fourier Transform - FFT, autocorrelation function, reconstruction of states space by time delay method, Hurst coefficients, 2D maps etc.) with the aim of characterizing each stage of an epileptic crisis dynamics.

Furthermore, we calculated for a total number of 19 patients, the Hurst coefficients for all stages of their epileptic crises.

The analyzed electroencephalograms were downloaded from the PhysioNet database (Guttag, 2010). This allows all researchers to access a free collection of physiological signals (PhysioBank), recorded from a wide range of patients, as well as specialized software for viewing and analyzing them.

The characteristics of the analyzed EEGs are as follows:

- the signals were collected on 23 channels;
- the resolution of each signal was 16 bit;
- sampling time of 4 ms;

Figure 2 graphically shows the signal recorded, for one patient, on channel FP1-F7. It can be observed that neuronal activity does not have regular dynamics. The brain's operating period can be divided into four areas of interest:

- the normal activity area of the brain (range 0-1800 s), which is characterized by a chaotic dynamic, with a relatively high signal amplitude;
- the pre-crisis area (range 1800-3000 s), characterized by a decrease in signal amplitude;
- the epileptic crisis zone (range 3000-3040 s), in which the amplitude of the signal reaches its maximum value in a very short period of time, having a more regular behavior due to the synchronization of the neurons activity;
- the post-crisis zone (range 3040-3600 s), where the signal amplitude decreases to a relatively small value, but increases to the value corresponding to the area of normal neuronal activity.

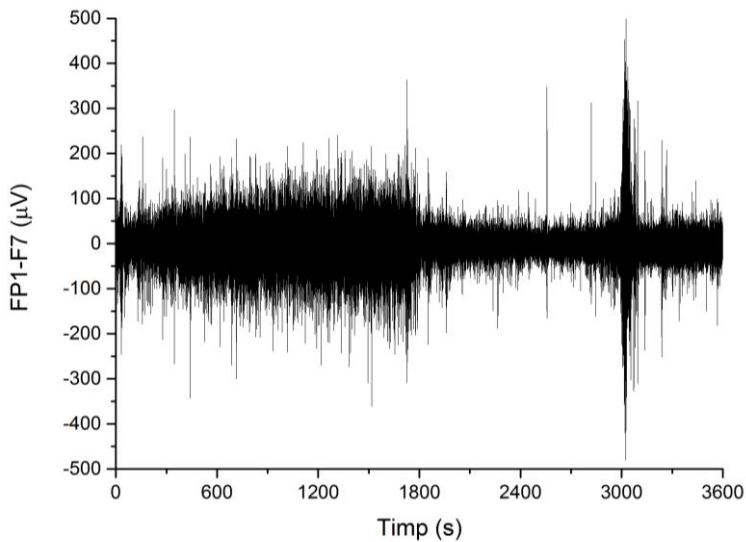


Fig. 2 - Graphical representation of the signal recorded on channel FP1-F7

Results

We present, in Figures 3-6, a detailed analysis for one of the 19 cases. We employed various mathematical procedures from nonlinear dynamics (Fast Fourier Transform - FFT, autocorrelation function, reconstruction of states space by time delay method, Hurst coefficients, 2D maps etc.) with the aim of characterizing each stage the epileptic crisis dynamics.

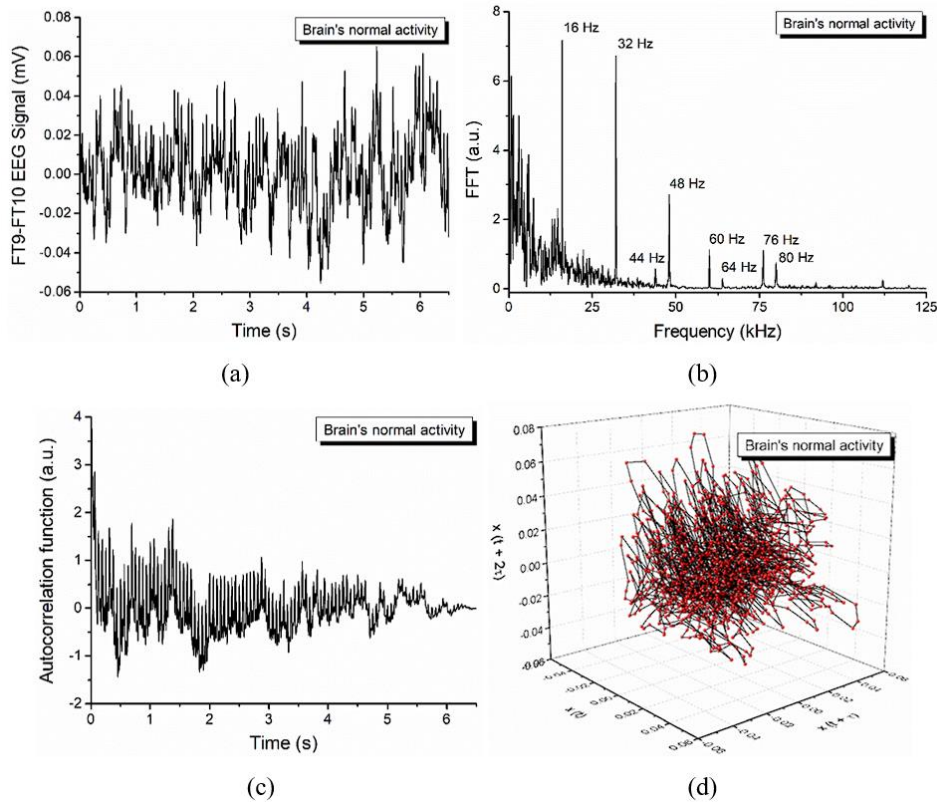


Fig. 3a-d. Time series of the EEG signal recorded between the electrodes FT9 and FT10 during the normal activity of the brain (a), their FFT's (b), their autocorrelation function (c) and the specific attractor corresponding to the states space (reconstructed by time delay method) (d)

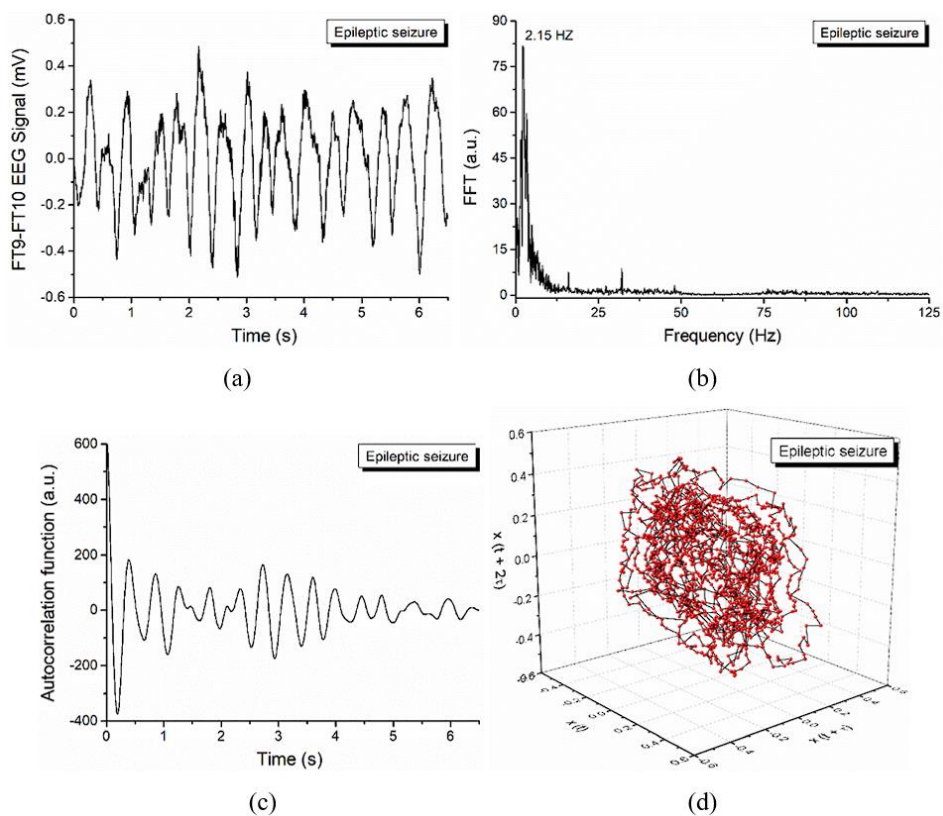


Fig. 4a-d. Time series of the EEG signal recorded between the electrodes FT9 and FT10 during the epileptic seizure (a), their FFT's (b), their autocorrelation function (c) and the specific attractor corresponding to the states space (reconstructed by time delay method) (d)

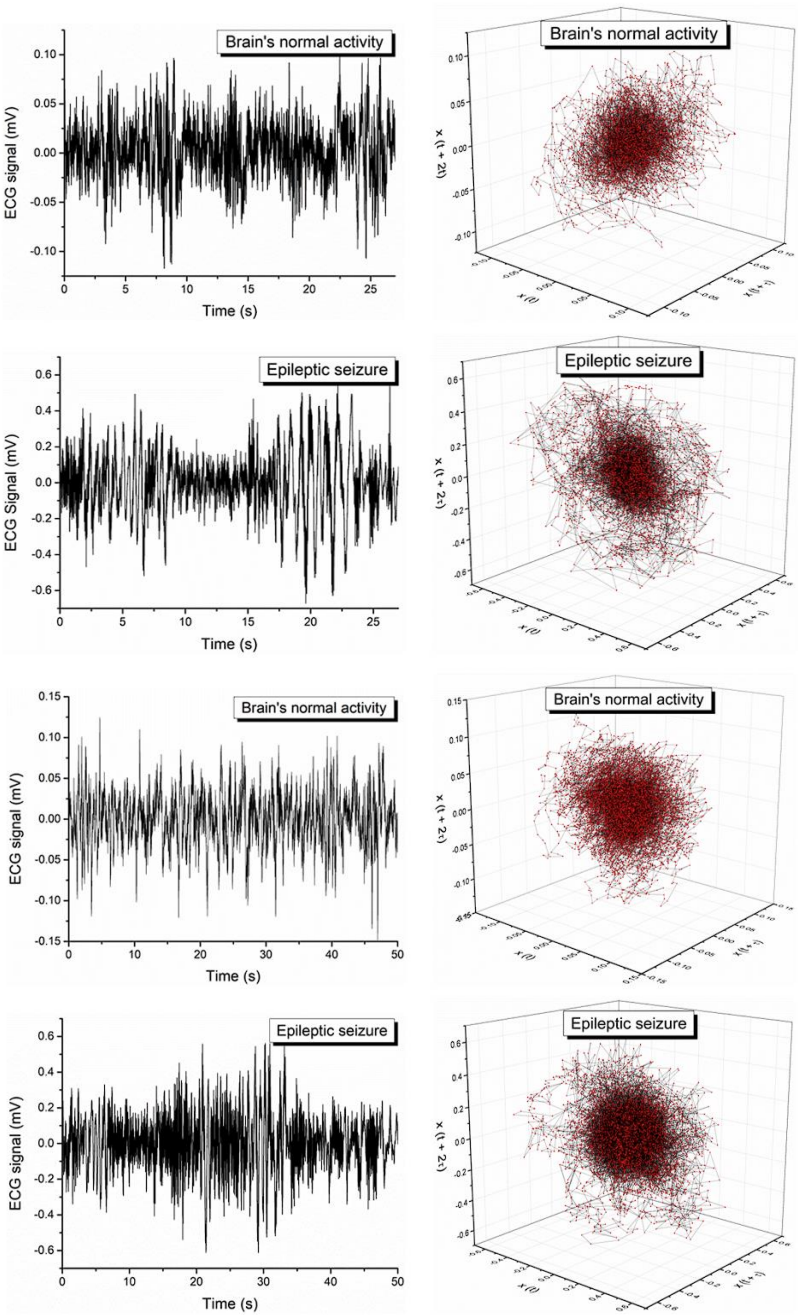


Fig. 5a-h. Time series and the specific attractors corresponding to the states space of the brain dynamics (reconstructed by time delay method) for normal functioning of the brain (a, b, e, f) and for the epileptic seizure (c, d, g, h).

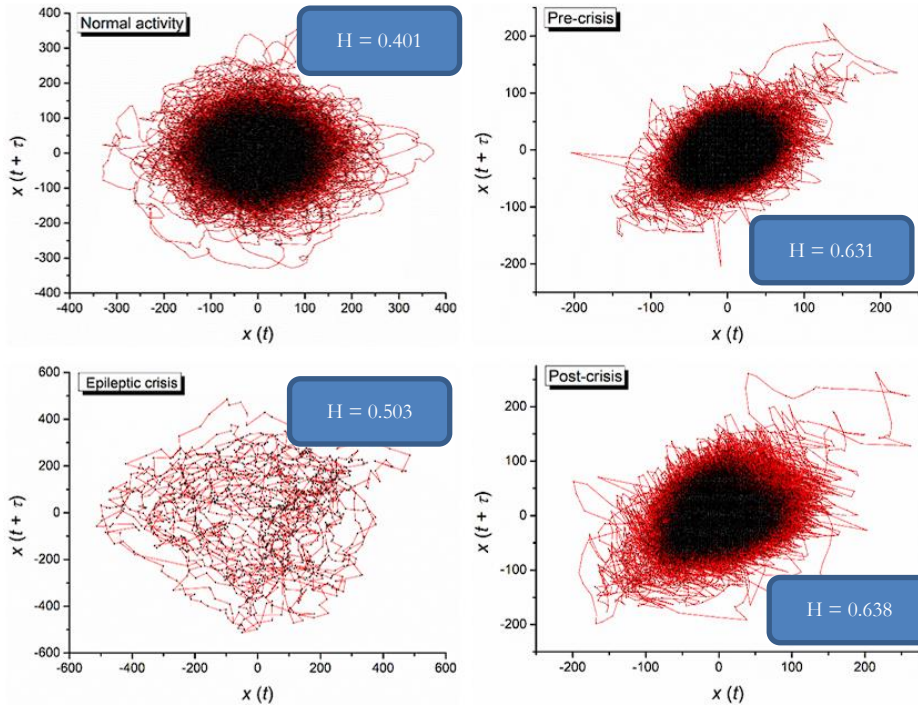


Fig. 6. 2d maps for the 4 stages of the recorded brain activity and their corresponding Hurst coefficient (H).

For all 19 cases, we calculated the Hurst exponents for each stage of the brain dynamics during an epileptic crisis. The results are presented in Table 1.

Table 1. Hurst exponents calculated for 19 persons, for each stage of the brain dynamics during an epileptic crisis

Person no.	Hurst exponent for normal activity	Hurst exponent for pre-crisis	Hurst exponent for epileptic crisis	Hurst exponent for post-crisis
1	0.401	0.531	0.500	0.538
2	0.378	0.525	0.502	0.549
3	0.394	0.544	0.499	0.555
4	0.382	0.535	0.497	0.528
5	0.407	0.519	0.503	0.561
6	0.388	0.517	0.501	0.542
7	0.405	0.528	0.489	0.534
8	0.403	0.529	0.505	0.542
9	0.399	0.531	0.500	0.536
10	0.406	0.533	0.482	0.546
11	0.389	0.529	0.504	0.531
12	0.411	0.527	0.508	0.548
13	0.388	0.531	0.499	0.546
14	0.405	0.544	0.501	0.536
15	0.402	0.530	0.497	0.532
16	0.407	0.517	0.504	0.561
17	0.379	0.519	0.489	0.548
18	0.406	0.531	0.503	0.539
19	0.403	0.530	0.505	0.536

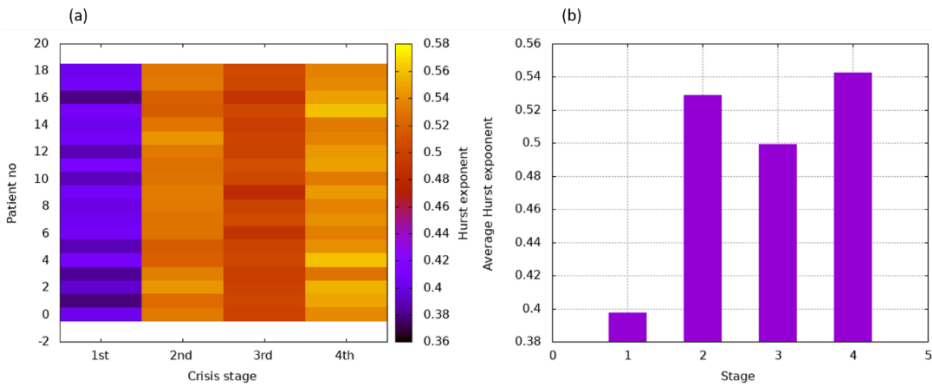


Figure 7. Heatmap of Hurst exponent at different stages of the crisis for 18 different persons. The color indicates the strength of Hurst exponent.

In figure 7 it is illustrated the strength of the Hurst exponent for 18 different persons across four stages: 1st stage corresponds to normal activity,

2nd stage corresponds to pre-crisis, 3rd stage represents the Hurst exponent in the epileptic stage and finally the 4th stage is the post crisis period.

The maximum value the of Hurst exponent is found for the 4th stage whereas normal activity it's been described by a reduced value of Hurst exponent for all persons investigated. A clear intensification of the Hurst exponent can be observed before the epileptic crisis which might indicate a great chance for this to happen.

Figure 7 shows the dependence of Hurst exponent for each person across all the crisis stages. As shown in Figure 6 there is a clear difference of the value for each stage. However, the measurements are slightly influenced by error represented by the vertical bars on the plot in figure 8. The maximum error is found normal activity about 2% whereas the most accurate value for Hurst exponent it's been obtained for pre-crisis period with an average error under 0.5%.

In order to understand whether there is a pattern in this series of Hurst exponent, it is important to calculate the autocorrelation function although the Hurst exponent is plotted as a function of each person. Therefore, it is necessary to define the p value as:

$$p_i = \frac{R_i}{R_0},$$

where R_i is the autocorrelation value for each person and R_0 is the initial autocorrelation value. R_i can be calculated following this equation:

$$R_i = (H_i - H_{mean}) \cdot (H_j - H_{mean})$$

where: H_i is the Hurst exponent of person i , H_{mean} is the average Hurst exponent, respectively H_j is the Hurst exponent of next person.

The p -value has been calculated for each series corresponding to temporal stage of the epileptic crisis as follows: 0.0036 (0.36%) for normal activity, 0.0019 (0.19%) for the pre-crisis stage, 0.0011 (0.11%) for the epileptic stage, and 0.0015 (0.15%) for the post-crisis stage.

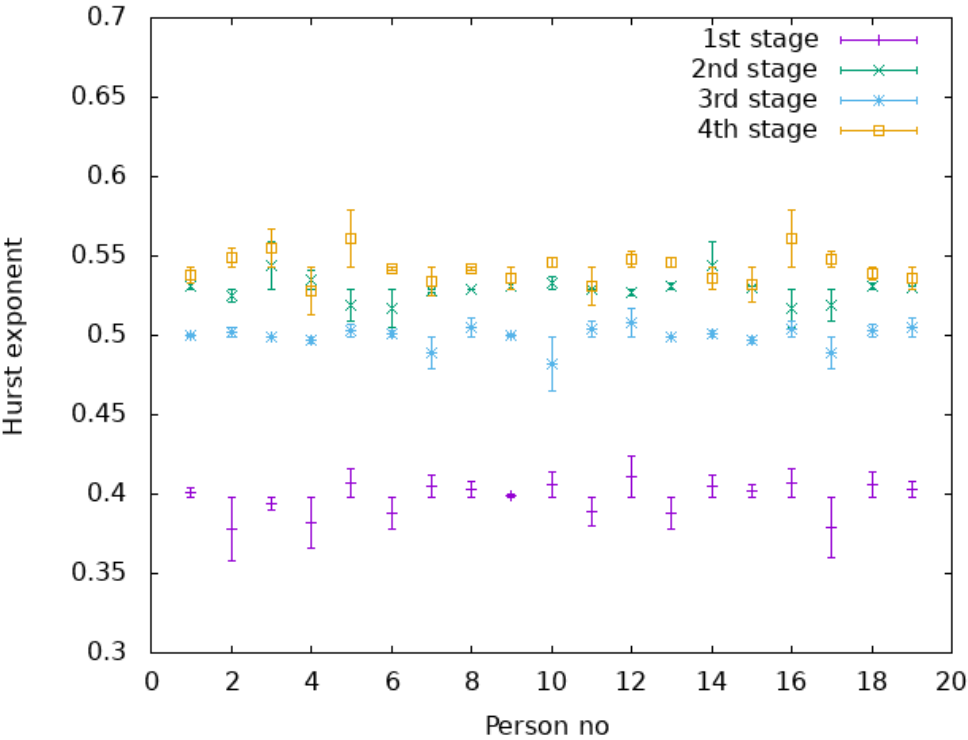


Figure 8: the dependence of Hurst exponent as a function of person number. The vertical bars represent the corresponding errors.

Discussions

The values of the Hurst coefficient range between 0 and 1. Based on the value of H , we can classify any time series into one of the three categories:

$H < 0.5$ — a mean-reverting (anti-persistent) series. The closer the value is to 0, the stronger the mean-reversion process is. In practice, it means that a high value is followed by a low value and vice-versa.

$H = 0.5$ — a geometric random walk.

$H > 0.5$ — a trending (persistent) series. The closer the value is to 1, the stronger the trend. In practice, it means that a high value is followed by a higher one.

As it can be seen, the normal activity of the brain corresponds to an anti-persistent series, the pre-crisis and post-crisis periods corresponds to a

persistent series, while, most importantly, the epileptic crisis corresponds to a geometric random walk.

In literature, there are few analyses like ours (Lau et al., 2022; Creaser et al., 2021) therefore our study brings a high degree of novelty through its approach.

On the other hand, some weak points of our study are that we analyzed a small number of cases and the data was taken from an open-source database. In order to further validate our findings, data collected in a clinical controlled setting must be obtained.

Conclusions

In this paper, by employing mathematical procedures specific to non-linear dynamics, we devised a method for analyzing all the stages of an epileptic crisis. It can be seen that a specific attractor (reconstructed in the states space by time delay method) can be associated with each stage of the brain dynamics: normal functioning and epileptic crisis (pre-crisis, epileptic seizure, post-crisis). Moreover, since for each attractor a Hurst coefficient can be determined, we can state that each stage of an epileptic seizure can be characterized either by calculating the specific Hurst coefficient, or by calculating its fractal dimension $D_F = 1 - H$.

Furthermore, the p -value calculated for the entire data set (19 cases) shows a strong correlation of our obtained results.

Therefore, our results show that this approach could be an alternative way for brain dynamics analysis, complementing the standard methods (Varsavsky et al., 2011; Jiang et al., 2023) and it could possibly lead to developing new ways in which early warnings for an epileptic seizure onset can be perceived.

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