Summary Processing of Radiophysical Complex MRTHR Signals
Multifractal Analisys of the Brain Microwave Radiation and Heart Rate Variability

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Abstract: The principles of processing signals of Radiophysical complex MRTHR for studying the role of autonomic regulation in the formation of the brain microwave radiation during the treatment process are presented. The feature of this complex is the possibility of registration and analysing the non-stationary short-term time series of the brain microwave radiation and heart rate variability signals. The processing is implemented via the method of multifractal cross-correlation analysis. The results of the fluctuation and cross-correlation Hurst exponent estimations of these signals are shown. The estimates for a group of relatively healthy patients have low levels of systemic discrepancy. For the patients group with ischemic stroke before treatment the systematic discrepancy of estimations are significantly larger than those of healthy patients. After rehabilitation course, the discrepancy between these estimates are reduced.

1 INTRODUCTION

Human brain is among the most complex biological system. Several interconnected systems take part in organization of the human brain functioning: neural networks, glia, cerebral velum, system of cerebrospinal fluid circulation, and the blood circulation system. Each of these systems are complex multiparametric biophysical structure with cross-interconnections. Is a between all mentioned systems the blood circulation system takes special place. This system is controlled by neurogenic, humoral, metabolic, and myogenic regulatory loops (Moskalenko, 1992).

Human brain functioning, behaviour and it's cognitive activity have abundance of features. The number of methods for diagnosis and identification of the information patterns formed by the various regulatory systems of the organism is also inexhaustible.

In present article, the brain microwave radiation is the object of the study. From the physical point of view, the brain emits radiation caused by the Brownian motion of micro-charges and microscopic currents (Rytov et al., 1989). In 80's of the last century, academician Y.V. Gulyaev and E.E. Godik formulated the hypothesis of parametric modulation of own physical fields of human by biochemical and biophysical processes in the organism (Godik and Gulyaev, 1991). The results of our experimental studies of the fluctuations of the brain microwave radiation confirm correctness of this hypothesis (Syskov et al., 2012; Kublanov, 2013). In these studies, the statistical methods and information analysis were applied.

One might ask: why obtaining knowledge about role of the autonomic regulation in the brain microwave radiation formation is important and relevant problem? Firstly, it is explained by the fact that suprasegmental departments of the autonomic nervous system (ANS) are involved in the regulation of the cerebral blood flow and cognitive processes (Guyton and Hall, 2011).

However, given the complexity of the regulatory systems that form studied biomedical signals, results obtained via statistical methods and information analysis do not completely and objectively reflect characteristics of these dynamic and autonomic processes.

Moreover, it is well known that biological systems are capable for self-organization. Self-organization is the process of spontaneous formation and development of complex regular structures. This does not contradict the thermodynamics laws as all living

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biological systems are not reserved and exchange energy with environment. Therefore, it is perspective to use methods of nonlinear analysis (Haken, 1996; Başar and Güntekin, 2007).

The subjects of analysis in this article are biomedical signals recorded by the Radiophysical complex MRTHR. This complex allows one to simultaneously record time series of the microwave radiation in the left and right parietal areas of the brain, and the electrocardiogram of the first limb lead. The heart rate variability (HRV) signals are consequently derived from electrocardiogram time series. The complex consist of the dual-channel microwave radiometer MRT-40, which is used for registration of the brightness temperature of deep structures of the brain, and the electrocardiogram recorder (Kublanov, 2013).

In (Ushakov and Bogomolov, 2014) it was shown that to improve the quality of identification of physiological patterns of biomedical signals, one must use appropriate mathematical methods for condition diagnosis. These methods include the diagnosis of conditions that describe the characteristics of the series methodology of diagnosis the risk of violating the state, methodology for synthesis of the integrated indicators and indexes of status.

Various biomedical signals reflect different physiological processes. As the connection between the ANS and formation of the brain microwave radiation is evident one might find their correlation in similar time windows of corresponding biomedical signals. We propose to use methods of multifractal formalism for evaluation of the information characteristics for signals of the brain microwave radiation and the HRV. Simultaneous registration and analysis of these signals give new opportunities that allow one to define a new integral indicator for the study of functional changes in the brain. This information can be obtained when the brain studies is in a state of preclinical and clinical practice in the early stages of development of these changes.

In (Kublanov et al., 2015), results were presented for simultaneous analysis of signals the brain microwave radiation and HRV time series (TS). These results indicate the relationship between multifractal parameters for group of healthy subjects. The changes of brain microwave radiation fluctuation with periods 20–40 seconds are connected with the changes of HRV in the time-scale boundaries 6.5–25 seconds. In addition, the fluctuations of the brain microwave radiation with periods 50–70 seconds are related with the changes of HRV in the boundaries of 25–300 seconds.

The aim of this paper is to apply the multifractal formalism for evaluation of autonomic regulation role in the brain microwave radiation formation during treatment process.

2 MATERIALS AND METODS

To evaluate the role of autonomic regulation the brain microwave radiation formation, we use the multifractal formalism estimations. These estimations are based on the multifractal detrended fluctuation analysis MFDFA (Kantelhardt, 2011).

To acquire summary estimation of the microwave radiation of human signals, which indicate the ANS variability, one must transform the original biomedical signals to equidistant TS with the same sampling frequency.

2.1 Multifractal Detrended Fluctuation Analysis

After interpolation, the investigated TS are divided into integer number of non-overlapping segments of equal length *s.* Argument s is related to the selected time windows (*i.e.,* time scale boundaries) for detecting biomedical signals fluctuations and defined as the uniform logarithmic apportionment between time windows boundary points.

Then we do the detrending procedure (Peng et al., 1995). The detrending starts with finding the function with the most suitable polynomial trend for each segment *v* from the TS. After that, the variations are calculated

$$F_x^2(s,v) = \frac{1}{s}\sum_{k=1}^{s}[x(k) - x_v(k)].^2 \quad (1)$$

The variations set for all segments can be characterized by the fluctuation function with the degree *q* in range *q*=[-5,5]. For nonzero values, the fluctuation function is defined by the equation (Ihlen, 2013)

$$F_{\mathrm{x}}(q,s) = \{\frac{1}{\mathrm{N_s}}\sum_{\mathrm{v}=1}^{Ns}[F_{\mathrm{x}}^2(s,v)]^{\mathrm{q}/2}\}^{1/\mathrm{q}}. \quad (2)$$

For *q*=0, we solve the following equation:

$$F_x(0,s) = \frac{1}{2N_s}\sum_{v=1}^{Ns} ln[F_x^2(s,v)]. \quad (3)$$

The fluctuation function for self-similar TS depends on the window width *s* as degree (Mandelbrot, 2002)

$$F_{x(q,s)} \approx s^{H_x(q)}. \quad (4)$$

The exponent degree in equation (4) is called the generalized Hurst exponent (GHE) and calculated from the slope of fluctuation function against s in logarithmic coordinates.

For monofractal signals, the GHE does not depend on q. For multifractal signals, positive q denotes behavior of large fluctuations; negative q denotes behavior of small fluctuations.

In general case, a multifractal set is characterized by the scaling exponent $s(q)$. The function $\tau(q)$ shows how heterogeneous the selected set is. The GHE is connected with scaling exponent $\tau(q)$ as follows:

$$\tau(q) = q * H_x(q) - 1. \quad (5)$$

The multifractal spectrum width is determined by the spectral distribution function D using Legendre transformation as probability distribution of q (Kantelhardt, 2011).

$$D(\alpha) = q * \alpha - \tau\,, \quad (6)$$

where $\alpha = \frac{d\tau}{dq}$ is the Hölder exponent.

The quantitative measure of the MFDFA is the Hurst exponent $h = \alpha|_{q=2}$ (Ihlen, 2013).

2.2 Multifractal Cross-Correlation Analysis

For investigation of cross-correlation between two TS, the one can use method of the Multifractal cross-correlation Analysis (MFCCA) (Podobnik and Stanley, 2008). The cross-correlation function are defined as followed:

$$F_{xy}^2(s,v) = \frac{1}{s}\sum_{k=1}^{s} [x(k) - x_v(k)] * * [y(k) - y_v(k)] \quad (7)$$

$$F_{xy}(q,s) = \{\frac{1}{N_s}\sum_{v=1}^{Ns}[F_{xy}^2(s,v)]^{q/2}\}^{1/q} \approx \approx s^{H_{xy}(q)} \quad (8)$$

$$F_{xy}(0,s) = \frac{1}{N_s}\sum_{v=1}^{Ns}\ln\left[F_{xy}^2(s,v)\right] \approx \approx s^{H_{xy}((q=0)} \quad (9)$$

After that, the Legandre transform is used similar to equations (5), (6). Finally, the cross-correlation Hurst exponent is estimated $h_{xy} = \alpha_{xy}|_{q=2}$. The exponent is used to detect long-term cross-correlation between two different signals (Krištoufek, 2011).

Usually, the values of the cross-correlation Hurst exponent are in range [0; 1.5]. The h=0.5 is a critical value, as it indicates that two investigated TS are not correlated or that TS are independent on a low scales. For h>0.5, two TS have cross-persistence. It is believed that increments of cross-persistent TS have a trend to keep fluctuation changes w.r.t. each other. For h<0.5, two TS have cross-anti persistence. Cross-anti persistent TS have a tendency for multidirectional trends in specific time window (Zhou, 2008).

2.3 Program of Research

The collective analysis of the HRV and brain microwave radiation signals was performed based on investigations that were conducted in the Sverdlovsk Clinical Hospital of Mental Diseases for Military Veterans (Yekaterinburg, Russian Federation).

The investigations were conducted on the following groups of patients: the first group was 20 neurologically healthy patients volunteers aging 18-20 years, the second group was 14 patients suffering from ischemic stroke (prior to the treatment), the third group was 7 patients from the second group after treatment processes, for whom the improvement was clinically proved.

The record of biomedical signals was obtained with the modernized Radiophysical complex MRTHR in two functional states of the patients: functional peace (F) and orthostatic load (O). Length of the signals in each states is approximately 300 seconds. The record of the brain microwave radiation (BMR) signals was performed simultaneously in the left and right parietal hemisphere of the human brain. At the same time, the HRV signals were registered.

3 DATA ANALYSIS AND DISCUSSIONS

The described method can be generalized for detection of long-term multifractal cross-correlation between two different biomedical signals recorded simultaneously. The HRV signals are not equidistant compared to signal of the brain microwave radiation. So, it is advised to use cubic spline interpolation prior to the HRV signals investigation (De Boor, 1978; Kukushkin et al., 2010). For summary multifractal estimate, evaluation of the HRV and the brain microwave radiation signals, the interpolation was implemented with the same sampling frequency equal to 10 Hz.

The following time windows were used to investigate the multifractal properties of short-term biomedical signals: 1–10, 10–20, 20–30, 30–40, 40–

50, 50–60, 60–70, 70–80, 80–90 and 90–100 seconds. The lower boundary of time windows is limited by interpolation noise (below one second). The upper boundary is defined by the N/3 ratio, where N is the length of TS (Kantelhardt, 2011).

3.1 Stages of Multifractal Analysis for Recorded Biomedical Signals

Here, we present stages of the MFDFA and MFCCA methods application to the HRV and the brain microwave radiation signals investigation for one patient volunteer from the first patient group in the functional state F.

Fig. 1 presents plots of the Hölder exponent: $\alpha_x(q)$ for the HRV signal, $\alpha_y(q)$ for the brain microwave radiation signal, $\alpha_{xy}(q)$ for the collective analysis of two signals, respectively.

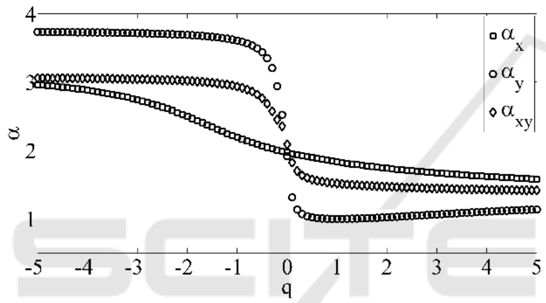

Figure 1: The Hölder exponent plots.

In Fig. 2 we present plots of scaling exponents: $\tau_x(q)$ – for the HRV signal, $\tau_y(q)$ – for the brain microwave radiation signal, $\tau_{xy}(q)$ – for the collective analysis of two signals, respectively.

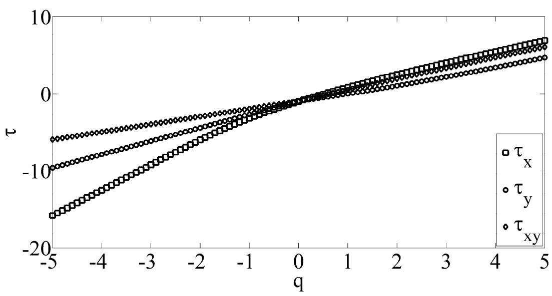

Figure 2: The scaling exponent plots.

Fig. 3 presents plots of the spectral distribution functions: $D_x(\alpha)$ for the HRV signal, $D_y(\alpha)$ for the brain microwave radiation signal, $D_{xy}(\alpha)$ for the collective analysis of two signals, respectively.

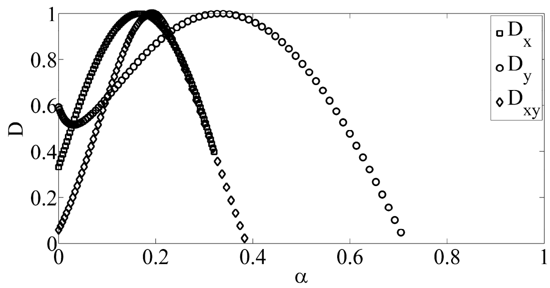

Figure 3: The multifractal spectrum plots.

3.2 Application of the Bland-Altman Criterion

Diagnostic possibility of the obtained multifractal features of selected biomedical time windows for two functional states was determined by the Bland-Altman criterion. Firstly, the systematic discrepancy is counted as difference of each for each pair of exponents $h_F^{signal} - h_O^{signal}$. After that, the mean value <Δ> and standard deviation σ for the differences are obtained. The standard deviation characterizes the scatter degree of results (Bland and Altman, 1986).

The final estimates of modulus of systematic discrepancy of the Hurst exponents obtained by the MFDFA and MFCCA for each time window for three group of patients are presented in the tables below. Here, the estimates are shown in bold type that have:

- low level of systematic discrepancy between two functional states for patients of the first group;
- high level of systematic discrepancy between two functional states for patients of the second group;
- reduction of this level for patients of the third group.

3.3 Multifractal Fluctuation Analysis of the Heart Rate Variability and Brain Microwave Radiation Signals

The estimates of modulus of systematic discrepancy obtained via the Bland-Altman criterion for difference of Hurst exponent $h_F^{HRV} - h_O^{HRV}$ and calculated for the HRV signals are shown in Table 1.

According to presented data, for patients in the first group there are time windows with the minimal systematic discrepancy: 20–40 and 50–70 seconds. We noted that the standard deviation σ of results for the first group of patients is relatively low, compared to the standard deviation σ of results for the second and third groups.

It is known, that fluctuations of very low frequency component VLF of HRV signal with periods in range 25–300 seconds is complex and have either two or three independent components (Fleishman, 2005). The obtained results are consistent with these ideas. Therefore, it is advisable to compute summary analysis of the HRV and brain microwave radiation signals not in all time windows, but in those, which have minimal value of systematic discrepancy.

Table 1: Mean and standard deviation of systematic discrepancy of Hurst exponent of HRV signals.

Time windows, seconds	$h_F^{HRV} - h_O^{HRV}$					
	First group		**Second group**		**Third group**	
	<Δ>	σ	<Δ>	σ	<Δ>	σ
1-10	0.01	0.10	0.04	0.11	0.11	0.28
10-20	0.02	0.07	0.05	0.34	0.07	0.48
20-30	**0.01**	**0.05**	**0.11**	**0.13**	**0.02**	**0.11**
30-40	**0.01**	**0.18**	**0.13**	**0.21**	**0.08**	**0.15**
40-50	0.03	0.10	0.19	0.52	0.16	0.25
50-60	**0.03**	**0.29**	**0.21**	**0.44**	**0.01**	**0.30**
60-70	**0.01**	**0.41**	**0.14**	**0.97**	**0.02**	**0.52**
70-80	0.23	0.67	0.39	0.49	0.02	0.82
80-90	0.02	0.40	0.17	0.85	0.27	0.61
90-100	0.12	0.64	0.39	1.05	0.19	1.41

In Table 2, we present modulus of the estimates of systematic discrepancy obtained via the Bland-Altman criterion for difference of the Hurst exponent $h_F^{BMR} - h_O^{BMR}$calculated for signals of the right channel of the microwave radiothermograph MRT-40 of modernized Radiophysical complex MRTHR.

Table 2: Mean and standard deviation of systematic diffeerence of Hurst exponent of the brain microwave radiation signals.

Time windows, seconds	$h_F^{BMR} - h_O^{BMR}$					
	First group		**Second group**		**Third group**	
	<Δ>	σ	<Δ>	σ	<Δ>	σ
1-10	0.05	0.07	0.03	0.21	0.01	0.04
10-20	0.03	0.21	0.03	0.17	0.05	0.10
20-30	**0.01**	**0.17**	**0.13**	**0.24**	**0.12**	**0.13**
30-40	**0.01**	**0.23**	**0.11**	**0.55**	**0.05**	**0.11**
40-50	0.08	0.24	0.14	0.45	0.20	0.38
50-60	**0.02**	**0.38**	**0.28**	**0.37**	**0.05**	**0.32**
60-70	**0.03**	**0.45**	**0.30**	**0.73**	**0.16**	**0.38**
70-80	0.25	0.78	0.45	0.87	0.19	0.61
80-90	0.09	0.69	0.76	1.53	0.47	0.67
90-100	0.25	1.33	0.10	0.35	0.75	1.65

For signals of the right channel of the microwave radiothermograph MRT-40, the mean values <Δ> and standard deviations σ of differences in time windows 20–40 and 50–70 seconds for patients in second group are higher than those of patients in first group. For patients in the third group, there is a tendency of reduction of the mean values <Δ> and standard deviations σ. The signals of the left channel of the microwave radiothermograph MRT-40 have the same properties.

In (Borisov and Kublanov, 2015), it was shown that the lowest discrepancy of the Hurst exponent h estimations between signals of the right and left channel of the microwave radiothermograph MRT-40 in functional states F and O for group of relatively healthy patients is observed for time windows 10–40 and 60–70 seconds. For that time windows, signals have anti-persistent properties. Fluctuations of the signal with periods more than 70 seconds have blended multifractal properties.

In present study, results of estimates of discrepancy of the Hurst exponent h obtained for groups with different nosological status do not contradict to previous results.

In addition, these results are adequate to earlier investigation of the nature of the brain microwave radiation in frequency band from 650 to 850 MHz (Kublanov et al., 2010). In that work, it was shown that fluctuations of radiation corresponds to different physical mechanisms

- fluctuations with periods from 6.5 to 40 seconds reflect dynamics of liquid transport in the intracellular and intercellular spaces of human brain tissues;
- fluctuations with periods higher than 40 seconds mostly reflect the thermodynamic changes in human brain tissues.

3.4 Summary Estimation of the Heart Rate Variability and Brain Microwave Radiation Signals

In this section, we present results of collective analysis of the HRV signals and fluctuations of the brain microwave radiation obtained via the Multifractal cross-correlation analysis.

The estimates of modulus of systematic discrepancy obtained via the Bland-Altman criterion for difference of the cross-correlation Hurst exponent $h_{xyF}^{HRV-BMR} - h_{xyO}^{HRV-BMR}$ and calculated for the HRV and brain microwave radiation signals between two functional states are shown in Table 3.

According to the data presented in Table 3, the estimates of differences of the cross-correlation Hurst exponent in time windows 20–40 and 50–70 seconds for patients in the first group have low level of systematic discrepancy.

Table 3: Mean and standard deviation of systematic discrepancy of the cross-correlation Hurst exponent of the HRV and brain microwave radiation signals.

Time windows, seconds	$\boldsymbol{h}_{xyF}^{HRV-BMR} - \boldsymbol{h}_{xyO}^{HRV-BMR}$					
	First group		**Second group**		**Third group**	
	<Δ>	σ	<Δ>	σ	<Δ>	σ
1-10	0.04	0.06	0.04	0.18	0.07	0.19
10-20	0.05	0.25	0.03	0.14	0.08	0.25
20-30	**0.01**	**0.15**	**0.10**	**0.34**	**0.03**	**0.31**
30-40	**0.01**	**0.13**	**0.05**	**0.34**	**0.05**	**0.51**
40-50	0.15	0.53	0.12	0.67	0.85	1.07
50-60	**0.05**	**0.18**	**0.30**	**1.36**	**0.20**	**0.73**
60-70	**0.01**	**0.32**	**0.10**	**1.54**	**0.05**	**0.83**
70-80	0.12	1.92	1.22	3.19	1.00	2.11
80-90	0.32	1.69	1.46	3.18	0.55	2.52
90-100	0.17	3.82	1.05	1.81	0.01	1.71

In Table 4, we present modulus of the estimates of systematic discrepancy obtained via the Bland-Altman criterion for difference of the cross-correlation Hurst exponent $\boldsymbol{h}_{xyF}^{RC-LC} - \boldsymbol{h}_{xyO}^{RC-LC}$ and calculated for signals of the right channel (RC) and left channel (LC) of the microwave radiothermograph MRT-40 of Radiophysical complex MRTHR.

Table 4: Mean and standard deviation of systematic discrepancy of cross-correlation Hurst exponent of right and left channels of the microwave radiothermograph MRT-40.

Time windows, seconds	$\boldsymbol{h}_{xyF}^{RC-LC} - \boldsymbol{h}_{xyO}^{RC-LC}$					
	First group		**Second group**		**Third group**	
	<Δ>	σ	<Δ>	σ	<Δ>	σ
1-10	0.03	0.09	0.04	0.15	0.01	0.04
10-20	0,11	0.25	0.04	0.25	0.12	0.15
20-30	**0.02**	**0.15**	**0.15**	**0.25**	**0.03**	**0.15**
30-40	**0.02**	**0.13**	**0.18**	**0.36**	**0.06**	**0.28**
40-50	0.32	1.11	0.35	0.56	0.19	0.81
50-60	**0.02**	**0.20**	**0.55**	**0.65**	**0.13**	**0.93**
60-70	0.28	1.57	0.38	1.34	0.62	2.22
70-80	0.07	3.12	0.43	1.54	1.12	2.09
80-90	0.18	2.24	0.36	1.50	0.22	1.11
90-100	0.58	4.42	0.04	2.07	0.14	2.70

Data presented in Table 4 show that estimates of difference of the cross-correlation Hurst exponent of simultaneously recorded right and left channels of the microwave radiothermograph MRT-40 have low level of systematic discrepancy in time windows 20–40 and 50–60 seconds for patients in the first group.

For patients in the second group, the estimates of difference of the cross-correlation Hurst exponent in mentioned time windows have higher values compared to estimates in the first group. The estimates of difference in time windows 20–40 and 50–60 seconds for patients in the third group have lower values compared to those in the second group. These results can be interpreted as the assessment of the treatment process efficiency for patients with clinically proved improvement.

It is worthy to note that the minimal level of systematic discrepancy between signals of the HRV and brain microwave radiation characterizes the similarity of dynamic changes in these signals. In this case, one can conclude that role of the autonomic regulation defined by the parameters of HRV signal in the formation of the brain microwave radiation is high.

4 CONCLUSIONS

The usage of methods of the multifractal fluctuation and cross-correlation analysis in processing of the short-term signals of the HRV and brain microwave radiation allowed one to obtain new knowledge about the studied biomedical signals.

It was found, that for the time windows 20–40 and 50–60 seconds in the functional rest and during the passive orthostatic load, the systematic discrepancy between the differences of the Hurst exponent of biomedical signals is minimal for the group of healthy patients. For patients suffering from ischemic stroke prior to the rehabilitation treatment, these values are greater. The systematic discrepancy between the difference of the Hurst exponent of biomedical signals decreases for patients from this group after rehabilitation treatment, for whom the improvement was clinically proved.

Application of the multifractal formalism demonstrated that the minimal level of systematic discrepancy of the HRV signals and brain microwave radiation characterize the similarity of dynamic changes of these signals. This, in turn, points the high role of the autonomic regulation in the formation of the brain microwave radiation. The approach proposed in the article can be used to monitor the medical process.

The processing of biomedical signal by the multifractal formalism during functional studies increases the quality of identification of their physiological patterns and extends capabilities of the modernized Radiophysical complex MRTHR.

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