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Multifractal Analysis of the Psychorelaxation Efficiency for the Healthy and Pathological Human Brain

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Abstract: Changes in EEG time series before, during and after removing a pain syndrome by applying the psychorelaxation technique are examined for healthy subjects and patients with chronic psychogenic pain disorders connected with disruptions of interrelations between cortex and subcortex on the thalamic and the brain-stem level. The degree of psychorelaxation and decrease of the pain syndromes is estimated as a change in the multifractality degree gained by the wavelet transform modulus maxima method. For the healthy subjects we observe the reliable decrease of the multifractality degree and the enhancement of the anticorrelated dynamics of consecutive EEG values during the pain and their recovery up to the previous values during psychorelaxation. The all healthy subjects notice that the pain syndrome disappears. The analogous dynamics in the multifractality and the improvement of the functional state are observed only for 70% "thalamic" patients. For other 30% patients of the group the multifractality degree remains less than for the healthy subjects. For all the "brain-stem" patients during relaxation the multifractality degree remains high and the singularity spectrum corresponds to both the correlated and anticorrelated dynamics. The study demonstrates that the changes in the multifractality give a good ability to estimate the psychorelaxation efficiency for the healthy and pathological human brain.
Keywords: EEG, Psychorelaxation technique, Multifractal analysis.

1 Introduction

It is well known that bioelectrical activity of the human brain recorded from the head surface as electroencephalography signal (EEG) can be considered as oscillatory processes exhibiting clearly defined variability and having the chaotic and fractal properties [2, 9]. Fractal dynamics of EEG is supported by the form with step-like features and some sort of self-similarity at least stochastically. In other words, on small scales EEG patterns are not identical to the whole signal but the self-similarity remains after averaging by statistically independent samples of the signal. Multifractality of the human brain is found in EEG time series in both healthy and pathologic states [5, 7]. The present work is devoted to the comparative analysis of the multifractality degree in EEG patterns of normal and pathological brain activities. Impairments connected with anxious phobic disorders are considered as pathology. Chronic pain complaints are specific for patients suffering these disorders. These complaints frequently

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are not confirmed by medical research and accompanied by emotional disturbances leading to a significant reduction in the level of social functioning [4]. Neural disorders of this type are rather resistant to medicinal treatment. That is why the development of various psychotherapeutic methods is of interest to clinical practice. These methods sometimes allow removing pain symptoms. One of the methods is psychorelaxation technique [3] in which the psychorelaxation is in switching attention from the pain sense on the perception of color spots arising spontaneously in the state of concentrating on the pain locus with closed eyes. Switching attention from the pain intensity to the color spots is accompanied by decreasing the pain symptoms up to their complete disappearance.

The aim of the work is to estimate the psychorelaxation efficiency for treatment of psychogenic pain in patients with anxious phobic disorders by the method of multifractal analysis. For solving the task we analyze EEG fragments recorded during the perception of psychogenic pain and during its removal by the psychorelaxation technique.

2 Experimental procedure

The scalp EEG data were recorded during 50 minutes with Ag/AgCl electrodes placed at the frontal F3, F4, Fz and occipital O1, O2, Oz sites from 15 healthy subjects and 18 patients with neural impairments connected with anxious phobic disorders. For healthy subjects the pain was evoked by a tactile stimulation on the midpoint between the first and second fingers during 1 minute. The pain was removed by psychorelaxation technique. For patients with psychogenic pain its reduction was perfomed during 10 - 20 psychorelaxation trials. So, the recordings were obtained for three states: before tactile pain stimulation (10 minutes), during it (20 minutes) and during relaxation (20 minutes) for the healthy subjects and during psychogenic pain and in relaxation state for the patients with neural disorders. The psychorelaxation technique [3] was is in switching attention from the pain sense on the perception of color spots arising spontaneously when concentrating on the pain locus with closed eyes. Thus, in the psychorelaxation state the pain sense transformed into a color image by the patient brain. The observed color spots could appear as achromatic (black or grey) colors or chromatic (red, orange, yellow or blue) ones and they could change the color. As attention was shifted from the pain to the color spots and their color was changed, the patient's condition could be improved up to the complete disappearance of pain symptoms.

The data were sampled at a rate 256 samples/sec with a resolution of 12 bits/sample. Then the data were digitally filtered using 1–45 Hz band pass filter. The each state included 256000 samples and it was divided into 20 segments of the duration 50 seconds. After repeated recordings 60 non- artifact segments of equal duration were randomly chosen from the sets: "before pain", "during pain" and "during psychorelaxation".

3 Estimation of EEG multifractality

To estimate multifractal scaling properties of EEG time series we applied the wavelet transform modulus maxima (WTMM) method [1]. The algorithm of the method consists of the following procedures.

1) The continuous wavelet transform of the time series describing the examined signal $x(t)$:

$$W(a,t_0)=\frac{1}{a}\int_{-\infty}^{+\infty}x(t)\psi^*\left(\frac{t-t_0}{a}\right)dt,$$

is used. Here a and t_0 are the scale and space parameters, $\psi((t- t_0)/a)$ is the wavelet function obtained from the basic wavelet $\psi(t)$ by scaling and shifting along the time, symbol * means the complex conjugate. As the basic wavelet we use the complex Morlet wavelet:

$$\psi(t)=\pi^{-1/4}e^{i\omega_0 t}e^{-t^2/2}.$$

The value ω=2π gives the simple relation between the scale a and the frequency f: f=1/a.

2) A set $L(a)$ of lines of local modulus maxima of the wavelet coefficients is found at each scale a.

3) The partition functions are calculated by the sum of q - powers of the modulus maxima of the wavelet coefficients along the each line at the scales smaller the given value a:

$$Z(q,a)=\sum_{l\in L(a)}\left(\sup_{a^*\leq a}\left|W(a^*,t_l(a^*))\right|\right)^q,$$

$t_l(a^*)$ determines the position of the maximum corresponding to the line l at this scale.

4) By the fact that the partition function is $Z(q,a)\sim a^{\tau(q)}$ at $a\to 0$ [1], the scaling exponent can be extracted as $\tau(q)\sim \log_{10} Z(q,a)/\log_{10} a$.

5) Choosing different values of the power q one can obtain a linear dependence $\tau(q)$ with a constant value of the Hölder exponent $h(q)=d\tau(q)/dq=const$ for monofractal signals and nonlinear dependence $\tau(q)=qh(q)-D(h)$ with large number of the Hölder exponents for multifractal signals.

6) The singularity spectrum (distribution of the local Hölder exponents) is calculated from the Legendre transform [1]: $D(h)=qh(q)-\tau(q)$.

Using the WWTM algorithm for the different EEG segments we obtain the multifractal parameter, namely, the width of the singularity spectrum $\Delta h = h_{\max} - h_{\min}$, where $h_{\max} = h\ (q = -5)$ and $h_{\min} = h\ (q = 5)$ are the maximal and minimal values of the Holder exponent corresponding to minimal and maximal fluctuation of the brain activity, respectively. Smaller Δh indicates that the time series tends to be monofractal and larger Δh testifies the enhancement of multifractality. To examine the differences between the mean values of the parameter obtained for all the segments of different sets of one subject the non-parametric Mann-Whitney test ($p < 0.05$) was applied.

4 Results and discussion

Power spectra of EEG of all the healthy subjects have no significant differences in three different states, namely, background (before the pain stimulation), during the pain stimulation and during psychorelaxation. Alpha activity [7 - 14] Hz dominates.

Multifractal analysis enables us to distinguish the EEGs in the three states. For the all examined electrode sites the width of the singularity spectrum (Δh) decreases during the pain stimulation and recovers up to previous values after pain removing. In the all states $h_{\max}$ <0.5 (Fig. 1), hence, the singularity spectrum corresponds to anticorrelated dynamics of consecutive EEG values.

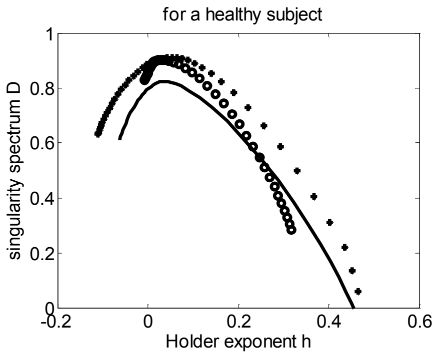

Fig. 1. The examples of singularity spectra of a healthy subject in three functional states (the curve denoted as "*" symbol corresponds the state before the tactile pain stimulation, the curve specified as "o" describes the state during the pain stimulus and the solid line corresponds to the psychorelaxation state.

Thus, persistent sequences are characterized by stochastically "up - down" patterns. The decrease of $h_{\max}$ during the pain stimulation testifies about the enhancement of the anticorrelation degree, so that the signal becomes less smooth and more singular and the randomness of the fluctuations increases. Therefore, the interval time series tend to become more random during the pain stimulation and recover during relaxation.

The decline of the width of the singularity spectrum during the pain stimulation shows a reduction of nonuniformity of the signal and a fall in the multifractality degree. This fall is due to weak fluctuations (for q<0, h>0), and at strong fluctuations (q>0) the time series become monofractal (uniform by scaling characteristics) and the singularity spectrum transfoms into a point (h=const).

In the state of concentration of the attention on the pain sense the all healthy subjects noticed achromatic colors (black or grey) and the short-wavelength colors (blue or green) in the relaxation state. The pain syndrome disappeared. The results agree with the previous data in which each color image caused a specified shift in the psychophysiological state of a subject and determined the presence of psychoemotional stress [6]. In the work [3] it has been revealed that psychotherapeutic influence relieving the stress, is accompanied by a reliable enhancement of colors of the short-wavelength part of visible light.

The patients with neural disorders were separated into two groups accordingly to the classification [8]. For the first group of patients (10 subjects) the disruptions of interrelations between cortex and subcortex on the thalamic level were found in the rest state. It was expressed in changing thalamo – cortical (vertical) and thalamo – thalamic (horizontal) links. Except for alpha activity describing optimal cortico – subcorctical relations, the EEG time series of the patients included theta activity specified pathological changes in these relations.

During the pain sense the power spectra are characterized by the increase in theta activity. It testifies about an enhancement of unstability of neurodynamic processes. During psychorelaxation theta activity falls in occipital sites of 45% of the group and remains or increases both in frontal and occipital sites (55% of the group). Improvement of psychophysiological state did not correlate with a decrease of theta activity. In other words, there were no reliable changes in power spectra.

During concentrating on the pain locus the patients observed mainly the long-wavelength colors (red, orange, yellow). These colors remained during the psychorelaxation for the 30% patients of the group. The other 70% patients noticed the transformation of color spots to the short-wavelength blue and the complete removal of the pain sense.

Multifractal analysis shows the reliable changes in the electrical brain activity. In all states of the patients with disruptions on the thalamic level the Holder exponent values and the width of the singularity spectrum are less than the values obtained for the healthy subjects. It means that the degree of anticorrelation of persistent sequences of EEG is higher and the randomness of “up – down” patterns increases. It corresponds to the enhancement of unstability of neurodynamic processes in the brain of the patients as compared with the healthy subjects.

During the pain sensation by the patients the multifractal parameter reduces in all electrode sites. During psychorelaxation the recovery of the Holder exponent values up to the values corresponding to the healthy subjects corresponds to the transformation of color spots to the short-wavelength blue (70% patients of the group) (Fig. 2). For other 30% patients the maximal values of the Holder exponent increase weakly during psychorelaxation and they do not reach the values obtained for the healthy subjects. The width of the singularity spectrum remains less than for the healthy subjects.

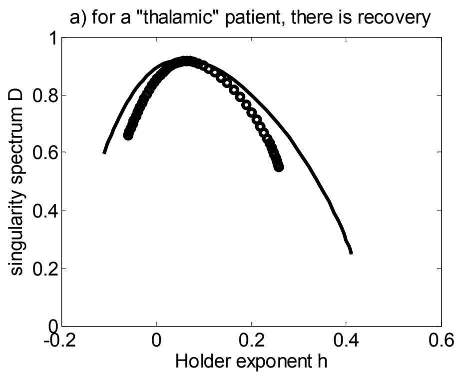

Fig. 2. The examples of singularity spectra of a subject with disruptions of cortico – subcortical links on the thalamic level during the pain sense and during the psychorelaxation (the curve specified as “o” describes the state during the pain sensation and the solid line corresponds to the psychorelaxation state)

Thus, the removal of pain syndromes for the first group patients corresponds to the fall in the degree of anticorrelation of persistent EEG sequences and decline of the randomness of “up – down” patterns observed in all electrode sites. Hence, the improvement of the functional state testifies about a decline of unstability of neurodynamic processes of the brain and optimization of cortico – subcortical links.

For the patients of the second group (8 subjects) disruptions in cortico – subcortical relations manifest on the brain-stem level that leads as a rule to distortion of the stem – cortical and cortico – thalamic (vertical) links. It results to the significant suppression of the alpha component and emergence of the theta acitivity. It is accompanied by the large unstability of neurodynamic processes and amplification of the psychoemotional stress. So, the theta acitivity is prevalent in the all states of this group of the patients . The spectra decline with increasing frequency remembering the spectrum of the pink noise with its inverse proportionality to frequency (~1/f).

The Holder exponent values and the width of the singularity spectrum are larger than the values obtained for the healthy subjects in all studied electrode sites. That is why the multifractality degree of the persistent sequences of EEG far exceeds the degree obtained for the healthy subjects.

During the pain sense the singularity spectrum ($0.1<h<0.9$) corresponds to the both correlated dynamics ($h>0.5$) and anticorrelated dynamics ($h<0.5$) (Fig.3). During relaxation at strong fluctuations ($q>0$) the Holder exponent values decline but the multifractality degree remains high and the singularity spectrum corresponds to both “up - down” and “up - up” patterns.

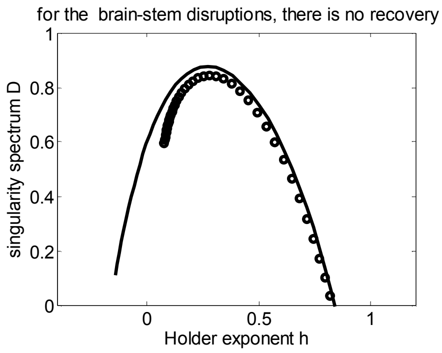

Fig3. The examples of singularity spectra of a subject with neural disorders on the brain stem level during the pain sense and during the psychorelaxation (the curve specified as “o” describes the state during the pain sensation and the solid line corresponds the psychorelaxation state)

The transformation of achromatic dark color spots is not observed for 81% patients. For others 19% achromatic dark colors change into long - wavelength red or orange (distant from colors for the healthy subjects). The both cases are characterized by the similar changes in the singularity spectra and the absence of the improvement of the psychophysiological state.

state	color image	width Δh, Qz	width Δh, Fz	pain removal
healthy subjects:				
before pain		0.59±0.05	0.48±0.05	
during pain	achromatic grey	0.32±0.03	0.26±0.03	
relaxation	blue or green	0.55±0.05	0.62±0.05	yes, in 100%
patients with thalamic disorders:				
during pain	red or yellow	0.28±0.03	0.21±0.03	
relaxation	red, orange or yellow	0.35±0.03	0.32±0.03	no, in 30%
relaxation	blue	0.52±0.05	0.59±0.06	yes, in 70%
patients with brain – stem disorders:				
during pain	achromatic black	1.22±0.11	1.15±0.11	
relaxation	black, red or orange	1.03±0.10	1.07±0.10	no, in 100%

Table 1. Comparison of the mean values of the width of the singularity spectrum obtained by averaging over subjects in different physiological states. The data are given for the Qz and Fz sites.

Training such patients to concentrate their attention on the pain locus and to switch attention on color spots arising spontaneously during 20 repeated trainings did not allow to remove the pain symptoms completely.

The averaged data represented in Table 1 illustrate that the pain removal is accompanied by the recovery of the Holder exponent values up to the values corresponding to the healthy subjects. Thus, there is the relationship between the change of the multifractal parameter and the improvement of the psychophysiological state during psychorelaxation for the patients suffering psychogenic pain.

5 Conclusions

The study demonstrates that power spectra of the patients with neural disorders do not always reflect variations of the psychorelaxation degree. Contrastingly, the changes in the multifractal parameter give a good ability to estimate changes in the healthy and pathological brain activity. Multifractality of the healthy brain is statistically stable as well as stable its neurodynamics. The both cases of unstability in two studied groups of the patients with anxious phobic disorders are connected with deviation (in different sides) of the multifractal parameter from the values specified for the healthy brain. The recovery of the values correlates to the improvement of the psychophysiological state of the patients during psychorelaxation trials. That is why the multifractal analysis can be applied for estimating the psychorelaxation efficiency of the human brain.

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