Fractal Analysis of EEG Signals for Identification of Sleep-Wake Transition

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Abstract. *Objective* is the combination of frequency filtering and nonlinear analysis methods for generating hypnograms through the analysis of electroencephalographic (EEG) signals in the somnological studies.
Methods. The frequency filtration methods are used for the primary preparation of the EEG signals for further nonlinear analysis. Among the nonlinear analysis methods, such fractal deterministic chaos methods as the Hurst standardized range method, approximate entropy method, and correlation integral computation with the Grassberger-Procaccia algorithm. To apply the two latter methods, we used the pseudo-phase space reconstruction method based on Taken's theorem. Relying upon the nonlinear analysis results, and as a result of the somnology examination of patients, the hypnograms of sleep stage transitions were made up. To verify the collected results, they were compared with the hypnograms generated with the classical method based on the Rechchaffen and Kales parameters. Moreover, the problems related to various disturbing factors are considered, the ways of mitigation of their influence on the final results are suggested.
Conclusion. With the properly selected method parameters, the accurate standardization of the input data and correct averaging of results, the given methods can be used to produce a hypnogram showing complete coincidence of the identified sleep phases for almost a half of the epochs registered by EEG. Interestingly, these results can be achieved with one EEG registration channel only. #COMESYSO1120

Keywords: Fractals, Deterministic Chaos, Hypnogram, Frequency Analysis, Electroencephalography.

1 Introduction

Timely diagnostics of sleep disorders may reveal and prevent the development of many serious diseases [1, 2]. Since many pathological processes may emerge or, vice versa, diminish during sleep, in last years the medicine of sleep studying the pathogenesis, clinic and treatment of the pathologies that emerge in the period of sleep has been rapidly evolving [3-5]. The commonly known sleep stage classification system was developed by Rechchaffen and Kales in 1968 [1, 2]. According to this method, the expert manually analyses electrophysiological parameter records of approximately eight hours length. For every thirty-second fragment of the record, the determination characteristics used to classify the segment as belonging to a certain sleep stage are subsequently computed. The Rechchaffen and Kales parameters-based hypnogram generation method is still very popular despite a number of significant limitations, such as high labor intensity and subjectivity of the interpretation. For this reason, at the present moment there is an urge for objective automated methods for sleep phase recognition which, combined with an electrophysiological signal registration device, would make a sleep disorder diagnostic system. Due to the fractal nature of the EEG signals, using fractal measures in this case appears the most natural [6]. Consequently, this method would produce more accurate results with less input data. In this paper, the sleep phase division problem was solved by fractal measures applied to the EEG channel analysis. In particular, this study requires the record of one EEG only (without EOG or EMG) and only one channel to formulate the results.

2 Nonlinear analysis methods

The fractal methods described below have been successfully used by the authors in their previous works, applied to a wide range of problems [7-13]. Particularly, the Hurst exponent computation-based method [11-13], the Grassberger-Procaccia method [13], the Takens' theorem-based method [11, 13], the approximate entropy computation method [11-13] and other nonlinear analysis methods [14] have been used in various ways [15]. The mathematical grounds of the mentioned methods are briefly presented below.

The Hurst standardized range method applied to the EEG signal time sampling computation. At the first stage of the Hurst exponent computation, the mean value of signal $\langle U \rangle_N$ for N time cycles:

$$\langle U \rangle_N = \frac{1}{N}\sum_{n=1} U(n)$$

Then the accrued deviation $U(n)$ from its mean value $\langle U \rangle_N$ is determined with the sum:

$$X(n,N) = \sum_{p=1}^{n} \{U(p) - \langle U \rangle_N\}$$

The deviation range is defined as follows:

$$R\langle N \rangle = \max_{1 \le n \le N} X(n,N) - \min_{1 \le n \le N} X(n,N)$$

Standard deviation can be calculated with the square root formula from the dispersion:

$$S(N) = \sqrt{\left(\frac{1}{N}\sum_{n=1}^{N}\{U(n) - \langle U\rangle_N\}^2\right)}$$

As demonstrated in the Hurst's studies, for the majority of temporal series, the observed standardized range can be described with the empirical relation [16]:

$$R / S = (\alpha N)''$$

where H is the Hurst exponent, and α is the arbitrary constant. It should be mentioned that the range is referred to as standardized as it has to be divided by the square root from the dispersion.

The phase space reconstruction method and Takens' theorem. Takens' theorem [17] can be used to calculate the correlation integral (to be described below) and the fractal dimensionality based on the temporal sequence measurements made for one component only. According to Takens, it is necessary

$$X_i = X(t_i) = \{x(t_i), x(t_i - \tau), \ldots, x(t_i - (m-1)\tau)\}$$

The Grassberger-Procaccia method for correlation integral computation. With the delay method described above, let us use the studied series to formulate the attractors in the m-dimensional pseudo-phase spaces for m = 1, 2, 3, ... Then, for every attractor in the m space, let us calculate the correlation integral with the formula [18]:

$$Ce(\varepsilon, N) = lim_{N\to\infty}\frac{1}{N(N-1)}\sum_i\sum_j\theta\left(\varepsilon - |x_i - x_j|\right), i \neq j,$$

where N is the number of attractor points, $\angle x_i - x_j \angle$ is the absolute distance between the i -th and j-th attractor points in the m-dimensional space, ε is the resolution cell size, θ is the Heaviside function. Basically, $Ce(\varepsilon, N)$ is the dependency of the number of attractor points in the m-dimensional space with the distance between them being <ε , on the size of the resolution cell, related to the total number of paired points, i.e. $\sim N^{-2}$ $(N(N-1)$ in the formula denominator due to the condition of $Ce(\varepsilon, N)$ $i \neq j$). The generated dependencies are plotted in double logarithmic scale on the plane (theoretically, it can be done with any logarithm base, but 10 is used for better visualization). Then, the linear segments of the plotted curves are indicated, and the least square method is applied to find the lines approximating them. For all the generated curves, $Ce(\varepsilon, N)$ the first derivative of the approximating line D_C is calculated and plotted as a function of m.

Approximate entropy. Being a measure of deterministic chaos, approximate entropy is intended to collect information on the complexity of processes occurring in the system based on short time series

$$X = [x(1), x(2), \ldots, x(N)]$$

where N is the length of the studied series, consisting of approximately 75 - 5000 readings [19]. The approximate entropy value depends on the dimensionality of the pseudo-phase space m based on the Takens method, "filtration factor" r and the studied series length *N*, calculated with the equation:

$$ApEn(m, r, N) = \Phi^{m}(r) - \Phi^{m+1}(r)$$

Here, $\Phi^{m}(r)$ and $\Phi^{m+1}(r)$ are derived from the equations:

$$\Phi^{m}(r) = \frac{1}{N-m}\sum_{i=1}^{N-m} ln\left(C_i^m(r)\right), \Phi^{m+1}(r) = \frac{1}{N-m}\sum_{i=1}^{N-m} ln\left(C_i^{m+1}(r)\right),$$

just as for the correlation integral, $C_i^m(r)$ and $C_i^{m+1}(r)$ are determined with the sums:

$$C_i^m(r) = \frac{1}{N-m+1}\sum_{j=1}^{N-m+1} \theta(r - |x(i) - x(j)|)\,,$$

$$C_i^{m+1}(r) = \frac{1}{N-m}\sum_{j=1}^{N-m} \theta(r - |x(i) - x(j)|).$$

As a result, the approximate entropy calculation process can be limited to the acquisition of the *ApEn* value with the general equation [20]:

$$ApEn(m, r, N) = \frac{1}{N-m}\left[\sum_{i=1}^{N-m} ln\left(\frac{C_i^m(r)}{C_i^{m+1}(r)}\right)\right],$$

followed by the computation of $C_i^m(r)$ values for every $C_i^{m+1}(r)$ *i*.

3 Frequency filtration methods as essential artifact combating methods used in nonlinear analysis

Studies of the EEG signals frequency parameters are successfully used both in modern medicine and in clinical studies [21]. The subject matter here is selecting certain fractal methods for solving particular tasks, selection of channels for analysis, and selection of frequency diapasons for filtration and particular method application specificities. Below, let us elaborate on the Zenkov artifact classification system [22] and the suggested solutions on elimination of artifacts in using the fractal method.

As remarked in [22], *the EMG potentials* are the pointed-shaped high-frequency activity of irregular frequency lying within the diapason of 15-100 Hz. For EEG signals, we suggest using a digital filter based on the fast Fourier transformation (FFT) method to crop the frequencies exceeding 40 Hz, as the peak of EMG activity dominates in the 70 Hz area.

The ECG potentials occur, as a rule, in the reference electrodes and are identified through a distinctive electrocardiogram shape [22]. This is explained by the fact that the pair of electrodes transmitting the signal are not equally spaced from their generation source, the heart. As such disturbance factors are classified as quasi-periodic, they make less impact on the fractal measures than spectral analysis.

The EOG potentials are associated with the eyeball moves and, therefore, the orientation of the electrical axis of the eye determined with the corneoretinal potential [22]. We found a partial solution of the problem through filtering the frequencies below 0.5 Hz to get rid of the eyeball move-related high-range EEG jumps. However, to minimize the influence made by these disturbance factors on automated recognition, the leads remote from the forehead area should be selected.

The swallowing-induced electrical potentials are represented by the high-range slow two and polyphased waves with the period of 0.5-2 seconds that normally occur in unipolar leads on all the channels [22]. According to the presented method, it is suggested to stick to one 30 second epoch throughout the entire period of sleep. As far as the produced hypnogram is concerned, the influence of such artifacts is expected to be quite short, 1-2 epochs long, and if during the automatic recognition the transition from the current sleep phase occurs, it cannot be registered according to Rechchaffen and Kales.

Network interference is the consequence of electromagnetic setting on the patient-electrodes-conductors system. The way of eliminating such interference is the same for any situation: they are eliminated by reducing the impedance between the electrode and the patient's skin to the required level during standard skin preparation routine and narrow-band filtering to the frequency area of the municipal illumination network, i.e. the so-called notch filtering. Our practice shows that in the majority of cases excluding the 47-53 Hz zone by means of FFT digital filtration is enough to get rid of such interference.

Skin condition change-related electrical potentials are mostly determined by the difference of potentials between the superficial and deep layers of the skin, perspiratory activity, skin circulation fluctuations and, therefore, skin resistance variations. As the frequency of their occurrence is 1-5 seconds, it is possible to partially get rid of them by filtering out the frequencies under 0.5 Hz. Further shift of the bottom filter threshold value towards the delta diapason will cause a significant distortion in the sleep station interpretation, as such disturbances appear to be the most problematic when they occur.

Summing up, there is a number of key recommendations for applying deterministic chaos fractal measures to the sleep stage identification in polysomnography:

- for various reasons, it is better to use the leads closest to the sagittal line in the bregma and central point area;
- for EEG signals, the digital filtration should be carried out with the FFT and the interpreted signal should be in the frequency diapason from 0.5 to 40 Hz.
- during the statistical processing of the fractal computation output, the obviously artifact-related deviations should be filtered out;
- to mitigate the short-term transitions from the sleep stage which may be related to artifacts of various origins, the considered epoch length shall not exceed 20-30 seconds.

4 Example of combining the frequency filtration and nonlinear analysis methods in hypnogram recording

The calculations were carried out on a computer using a specially developed program based on Borland C++ Builder medium. The program calculation results were verified by means of comparing the results with those acquired by the authors in other researches and with the results collected by other authors [23-25]. Fig. 1 presents the hypnogram recorded by the specialists and the output of the EEG computations by fractal methods for the given epochs.

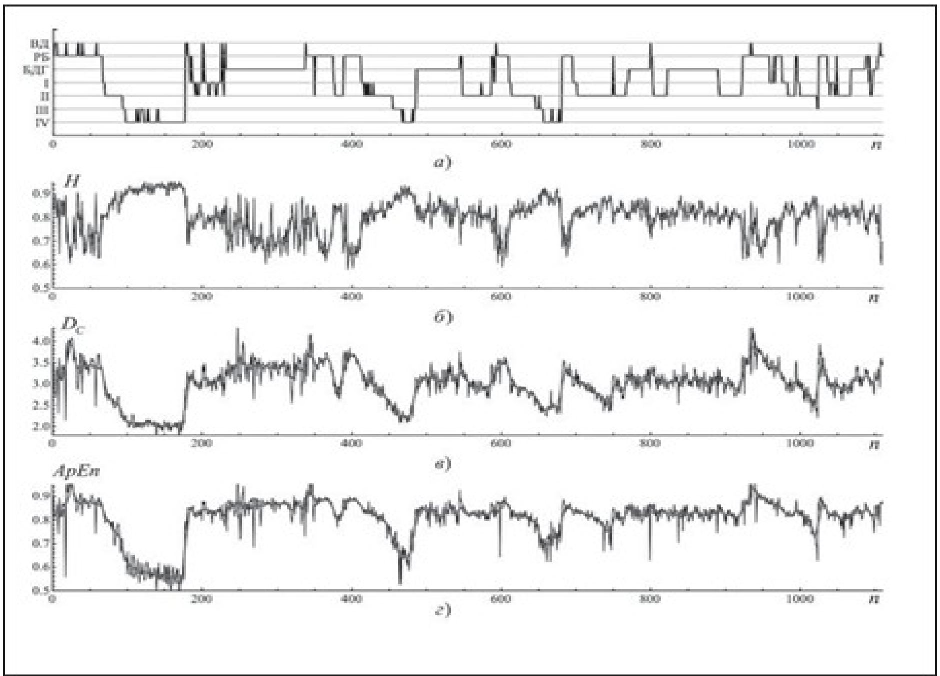

Fig. 1. Hypnogram comparison with different fractal measure values for the respective epochs: a – hypnogram recorded by the specialists; b – Hurst exponent value, c – correlation dimensionality value, d – approximate entropy value. For the fractal measures, the thin lines present the unprocessed values; the bold lines present the values after the averaging method has been applied.

The hypnograms produced with all the three methods presented in this paper are shown in Fig. 2 as dashed lines. The hypnogram recorded by the specialists is presented in the same figure as a solid line.

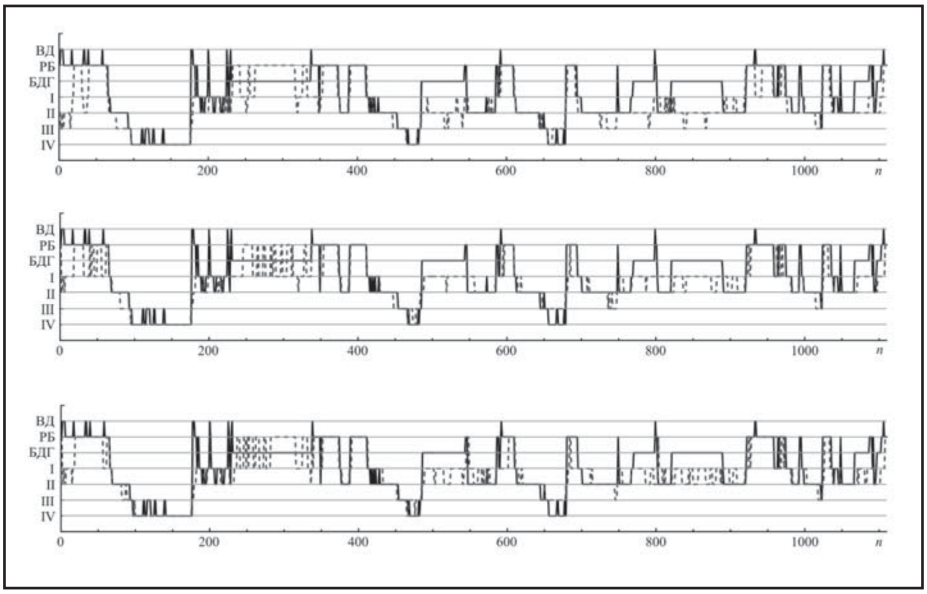

Fig. 2. Comparison of the hypnogram recorded by the specialists (solid line) with the hypnograms recorded with the following fractal deterministic chaos methods (dashed line): a – Hurst standardized range method; b – Grassberger-Procaccia method; c – approximate entropy method.

On the horizontal axis, the numbers of epochs since the EEG recordings are plotted. On the vertical axis, the following phases are plotted [26]: MT – motion time (unrecognizable phase associated with the presence of motion artifacts of approximately 25% of the epoch duration long), RW – relaxed wake, REM – rapid eye movement phase (paradoxical sleep phase), I, II, III, IV – 1st, 2nd, 3rd and 4th stages of sleep respectively.

5 Conclusion

As a result of the combined application of the frequency filtration methods for the preliminary processing of the EEG signals and the nonlinear dynamics methods as a way of assessing the depth of asynchronization of the brain activity processes during sleep, some satisfactory hypnograms were generated. As we can see from the collected results, the combination of all the three fractal nonlinear analysis methods made up the complete picture of sleep, as the deep delta sleep and the transition to the RW phase were clearly differentiated. The superficial sleep recognition was only complicated by the absence of the paradoxical sleep phase recognition. The qualitative characteristics of the coincidence between the hypnograms made up by means of different methods used in the program and the hypnograms manually recorded by the specialists were the following: the Hurst standardized range method results – 52.2%, Grassberger-Procaccia correlation integral – 47.8%, approximate entropy – 48.5%. The percentage indicates the numbers of epochs that show the complete coincidence of the sleep phases with the hypnogram recorded by the specialists. This indicates good differentiation of the sleep phases in the little input information. Both approaches, the frequency and nonlinear ones, should be considered not as competitive but as mutually supplementary; the combination of the methods opens wider perspectives than separate and independent use.

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