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Wavelet Analysis of the Human Brain Lability to Reproduce the External Rhythm

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Abstract: The task is to evaluate the differences in the human brain lability involving its opportunity to forget or reproduce the external rhythm for patients with neural disorders connected with disruptions of the thalamo-cortical or stem-cortical links. For solving the task the EEG segments before, during and after periodic light stimulation are examined by the wavelet transform method. The degree of the human brain lability is estimated by changing in the maximums of the global wavelet spectra and by the coefficients of reproduction and holding the rhythm. Maximal reproduction of the external frequency is observed in the ranges specific for the both groups of the patients. For the patients with stem-cortical disruptions the all parameters essentially differ from the parameters obtained for the patients with thalamo-cortical disorders. Thus, the study demonstrates the possibility of the wavelet analysis to estimate quantitatively the human brain lability of perception of light stimuli.

Keywords: EEG, Wavelet transform, Reproduction of external rhythm.

1. Introduction

Bioelectrical activity of the human brain recorded from the head surface as electroencephalography time series (EEG) during solving the complex imaginary and real visual-motor tasks or during awake and various sleep stages in healthy state exhibits nonstationary, chaotic and multifractal dynamics [1, 2, 3]. The comparative analysis of the dynamics in EEG patterns of normal and pathological brain activities is one of the tools of elucidation of the degree the brain seizures [4, 5] and estimation of the efficiency of the drug or psychological treatment [6]. Photostimultaion, that is the light stimulation of the given frequency, is one of the functional probes applied for determining of the human brain lability to reproduce or to reject the suggested rhythm [7]. The degree of such lability characterizes the level of nerve excitability and can classify persons for whom drugs hyperactivating the nervours system are unsuitable due to their own hyperexcitability.

The aim of the work is to evaluate the differences in the potentialities of the human brain to forget or reproduce the external light rhythm for patients with chronic pain complaints rather resistant to medicinal treatment. These patients can be divided into two groups accordingly to the classification connected with the disruptions on the thalamic level or on the brain-stem level that leads as a

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rule to changing the thalamo–cortical links in the first case and the stem–cortical links in the second case [8]. It results to the significant suppression of the alpha component prevailing for the healthy persons and the emergence of the theta acitivity or occurrence of polymorphous small amplitude activity, that is, to essential deviation from the healthy EEG patterns.

2. Experimental procedure

The scalp EEG data were recorded with Ag/AgCl electrodes from 10 healthy subjects and 16 patients with neural impairments connected with chronic pain complaints. Signals of reproducing the light rhythm propagate symmetrically and have maximal amplitude in the occipital lobes of the human brain, that is why the data were collected with electrodes placed at the occipital O1, O2, Oz sites. The recordings were obtained for three states: before the light rhythmic stimulation (the interval $[0, t_A]$), during it (the interval $[t_A, t_B]$) and during relaxation (the interval $[t_B, t_K]$) with eyes closed. The duration of each interval was 20 seconds. The data were sampled at a rate 256 samples/sec with a resolution of 12 bits/sample. Then the data were digitally filtered using 1–30 Hz band pass filter. After repeated recordings 60 non- artifact segments of equal duration were randomly chosen from the sets: “before stimulus”, “during stimulus” and “during relaxation”.

3. Estimation of the global energy of the EEG segment

To estimate the global energy of EEG segment we applied the continuous wavelet transform of a time series x(t):

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

where 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:

$$\psi(t)=D\exp(-0.5t^2)[\exp(-i\omega_0 t)-\exp(-0.5\omega_0^2)],$$

$$D=\frac{\pi^{-1/4}}{\sqrt{1-2\exp(-0.75\omega_0^2)+\exp(-\omega_0^2)}}.$$

The value $\omega_0=2\pi$ gives the simple relation between the scale a and frequency f: $f=1/a$.

The square of the modulus $|W(f, t_0)|^2$ characterizes the instantaneous distribution of energy over frequencies at the time t_0, that is, the local spectrum of the signal energy.
The value

$$E(f) = \int_{t_1}^{t_2} |W(f, t_0)|^2 \, dt_0$$

describes the global wavelet spectrum, i.e., the integral of energy distribution over frequency range on the interval $[t_1, t_2]$.
The value

$$E(t_0) = \int_{f_1}^{f_2} |W(f, t_0)|^2 \, df$$

represents the integral of energy distribution over time shifts in the frequency range $[f_1, f_2]$.

4. The light time series

The light time series limited on the interval $[t_A, t_B]$ was described as a sequence of k Gauss impulses following each other with frequency f_C equal to 4, 6, 8, 10, or 16, 20 Hz. The each impulse had the width r_O =10 ms. The centres of the impulses were in points

$$t_{0i} = t_A + i / f_c, \qquad \mathrm{i} = 0, \ldots, k-1,$$

where t_A is the time of switching of the light series, that is the time of the beginning of the first impulse in the sequence.
Thus, the light stimulus can be described as

$$p(t) = \sum_{i=0}^{k-1} \frac{0.5}{r_0 \sqrt{\pi}} \exp\left(-\frac{(t - t_{0i})^2}{4 r_0^2} \right).$$

The continuous wavelet transform of the light time series $p(t)$ can be calculated in the form:

$$W(f, t_0) = \frac{Df}{\sqrt{s}} \exp\left(-\frac{z^2 + 2(\omega_0 f r_0)^2}{2s} \right) \left[\exp\left(-\frac{i \omega_0 z}{s} \right) - \exp\left(-\frac{i \omega_0^2}{2s} \right) \right],$$

where $s = 1 + 2(f r_0)^2$, $z = f(t - t_0)$ is non-dimensional time measured from time t_O.

5. Estimation of the coefficients of reproduction and holding the rhythm

Let $E_{X1}(\Delta f)$ and $E_{X2}(\Delta f)$ be the global wavelet spectra of the EEG time series in the frequency range Δf over the intervals $[0, t_A]$ and $[t_A, t_B]$, i.e. before and during photostimulation.

The reproduction coefficient of the suggested rhythm can be estimated as the ratio of the maximum of the global spectrum during the light time series to the maximum of the global spectrum before photostimulation:

$$k_R(\Delta f) = \max E_{X2}(\Delta f) / \max E_{X1}(\Delta f).$$

If the frequency value corresponding to the max $E_{X2}(\Delta f)$ does not coincide with the light time series frequency f_C then there is no reproduction of the rhythm in the range $\Delta f = f_C \pm \Delta$, where Δ=0.5 Hz. The larger $k_R(\Delta f)$ value, the better the reproduction of the suggested rhythm.

Let us $E_X(t)$ and $E_P(t)$ denote the normalized integral distributions of energies of the EEG and light time series in the frequency range $[f_1, f_2]$:

$$E_X(t) = E_X(t) / \max E_X(t) \text{ and } E_P(t) = E_P(t) / \max E_P(t).$$

Examples of the normalized integral distributions $E_X(t)$ and $E_P(t)$ for f_C =4 Hz are given in Fig. 1.

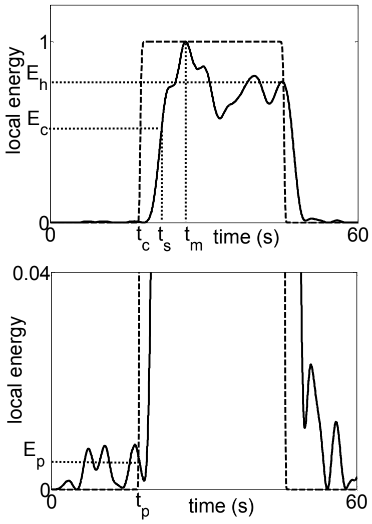

Fig. 1. The normalized energy distributions of the EEG time series (solid line) and the light time series (dashed line). The lower figure is represented in the enhanced scale to see the point (t_P, E_P) of intersection of the integrals $E_X(t)$ and $E_P(t)$.

The integrals $E_X(t)$ and $E_P(t)$ cross each other in two points (t_P, E_P) and (t_h, E_h) after switching on and switching off the light time series.
The value E_h is taken as the coefficient of holding the suggested rhythm:

$$k_H(\Delta f) = E_h(\Delta f).$$

The smaller the value, the more badly the rhythm of photostimulation is kept by the human brain.

6. Estimation of the time of remembering the external rhythm and the delay time of the brain response on the rhythm

If the EEG response on the light time series reaches the maximal value at the moment t_m, then the difference

$$T_R(\Delta f) = t_m(\Delta f) - t_P(\Delta f)f)$$

can characterize the time of remembering the rhythm. The smaller the value, the faster the brain begins to generate the external frequency.
The delay time of the EEG response from the moment of switching on the light time series can be estimated as

$$T_D(\Delta f) = t_S(\Delta f) - t_C(\Delta f),$$

where t_C is the moment when the condition

$$E_C(\Delta f) = 0.5\,(1 - E_P(\Delta f))$$

is satisfied.

7. Results and discussion

Examples of global wavelet spectra of EEG for the healthy subject and patients with changes in the stem-cortical or thalamo-cortical links in two functional states, namely, before and during the light stimulation are given in Fig. 2.
The spectra calculated in the broad frequency range [2, 20] Hz differ by the width as well as by the position and value of maximum.
In the rest state with closed eyes the EEG time series of a healthy person is characterized by narrow frequency interval [8, 16] Hz and the large value of the global energy, maximum of which is equal to $5 * 10^4\ \mu V^2$. The disruptions of neuronal links on the brain-stem level are exhibited in the form of

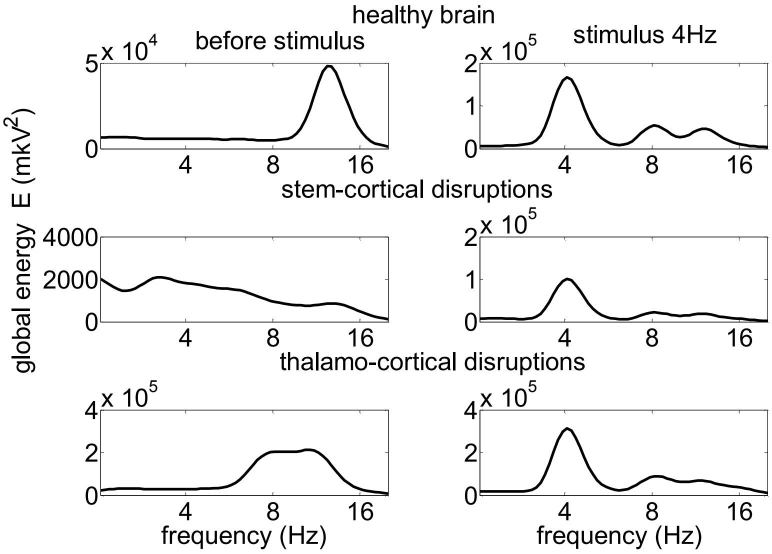

Fig.2. Examples of global wavelet spectra of EEG for the healthy subject and two groups of patients before and during the light time series of f_C =4 Hz.

polymorphous activity of the smaller amplitude and broaden frequency range [0, 12] Hz. The maximal global energy is 10 times less than the value obtained for the healthy person. The thalamo-cortical disruptions are manifested by the extended spectrum in the frequency interval [6, 14] Hz and the significant increase (almost in 10 times) as compared with the maximum of the global spectrum for the healthy brain and in 100 times in comparison with the global energy for the stem-cortical disruptions.

The light stimulus of frequency 4 Hz leads to the emergence of the detectable maximums in all the considered cases. The value of the global energy increases in 4 times for the healthy subject and in 1.5 times for the patient with thalamo-cortical disorders. This value grows in almost 100 times for the patient with stem-cortical defects. The occurrence of the visible maximum of the global energy at the frequency of the external stimulus means the good reproduction of the suggested rhythm.

Reproduction of the external rhythm is observed for all the subjects and the frequencies 4, 6, 8, 10 and 12 Hz and only for the healthy and persons with thalamo-cortical disruptions at 16 and 20 Hz.

The coefficients of reproduction (k_R (Δf)) and holding (k_H (Δf)) the rhythm estimated by the wavelet spectra are given in the Table 1.

The time of remembering the rhythm (T_R (Δf)) and the delay time of the EEG response from the moment of switching on the light time series (T_D (Δf)) are represented also in the Table 1.

f_C =4 Hz				
	k_R	k_H	T_R (s)	T_D (s)
healthy	4.2±0.6	0.52±0.06	11.1±1.2	1.9±0.4
group 1	95±5	0.85±0.07	6.2±0.8	0.9±0.2
group 2	2.1±0.4	0.49±0.05	12.5±1.7	1.5±0.3
f_C =10 Hz				
healthy	6.1±0.7	0.95±0.09	0.9±0.2	0.3±0.11
group 1	2.1±1.3	0.41±0.05	13.2±1.3	2.1±0.5
group 2	5.3±0.6	0.69±0.07	1.5±0.4	0.5±0.1
f_C =16 Hz				
healthy	4.5±0.4	0.81±0.07	5.3±0.4	1.1±0.3
group 1	there is no reproduction of the rhythm			
group 2	3.7±0.3	0.77±0.06	7.1±0.8	2.1±0.5

Table 1. The comparison of the mean values averaged over 10 healthy subjects and 8 persons in each group of patients. The site is Qz. The patients with the thalamo – cortical disruptions are denoted as “group 1” and patients with the stem – cortical defects are depicted as” group 2”.

For each frequency of the light time series (f_C) the both coefficients of reproduction and holding the rhythm are largest for the subjects who have the eigen oscillations at this frequency in the rest state.

The time of remembering the rhythm and delay of the EEG response from the moment of switching on the light time series are smallest in the presence of eigen oscillations. These times grow in the non-specific frequency range.

The spectra of the patients of two groups differ by four considered parameters.

The stem – cortical defects are characterized by the absence of the external rhythm reproduction at frequencies larger than 16 Hz and the fast maintenance of the rhythm in the range [2, 6] Hz.

The EEG time series of the patients with the thalamo–cortical disruptions have the large eigen oscillations in the interval [6, 14] Hz and larger values of both coefficients k_R and k_H and smaller times T_R and T_D comparing with the EEG of the first group.

8. Conclusion

The work supports that the human brain is a rather stable dynamic system and rearranges slowly on external rhythm of non-specified frequency range. The parameters found from the wavelet spectra give an opportunity to evaluate quantitatively the brain lability of perception of the light time series.

These parameters can help to estimate the nerve excitability level of a subject for the purpose of the appropriate drug treatment, that is, to exclude the drug administration hyperactivating the nervous system for patients with the enhanced personal excitability in the rest state.

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