

Higuchi's fractal dimension for analysis of the effect of external periodic stressor on electrical oscillations in the brain

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Abstract This study addresses application of Higuchi's fractal dimension (FD) as a measure to evaluate the effect of external periodic stressor on electrical oscillations in the brain. Modulated microwave radiation was applied as a weak periodic stressor with strongly inhomogeneous distribution inside the brain. Experiments were performed on a group of 14 volunteers. Ten cycles (1 min on, 1 min off) of 450-MHz microwave radiation modulated at 40 Hz were applied. Higuchi's FD was calculated in eight symmetric electroencephalographic (EEG) channels located in frontal, temporal, parietal, and occipital areas. FD values averaged over a group detected a small (1–2%) but statistically significant increase with exposure in all EEG channels. FD increased for 12, decreased for one, and was constant for one subject. FD showed the most remarkable effect in temporal and parietal regions of the left hemisphere where the microwave field was maximal. Changes of FD in these regions of the right hemisphere were much higher than expected in accordance with the field distribution. Correlation of FD between different EEG channels was high and retained its value in exposed conditions. Spreading of disturbance between different brain areas is supposed to be crucial for the effect of exposure on the electrical oscillations in the brain.

Keywords EEG analysis · EEG rhythm · EMF effect · Fractals · Nonlinear signal processing

1 Introduction

The effects of the radio frequency electromagnetic field on human brain physiology have become of major interest with increasing applications of telecommunication devices [5, 17]. Telecommunication devices employ radiofrequency radiation modulated at different low frequencies. Exposure to modulated radiofrequency radiation leads to periodic alterations in the brain's bioelectromagnetic activity by the external field. The modulation has been shown to play a crucial role in the radiofrequency radiation effect on the brain [8, 11]. However, the effect of microwave exposure to brain oscillations at non-thermal level of radiation is weak and therefore difficult to detect [5, 6, 8, 11, 17].

Modern methods of brain imaging for the detection of weak effects must be carefully selected to avoid dumping of the effect affecting the brain by the much stronger fields induced by measurement devices [3]. For example, the magnetic resonance spectroscopic imaging (MRSI) procedure that can be performed within clinical MRSI system limits has been shown to stimulate the human brain [16]. The MRSI scan induces electric fields that are associated with reported alterations in subjects under investigation [16]. The electroencephalographic (EEG) method has advantages in detection of weak effects as a passive method with sufficient temporal and spatial resolution [15].

External periodic electromagnetic exposure is expected to induce alterations in the brain's bioelectric rhythms and EEG signals. Therefore, EEG-based indicators can be an efficient measure of the electromagnetic field effect. However, the effect of low-level modulated microwave radiation

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on the EEG is usually very small and hidden in natural variability of the EEG signal. Analysis of dynamics of the EEG signal becomes complicated due to the irregular nature of the signal. This is one of the reasons why the question of whether any feasible effect of a low-level radiation on brain's bioelectric activity exists is still under discussion.

Linear EEG analysis has sometimes limited possibilities for providing a reliable and statistically significant distinction between the signals with and without radiation. The advantages of nonlinear EEG analysis for detection of the microwave effect have been demonstrated in our previous study [2]. Higuchi's fractal dimension (FD) in time domain shows changes of the signal's complexity in time [7, 14]. The mean FD value averaged over a longer period of time serves as a meaningful characteristic of studied biosignals and potential of FD to respond to different states of cortical activity has been demonstrated [14, 18].

The external microwave exposure by an antenna located from one side of the head has strongly inhomogeneous distribution inside the brain [4]. Therefore, intensity of the effect of microwave radiation in different brain areas is expected to be highly inhomogeneous. The alterations in the EEG signal parameters in the fixed brain area can be introduced directly by the external field as well as by connections with the other brain areas more strongly affected. Comparison of the field distribution inside the brain with the alterations in the EEG signal in different brain areas provides the possibility to estimate the role of interbrain connections in periodic exposure of the brain.

The study addresses the application of Higuchi's FD as a nonlinear measure to evaluate the effect of external electromagnetic periodic on bioelectrical oscillations (EEG) in the brain [7, 14]. The first hypothesis is that an external periodic stressor causes changes in structure rather than in power of the EEG signal and therefore the Higuchi's FD is a better measure to detect alterations than methods based on the EEG rhythms power analysis [17]. The second hypothesis is that due to strongly inhomogeneous distribution of the electromagnetic field inside the brain, the distribution of related alterations is also inhomogeneous. Conformity of EEG alterations in different brain areas to the microwave field distribution inside the brain provides information about roles of the direct field effect and the connectivity between different brain areas in alterations of bioelectromagnetic activity of the brain.

2 Methods

2.1 Subjects

The experiments were carried out on a group of healthy volunteers consisting of 14 young persons (aged 21–24), seven male and seven female.

All the subjects selected were without any medical or psychiatric disorders. A questionnaire and a clinical interview were used to evaluate their physical and mental condition (tiredness, sleepiness) before the experiment. The persons who declared tiredness or sleepiness before the experiment were excluded.

EEG recording was performed for a subject during a day between time interval 9:00 a.m. to noon. The room of the experiments was dark and the subjects were lying in a relaxed position, eyes closed, and ears blocked during the experiments.

After the recordings, they were asked how they were feeling during the experiment. The subjects reported neither alertness nor any strain experienced during the recordings. The experiments were conducted with understanding and written consent of each participant.

The study was conducted in accordance with the Declaration of Helsinki and was formally approved by the local Medical Research Ethics Committee.

2.2 Exposure

Microwave radiation at the non-thermal level of field power density was selected to be identical to that in our previous studies [8, 9]. Whereas microwaves cannot cause any regular changes in the movement of ions due to their small cross section of absorption (the wavelength of the microwave is much larger than the dimensions of a cell) as well as their inertial properties and viscosity of the liquid medium [1], the effect may depend on the modulation frequency rather than on the radio frequency. The frequency of 450 MHz was selected because of the deeper depth of penetration compared to higher frequencies used in telecommunication.

Exposure conditions were the same for all subjects in the group. The 450-MHz electromagnetic radiation was generated by the Rohde & Swartz signal generator model SML02. The RF signal was 100% pulse-modulated by the Rohde & Swartz pulse modulator SML-B3 at 40-Hz frequency, duty cycle 50%. The signal from the generator was amplified by the Dage Corporation power amplifier model MSD-2597601. The generator and amplifier were carefully shielded. The 1-W electromagnetic radiation output power was guided by a coaxial lead to a 13-cm quarter-wave antenna NMT450 RA3206 by Allgon Mobile Communication AB, located close to the ear 10 cm from the skin on the left side of the head. The Central Physical Laboratory of the Estonian Health Protection Inspection measured the spatial distribution of the electromagnetic radiation power density by the Chauvin Arnoux Fieldmeter CA 43 field strength meter. The used measurement equipment passed calibration by the Estonian Technical Surveillance Authority. The calibration curves of dependence of the field power density on the

distance from the radiating antenna were obtained from these measurements performed under real experimental conditions. The average field power density of the modulated microwave at the skin from the left side of the head was 0.16 mW/cm^2 , as estimated from the measured calibration curves. During the experiments, the stability of the electromagnetic radiation level was monitored by an IC Engineering Digi Field C field strength meter. The spatial distribution of the field density around head and upper torso was non-uniform: the Digi Field C field strength meter indicated a maximal level of $0.16 + 0.02$ (mean plus or minus the standard error of the mean) mW/cm^2 at the left side of the head and a minimal level of $0.025 + 0.01 \text{ mW/cm}^2$ at the right side of the head and $0.08 + 0.01 \text{ mW/cm}^2$ above head. The measured field power density was $0.8 + 0.2 \text{ mW/cm}^2$ near the neck and shoulder on the left side and $0.03 + 0.01 \text{ mW/cm}^2$ near the neck and shoulder on the right side.

The specific energy absorption rate (SAR) was calculated using SEMCAD software [9]. The finite difference time domain (FDTD) computing method with specific anthropomorphic mannequin specified in IEEE Standard 1528 was applied [12]. The calculated spatial peak SAR averaged over 1 g has its maximum 0.303 W/kg in middle of the left hemisphere near the left ear [9].

2.3 Recording protocol and equipment

The resting eyes closed EEG was continuously recorded for 20 min. During every even minute the subject was exposed to 450-MHz microwave radiation modulated at 40 Hz. For the duration of each even minute of the recording, the microwave exposure was switched on, and during each odd minute it was switched off. Ten cycles of 60-s exposure and resting half-periods were applied during the recording.

The Cadwell Easy II EEG equipment was used for the EEG recordings. The EEG was recorded in 0.5–40 Hz frequency band using nine electrodes, which were placed on the subject's head according to the international 10–20-electrode position classification system. The channels for analysis were chosen to cover the entire head: frontal- FP1, FP2; temporal- T3, T4; parietal- P3, P4; occipital- O1, O2; and the reference electrode Cz.

Artefacts can be induced by parasitic demodulation of the radio-frequency electromagnetic components on the EEG electrodes and equipment. To detect possible parasitic interaction between the recording and radio-frequency equipment, the set-up was validated before the experiments. To conduct testing, an EEG cap was placed on a passive phantom of a human head. The recordings on the phantom were conducted in accordance with the procedure of the study. Multichannel recordings in frequency band 0.5–48 Hz detected spectral components at the modulation frequency 40 Hz in some of the channels. No other spectral

components were detected. The artefacts at the modulation frequencies were removed from the EEG signals by off-line filtering during the pre-processing of the signals in the LabVIEW programming and signal-processing environment. The recorded EEG signals were stored on a computer in 0.5–38 Hz frequency band at an 80-Hz sampling frequency.

2.4 EEG analysis

Higuchi's FD method was applied for EEG analysis [7, 14]. Higuchi's algorithm calculates FD of time series directly in the time domain [7, 14]. It is based on a measure of length $L(k)$ of the curve that represents the considered time series while using a segment of k samples as a unit.

The value of FD was calculated according to the following algorithm [14]. From the given time series: $X(1)$, $X(2)$, $X(3)$, ..., $X(N)$ a new series X_k^m is constructed as:

$$X_k^m : X(m), X(m+k), X(m+2k), \dots, \\ X\left(m + \text{int}\left(\frac{N-m}{k}\right)k\right), \quad m = 1, 2, \dots, k.$$

The length $L_m(k)$ of every curve X_k^m is calculated according to the formula:

$$L_m(k) \\ = \frac{1}{k} \left[\left(\sum_{i=1}^{\text{int}\left(\frac{N-m}{k}\right)} |X(m+ik) - X(m+(i-1)k)| \right) \frac{N-1}{\text{int}\left(\frac{N-m}{k}\right)k} \right]$$

The length $L(k)$ of the curve for time interval k is defined as average over k values of $L_m(k)$, $m = 1, 2, \dots, k$. If $L(k)$ scales like $L(k) \sim k^{-FD}$, the curve has FD, which is calculated using linear regression of the graph:

$$\ln(L(k)) \sim \ln\left(\frac{1}{k}\right)$$

according to the following formula:

$$FD = \frac{n \sum (x_k y_k) - \sum x_k \sum y_k}{n \sum (x_k^2) - (\sum x_k)^2},$$

where $x_k = \ln\left(\frac{1}{k}\right)$, $y_k = \ln L(k)$, $k = k_1, \dots, k_{\max}$, and n denotes the number of k -values for which the linear regression is calculated ($2 \leq n \leq k_{\max}$).

FD was calculated in 400 samples (5 s) window, and the window was shifted by 40 samples (0.5 s) with parameter $k_{\max} = 8$. The total number of calculated FD values during microwave exposure or resting half-period was 120. An original program for calculations on a PC was developed in C language, which was chosen for speed reasons. Calculation of FD for 20-min, eight-channel EEG recordings takes only 2 s with a 1.8-GHz processor.

Next, the calculated FD values were divided into two series as follows:

- the first series contained all 1-min-long periods of the signal (120 FD values) without exposure (all the odd minutes from the initial EEG recording),
- the second series contained all minutes with microwave exposure (all even minutes of the initial EEG recording).

Average values, correlation coefficients, and inter-hemispheric asymmetry of FD were calculated for each of ten cycles of exposure and two series of calculated FD values for all subjects. Correlation coefficients between FD series in different EEG channels were calculated for all combinations of the channels. Interhemispheric asymmetry A_s was calculated for a subject s as a relative difference between FD in left FD_L and right FD_R hemisphere symmetric EEG channels.

$$A_s = \frac{FD_{sL} - FD_{sR}}{FD_{sL} + FD_{sR}} \times 200\%.$$

Averaging over ten exposure cycles and a group of subjects was performed.

Distribution of FD in the head was calculated using the average FD values in the EEG electrode location points as the input data set. LabVIEW function General Linear Fit VI was applied to find the three-dimensional linear curve values and the set of three-dimensional linear fit coefficients, which describe the three-dimensional linear curve that best represents the input data set using the least square method. Distribution of SAR in the specific anthropomorphic head model [12] was calculated using the FDTD method and SEMCAD software.

Statistical analysis for calculated FD values between the series with and without microwave exposure was performed. Student's t test with Bonferroni correction for multiple comparisons was applied for statistical evaluation. A confidence level of 0.05 was considered statistically significant to the Bonferroni corrected p values.

3 Results

Figure 1 presents as an example results of calculated FD values for one experiment of ten exposure cycles for a subject. Visual observation reveals some changes of FD values with the microwave radiation on–off cycles in the last row. The most noticeable difference between segments with and without exposure occur in the area of highest microwave field inside the head (middle of the left hemisphere, channel P3).

As shown in Fig. 2, an increase of FD with microwave exposure occurs in all EEG channels. However, alteration compared to the rest condition averaged over all channels

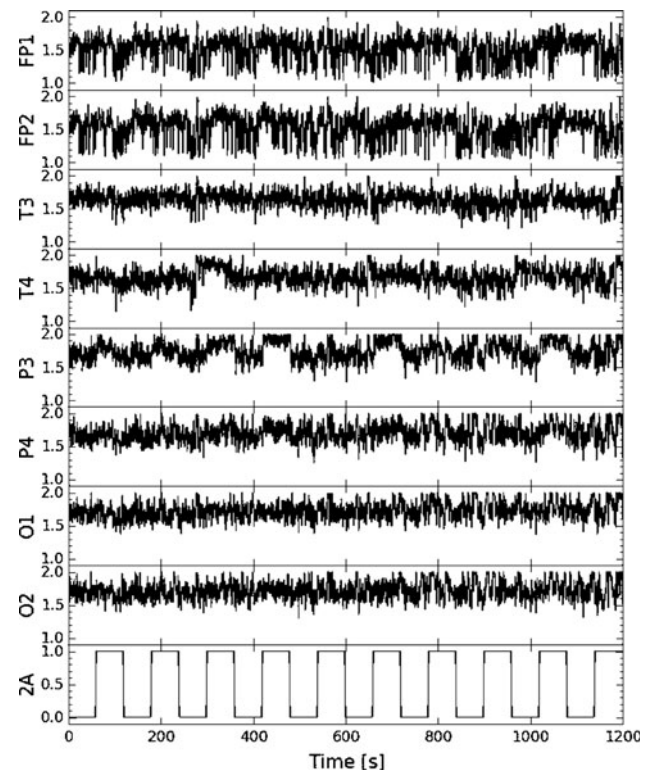


Fig. 1 Calculated FD values for a subject in eight EEG channels during 20 min of recording. The lowest graph denotes the time scale of microwave radiation on–off switching

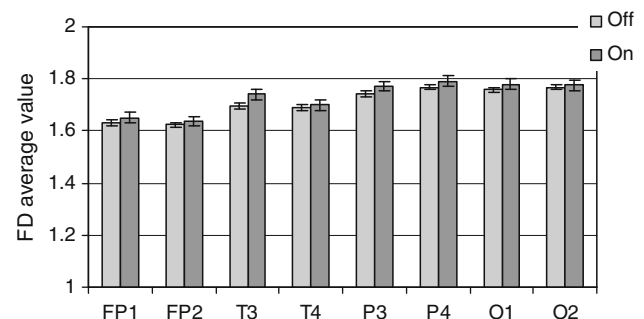


Fig. 2 FD values averaged over the cycles of exposure ($c = 10$) and over the group of subjects ($s = 14$) in different EEG channels with and without microwave exposure

is only 1.3%. Statistical evaluation confirmed a significant difference between the resting and exposed conditions for the group ($p = 0.002$). The alterations were statistically significant for the group also in all separate EEG channels ($p < 0.04$).

Analysis of FD alterations caused by exposure was also performed for individual subjects. Figure 3 shows that exposure causes an increase of FD for 12, a decrease for one, and no effect for one subject. The difference between FD series with and without exposure was statistically significant for four individual subjects.

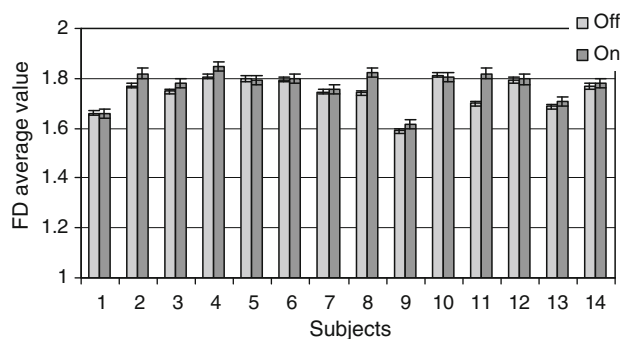


Fig. 3 FD values averaged over all cycles of exposure ($c = 10$) for individual subjects in the P3 channel. Statistically significant differences between results in series at rest and exposure conditions occur for subjects 2, 4, 8, and 11

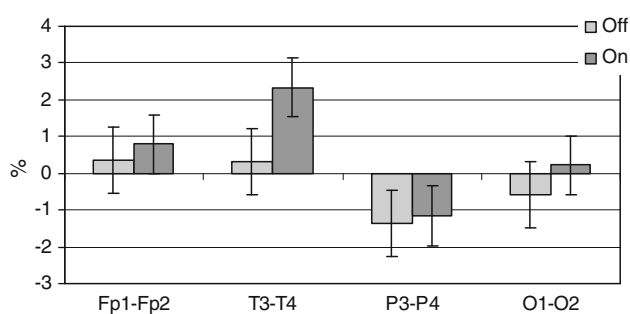


Fig. 4 FD asymmetry values averaged over the cycles of exposure ($c = 10$) and over the group of subjects ($s = 14$) between the frontal Fp1-Fp2, temporal T3-T4, parietal P3-P4, and occipital O1-O2 symmetric EEG channels

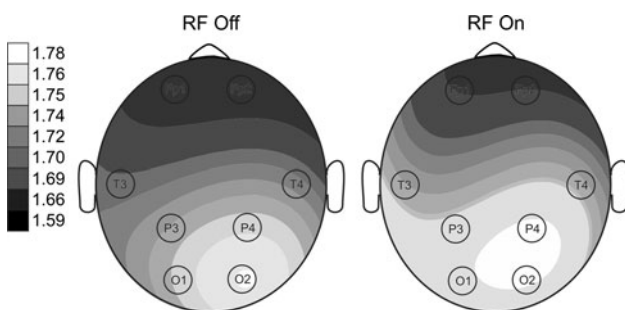


Fig. 5 Distribution of FD over the head: 1 FD average values without exposure, 2 FD average values with exposure

As shown in Fig. 4, calculated interhemispheric asymmetry values indicate an increase of FD with exposure in the left hemisphere in all pairs of symmetric EEG channels. Differences in FD asymmetry in conditions with and without exposure were not statistically significant.

Figure 5 presents spatial distributions of FD in the head at the conditions with and without exposure. Caused by exposure increase of FD is observed in the middle of the head, in temporal and parietal areas. The increase is most remarkable near the left ear. Distribution of the effect as

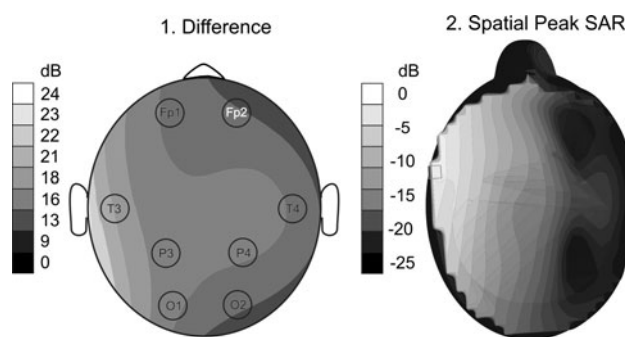


Fig. 6 Distribution of the effect of microwave exposure as presented by difference of FD values between the exposure on–off conditions and SAR over the head: 1 difference of average FD values between on–off conditions, 0 dB corresponds to 0.2% relative difference level; 2 distribution of SAR, 0 dB corresponds to 0.303 W/kg averaged over 1 g for 1-W antenna input power

relative differences of FD at the conditions with and without exposure was calculated for comparison with spatial distribution of the microwave exposure. Figure 6 presents relative spatial distributions of the effect and calculated SAR values in the head model. Strongly inhomogeneous distribution of SAR has maximum near the left ear close to the location of antenna. The most remarkable effect occurs in the same area. However, changes of FD in parietal and temporal regions, especially in the right hemisphere, are obviously much stronger than expected according to the SAR distribution.

Table 1 presents calculated correlation coefficients between all EEG channels. Figure 7 illustrates the correlation in the most strongly affected parietal area. Regular decrease of the correlation with increase of distance between the channels is obvious for both resting and exposed conditions. The effect of exposure behaves differently in different combinations of channels. Some decrease of correlation with exposure can be mentioned, especially between the reference (regarding to which correlation is calculated) and symmetric to this channel from different hemisphere. Performed statistical analysis showed significant decrease of correlation caused by exposure between only parietal and occipital channels (P3-P4; P4-O1; P4-O2).

4 Discussion and conclusions

Results of the performed experiments demonstrated an increase of FD of the recorded EEG signals caused by the external periodic electromagnetic exposure. Low-level nonspecific (without specific physiological sensor) electromagnetic stressor causes small (1–2%) but statistically significant alteration in FD of the EEG signal (Figs. 2, 3). We can conclude that a weak external periodic exposure

Table 1 FD correlation coefficients averaged over all cycles of excitation ($c = 10$) and over the group of subjects ($s = 14$) between different EEG channels without excitation “off” and with excitation “on”

		FP1	FP2	T3	T4	P3	P4	O1	O2
FP1	Off								
	On								
FP2	Off	0.91							
	On	0.84							
T3	Off	0.34	0.35						
	On	0.41	0.44						
T4	Off	0.42	0.42	0.54					
	On	0.25	0.39	0.51					
P3	Off	0.30	0.32	0.64	0.54				
	On	0.34	0.43	0.61	0.60				
P4	Off	0.26	0.26	0.50	0.63	0.80			
	On	0.23	0.31	0.54	0.67	0.70			
O1	Off	0.22	0.24	0.49	0.56	0.87	0.84		
	On	0.25	0.31	0.51	0.52	0.77	0.72		
O2	Off	0.21	0.22	0.43	0.56	0.79	0.92	0.92	
	On	0.19	0.22	0.46	0.54	0.68	0.82	0.85	

Numbers for statistically significant differences between “off” and “on” series marked in *bold*

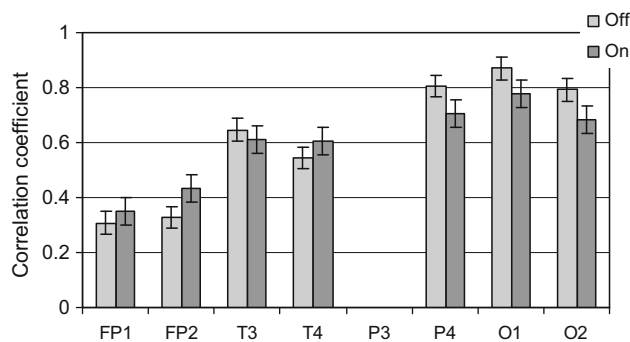


Fig. 7 Correlation coefficients averaged over the cycles of exposure ($c = 10$) and over the group of subjects ($s = 14$) calculated between channel P3 and other EEG channels

leads to more a complicated character of neuronal oscillations compared to resting conditions and consequently to higher FD values of the EEG signal.

A small value of the effect can be related to the level of applied SAR 0.303 W/kg much lower than the recommended basic restrictions for exposure of the general public 2 W/kg [13]. Duration of the exposure longer than 60 s was not expected to increase the effect because results of our previous study showed a statistically significant increase in the EEG power only during the first 30 s of the exposure interval [8].

Our previous results showed that modulated microwaves caused an increase in the average EEG alpha (8–14 Hz)

and beta (15–38 Hz) power [8]. Therefore, we can expect that the EEG frequency band 0.5–38 Hz selected for FD calculation is sufficient for providing information about alterations caused by the radiation. The microwave exposure was shown to increase the EEG power at the EEG frequencies lower or close to the modulation frequency [8]. The selected modulation frequency of 40 Hz is higher than the EEG alpha and beta frequency band and is therefore expected to affect the EEG in a most sensible way.

A parallel can be drawn with experiments performed earlier at similar conditions [8, 9]. Relative change in the EEG rhythms power has been used as a measure for detecting the effect of modulated microwave radiation in these studies [8, 9]. The applied measure revealed statistically significant changes in alpha and beta rhythms for a group averaged over all channels and separately in parietal and temporal channels [8, 9]. Higuchi's FD measure provides lower dispersion of the results and therefore more reliable detection of the effect. As a result, statistically significant alterations were detected between on–off conditions for a group in all EEG channels.

Increase of the FD caused by periodic exposure was detected in all EEG channels (Fig. 2). Calculated FD revealed the most noticeable effect in temporal and parietal regions of the left hemisphere in the brain area of the highest microwave field (Figs. 5, 7). An increase of the FD in temporal and parietal regions of the right hemisphere is much higher than expected according to the SAR distribution (Fig. 7). Consequently, the revealed effect is determined not only by direct electrical coupling between the external field and the brain neuronal electrical oscillations but is also related to spreading of disturbance inside the brain due to connections between different brain regions and hemispheres. This conclusion is also supported by unexpected results for interhemispheric asymmetry (Fig. 4). The trend of increase of asymmetry with exposure is mentioned in all brain areas except the most strongly affected parietal region. A low value of alterations of FD asymmetry in the most strongly affected brain areas seems possible only at conditions of symmetric effect of exposure. Consequently, the disturbance should move from the left hemisphere with high level of exposure to the right hemisphere with much lower level of exposure.

The correlation between FD between different EEG channels has a normal trend of decrease with the increase of distance between the brain areas. This trend retained at exposure conditions (Table 1, Fig. 7). Statistically significant changes of correlation were revealed only in parietal EEG channels where the correlation of FD decreased with exposure. Decrease of correlation can be considered as an additional noise in the system. The additional noise in the system affects information processing in the brain. The small but statistically significant effect of similar periodic

microwave exposure on visual cognition has been demonstrated in our previous study [10].

The experimental results and discussion above lead to the conclusion that the weak periodic electromagnetic exposure causes an increase of FD of the recorded EEG signals. The effect is mild but statistically significant in all EEG channels. Spreading of disturbance between the different brain areas is supposed to play a crucial role in the effect of external periodic stressor on the brain's bioelectric oscillations.

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