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Sleep-EEG Analysis Using Higuchi's Fractal Dimension

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Abstract– We analyze sleep EEG-data using Higuchi's fractal dimension of the signal. We demonstrate that the method well differentiates between sleep stages, so it helps to construct hypnograms, while it does not differentiate between healthy subject and insomniacs.

1. Introduction

Insomnia and other sleep disorders are more and more serious medical problems of the civilized world today. Improvement of sleep disorders diagnostics requires better and quicker assessment of sleep dynamics through analysis of various biosignals, called *polysomnograms* when recorded together during sleep. The most important is analysis of all-night EEG-signals.

Biosignal record is a pattern called a *waveform* – a planar curve that proceeds only forward; in computer memory a waveform is represented by its values in discrete moments, i.e. by a *time series*.

Time series representing EEG-signals are *nonstationary*. A stationary time series is one whose statistical description is invariant with respect to time origin or time shifts. *Nonstationary time series* mean time series is one whose average value is not constant but exhibits abrupt discontinuities, trends or seasonalities; *nonstationary covariance time series* is one whose correlation or covariance structure changes with time [1].

Medicine may benefit from methods of time series analysis developed in Nonlinear Dynamics and Deterministic Chaos Theory, in particular from fractal and symbolic methods of analysis in time domain (cf. [2], [3]). As yet there is no consensus on the appropriate mathematical analysis of EEG-signals. Since a clinician must remain a necessary 'component' of diagnostic procedure he/she must understand the strength and the limitations of the computer-assisted assessment procedure. That is why, despite inherent nonlinearity and nonstationarity of EEG, applied methods must be sufficiently simple to be understandable for clinicians. It seems that fractal and symbolic methods may fulfill these demands of relative simplicity [4].

Fractal dimension of a waveform representing EEG-signal in time domain **should not be confused** with fractal dimension (e.g. pointwise correlation dimension) of an attractor eventually observed when EEG time series are embedded in so called *phase space* [5]. Fractal dimension is a measure of *signal complexity* and so the measure of complexity of the processes that generate the signal under consideration.

In the presented paper we consider sleep-EEG analysis based on *Higuchi's fractal dimension*, D_f ([6], [7]]). The method clearly shows quasi-periodicity of sleep - during the whole-night sleep each subject passes several (4-5) times through consecutive sleep stages (1, 2, 3, 4, and REM - Rapid Eye Movements); it helps to construct *hypnograms* i.e. diagrams: sleep stage *vs.* time.

2. Materials and Methods

Data for analysis were provided by the Department of Psychiatry, Medical University of Warsaw (Chair Prof. W.Szelenberger). Polysomnograms were collected using data acquisition system DigiTrack™ made in Poland by P.I.M. ELMIKO, Warsaw. EEG-signals in these polysomnograms were collected according to standard 10-20 system from 16 channels, filtered with a bandpass filter 0.5 – 70.0 Hz and sampled with 128 Hz.

EEG-signals were registered on 19 electrodes of 10-20 system. We calculated mean values and standard deviations of Higuchi's fractal dimension in wake and in different sleep stages for two groups of persons - 15 healthy persons and 15 patients with insomnia - using so called *Current Source Density* (CSD) signals, i.e. the signals measured relatively to the average local value (that are also the first approximation of the surface Laplacian). For further considerations we choose C3_CSD signal (Fig.1 and Table 1; cf. [8], [9]). Running fractal dimension was calculated using 4-second sliding window; for the parameter k_{max} of Higuchi's algorithm we choose value equal 8, since for sampling frequency 128 Hz the results practically do not depend on this parameter for $k_{max} > 8$.

3. Results

We performed several statistical tests using STATISTICA package [6]. Here we reproduce results of nonparametric Friedman's analysis of variance for CSD signals on nine electrodes - Chi Square and p-level in 2 groups (normal and insomniacs, Table 2), and in 6 stages (wake, stages 1, 2, 3, 4, and REM, Table 3). The differences of Higuchi's fractal dimension values between the groups of healthy persons and insomniacs (cf. Fig. 2) turned to be not statistically important - the null hypothesis that mean fractal dimension is equal for the two groups cannot be rejected in any tested case. On the other hand, the differences of Higuchi's fractal dimension values between 6 stages are statistically important, both in healthy persons and insomniacs, so this method is suitable for automatic construction of hypnograms, when using appropriately chosen intervals of mean fractal dimension for each stage. One of important advantages of Higuchi's algorithm is that the mean fractal dimension in different sleep stages is not very sensitive to artifacts [8].

The difference of mean Higuchi's fractal dimension are not statistically significant between healthy and insomniac groups in any given sleep stage. But for both groups we observe the same trend (cf. Fig. 2) - the value of fractal dimension is maximal for wake stage; it decreases when sleep becomes deeper; for REM stage it again increases, but remain lower than in wake stage. Such trend is noticed in each of CSD signals on nine electrodes that we analysed. Based on these observations, taking into account ranges of fractal dimension for different sleep stages as determined from sleep EEG and corresponding hypnograms made by clinicians specialized in sleep disorders, we may construct hypnograms automatically (cf. Fig. 3).

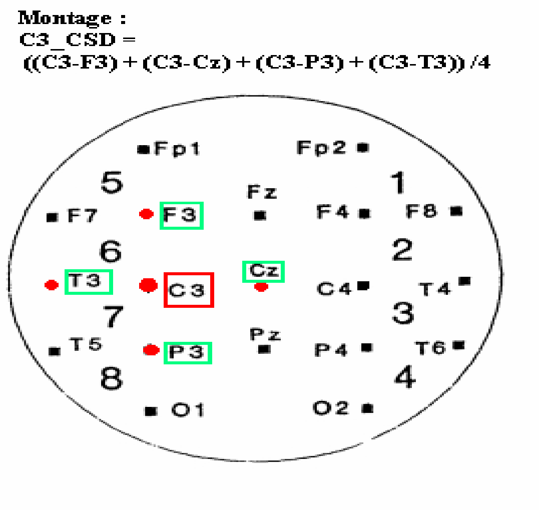


Fig. 1. 10/20 electrode placement system and calculation of Current Source Density signals

Table 1.
Mean fractal dimension and its standard deviation for each of nine electrodes in wake and in five sleep stages (stage 1, 2, 3, 4, and REM) calculated for two groups: 15 healthy persons and 15 persons suffering with insomnia

F3	**normal**		**insomnia**		**Fz**	**normal**		**insomnia**		**F4**	**normal**		**insomnia**	
	Mean	**Std.D.**	**Mean**	**Std.D**		**Mean**	**Std.D**	**Mean**	**Std.D**		**Mean**	**Std.D**	**Mean**	**Std.D**
wake	1.662	0.105	1.711	0.102		1.602	0.093	1.584	0.092		1.660	0.140	1.715	0.107
stage1	1.537	0.105	1.529	0.094		1.491	0.090	1.520	0.178		1.552	0.120	1.554	0.126
stage2	1.409	0.076	1.406	0.078		1.379	0.066	1.413	0.190		1.441	0.106	1.435	0.086
stage3	1.311	0.055	1.314	0.084		1.287	0.055	1.339	0.217		1.343	0.102	1.359	0.104
stage4	1.263	0.059	1.289	0.082		1.246	0.058	1.310	0.217		1.296	0.112	1.315	0.088
REM	1.502	0.111	1.489	0.082		1.481	0.103	1.486	0.175		1.542	0.143	1.505	0.076
C3	**normal**		**insomnia**		**Cz**	**normal**		**insomnia**		**C4**	**normal**		**insomnia**	
	Mean	**Std.D**	**Mean**	**Std.D**		**Mean**	**Std.D**	**Mean**	**Std.D**		**Mean**	**Std.D**	**Mean**	**Std.D**
wake	1.659	0.086	1.660	0.126		1.577	0.077	1.595	0.114		1.685	0.097	1.659	0.081
stage1	1.537	0.100	1.527	0.115		1.485	0.085	1.495	0.091		1.541	0.079	1.535	0.104
stage2	1.439	0.067	1.414	0.080		1.384	0.061	1.385	0.052		1.424	0.051	1.420	0.077
stage3	1.327	0.034	1.313	0.056		1.297	0.039	1.300	0.048		1.325	0.037	1.329	0.058
stage4	1.275	0.050	1.282	0.049		1.257	0.048	1.276	0.048		1.275	0.042	1.295	0.050
REM	1.513	0.086	1.483	0.088		1.441	0.096	1.446	0.086		1.521	0.079	1.490	0.087
P3	**normal**		**insomnia**		**Pz**	**normal**		**insomnia**		**P4**	**normal**		**insomnia**	
	Mean	**Std.D**	**Mean**	**Std.D**		**Mean**	**Std.D**	**Mean**	**Std.D**		**Mean**	**Std.D**	**Mean**	**Std.D**
wake	1.477	0.071	1.485	0.083		1.457	0.068	1.459	0.077		1.565	0.090	1.618	0.155
stage1	1.483	0.080	1.500	0.093		1.456	0.070	1.477	0.092		1.494	0.077	1.520	0.100
stage2	1.426	0.056	1.428	0.065		1.399	0.051	1.405	0.064		1.433	0.076	1.435	0.075
stage3	1.327	0.040	1.345	0.064		1.313	0.043	1.325	0.049		1.343	0.070	1.358	0.070
stage4	1.277	0.051	1.317	0.059		1.264	0.053	1.297	0.045		1.302	0.075	1.335	0.076
REM	1.477	0.071	1.485	0.083		1.457	0.068	1.459	0.077		1.500	0.089	1.499	0.089

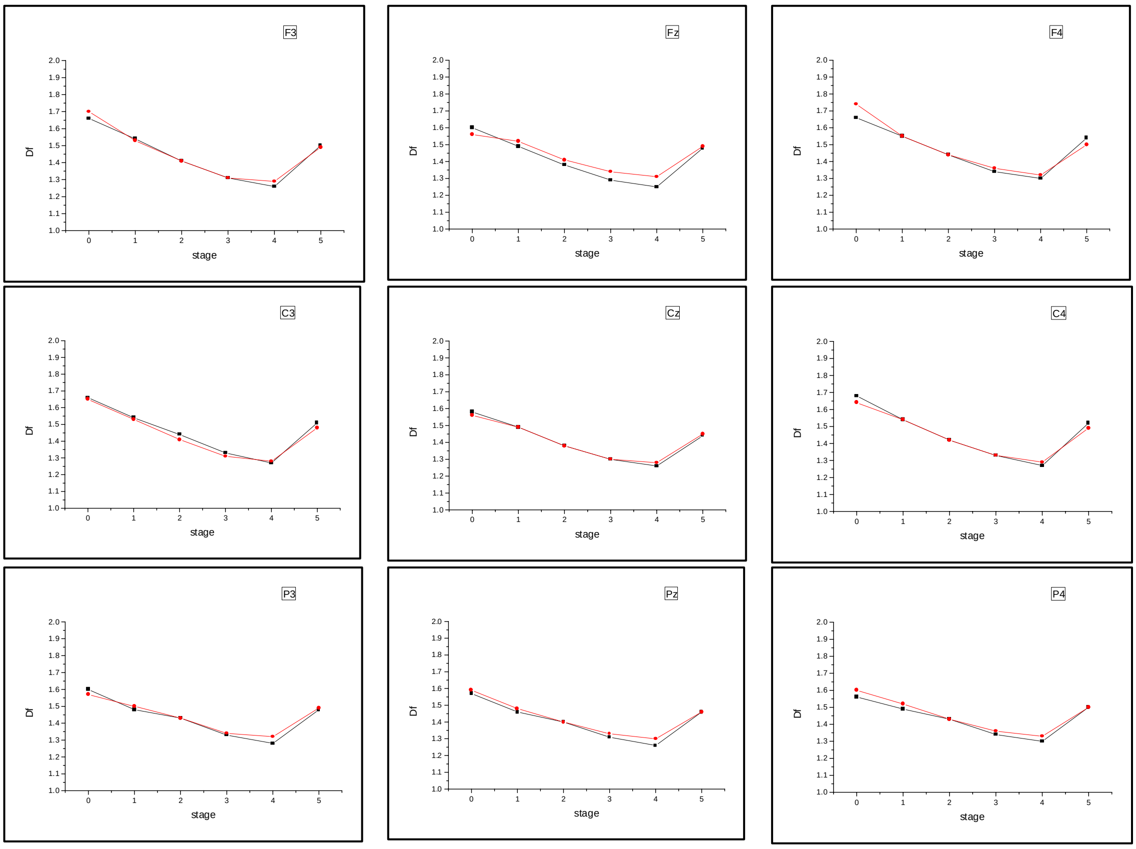
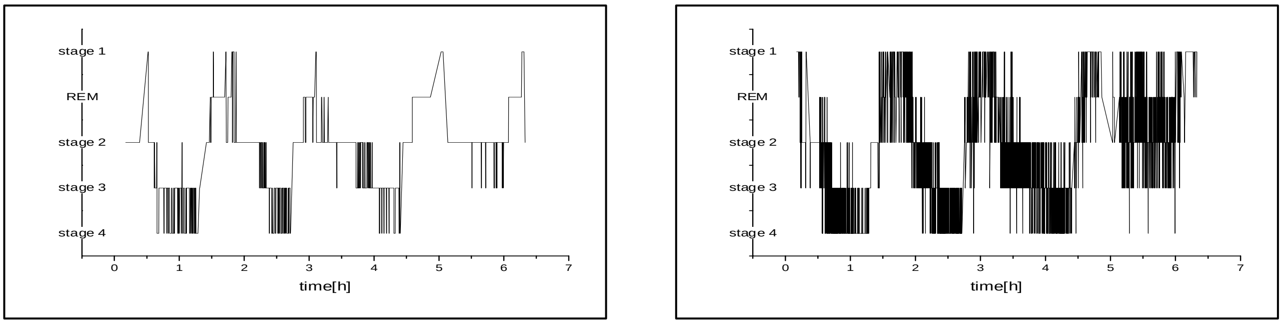


Fig. 2. Mean fractal dimension of CDS signals for different sleep stages (stage = 0 for wake; stage = 5 for REM) in a group of 15 healthy persons (squares) and a group of 15 persons with insomnia (circles) calculated on 9 electrodes of 10/20 system (the same arrangement as shown in Fig. 1. and in Table 1.)



a. **b.**

Fig. 3. Example of a hypnogram constructed automatically using Higuchi's fractal dimension method.
a. Hypnogram made 'by hand' by a doctor while using 20-second window, based on the whole polysomnogram;
b. Automatic hypnogram for the same sleep constructed based on fractal dimension of EEG-signal (C3_CSD).

4. Conclusions

We demonstrated that each sleep stage can be characterized by a certain range of Higuchi's fractal dimension of EEG signals; based on this principle we have made a sleep stager software that automatically (in only ca. 3 min. on a PC with Pentium 2 GHz) constructs a hypnogram based on the whole-night sleep EEG-signal. One should not forget that a medical hypnogram, done by a specially trained clinician, is based not just on one-channel EEG-signal but on the whole original polysomnogram that contains multi-channel EEG, ECG, EOG, and others biosignals; even despite of that, the accuracy of medical hypnograms is believed to be of the order of about 70%.

In general, application of methods borrowed from Nonlinear Dynamics and from Symbolic Dynamics to EEG-signal analysis, aimed at more efficient and more user-friendly computer-assisted diagnosis of sleep disorders, seems really very promising.

Table 2.
Friedman ANOVA for 9 electrodes, 6 stages (df=(6-1)) in 2 groups – healthy persons and insomniacs

	healthy Chi Sqr. (N=15, df=5)	p	insomnia Chi Sqr. (N=15, df=5)	p
F3	68.238	0.000	63.953	0.000
Fz	71.291	0.000	47.484	0.000
F4	68.371	0.000	59.315	0.000
C3	68.757	0.000	63.238	0.000
Cz	68.263	0.000	61.578	0.000
C4	70.019	0.000	63.061	0.000
P3	68.111	0.000	61.478	0.000
Pz	69.395	0.000	63.937	0.000
P4	61.609	0.000	49.333	0.000

Table 3.
Friedman ANOVA for 9 electrodes, 2 groups (df=(2-1)) in 6 stages - wake, sleep stages 1, 2, 3,4, and REM

	wake Chi Sqr. (N=15, df=1)	p	stage 1 Chi Sqr. (N=15, df=1)	p	stage 2 Chi Sqr. (N=15, df=1)	p
F3	1.143	0.285	0.286	0.593	0.286	0.593
Fz	1.143	0.285	0.067	0.796	0.067	0.796
F4	4.571	0.033	1.667	0.197	1.143	0.285
C3	0.286	0.593	0.067	0.796	0.067	0.796
Cz	1.143	0.285	0.077	0.782	0.286	0.593
C4	2.571	0.109	0.600	0.439	1.667	0.197
P3	0.000	1.000	0.600	0.439	0.600	0.439
Pz	0.286	0.593	1.143	0.285	0.286	0.593
P4	0.286	0.593	0.000	1.000	0.067	0.796

	stage 3 Chi Sqr. (N=15, df=1)	p	stage 4 Chi Sqr. (N=15, df=1)	p	REM Chi Sqr. (N=15, df=1)	p
F3	0.600	0.439	0.067	0.796	0.067	0.796
Fz	0.286	0.593	0.000	1.000	0.067	0.796
F4	0.067	0.796	1.667	0.197	1.143	0.285
C3	1.923	0.166	0.067	0.796	0.067	0.796
Cz	0.692	0.405	1.667	0.197	0.067	0.796
C4	0.000	1.000	0.600	0.439	0.600	0.439
P3	1.143	0.285	1.143	0.285	0.600	0.439
Pz	0.600	0.439	1.923	0.166	0.600	0.439
P4	0.067	0.796	0.286	0.593	0.077	0.782

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References

[1] G.Kitagawa, W.Gersch, “Smoothness Priors Analysis of Time Series”, Lecture Notes in Statistics 116, Springer, NY, Berlin, Heidelberg, 1996.

[2] W.Klonowski, E.Olejarczyk, R.Stepien, and W.Szelenberger, “Complexity of Polysomnogram Signals” *WSEAS Transactions on Computers*, vol. 3(5), pp. 1290-1294, 2004,

[3] S.N.Sarbadhikari, and K.Chakrabarty, “Chaos in the brain: a short review alluding to epilepsy, depression, exercise and lateralization”, *Med.Eng. & Phys.* vol. 23, pp. 445-455., 2001.

[4] N.Wessel, U.Schwarz, P.J.Saparin, and J.Kurths, “Symbolic Dynamics for Medical Data Analysis”, in: *Attractors, Signals, and Synergetics*, W.Klonowski (Ed.), Proceedings of EUROATTRACTOR2000, Frontiers on Nonlinear Dynamics vol. 1, Pabst Science Publishers, Lengerich, Berlin, pp. 45-61, 2002.

[5] H.Preissl, W.Lutzenberger, F.Pulvermueller, and N.Birbaumer, “Fractal dimensions of short EEG time series in humans”, *Neuroscience Letters*, vol. 225, pp. 77-80, 1997,

[6] T.Higuchi, “Approach to an irregular time series on the basis of the fractal theory”, *Physica D*, vol. 31, pp. 277-283, 1988,

[7] A.Accardo, M.Affinito, M.Carrozzi, and F.Bouquet, “Use of the fractal dimension for the analysis of electroencephalographic time series”, *Biol.Cybern.* vol. 77, pp. 339-350, 1997

[8] E.Olejarczyk, “Analysis of EEG signals using fractal dimension”, PhD Thesis, Supervisor W.Klonowski, Institute of Biocybernetics and Biomedical Engineering, Polish Academy of Sciences, Warsaw, 2003.

[9] W.Klonowski, E.Olejarczyk, and R.Stepien, “Chaocity and Dimensional Complexity of EEG-Signal”, in: *Proceedings of 2001 International Symposium on Nonlinear Theory and its Applications (NOLTA 2001)*, Miyagi, Japan, pp. 399-402, 2001.