Correlation Dimension versus Fractal Exponent During Sleep Onset

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Abstract. *This study was concentrated on changes of complexity of EEG signals during the sleep onset process and the comparison of sleep onset with relaxation. The ability of two complexity measures - correlation dimension D_2 and fractal exponent γ - to distinguish these slightly distinct states was examined. Both measures confirmed decreased complexity of EEG signals during sleep onset process, on the contrary the complexity during the relaxation slightly increased.*

Keywords: sleep onset, relaxation, EEG, correlation dimension, fractal exponent

1. Introduction

Sleep onset is complex process, which can be identified via several kinds of markers: behavioural features such as decrease of attention, frequency of eyelid closure, slow eye movements; physiological features such as changes in electrical resistance and temperature of skin, slowing down the frequency of breathing and heart-beat intervals, etc; and changes in electroencephalogram (EEG) [1]. However, physiological and behavioural features show large inter-subject variability and ambiguity. Analysis of EEG seems to be the most reliable method with respect to automatic detection of sleep onset.

In sleep research and also in clinical practice Rechtschaffen and Kales system [2] is widely used for scoring states of vigilance. In the case of sleep – wakefulness transition three states of vigilance are important: wakefulness, Stages 1 and 2 of non rapid eyes movement sleep. Hori et al. [3] sub classified these three classical stages into 9 novel stages, which described more precisely the process of sleep onset. After Hori's system sleep onset process begins when the alpha activity is reduced below 50 % of the scored epoch and ends with appearance the wave patterns sleep spindles or K-complex.

Classical spectral analysis has been applied on EEG during wake – sleep transition by several authors, however their results are not uniform. Germain and Nielson [4] reported that during the sleep onset power decreased in all frequency bands but delta and the decrease was observed most significantly in the frontal area of the brain. Tichý et al. [5] investigated the relationship between power in spectral bands and gradual loss of attention ending with micro sleeps. After their results during good concentration and attention the dominant power was in alpha band (8-12 Hz) and during micro sleep the prominent peak was shifted to lower frequencies – to delta band (0-4 Hz). Tietze [6] noticed that first features of fatigue were coherent with alpha waves, the more tired subject, the longer alpha events and the less period between successive alpha events.

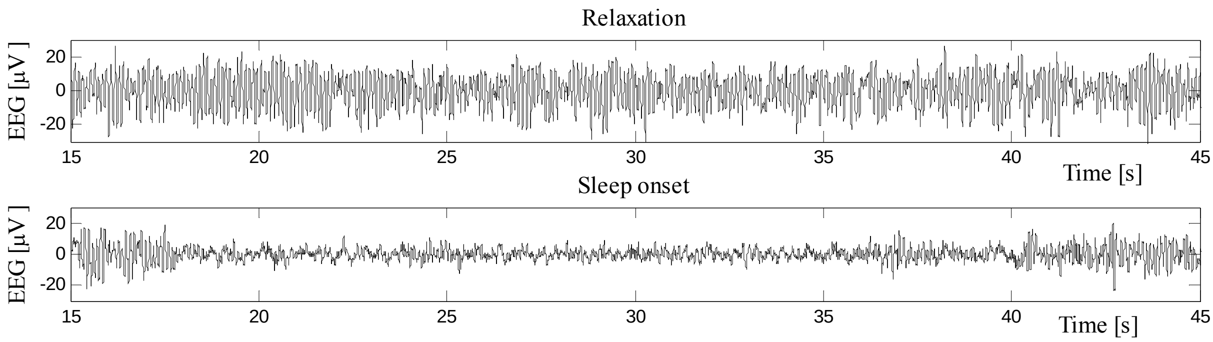

Figure 1. Two examples of 30 s long EEG from the same subject – during relaxation and sleep onset. Relaxation is characterized with continuous alpha activity, sleep onset with alternation of epochs with alpha activity and epochs with decreased amplitude and mixed frequency EEG.

However, little literature is available on computing complexity measures of EEG during sleep onset. In this work the ability of two complexity measures – correlation dimension D_2 and fractal exponent γ to discriminate the subtle changes in human EEG during relaxation and sleep onset was compared. From application of D_2 to EEG measured during anaesthesia [7] and sleep [8, 9] it was evident that the deeper the state of consciousness - the lower value of D_2. Similarly, the hypothesis in this work was that there should exist a shift into lower complexity of the system during sleep onset process.

2. Subject and Methods

Data came from a relaxation experiment, where 8 subjects were trained in relaxation during 25 sessions. The subjects were instructed to relax, but four subjects overslept several times during the whole training. 3 min. long EEG from 6 channels was recorded, EEG derivations were: c3p3, c4p4, f3c3, f4c4, p3o1, and p4o2 after international 10-20 electrode placement system for EEG measurement. EEG was sampled at 500 Hz and filtered from 0,75 Hz. After subjective scoring the records were selected into two groups: records of sleep onset and records of relaxation state. In Figure 1 you can see two examples of 10 s long EEG during relaxation and during sleep onset. For more detailed description of data and the experiment see [10].

Correlation dimension was computed after Grassberger - Proccacia algorithm (GPA) [11]. First, vectors in the phase space are reconstructed after Takens theorem. GPA is based on computation of the correlation sum:

$$C_2(\varepsilon) = \frac{2}{(N)(N-1)} \sum_{i=0}^{N} \sum_{j>i}^{N} \Theta(\varepsilon - \| x_i - x_j \|) \tag{1}$$

where $\mathbf{x}_i$, $\mathbf{x}_j$ are vectors in the phase space, N is the number of vectors and $\Theta(\varepsilon - \| x_i - x_j \|)$ is the Heaviside function, which is equal one if the pair of vectors $\mathbf{x}_i$, $\mathbf{x}_j$ are less than a geometrical distance ε and zero otherwise. D_2 is then defined as:

$$D_2 = \lim_{\varepsilon \to 0} \lim_{N \to \infty} \frac{\ln C_2(\varepsilon)}{\ln \varepsilon} \tag{2}$$

For deterministic signals $C_2(\varepsilon)$ shows a power-law behaviour, so if we take the local slope of ln C_2 against ln ε, then the value of the plateau is taken as the estimate of D_2. The precision of GPA is sensitive to the quality and amount of data, with less amount of data GPA will produce underestimate value of D_2 [12].

Fractal exponent γ is a measure used for fractal stochastic processes. Power spectra of stochastic signals can show power-law behaviour with $1/f^{\gamma}$, where γ is

	C3P3		C4P4		F3C3		F4C4		P3O1		P4O2	
	γ	D_2	γ	D_2	γ	D_2	γ	D_2	γ	D_2	γ	D_2
Relax.	2,35	4,28	2,33	4,33	2,23	4,46	2,26	4,41	2,16	4,43	2,12	4,53
Sleep	2,56	4	2,57	3,99	2,55	4,29	2,55	4,07	2,46	3,95	2,58	3,88
Rel. dev	-9,03	6,58	-10,24	7,78	-14,22	3,77	-12,47	7,7	-13,69	10,82	-21,48	14,27

Table 1. Topographical characteristics of D_2 and γ. Relax. – relaxation state, Sleep – sleep onset, Rel. dev – relative deviation, which was computed as 100*(Relax. - Sleep)/Relax [%]

	Relaxation		Sleep onset	
	D_2	γ	D_2	γ
Tendency to oversleep	4,04 ± 0,46	2,45 ± 0,21	3,95 ± 0,46	2,59 ± 0,21
No tendency to oversleep	4.68 ± 0,46	2,09 ± 0,24	-	-

Table 2. Mean and standard deviation of D_2 and γ for subgroups of subjects with and without the tendency to oversleep

the slope of linear fit of the power spectrum density in the double logarithmic graph. Fractal exponent γ is negatively correlated with D2, so for less complex signal D_2 shows lower value and γ higher value.

3. Results

36 records of sleep onset EEG and 339 records of EEG during relaxation were analyzed. The EEG data were visually scored for sleep onset markers and compared with the behaviour of D_2 and γ. In most cases, observed features of sleep onset were the reduction of alpha activity - the change from continuous alpha to alternation of epochs with alpha activity and epochs with decreased amplitude and mixed frequency EEG, see Figure 1.

The whole mean of D_2 over all subjects and EEG derivations for relaxed data was 4,41 ± 0,6 and for sleep onset data D_2 was equal 3,95 ± 0,46. In the same way, γ for relaxed data was 2,24 ± 0,34 and for sleep onset signals γ was equal 2,59 ± 0,21.

With regard to topographic characteristics of brain all files were sorted after the derivation of EEG. D_2 and γ averaged over signals with the same EEG derivation are in the Table 1. The highest difference between relaxation and sleep onset appeared in the occipital area (especially in p4o2) for both D_2 and γ. For γ the relative change in absolute value was higher than for D_2 in all derivations, therefore γ appeared to be more sensitive and hence more appropriate for discriminating these states of brain.

With the aim to reveal possible inter-subject differences D_2 and γ were averaged over all channels for individual subject. Interesting findings were observed – subjects with tendency to oversleep (four subjects) showed lower D_2 during relaxation than subjects that had never overslept. Subjects were divided into two subgroups after this tendency to oversleep, the averaged value of D_2 and γ for these two subgroups are in Table 2. Within the subgroup with the tendency to oversleep the hypothesis that D2 shows higher values during relaxation (wakefulness) than during sleep onset was confirmed in 2 subjects from 4; γ was lower in relaxation than in sleep onset in 3 subjects from 4.

Furthermore the ability of D_2 and γ to catch the process of sleep onset was examined. D_2 and γ were computed for EEG fragmented into 10 equal parts (each 18 s long, 4833 points). Linear fit of averaged evolutions of D_2 and γ was obtained, see Figure 2. Slopes during relaxation (both groups of people) were for

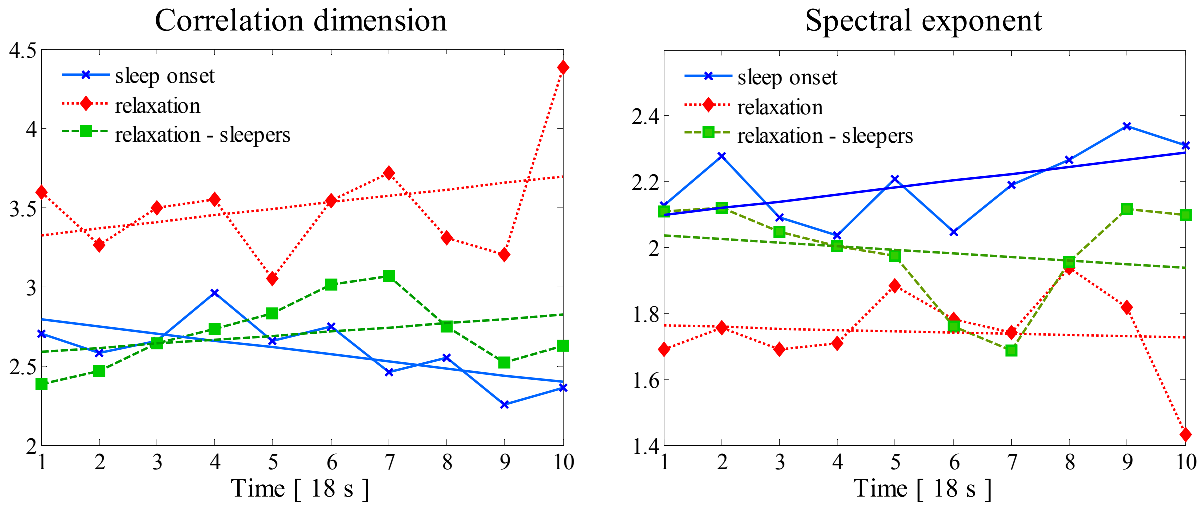

Figure 2. Average evolution of correlation dimension and spectral exponent during sleep onset and relaxation (both groups of people - with and without tendency to oversleep)

D_2 positive, in contrast with the negative slope of sleep onset. Also γ showed lower complexity for sleep onset than for both groups of relaxation.

4. Discussion and Conclusions

The main objective of this study was to analyze the process of sleep onset from the point of view of complexity measures – correlation dimension and fractal exponent and to find differences between sleep onset and relaxation.

First averaged results computed for 3 min long intervals were in good agreement with hypothesis of lower complexity of EEG during sleep onset. However, after looking for inter-subjects differences and dividing people into subgroups with and without tendency to oversleep it was proved that higher contribution to the difference was due to high complexity of EEG signals of people which overslept not one during the whole training. If only subjects with the tendency to oversleep were taken into account D_2 did not show significantly different values between relaxation and sleep onset, γ supported the hypothesis in 3 subjects from 4.

However, during the sleep onset process the slopes of linear fit of the average evolutions of both measures showed decreasing trends in the complexity of EEG signals, in contrast with the relaxation during which the trends were slightly increasing.

Interesting finding was within the group of people with the tendency to oversleep – the level of complexity of EEG at the beginning of the 3 min interval was approximately the same also for sleep onset and also for relaxation, only later changed depending on conditions.

The average evolution of both measures for both groups of people was very similar, they differed only in absolute value of complexity. These unusual different values of D_2 and γ during relaxation were confronted with the ability to improve the relaxation during the training process (25 sessions). Several authors found that long-term averaged decrease of D_2 was a sign of improving relaxation [13]. In this study the tendency not to oversleep was highly correlated with higher trend in improving the relaxation.

The range of values of D_2 computed from 3 min long intervals differ with values of the evolutions, where D_2 was computed from 18 s long intervals. The value of D_2 can be underestimated due to less amount of data [12].

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