Fractal Dimension of EEG in Sleep Onset

Jussi Virkkala
Brain and Work Research Units
Finnish Institute of Occupational Health
Topeliuksenkatu 41 a A
FIN-00250 Helsinki
FINLAND
jussi.virkkala@ttl.fi, www.ttl.fi/users/jussi.virkkala

Alpo Värri
Institute of Signal Processing
Tampere University of Technology
P.O. Box 55
FIN-33101 Tampere
FINLAND
alpo.varri@tut.fi, http://www.cs.tut.fi/~varri/

Sari-Leena Himanen
Department of Clinical Neurophysiology
Tampere University Hospital
P.O. Box 2000
FIN-33521 Tampere
FINLAND
shimanen@tays.fi

Joel Hasan
Department of Clinical Neurophysiology
Tampere University Hospital
P.O. Box 2000
FIN-33521 Tampere
FINLAND
jhasan@tays.fi

Abstract: - Sleep onset is typically monitored using EEG, EMG and EOG. Scoring rules of Rechtschaffen and Kales (RK) are normally used in 30 s epochs for scoring wakefulness (S0) and sleep stages (S1, S2, S3, S4 and REM). One daytime sleepiness test is Maintenance of Wakefulness Test (MWT) where the subject is instructed to stay awake under soporific circumstances. We analyzed 17 of 40 minute MWT recordings using linear and non linear analysis to study vigilance fluctuations beyond 30 s RK scoring. Using adaptive epoch lengths with minimum epoch duration of 2 seconds a total of 768 wake-sleep and sleep-wake transitions were used to study change in fractal dimension (FD) in sleep onset and in following awakenings. Time domain fractal dimension was calculated using Higuchi algorithm (kmax=8, 16) for 2 seconds before and 2 seconds after each sleep onset and awakenings. Ratios of dimensions were calculated. Using kmax=8: For sleep onset (S0-S1) transitions fractal dimension changed from 1.28±0.08 to 1.32±0.09 and fractal dimension ratio was 1.03±0.07 and for sleep-wake (S1-S0) transitions ratio was 1.00±0.06. Using kmax=16: For sleep onset (S0-S1) transitions fractal dimension changed from 1.52±0.09 to 1.52±0.10 and fractal dimension ratio was 1.00±0.05 and for sleep-wake (S1-S0) transitions ratio was 1.04±0.06. Findings using kmax=8 are in contradiction of lower frequencies (theta activity of S1) resulting in lower FD than higher frequencies (alpha activity of S0). Our results indicate that fractal dimension could be used as an assisting parameter in computer assisted sleep onset detection.

Key-Words: - EEG, Fractal Dimension, Sleep Onset, Adaptive Scoring, MWT

1. Introduction

Sleep onset process (SOP) can be studied in various ways. Changes are seen in behavioural, subjective, physiological and electrophysiological measures [1, 2]. Scoring is usually done according Rechtschaffen and Kales (RK) in 30 s epochs [3]. Shorter epochs with more sleep categories have been used to increase temporal resolution and detection of smaller vigilance fluctuations [4]. We have recently been interested in using adaptive epochs instead of fixed epoch duration [5]. In this work we looked how fractal dimension of EEG calculated in time domain change in transitions from wake to sleep (sleep onset) and from sleep to wake (awakening) using adaptive epoch lengths.

Computer assisted sleep, vigilance scoring is usually based on eye movement, electromyography (EMG) and electroencephalography (EEG) [6]. In sleep onset most often EEG alpha (7-12 Hz) frequencies change to theta (4-7 Hz) frequencies. Fractal dynamics has been studied in physiology, especially in heart rate time series [7]. Changes in fractal dimensions of EEG are seen using time domain algorithms [8, 9]. Fractal dimension changes between sleep stages, lower values with deepening of sleep [9, 10].

2. Material and methods

Seventeen train drivers and controllers participated in this study. Maintenance of Wakefulness Test (MWT) was administrated after full night polysomnography [11]. From four 40 minutes sessions from each subject ones starting at 14:00 were selected for further analysis. Visual adaptive scoring was done using minimum epoch duration of 2 s and only differentiating between wake (S0) and sleep (S1) sleep stages [12]. This method is modified from original Visual Adaptive Scoring System (VASS) using fewer sleep stages and reduced temporal resolution [5]. From seven EEG (Fp1-M2, C3-M2, O1-M2, Fp2-M1, C4-M1, O2-M1, M2-M1), two EOG and single EMG channels recorded in this study we analysed only posterior channel O1-M2. EEG was sampled at 200 Hz and filtered 0.5-30 Hz before analysis to exclude possible 50 Hz line interference.

Variance and power spectrum of EEG (O1-M2) was calculated in 2 s time windows in epoch borders. Power spectrum was calculated either using single 200 point Hanning window discrete fourier transform (DFT) (Table 1) or using overlapped 100 point Hanning window DFT (Table 3). Ratios of variance, of theta (4-7 Hz) and of alpha (7-12 Hz) power were calculated. Ratios greater than one indicates increase of power across epoch border.

Time domain calculation of fractal dimension was done using Higuchi algorithm [8] in 2 s time window. With Higuchi algorithm mean length of curve L(k) is calculated in segments of k samples from original time series y(i) (1)

$$L_m(k) = \frac{(N-1)}{\mathrm{fix}((N-m)/k)*k^2} \sum \left| y(m+i*k) - y(m+(i-1)*k) \right| \tag{1}$$

Mean length L(k) is calculate using m=1, 2, …k in $L_m(k)$. With varying k=1, 2, …, kmax logarithmic values ln(1/k), ln(L(k)) can be plotted, and the slope of the fitted line indicates the time domain fractal dimension (FD).

The properties of fractal dimension were studied using simulated sine wave signal. In the first test the signals were pure sinusoids without noise. In the second test white noise was added to the signal. In all tests the fractal dimension was studied in 2 s sliding windows.

The effect of different values of kmax was studied with a selected EEG sample. The tested kmax values were 8 and 16 because they appeared most relevant to practical realisations of the method with the used window length.

3. Results

Tables 1 and 2 show the results of the linear and nonlinear analysis for all subjects with kmax=8 and 200 point DFT, (tables 1 and 2) and using kmax=16 and 100 point DFT (tables 3 and 4).

Table 1. Average power ratios and fractal dimensions, ratios for all 17 subject in Wake-S1 transitions and S1-Wake transitions. Using kmax=8 and 200 point DFT.

	Wake-S1 transition						S1-Wake transition					
Epochs	Power ratio	Theta ratio	Alpha ratio	FD1	FD2	FD2/FD1	Power ratio	Theta ratio	Alpha ratio	FD1	FD2	FD2/FD1
1	0.94	1.66	0.83	1.24	1.24	1.00	1.42	3.56	4.21	1.27	1.19	0.94
5	0.91	4.26	1.18	1.26	1.26	1.00	1.14	1.41	1.53	1.32	1.31	0.99
19	1.34	2.62	3.06	1.30	1.28	0.98	0.73	2.82	2.01	1.28	1.30	1.01
21	0.91	2.07	1.12	1.26	1.27	1.01	1.08	1.41	1.12	1.26	1.26	0.99
10	0.95	1.75	0.92	1.41	1.40	1.00	1.03	1.88	1.26	1.35	1.35	1.00
4	0.84	1.04	0.34	1.31	1.40	1.07	1.31	1.17	5.54	1.37	1.30	0.95
35	0.80	1.78	0.98	1.23	1.25	1.02	1.24	3.05	3.87	1.25	1.25	1.00
68	0.75	2.08	0.71	1.23	1.26	1.03	1.11	1.42	2.90	1.27	1.29	1.02
5	1.07	14.89	2.68	1.32	1.25	0.95	1.12	2.25	0.77	1.26	1.31	1.05
22	0.68	1.60	0.75	1.24	1.30	1.05	1.55	0.97	7.65	1.34	1.28	0.95
2	0.91	3.37	1.11	1.23	1.27	1.03	0.98	1.00	1.33	1.25	1.25	0.99
68	0.63	1.70	1.13	1.32	1.46	1.11	1.40	2.89	1.87	1.49	1.43	0.96
7	0.83	3.39	1.11	1.29	1.34	1.04	1.14	1.01	1.30	1.30	1.36	1.04
44	0.84	1.44	1.20	1.31	1.34	1.02	1.18	1.81	1.68	1.34	1.34	1.00
16	0.88	4.17	0.78	1.24	1.26	1.01	1.11	1.34	2.55	1.23	1.25	1.01
8	0.79	0.59	0.74	1.37	1.43	1.04	1.00	1.15	0.94	1.39	1.42	1.02
48	1.02	4.06	2.88	1.30	1.28	0.99	1.05	1.97	1.66	1.27	1.31	1.04

Table 2. Average power ratios and fractal dimensions, ratios with SD across all 17 subject in Wake-S1 transitions and S1-Wake transitions. Using kmax=8 and 200 point DFT.

	Wake-S1 transition						S1-Wake transition					
Epochs	Power ratio	Theta ratio	Alpha ratio	FD1	FD2	FD2/FD1	Power ratio	Theta ratio	Alpha ratio	FD1	FD2	FD2/FD1
393	0.86	2.42	1.33	1.28	1.32	1.03	1.25	2.01	2.50	1.33	1.32	1.00
SD	0.41	5.73	2.91	0.08	0.09	0.07	0.38	5.81	4.45	0.10	0.08	0.06

Table 3. Average power ratios and fractal dimensions, ratios for all 17 subject in Wake-S1 transitions and S1-Wake transitions. Using kmax=16 and 100 point DFT.

	Wake-S1 transition						S1-Wake transition					
Epochs	Power ratio	Theta ratio	Alpha ratio	FD1	FD2	FD2/FD1	Power ratio	Theta ratio	Alpha ratio	FD1	FD2	FD2/FD1
1	0.94	0.34	0.62	1.50	1.44	0.96	1.42	1.10	4.56	1.45	1.45	1.00
5	0.91	0.86	1.04	1.52	1.50	0.99	1.14	3.15	2.15	1.55	1.59	1.03
19	1.34	1.56	1.34	1.50	1.46	0.97	0.73	1.42	1.57	1.40	1.45	1.03
21	0.91	1.29	1.01	1.50	1.50	1.00	1.08	1.44	1.48	1.45	1.48	1.02
10	0.95	0.84	0.83	1.57	1.54	0.98	1.03	0.88	0.95	1.50	1.53	1.02
4	0.84	0.42	0.44	1.57	1.64	1.04	1.31	0.91	2.16	1.55	1.61	1.04
35	0.80	1.12	0.56	1.46	1.44	0.99	1.24	1.57	3.47	1.41	1.47	1.04
68	0.75	1.42	0.53	1.46	1.45	0.99	1.11	0.89	2.45	1.43	1.52	1.07
5	1.07	3.48	1.06	1.55	1.43	0.93	1.12	1.91	1.20	1.41	1.48	1.05
22	0.68	1.07	0.50	1.52	1.53	1.00	1.55	1.53	8.37	1.53	1.57	1.03
2	0.91	1.47	0.39	1.50	1.48	0.99	0.98	0.98	1.43	1.51	1.50	0.99
68	0.63	1.06	0.85	1.60	1.67	1.04	1.40	1.57	3.56	1.66	1.66	1.00
7	0.83	1.33	2.62	1.54	1.54	1.00	1.14	1.48	1.44	1.47	1.59	1.08
44	0.84	1.13	0.82	1.59	1.57	0.99	1.18	1.19	2.01	1.53	1.60	1.04
26	0.60	0.39	0.50	1.33	1.37	1.03	1.70	4.71	5.93	1.38	1.37	0.99
8	0.79	0.80	0.79	1.60	1.61	1.01	1.00	1.02	1.23	1.57	1.64	1.05
48	1.02	2.84	1.16	1.54	1.48	0.96	1.05	1.12	1.49	1.42	1.51	1.07

Table 4. Average power ratios and fractal dimensions, ratios with SD across all 17 subject in Wake-S1 transitions and S1-Wake transitions. Using kmax=16 and 100 point DFT.

	Wake-S1 transition						S1-Wake transition					
Epochs	Power ratio	Theta ratio	Alpha ratio	FD1	FD2	FD2/FD1	Power ratio	Theta ratio	Alpha ratio	FD1	FD2	FD2/FD1
393	0.86	1.36	0.82	1.52	1.52	1.00	1.25	1.53	2.96	1.49	1.54	1.04
SD	0.41	2.04	1.32	0.09	0.10	0.05	0.38	2.02	3.99	0.11	0.10	0.06

Figures 1 to 3 show the effect of additive noise in the calculation of the fractal dimension. In figure 1 no noise was added to the signal and in figures 2 and 3 the noise variance was 1 and 2, respectively. Figure 3 shows that the properties of the noise are more influential to the fractal dimension than the frequency of the underlying sine wave when the variance of the noise is high enough.

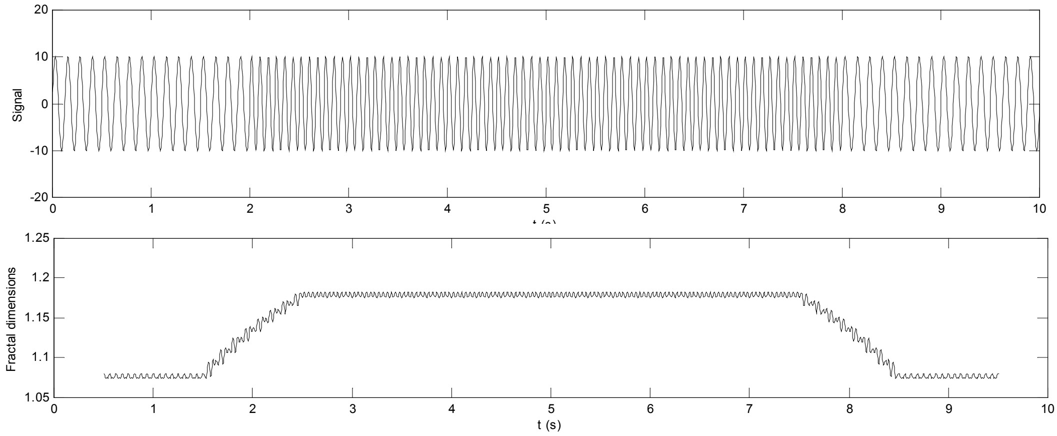

Fig 1. Example of 10 s time series with 2 s sliding window in fractal dimension calculation. The signal is a 8 Hz sine wave in beginning and end. In the middle there is a 6 s 12 Hz sine wave. In the lower part the time varying fractal dimension was calculated using kmax=8 and N=200.

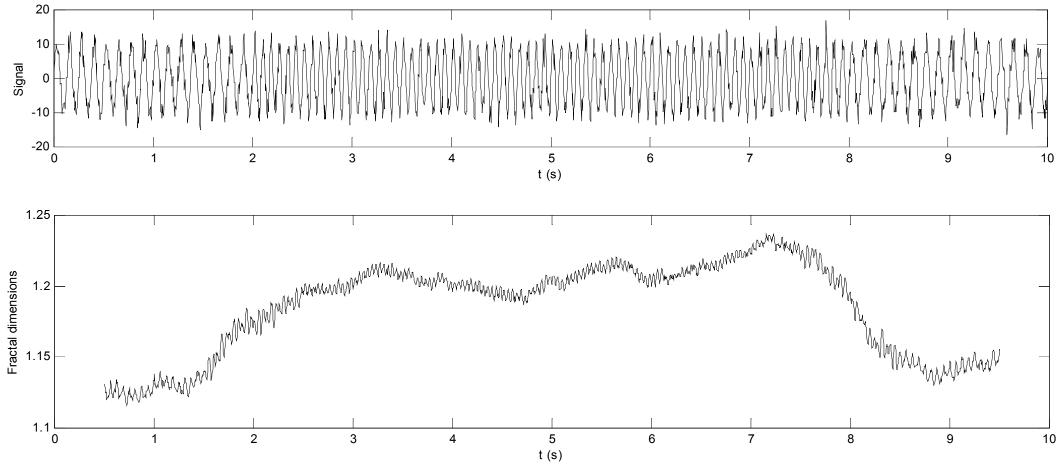

Fig 2. Example of 10 s time series with 2 s with 8 Hz sine wave in beginning and end. In middle 6 s 12 Hz sine wave, Noise with unit variance of 1 was added to time series. In lower part time varying fractal dimension was calculated using kmax=8 and N=200.

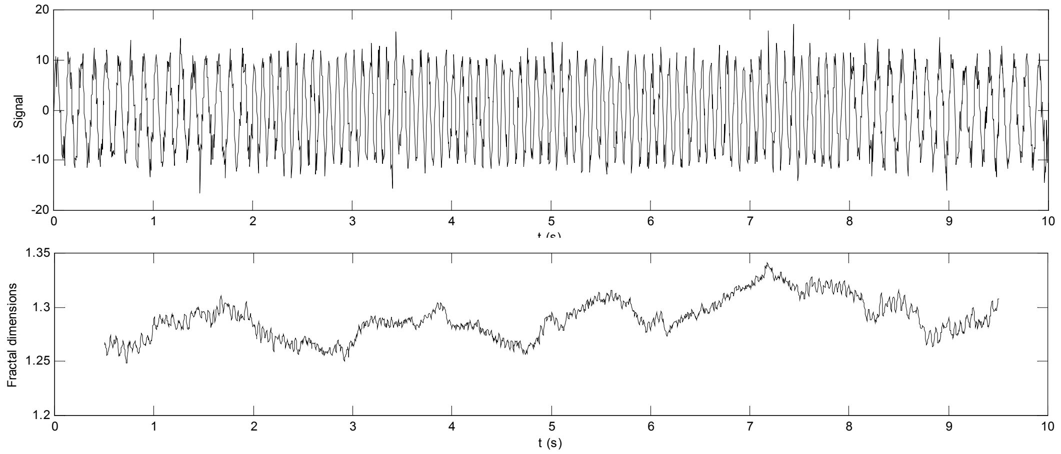

Fig 3. Example of 10 s time series with 2 s with 8 Hz sine wave in beginning and end. In middle 6 s 12 Hz sine wave, Noise with unit variance of 2 was added to time series. In the middle panel the time varying fractal dimension was calculated using kmax=8 and N=200.

Figure 4 shows the effect of kmax and N in fractal dimension calculation. The variation of the fractal dimension is higher when N is 200 than when it is 400.

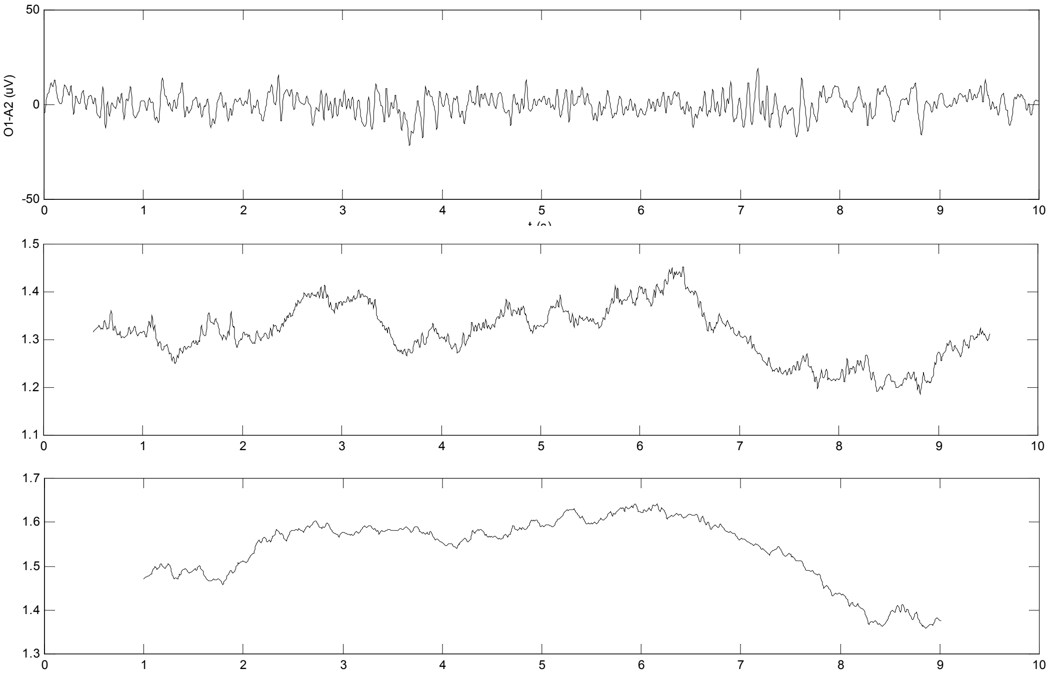

Fig 4. Example of 10 s EEG (O1-M2) and corresponding time varying fractal dimension using kmax=8 and N=200 and kmax=16 and N=400.

Finally, to test predictive value of each parameter receiver operating characteristic curves (ROC) were calculated. Area under curve (AUC) values were using kmax=8 and 200 point DFT: 0.82 for Power ratio, 0.72 for Alpha ratio and 0.63 for FD1 and 0.62 for FD2/FD1. Similarly using kmax=16 and 100 point DFT: 0.82 for Power ratio, 0.83 for Alpha ratio and 0.60 for FD1 and 0.69 for FD2/FD1.

4. Discussion and conclusions

Our results indicate that fractal dimension changes during sleep onset defined by visual adaptive scoring using adaptive epoch lengths. Changes are variable and effect of noise level and kmax is notable. Further studies are needed to choose optimal filtering and kmax. Fractal dimension alone is not able to detect the change from S0 wakefulness to S1 sleep or vice versa reliably. Combining fractal dimension changes to spectral parameters could increase the sensitivity of realtime detection of sleep onset.

References

[1] Ogilvie, RD: The process of falling asleep. Sleep Medicine Reviews, vol. 5, 2001, pp. 247-270.

[2] Santamaria, J and Chiappa KH: The EEG of drowsiness in normal adults. J Clin Neurophysiol, vol. 4, 1987, pp. 327-82.

[3] Rechtschaffen, A and Kales A: A Manual of Standardized Terminology, Techniques, and Scoring System for Sleep Stages of Human Subjects. US Department of Health, Education and Welfare, Public Health Service, 1968

[4] Hori, T, Hayashi M, and Morikawa T: Topographic EEG changes and the hypnagogic experience, in Sleep Onset: Normal and Abnormal Processes, Ogilvie R and Harsh J, Eds. American Psychological Association, 1994.

[5] Himanen, S-L: New Visual Adaptive Scoring System for Sleep Recordings : Development and Application to the Multiple Sleep Latency Test. Doctoral dissertation. Acta Universitatis Tamperensis, vol. 769, 2000, pp. 1-125.

[6] Hasan, J: Past and future of computer-assisted sleep analysis and drowsiness assessment. J Clin Neurophysiol, vol. 13, 1996, pp. 295-313.

[7] Goldberger, AL, Amaral LA, Hausdorff JM, Ivanov P, Peng CK, and Stanley HE: Fractal dynamics in physiology: alterations with disease and aging. Proc Natl Acad Sci U S A, vol. 99 Suppl 1, 2002, pp. 2466-72.

[8] Accardo, A, Affinito M, Carrozzi M, and Bouquet F: Use of the fractal dimension for the analysis of electroencephalographic time series. Biol Cybern, vol. 77, 1997, pp. 339-50.

[9] Klonowski, W, Olejarczyk E, and Stepien R: Complexicity of EEG-signal in Time Domain - Possible Biomedical Application. Experimental Chaos, 2001

[10] Pereda, E, Gamundi A, Nicolau MC, Rial R, and Gonzalez J: Interhemispheric differences in awake and sleep human EEG: a comparison between non-linear and spectral measures. Neurosci Lett, vol. 263, 1999, pp. 37-40.

[11] Doghramji, K, Mitler MM, Sangal RB, Shapiro C, Taylor S, Walsleben J, Belisle C, Erman MK, Hayduk R, Hosn R, O'Malley EB, Sangal JM, Schutte SL, and Youakim JM: A normative study of the maintenance of wakefulness test (MWT). Electroencephalogr Clin Neurophysiol, vol. 103, 1997, pp. 554-62.

[12] Virkkala, J, Velin R, Himanen S-L, Härmä M, Pihl S, and Müller K: Scoring Maintenance of Wakefulness Test with Adaptive Epoch Length. Sleep, Abstract Supplement, vol. 24, 2001, pp. A398.