Proceedings of the Estonian Academy of Sciences,
2014, **63**, 3, 322–327
doi: 10.3176/proc.2014.3.05
Available online at www.eap.ee/proceedings

BIOMEDICAL
ENGINEERING

Spectral asymmetry index and Higuchi's fractal dimension for detecting microwave radiation effect on electroencephalographic signal

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Received 21 February 2014, revised 19 June 2014, accepted 20 June 2014, available online 28 August 2014

Abstract. This study is aimed to the comparison of the sensitivity of linear spectral asymmetry index (*SASI*) and nonlinear Higuchi's fractal dimension (*HFD*) methods for detecting modulated microwave effect on human electroencephalographic (EEG) signal at non-thermal level of exposure. The experiments were carried out on a group of 14 healthy volunteers exposed to 450 MHz microwave radiation modulated at 40 Hz frequency. The applied microwave power was 1 W and the field power density near the head was 0.16 mW/cm^2. The EEG signal was recorded from 8 channels: frontal – FP1, FP2; temporal – T3, T4; parietal – P3, P4; and occipital – O1, O2; with the common recording reference Cz. Microwave exposure increased the group averaged *SASI* value about 64%. However, the alteration was not statistically significant (p = 0.2). The *HFD* method detected small (about 1.7%) but statistically significant (p = 0.008) enhancement of its value with microwave exposure.

Key words: EEG analysis, microwave radiation, spectral asymmetry, fractal dimension, EMF effect.

1. INTRODUCTION

Brain activity is based on neuronal bioelectrical processes, which create electroencephalographic (EEG) signal. The oscillations are a prominent feature of neuronal processes and the synchronization of the oscillations is a likely mechanism for cerebral integration for neural communication [1,2]. The properties of neuronal oscillators are the result of the physical architecture of neuronal networks and the limited speed of neuronal communication due to axon conduction and synaptic delays [3]. The unperturbed brain is a complex system of numerous self-governed oscillations, but the content of these rhythms is still poorly understood [4]. Some results reported in recent studies by several researchers demonstrate that the brain neuronal oscillators behave as physical electric oscillators. Brain oscillators, like most biological rhythms, belong to limit-cycle and weakly chaotic oscillators and share features of both harmonic and relaxation oscillators [1]. Detailed biophysical studies have revealed that even single neurons are endowed with complex dynamics, including their intrinsic abilities to resonate and oscillate at multiple frequencies [5].

The spectrum of brain oscillations covers frequency range from single neurons spiking to long-range communication between different neural assemblies [1,2]. The ability of neuronal assemblies to synchronize depends on the coupling strength and the distribution of natural frequencies [1]. The spectrum of the natural frequencies describes the state of an undisturbed brain. Therefore, the spectrum of the resting EEG signal is determined by the state of the brain. Proposed in our previous studies spectral asymmetry index (*SASI*) has been shown to detect declination in the balance of spectral powers caused by mental disorders as depression [6,7].

On the other hand, brain electrical oscillations can be affected by external electromagnetic field. External periodic electromagnetic stressor is expected to induce alterations in the brain bioelectric rhythms and EEG signal. Effects of the radio frequency electromagnetic

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field on human brain physiology have become of major interest with increasing applications of telecommunication devices [8–10]. Telecommunication devices employ radiofrequency radiation, modulated at different low frequencies. Exposure to modulated radiofrequency radiation leads to periodic alterations in the brain bioelectromagnetic activity. The modulation has been shown to play a crucial role in the radiofrequency radiation effect on the brain; however, the mechanism of the effect at non-thermal level of exposure has been unclear during decades [11–13]. The proposed in our previous study parametric model of excitation, based on the theory of electrical oscillations, has been successful in explaining the mechanism of the non-thermal effect of modulated microwave radiation [14]. The idea of parametric excitation is supported by our original experimental data and can contribute to interpretation of results reported by other authors [11–14].

The effect of microwave exposure on the brain electrical oscillations is weak and therefore difficult to reveal. Special linear and some nonlinear measures have been successfully applied for detecting the effect [15–17]. *SASI* has demonstrated very high sensitivity in detecting depression EEG [7]. The applicability of *SASI* for the detection of characteristic changes in the EEG signal related to microwave radiation is an interesting question.

The aim of the study is the comparison of the sensitivity of linear *SASI* and nonlinear *HFD* methods for detecting modulated microwave effect on EEG at nonthermal level of exposure. For this purpose, the *SASI* and *HFD* methods were applied to the identical human EEG data, recorded during the experiments.

2. METHODS

2.1. Experimental procedure and equipment

The experiments were carried out on a group of 14 healthy young volunteers (aged 21–24), 7 male and 7 female. The EEG recording was performed for a subject during a day in a time interval from 9 a.m. to noon. The room of experiments was dark and the subjects were lying in a relaxed position, eyes closed and ears blocked during the experiments.

The resting eyes closed EEG was continuously recorded during 20 min. The computer switched the microwave radiation on during each even minute and off during each odd minute of the recordings.

The EEG recordings were made using Cadwell Easy II EEG equipment. The EEG signal was recorded in 0.5–40 Hz frequency band using 8 channels, 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; with the common reference Cz. The recorded EEG signals were stored on a computer in 0.5–38 Hz frequency band at 80 Hz sampling frequency.

The study was conducted in accordance with the Declaration of Helsinki and was formally approved by the Tallinn Medical Research Ethics Committee. The experiments were conducted with understanding and written consent of each participant.

Microwave radiation at the nonthermal level of field power density was selected to be identical to that in our previous studies [13,18]. 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 radiofrequency 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 the quarter-wave antenna NMT450 RA3206 by Allgon Mobile Communication AB, located close to ear, 10 cm from the skin on the left side of the head. The Central Physical Laboratory of the Estonian Health Board measured the spatial distribution of the electromagnetic radiation power density by the Chauvin Arnoux Fieldmeter CA 43 field strength meter. 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 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.

The specific absorption rate (SAR) was calculated using SEMCAD (Schmid & Partner Engineering AG, Zurich, Switzerland) software. The finite difference time domain (FDTD) computing method with specific anthropomorphic mannequin (SAM), specified in IEEE Standard 1528, was applied. The calculated spatial peak SAR, averaged over 1 g, was 0.303 W/kg. During the experiments, the stability of the electromagnetic radiation level was monitored by the IC Engineering Digi Field C field strength meter.

2.2. EEG analysis: *SASI* method

First, all the recorded EEG signals were divided into exposed and nonexposed signals as follows: the signal without microwave exposure contained all odd minutes intervals from the initial EEG recordings whereas the signal with microwave exposure contained all even minutes intervals from the initial EEG recordings.

SASI was calculated for a single channel as a relative difference between the powers of the EEG frequency

bands selected higher and lower than the maximum of the EEG spectrum (alpha band) [6,7]. The balance of the powers characterizes the EEG spectral asymmetry. Important aspect of the method is exclusion of the alpha frequency band from the analysis. Therefore the boundary frequencies for the selected bands were adjusted taking into account the alpha frequency range in the EEG power spectrum for each individual subject.

The frequency with the maximum spectral power $f_{\max}$ in the region of alpha band 8–13 Hz was estimated calculating the power spectral density of the recorded EEG signal by means of Welch's averaged periodogram method. Thereafter the parabolic approximation was applied to the spectrum of the EEG central frequency band $(f_{\max} \pm B)$ Hz, where $B = 2$ Hz was half-width of the band. The best parabolic fit for power spectral distribution was calculated by applying the Matlab POLYFIT tool. The maximum point of the fitted parabola f_c was taken as a centre of the central band. The frequencies of the lower and higher frequency bands were related to the estimated central frequency f_c. The lower frequency band was selected from $F1$ to $F2$, where

$$F1 = (f_c - 6) \text{ Hz and } F2 = (f_c - 2) \text{ Hz}.$$

The higher frequency band had boundary frequencies $F3$ and $F4$, where

$$F3 = (f_c + 2) \text{ Hz and } F4 = (f_c + 26) \text{ Hz}.$$

The EEG signal powers W_{lmn} and W_{hmn} in the lower and in the higher EEG frequency bands respectively were calculated for each EEG channels (indexed by $m \in [1, 8]$) and subject (indexed by $n \in [1, 14]$) as

$$W_{lmn} = \int_{F1}^{F2} S(f)_{mn}\, df, \quad W_{hmn} = \int_{F3}^{F4} S(f)_{mn}\, df, \tag{1}$$

where $S(f)_{mn}$ is the power spectral density of the recorded EEG signal in a channel m for a subject n.

Finally, the spectral asymmetry index was calculated as

$$SASI_{mn} = \frac{W_{hmn} - W_{lmn}}{W_{hmn} + W_{lmn}}. \tag{2}$$

The calculations of the *SASI* were performed for each subject and EEG channel.

2.3. EEG analysis: the *HFD* method

The *HFD* algorithm calculates fractal dimension of time series directly in the time domain [19]. 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 if $L(k)$ scales like

$$L(k) \sim k^{-FD}. \tag{3}$$

The value of the fractal dimension *FD* was calculated according to the following algorithm [19]. From given time series: $X(1), X(2), X(3), \ldots, X(N)$ a new series X_k^m is constructed as:

$$X_k^m : X(m), X(m+k), X(m+2k), \ldots, X\left(m + \left[\frac{N-m}{k}\right]k\right), \quad m = 1, 2, \ldots, k, \tag{4}$$

where [ ] indicates the Gauss' notation.

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

$$L_m(k) = \frac{1}{k}\left\{\left(\sum_{i=1}^{\left[\frac{N-m}{k}\right]} \left|X(m+ik) - X(m+(i-1)k)\right|\right)\frac{N-1}{\left[\frac{N-m}{k}\right]k}\right\}. \tag{5}$$

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

$$\ln(L(k)) \sim \ln\left(\frac{1}{k}\right), \tag{6}$$

where $k = 1, \ldots, k_{\max}$. The slope of the obtained line is the estimate of the fractal dimension.

FD was calculated in 400 samples (5 s) window, and the window was shifted by 40 samples (0.5 s). A value of 8 was chosen for $k_{\max}$. *FD* for a subject and channel was achieved using averaging over all *FD* values for a signal of 10 min length.

2.4. Statistics

Student's *t*-test for two-tailed distribution with two-sample unequal variance was applied for statistical evaluation of the difference between the calculated *SASI* and *HFD* series with and without microwave exposure. The confidence level of $p < 0.05$ was considered statistically significant.

3. RESULTS

Figure 1 presents *SASI* values averaged over a group at conditions without and with microwave exposure. The average values of *SASI* are negative at both conditions. The averaged *SASI* value at microwave exposure is about three times higher. Microwave exposure increases

the averaged *SASI* value for about 64% from its initial level. However, the alteration is not statistically significant ($p = 0.2$).

SASI values for individual subjects are presented in Fig. 2. *SASI* is positive for 4, negative for 8, and close to zero for 2 subjects. Microwave exposure increases *SASI* value for 6 and decreases for 4 subjects, while no considerable change in *SASI* value is observed for 4 subjects.

Figure 3 is an example, illustrating the least-squares linear best-fit curve calculated on the $\ln(L(k))$ versus $\ln(1/k)$, indicating that the data follow power law.

HFD values averaged over a group are presented in Fig. 4. Microwave exposure increases the value for about 1.7% and the alteration is statistically significant ($p = 0.008$).

Figure 5 presents *HFD* values for individual subjects. Microwave exposure increases *HFD* value for 12 and decreases for 1 subject, almost no change is observed for 1 subject.

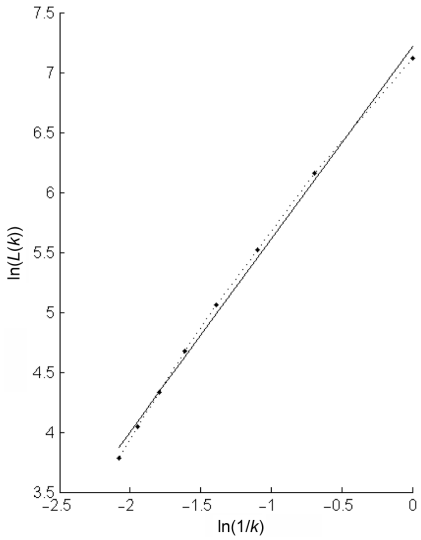

Fig. 3. An example of the least-squares linear best-fit curve $\ln(L(k))$ vs $\ln(1/k)$.

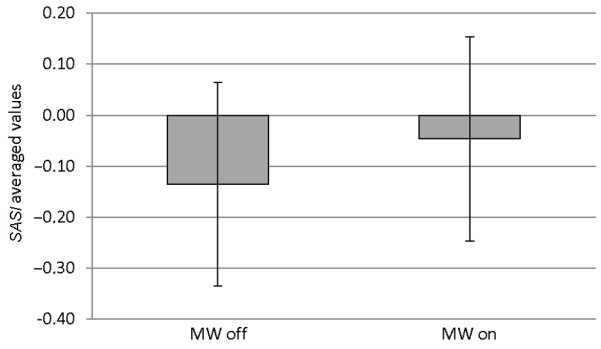

Fig. 1. Values of *SASI*, calculated for recordings with and without microwave exposure averaged over a group of 14 subjects and 8 EEG channels; vertical bars denote standard deviation.

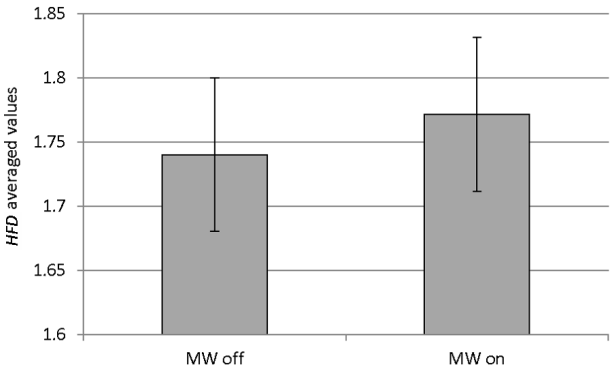

Fig. 4. Values of *HFD*, calculated for recordings with and without microwave exposure, averaged over a group of 14 subjects and 8 EEG channels; vertical bars denote standard deviation.

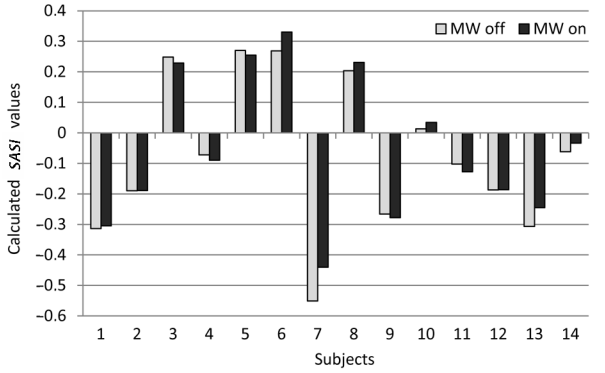

Fig. 2. Values of *SASI*, calculated for recordings with and without microwave exposure for individual subjects in channel P3.

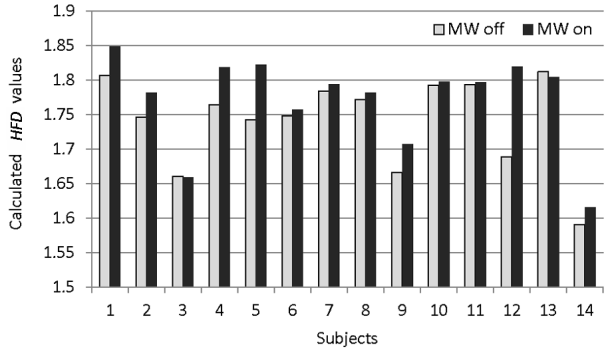

Fig. 5. Values of *HFD*, calculated for recordings with and without microwave exposure for individual subjects in channel P3.

4. DISCUSSION

The *SASI* method shows more remarkable enhancement with microwave exposure (64%) compared to the *HFD* (1.7%). However, the alterations, detected by *SASI*, are not statistically significant. The advantages of *SASI* become ineffectual due to high variability of results.

The calculated values of *SASI* and *HFD* have remarkable differences between individual subjects. High inter-individual variability is characteristic for physiological processes and parameters. Such variability causes high standard deviation in the measures calculated for a group (Figs 1 and 4). Therefore, inter-individual variability reduces the probability of detecting alterations, caused by microwave exposure. The statistical analysis shows that *SASI* is more affected by inter-individual variability compared to *HFD*.

In addition, the results are obviously affected by the individual sensitivity of subjects to microwave radiation; the expected rate of affected subjects is about 30% [18]. This rate explains the numbers of subjects with clear alterations caused by microwave radiation: 4 subjects according to *SASI* and 6 subjects according to *HFD* (Figs 2 and 5).

Diverse results, achieved using *SASI* and *HFD*, can be explained by different nature of the methods. *SASI* presents the balance of EEG power at higher-lower frequencies, which are expected to take place during normal nondisturbed activity of the brain [7]. The microwave exposure disturbs the brain and can affect both, the power at lower and at higher EEG frequencies. As our previous studies showed, the microwave exposure enhances the level of the EEG power at a fixed EEG frequency band [20]. Whereas the powers at the lower and at the higher EEG frequency bands both can be enhanced by the microwave exposure, the balance between the powers might be not so clearly affected.

The microwave exposure, disturbing the brain, is expected to enhance the complexity of the bioelectric processes in the brain. Therefore, *HFD* is more suitable for revealing alterations, caused by microwave exposure, compared to *SASI*. On the other hand, the absolute values of *HFD* are not graded according to the state of the brain. It is not possible to make decision about the mental state or disturbance of the brain for an individual based on a *HFD* value, while *SASI*, introduced for detection of depression, differentiates depressive with positive and healthy subjects with negative values [6,7]. The *SASI* values became more positive also with microwave exposure. However, the microwave exposure does not alter the state of the brain and does not change the polarity of the *SASI* value.

5. CONCLUSION

The *SASI* method, based on the balance of the powers of two EEG frequency bands, is less suitable for the detection of the microwave effect, compared to the *HFD*.

ACKNOWLEDGEMENTS

This study was financially supported by the Estonian Ministry of Education and Research under institutional research financing IUT 19-2 and by the European Union through the European Regional Development Fund.

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Spektraalse asümmeetria indeks ja Higuchi fraktaaldimensioon mikrolainekiirguse mõju leidmiseks elektroentsefalograafilises signaalis

Maie Bachmann, Jaanus Lass, Anna Suhhova ja Hiie Hinrikus

Käesoleva uuringu eesmärgiks oli elektroentsefalograafilise signaali (EEG) analüüsi lineaarse meetodi, spektraalse asümmeetria indeksi (*SASI*), ja mittelineaarse meetodi, Higuchi fraktaaldimensiooni (*HFD*) tundlikkuse võrdlemine moduleeritud mikrolainekiirguse mittesoojusliku mõju leidmisel. Uuringus osales 14 tervet vabatahtlikku, keda kiiritati 40 Hz sagedusega moduleeritud 450 MHz mikrolainekiirgusega.

Mikrolainekiirguse võimsus oli 1 W ja väljatugevuse tihedus pea vahetus läheduses 0,16 mW/cm^2. Uuringu käigus registreeriti EEG-signaal kaheksas kanalis, kasutades ühist referentselektroodi Cz: frontaalsetes FP1 ja FP2, temporaalsetes T3 ning T4; parietaalsetes P3 ja P4 ning oktsipitaalsetes O1 ja O2. Mikrolainekiirgus põhjustas uuritavate grupil *SASI* keskväärtuse suurenemise 64%. Muutus ei osutunud aga statistiliselt oluliseks (p = 0,2). *HFD*-meetod tuvastas mikrolainekiirguse korral väikese (umbes 1,7%), kuid statistiliselt olulise (p = 0,008) fraktaaldimensiooni väärtuse suurenemise.