

Determination of the type of intermittency in the analysis of sigma rhythm spindles in the electroencephalogram of nocturnal activity of the human brain

© M.O. Zhuravlev^{1,2}, A.S. Akimova¹, A.O. Selskii¹, A.R. Kiselev²

¹ Saratov National Research State University, Saratov, Russia

² National Medical Research Center for Therapy and Preventive Medicine, Moscow, Russia

E-mail: selskiiao@gmail.com

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A modified method for the automatic detection of sigma rhythm spindles in nocturnal EEG recordings based on a continuous wavelet transform is proposed. The occurrence of sigma rhythm spindles can be described in terms of intermittent dynamics. Numerical analysis of the duration of laminar and turbulent phases allows for the detection of a type of intermittent dynamics distinct from that observed in epileptic activity.

Keywords: intermittency, wavelet transform, sleep spindles, polysomnography.

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Nonlinear dynamics and radio physics methods are widely used in interdisciplinary research [1] due to successfully implemented applications [2] and adequate simulation of complex system behavior in digital images in a wide range of control parameters [3]. In particular, intermittency [4] which is present both in mathematical simulation [5] and in various physical phenomena, including nonlinear behavior of fluids [6], is a widely observed effect simulated within nonlinear dynamics approaches. However, intermittency has been also found during study of living systems in medicine [7], neuroscience [8], genetics [9], etc.

Only three various types of chaotic intermittency were initially classified: I, II and III [4], but other types of intermittence such as on-off [10], needle's eye [11], ring [12], X, V [13] and, finally, intermittency of intermittencies [14] have been identified later. In spite of their similarity (two alternating behavior modes existing in time series), causes of each type of intermittent behavior are different. Each of the intermittency types has its own statistical characteristics: mean laminar phase duration vs. system control parameters, and distribution of laminar phase durations with fixed control parameter values.

The study investigated statistical characteristics of the chaotic intermittency during NREM sleep. Nocturnal polysomnography (PSG) makes it possible to gather long-term recordings of brain activity in relatively steady-state conditions with as low as possible effect of environmental factors and sensory systems. For sleep spindles and absence states of animal models, the presence of the on-off intermittency has been already demonstrated [15]. Correlation between the statistical characteristics of intermittency during sleep and hypertension level in patients has been also shown [16]. At present, sleep is generally studied not only from the fundamental standpoints of this physiological phenomenon, but also as part of the application-oriented search

for relevant symptoms and even predictors of diseases, for example, early detection of neurodegenerative states [17].

The study used EEG recordings from participants of a clinical study ($n = 10$, male/female 5/5, average age 28.3 ± 4.6 years) during nocturnal PSG using a certified expert polysomnograph made by Medicom MTD (Taganrog, Russia). The nocturnal sleep study involved recording of 19 EEG channels in the standard International 10–20 system using ear reference electrodes (Figure 1, *a*), ECG, PPG (photoplethysmogram), respiratory signal, EMG (electromyography) of chin and limbs, and EOG (electrooculography). EEG, ECG and respiratory function signals were filtered with a bandwidth of 0.1–40 Hz and digitized at 250 Hz. Electrode resistance was maintained below 10 k Ω . For all PSG recordings, sleep staging was performed by a certified somnologist. All electroencephalography signals were pre-treated before digital processing, i.e. filtered via the Gram–Schmidt process to remove oculomotor artifacts with additional usage of EOG [18], and also via expansion in fundamental empirical modes to remove artificial noise and muscle artifacts [19].

Sleep spindles were detected via a numerical analysis of activity recorded in 19 EEG channels arranged as shown in Figure 1, *a*. Sleep spindle detection technique uses frequency-and-time approaches [20], which are supplemented by the evaluation of individual characteristics and consider EEG multichanneling. EEG frequency-and-time structure was evaluated using the continuous wavelet transform (CWT) [21]:

$$W(f, t_0) = \int_{t_0-4/f}^{t_0+4/f} x(t)\psi_{f,t_0}^*(t)dt, \quad (1)$$

where the complex conjugation is marked by an asterisk, $\psi_{f,t_0}^*(t)$ is the Morlet mother wavelet. The CWT

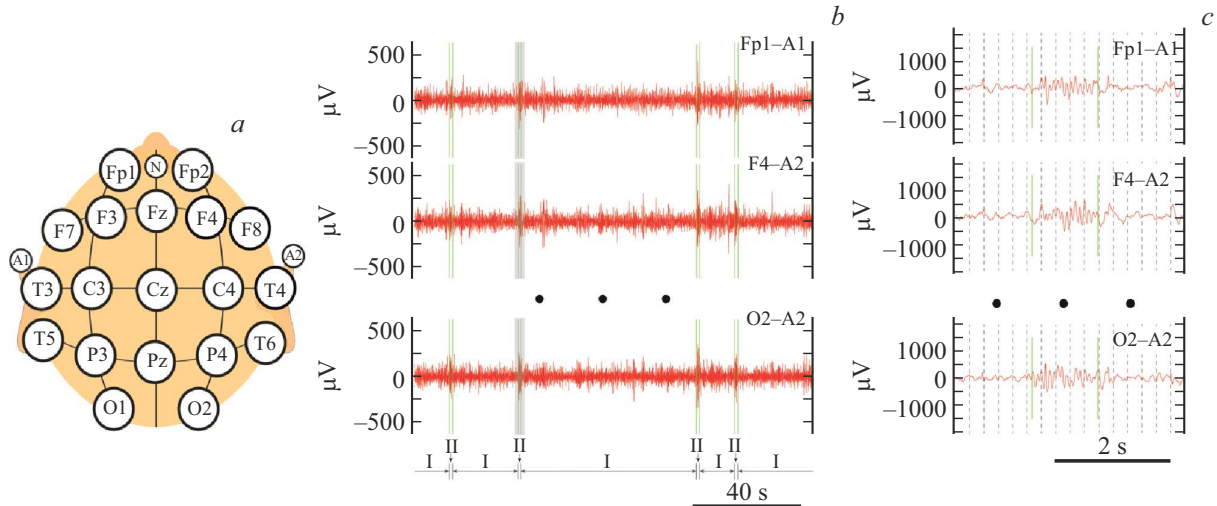


Figure 1. *a* — scheme of brain electrical activity recording during PSG using EEG electrodes located in accordance with the 10–20 system. *b* — typical view of brain electrical activity in some EEG leads during NREM sleep. Times of detected sleep spindles (turbulent phases) are marked by vertical lines and Roman numerals II, EEG laminar phases between the detected sleep spindles are marked by the Roman numeral I. *c* — typical view of brain electrical activity in some EEG leads during sleep spindle detection.

energy $E(f, t_0) = |W(f, t_0)|^2$ characterizes the power of the corresponding frequency f at time t_0 . For each i -channel of EEG at any time t , the total instantaneous CWT energy $E_{all}^i(t)$ falling within a frequency range from 1 Hz to 20 Hz is calculated. $E_{all}^i(t)$ is used for normalization of instantaneous powers of each frequency range, which reduces the effect of individual characteristics of participants, muscle and other artifacts on recording. Normalized CWT energies for each EEG channel were calculated in the frequency ranges $\Delta f_1 \in [1; 4]$ Hz, $\Delta f_2 \in [8; 12]$ Hz, $\Delta f_3 \in [11; 15]$ Hz and $\Delta f_4 \in [15; 20]$ Hz

$$\xi_{1...4}^i(t) = \frac{\sum_{f=1...4} E_i(f, t)}{E_{all}^i(t)}. \quad (2)$$

The choice of frequency ranges is conditioned by the oscillatory activity mode of sleep spindles. Three relative coefficients were estimated at each t for each EEG channel:

$$\kappa_1^i(t) = \frac{\xi_3^i(t)}{\xi_1^i(t)}, \quad \kappa_2^i(t) = \frac{\xi_3^i(t)}{\xi_2^i(t)}, \quad \kappa_3^i(t) = \frac{\xi_3^i(t)}{\xi_4^i(t)}. \quad (3)$$

κ_1^i , κ_2^i and κ_3^i (3) are used to introduce a sleep spindle existence condition at a specific time t for an EEG's i -channel

$$\mu^i(t) = \begin{cases} 1, & \text{if } \kappa_1^i(t) > 1, \text{ and } \kappa_2^i(t) > 1, \text{ and } \kappa_3^i(t) > 1, \\ 0, & \text{if } \kappa_1^i(t) \leq 1, \text{ or } \kappa_2^i(t) \leq 1, \text{ or } \kappa_3^i(t) \leq 1. \end{cases} \quad (4)$$

If $\mu^i(t)$ (4) is equal to 1 and t falls within the NREM sleep stage, then a sleep spindle is detected in the i -channel. A total coefficient is estimated for each t

$$\tau(t) = \sum_{i=1}^{19} \mu^i(t), \quad (5)$$

to detect a sleep spindle existing in the integral brain electrical activity

$$\tau(t_1) \geq 15, \quad \tau(t_2) < 5, \quad (6)$$

where t_1 refers to the beginning of a sleep spindle, and t_2 refers to the end of this spindle.

Sleep spindles were detected for the whole array of nocturnal EEG. Automated evaluation and somnologist's staging results were compared on an array of four PSG recordings. Evaluation of automated extraction of sleep spindles has shown the following parameters: accuracy 85.5%, $F1$ -score (harmonic mean of accuracy and completeness of the method) 87.6% [22], sensitivity 76%, specificity 97% [23], false detection coefficients $FP(\text{proportion}) \approx FP(\text{amount}) \approx 0.24$ [24,25], error of detection of the beginning and end of sleep spindles was 0.16 ± 0.06 and 0.12 ± 0.1 s, respectively. High specificity and coincidence of false detection errors are associated with artificial reduction of analyzed PSG segments only for NREM sleep stages N2.

Mean time of a sleep spindle was 2 s, and mean time between spindles was 20–40 s, which adequately agrees with results of [26] and is illustrated in Figure 1, *b*, *c*.

Thus, duration of time intervals between consecutive sleep spindles is much longer than that of spindles themselves, which makes it possible to describe brain electrical activity behavior from the chaotic intermittency standpoints — a sequence of alternating regular (laminar) phases and irregular bursts (or turbulent phases), i. e. sleep spindles.

Determination of an intermittency type in nocturnal EEG recordings arouses interest because, as has been shown earlier, the on-off type is observed for non-clinical animal models. The number of sleep spindles in participants exceeds 400 events per nocturnal recording on average,

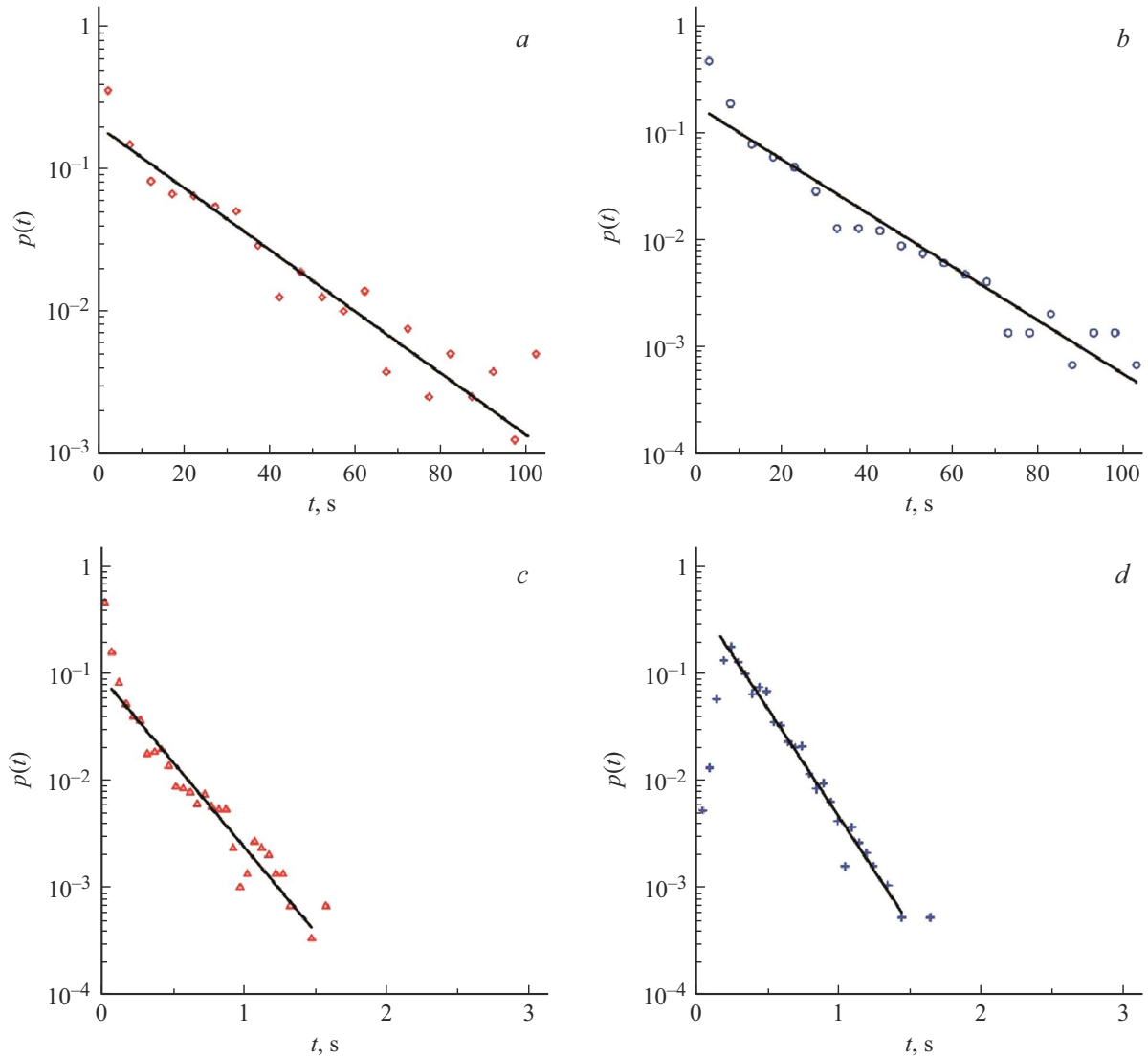


Figure 2. *a* and *c* are distributions of laminar and turbulent phase durations for volunteer 4; *b* and *d* are the same distributions for volunteer 6. Experimental data are shown in the form of points, approximation (7) is shown as a line.

which makes it possible to carry out a standard analysis of statistical characteristics of this intermittency, i.e. to evaluate the laminar and turbulent phase time distributions and then to compare them with laws described for various types of intermittency. Typical examples of plotted laminar and turbulent phase time distributions are shown in Figure 2. Numerical evaluation of distribution laws has demonstrated proximity to the exponential law, which is typical for two types of intermittency, i.e. ring [12]:

$$p(t) \sim A \exp(kt), \quad (7)$$

needle's eye [18]:

$$p(t) = T^{-1} \exp(-t/T). \quad (8)$$

The approximation of laminar phase time distribution has demonstrated the best results when (7) was used, approximation parameters for the study participants are

shown in the table. Variability of the given approximation parameters for turbulent phases ($k = -3.52 \pm 1.05$, $A = 0.27 \pm 0.16$) is much high than that for laminar phases ($k = -0.06 \pm 0.01$, $A = 0.21 \pm 0.06$). Values of k differ reliably for laminar and turbulent phases ($p < 0.001$).

Justification of conclusion that there is a particular type of intermittency generally requires additional evaluations, i.e. plotting of the mean laminar phase time vs. supercriticality parameter [14] or analysis of a phase path on a rotating plane at the onset of the turbulent phase [14,16]. However, variation of the supercriticality parameter and indirect evaluation of the phase path behavior are impossible in a real biological system, which makes further refinement of an intermittency type in nocturnal EEG recordings cumbersome.

Nevertheless, the findings are of interest because the described intermittency types (ring/needle's eye) are typical for unidirectionally coupled oscillators, where one of the

Values of k and A from relation (7), which were used during approximation of the laminar and turbulent phase time distribution for all volunteers

| Volunteer | k_{lam} | A_{lam} | k_{turb} | A_{turb} |
|-----------|-----------|-----------|------------|------------|
| 1 | -0.065 | 0.213 | -3.235 | 0.160 |
| 2 | -0.072 | 0.085 | -1.569 | 0.113 |
| 3 | -0.079 | 0.186 | -2.631 | 0.204 |
| 4 | -0.052 | 0.208 | -3.518 | 0.089 |
| 5 | -0.094 | 0.324 | -4.683 | 0.474 |
| 6 | -0.064 | 0.221 | -4.709 | 0.475 |
| 7 | -0.063 | 0.179 | -3.580 | 0.265 |
| 8 | -0.062 | 0.245 | -3.524 | 0.280 |
| 9 | -0.053 | 0.179 | -3.411 | 0.284 |
| 10 | -0.086 | 0.243 | -5.131 | 0.527 |

oscillators is the master and the other is the slave. This fact considerably differentiates the detected mechanism of intermittency in the brain electrical activity of sleeping patients from on-off intermittency descriptions obtained for non-clinical studies of animal models [15]. Fundamental differences in dynamic structure of the EEG oscillatory activity can be associated with different modes of sleep (polyphasic sleep in rodents and monophasic sleep in humans) and also caused by pathological changes in brain activity in absence epilepsy observed in animal models.

Future study of characteristics of intermittent sleep spindles will be focused on the association between laminar phase approximation parameters and participants' state and on building a mathematical model of intermittency in human brain activity EEG during NREM sleep.

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Compliance with ethical standards

All procedures performed within the study involving human participants meet the ethical standards of the institutional and national research ethics committee and the Declaration of Helsinki 1964 as subsequently amended or comparable ethical standards. Informed voluntary consent was obtained from each study participant.

Conflict of interest

The authors declare no conflict of interest.

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