Neurocomputing 165 (2015) 361–374

Contents lists available at ScienceDirect

Neurocomputing

journal homepage: www.elsevier.com/locate/neucom

Wavelet and multifractal estimation of the intermittent photic stimulation response in the electroencephalogram of patients with dyscirculatory encephalopathy

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ARTICLE INFO

Article history:
Received 27 April 2014
Received in revised form
10 January 2015
Accepted 8 March 2015
Communicated by Sanqing Hu
Available online 18 March 2015

Keywords:
Wavelet transform
EEG
Intermittent photic stimulation
Dyscirculatory encephalopathy

ABSTRACT

The task is to elucidate quantitative characteristics in electroencephalographic (EEG) patterns giving the possibility to estimate the disruptions of the functional state of the central nervous system caused by dyscirculatory encephalopathy of different severity. For solving the task the background and reactive EEG patterns are analyzed by the continuous wavelet transform and the wavelet-transform modulus maxima methods. The EEG responses to intermittent photic stimulation are used as reactive patterns. There are no statistical differences between the width of the singularity spectra of background and reactive *patterns f*or all the subjects. *Therefore*, *the degree* of multifractality determined by this parameter does not change considerably during the photic stimulation. By contrast, the coefficients of photic driving and holding and the energy increase times gained in EEG patterns of patients with dyscirculatory encephalopathy differ significantly from the parameters determined for the healthy subjects. The reactive patterns have been demonstrated to have the different photic driving of beta, theta and alpha ranges for the patients of various groups. Frequencies of the theta range are reproduced mainly in the EEG patterns of patients with hypertension disease and with vertebrobasilar insufficiency. The maximal photic driving reaction of the beta range is noticed in the group with the vegetovascular dystonia. Frequencies of the alpha range are predominantly reproduced by the group with hypertension disease. The study demonstrates the opportunity to estimate quantitatively the dynamics of changes in energy characteristics of EEG patterns for various groups of patients having cerebrovascular disturbances. The results can be applied for an appropriate choice of treatment for such patients with the regard for their photic driving reactions.

1. Introduction

Bioelectric activity of the human brain recorded from the head surface as electroencephalography (EEG) time series reflects non-stationary dynamics of synchronized and unsynchronized relations between large neuron ensembles [1]. The comparative analysis of this dynamics is a possible tool for elucidating the degree of the brain seizures [2–4] or for estimating the drug or psychotherapeutic treatment efficiency [5]. Sometimes elucidation of changes in EEG patterns is a rather complex problem. For example, it is difficult to distinguish the diffuse neuronal activity arising as a late effect of traumatic brain injuries, neuroinfections or cerebrovascular disturbances from the normal one. Notice that such disorders are much more typically in clinical practice than severe brain tissue damages. Organic lesions of the brain lead as a rule to well detectable local disruptions and paroxysmal forms of EEG [6]. There is no such specificity in EEG patterns of the diffuse activity [7]. It forces investigators to search new analytic methods [8,9]. In this connection, the concept of the functional state of the central nervous system and its features such as excitability, lability and stability assumes great importance [10].

To identify changes in the functional state clinicians use the functional probe as photic stimulation since sometimes variations in background EEG break down to reveal the changes. For example, in geriatric clinical work, only the decreased driving reaction differentiated the patients suffering from early dementia from age-matched depressed ones, whereas the resting EEG did not show any differences [11]. Intermittent photic stimulation can induce a phenomenon of photic driving in EEG patterns as a normal physiologic response triggered by specific visual stimuli [12]. The response, as a rule, is time-locked to the light stimulus at a frequency that identical or harmonically related to the frequency of light flashes [13]. Photic stimulation is applied for determining the human brain lability to reproduce or to reject the suggested

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http://dx.doi.org/10.1016/j.neucom.2015.03.025
0925-2312/

rhythm [14]. The degree of such lability can characterize the level of nerve excitability [15].

When evaluating responses in the EEG to photic stimulation the emphasis is usually given to the elucidation of photoparoxysmal responses with the aim of founding a locally increased activation of slow frequencies indicating a focal disturbance [15,16]. For non-paroxysmal responses to intermittent photic stimulation, cortical lesions of a destructive type may cause ipsilateral depression or attenuation of driving, whereas irritative lesions, such as those of epileptic scars, may lead to an increased response on the side of a focus [17,18]. A locally increased rhythmic response in delta or beta frequencies may also indicate a focal disturbance [17]. A reduced or hypersynchronized response within the alpha band may reflect certain functional alterations [18].

Considerable recent attention has been focused upon diagnostics of alternations in cortical excitability by the method of repetitive transcranial magnetic stimulation (rTMS) [19]. However, in numerous works the contradictory data about the effect of the duration and frequency of rTMS on cortical excitability have been obtained. For example, it has been shown that short high-frequency trains seem to be more effective than longer trains with low-frequency [20]. The results of the other work testify about the absence of significance changes in cortical excitability produced by any of the stimulation condition [21]. Thus, question about the changes in the central nervous system excitability in response to external disturbance remains unclear.

The response severity is determined by several factors, namely, the state of conduction tracts from the eye's retina through thalamic ganglia in the cortex and the state of cortical neurons [22,23]. Healthy subjects, as a rule, demonstrate the photic driving reaction at the frequency from 8 to 20 Hz, i.e. in the range of natural frequencies, but the absence of photic driving is also normal individual response to stimulation [18]. A shift of the photic driving frequency range in the side of high or low frequencies as compared with natural ones is considered as a criterion of pathological response [15,16].

Changes in EEG patterns under the influence of intermittent photic stimulation can be very useful for clinical practice in the cases of cerebrovascular disturbances, vasomotor headaches, vegetative regulatory dysfunctions and asthenoneurotic syndromes. Due to the fact that major modifiable risk factors for developing cerebrovascular diseases include the widespread provocative factors such as stress, hypertension, smoking, obesity and diabetes, it becomes evident the prevalence of these diseases in the world. Determination of the excitability degree based on the photic driving reaction for a subject with the functional state disorder connected with dyscirculatory encephalopathy and the intrinsic hyperexcitability can allow a physician to avoid administration of drugs having the hyperactivating side effect.

The aim of the work is (1) to find in EEG patterns the quantitative parameters determining the potentialities of the healthy and ill human brain to reproduce the external light rhythm and (2) to estimate the parameters of the photic driving reaction for patients with disruptions of the functional state of the central nervous system such as dyscirculatory encephalopathy.

2. Materials and methods

2.1. Patients

We examined 20 healthy volunteers (women, mean age 43.2 ± 6.7 years) and 56 patients with dyscirculatory encephalopathy of various intensity degree (women, mean age 47.7 ± 5.7 years). Among the patients 16 subjects (mean age 40.3 ± 2.1 years) have initial manifestations of dyscirculatory encephalopathy in the form of vegetovascular dystonia (VD group), 14 patients (mean age 46.3 ± 3.1 years) have more severe symptoms in the result of hypertension disease (HD group), 14 subjects (mean age 49.2 ± 3.5 years) have arteriosclerotic damage of cerebral blood vessels (AD group) and 12 persons (mean age 53.1 ± 6.1 years) have signs of vertebrobasilar insufficiency as a result of cervical osteochondrosis (VBI group). All the patients have chronic headache complaints, defects in memory and attention, increased irritability, rapid fatigability and sleep disruption.

2.2. EEG recording

The scalp EEG data were collected from recordings with Ag/AgCl electrodes placed at the occipital O1, O2, Oz loci where the signals reproducing the light rhythm have maximal amplitude. The data were sampled at a rate 256 samples/s with a resolution of 12 bits/sample during long-term video-EEG monitoring. Then the data were digitally filtered using 1–45 Hz band pass filter. The recordings contained non-artifact segments in the three states: under resting condition with eyes closed, during photic stimulation and during relaxation between stimulations (intervals $[0, t_A]$, $[t_A, t_B]$ and $[t_B, t_K]$, respectively).

The photostimulator was a xenon lamp with energy 0.3 J positioned in the dark room at a distance of 30 cm from the eyes. Intermittent photic stimulation was performed at 2, 4, 6, 8, 10, 12, 14, 16, and 18 Hz. The stimulation lasted 9 s for each frequency, with a resting interval between frequencies of 30 s. The subjects kept their eyes closed throughout the experiment.

The data were collected in the St. Petersburg Neurological Clinic during the neurological treatment of the patients. All the subjects were restudied in three trials, each at least one week apart. The study was approved by the local Ethics Committee. Written informed consent was obtained from all the participants.

The EEG patterns were estimated visually by classification [24] as well as by the continuous wavelet transform (CWT) [25] and the wavelet-transform modulus maxima (WTMM) methods [26].

2.3. Visual estimation of background patterns

In background recordings we estimated an index of alpha rhythm as the ratio of time of the presence of the alpha rhythm to the time of non-artifact background recording. As known, namely, alpha rhythm reflects optimal cortico-subcortical relations.

2.4. Estimation of the energy properties of the EEG fragment

To estimate the energy characteristics of EEG fragments and their variations taking place during the photic stimulation we applied the continuous wavelet transform

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

where $x(t)$ is the examined EEG time series, $\psi((t-t_0)/a)$ is the wavelet function obtained from the basic wavelet $\psi(t)$ by scaling (stretching or compressing) and shifting along the time, symbol $*$ means the complex conjugate. The scale a determines the wavelet width and the space parameter t_0 gives the shift of the wavelet function along the time. So, the wavelet transform of the EEG time series consists in decomposing into elementary space-scale contributions associated to wavelets which are constructed from one function (the basic mother wavelet) by means of scaling and shifting.

The complex Morlet wavelet is the most popular basic wavelet for studying nonstationary oscillations like as EEG time series [25]

$$\psi_0(t) = \pi^{-1/4} \exp(-0.5t^2) \left(\exp(i\omega_0 t) - \exp(-0.5\omega_0^2) \right), \quad (2)$$

where the second component in brackets can be neglected at $\omega_0 = 2\pi > 0$, the multiplier factor $\exp(i\omega_0 t)$ is a complex form of a harmonic function modulated by the Gaussian $\exp(-0.5t^2)$, the coefficient $\pi^{-1/4}$ is necessary to normalize the wavelet energy. The value $\omega_0 = 2\pi$ gives the simple relation $f = 1/a$ between the scale a