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Mechanism of low-level microwave radiation effect on nervous system

Hiie Hinrikus, Maie Bachmann, Denis Karai, and Jaanus Lass

Department of Biomedical Engineering, Technomedicum of the Tallinn University of Technology, Tallinn, Estonia

ABSTRACT

The aim of this study is to explain the mechanism of the effect of low-level modulated microwave radiation on brain bioelectrical oscillations. The proposed model of excitation by low-level microwave radiation bases on the influence of water polarization on hydrogen bonding forces between water molecules, caused by this the enhancement of diffusion and consequences on neurotransmitters transit time and neuron resting potential. Modulated microwave radiation causes periodic alteration of the neurophysiologic parameters and parametric excitation of brain bioelectric oscillations. The experiments to detect logical outcome of the mechanism on physiological level were carried out on 15 human volunteers. The 450-MHz microwave radiation modulated at 7, 40 and 1000 Hz frequencies was applied at the field power density of 0.16 mW/cm^2. A relative change in the EEG power with and without radiation during 10 cycles was used as a quantitative measure. Experimental data demonstrated that modulated at 40 Hz microwave radiation enhanced EEG power in EEG alpha and beta frequency bands. No significant alterations were detected at 7 and 1000 Hz modulation frequencies. These results are in good agreement with the theory of parametric excitation of the brain bioelectric oscillations caused by the periodic alteration of neurophysiologic parameters and support the proposed mechanism. The proposed theoretical framework has been shown to predict the results of experimental study. The suggested mechanism, free of the restrictions related to field strength or time constant, is the first one providing explanation of low-level microwave radiation effects.

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KEYWORDS
EMF effect; water polarization; hydrogen bond; diffusion; neural oscillations; human EEG

Introduction

Application of telecommunication and information technology in our everyday life has raised a concern about possible health effects of radio-frequency electromagnetic field (EMF). Recommendations and guidelines for limiting exposure to microwave radiation are still based on thermal effects resulting from tissue heating. Reports on possible effects of low-level microwave radiation are often contradictory; moreover, mechanisms behind the effects are still under discussion (Cook et al., 2006; Juutilainen et al., 2011; Valentini et al., 2007). Relatively low levels of microwave field in tissues and high frequencies of radiation compared to physiological processes in addition to the contradictory experimental data have caused doubts in low-level effects. There are two principal problems making the explanation of the low-level microwave effects so complicated.

The main problem is that microwave field strength inside the living tissue is much less compared to intramolecular forces. Microwave radiation 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 (Adair, 2002).

Additional problem is that the time constant of various possible mechanisms proposed for EMF effects (signal averaging, coherent detection, nonlinear dynamical systems, radical pair mechanism, role of magnetite) limits the applicability of the theories at high frequencies. Quantitative assessment of the mechanisms has lead to conclusion that these mechanisms are not realistic at microwave frequencies (Sheppard et al., 2008). None of these special mechanisms has been validated experimentally for microwave radiation. Nowadays, commonly accepted mechanism of low-level microwave effect is still absent (Apollonio et al., 2013).

However, experimental findings have demonstrated the effect of microwave radiation at the field power densities and specific absorption rate (SAR) levels much lower than the threshold of thermal effect (Curcio et al., 2005; Huber et al., 2002; Huber et al., 2005; Hinrikus et al., 2008a).

CONTACT Hiie Hinrikus hiie@cb.ttu.ee Department of Biomedical Engineering, Technomedicum of the Tallinn University of Technology, 5 Ehitajate Rd, 19086, Tallinn, Estonia.

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This study is aimed to the clarification of low-level microwave radiation effect on bioelectromagnetic processes in the brain. We presume that modulated low-level microwave radiation, rotating dipolar molecules, affects hydrogen bonds, consequently enhancing diffusion and causes periodic modulation of neurophysiologic parameters that finally, as a logic outcome on physiological level, results in parametric excitation of neuronal oscillations at parametric resonance frequencies. The experiment is designed to confirm the final outcome of the mechanism – alterations in EEG at the frequencies predicted by the theory of parametric excitation. Eyes closed resting EEG is selected for investigation to minimize the natural variability of the EEG signal. The experimental part of this study partly replicates our previous studies (Hinrikus et al., 2008a, 2011). Compared to our previous studies, where the most effective (40 Hz) and less effective (7 Hz) modulation frequencies were tested on different groups, in this study, all modulation frequencies were tested on the same group of subjects.

Mechanism of low-level microwave effect

Each positively charged hydrogen ion in a water molecule is attracted by the negatively charged oxygen ions in other molecule. These hydrogen bonding intermolecular attractive forces are much less compared to intramolecular forces that hold a molecule together (Petrucci et al., 2007). Figure 1 presents a picture of a group of water molecules with possible electric forces between nearest positive–negative ions in different water molecules. The electric forces between molecules have maximal strength while positive and negative charges are oriented directly to each other (Figure 1A). Due to random Brownian movement, hydrogen bonds are being constantly broken and reformed in liquid water. Hydrogen bonding is directional and distributed in all directions in non-polarized water. However, even partial alignment of the water molecules with the electric field affects and reorganizes hydrogen bonds.

Microwave radiation rotates dipolar water molecules and causes polarization of water and living tissues (Foster and Schwan, 1996). Consequently, microwave radiation, causing partial alignment of dipolar water molecules, disturbs the structure of hydrogen bonds. Mutual orientation of positive and negative charges is disturbed and electrical forces between molecules are weakened (Figure 1B). Consequently, microwave radiation, polarizing water, affects also hydrogen bonding. Due to small time constant, there is no restriction for microwave frequencies (Lucar and Chandler, 1996). The radiation, rotating dipolar water molecules, causes fast breaking and reorientation of hydrogen bonds, "shakes" the bonds with the frequency of radiation.

Hydrogen bonds are major factors determining the water's viscosity, boiling temperature and other properties (Petrucci et al., 2007). Consequently, microwave radiation generating orientational disorder and weakening hydrogen bonds decreases water viscosity. As a result, microwave radiation increases diffusion. According to the first Fick's law, the density of diffusion current (j_D) is defined as follows:

$$j_D = -D\nabla c \tag{1}$$

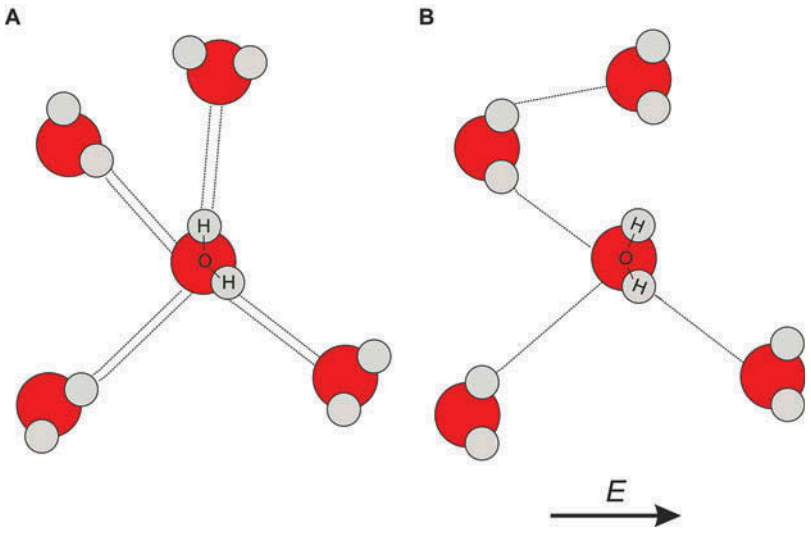

Figure 1. Structure of possible hydrogen bonds between water molecules: (A) without external electric field, the bonding forces between molecules are strong (double lines); (B) polarized by external electric field water, the bonding forces between molecules are weaker (single lines).

where ∇c is ions concentration gradient and D is diffusion coefficient. Stokes–Einstein equation gives for the diffusion coefficient $D = kT/f$, where k is Boltzmann constant, T is temperature and f is friction coefficient determined by viscosity and, consequently, by hydrogen bonds.

The enhance of diffusion has been suggested to explain the overall reaction rate changes under microwave heating compared with conventional heating (Antonio and Deam, 2007). Low-level microwave radiation has been proved to enhance diffusion in water also at constant temperature (Hinrikus et al., 2014).

Diffusion plays important role in many fundamental physiological processes (Schmidt and Thews, 1989). Enhancement of diffusion caused by microwave exposure has direct consequences in neurophysiologic processes. First, enhanced diffusion increases transfer rate of neurotransmitters in synapses. Second, altered diffusion disturbs the balance between ions movement related to diffusion and electric forces.

Neuronal processes are based on the balance of ions movement caused by concentration gradient forces and electric field. Nernst–Planck equation describes the influence of an ionic concentration gradient ∇c and an electric field E on the ions flux density F as follows (Malmivuo and Plonsey, 1995):

$$F = j_D + j_E = -D\nabla c - cqE \tag{2}$$

where c is ions concentration, q is an ion charge and $j_E = cqE$ is electrical current density. Nernst potential V across a membrane is determined based on the condition of zero current at equilibrium as (Malmivuo and Plonsey, 1995)

$$V = -\frac{D}{q}\ln\frac{c_i}{c_o} \tag{3}$$

where c_i is intracellular concentration of the ions and c_o is extracellular concentration of the ions.

Microwave radiation enhances the diffusion rate and consequently increases diffusion coefficient D (Antonio and Deam, 2007; Hinrikus et al., 2014). According to Equation (1), microwave radiation increasing diffusion coefficient D also increases diffusion current. Increased diffusion current causes disturbance of balance in Nernst–Planck Equation (2) and finally alteration of Nernst potential (3).

Microwave radiation is expected to cause perturbation of nervous system affecting at least two parameters of the system, neurotransmitters transit time in synapses and resting potential of neurons. In the case of low-level field, the perturbation is weak and nervous system can adapt to small permanent alterations caused by diffusion. However, the adaptation of neurophysiologic process cannot follow quick changes in external perturbation. Therefore, modulation of microwave radiation is crucial for revealing the effect (Huber et al., 2002, 2005; Lin-Liu and Adey et al., 1982). Modulated at low-frequency f, microwave radiation causes periodic alteration of diffusion coefficient

$$D = D_0(1 + M\cos 2\pi ft) \tag{4}$$

where parameter M is depth of modulation for diffusion rate and t is time. Periodic alteration of diffusion causes also periodic changes in neurotransmitters transit times and resting potentials of neurons with modulation frequency f.

Based on the theory of parametric excitation, even a very small periodic force can result in excitation of the oscillating system at fixed frequencies predetermined by the frequency of the periodic force (Butikov, 2004; Tso and Caughey, 1965). Parametric excitation of nonlinear excitable system can occur at the condition $nf/4 = f_0$, $n = 1, 2,\ldots$, where f is the frequency of parametric excitation and f_0 is the frequency of the excitable system and n is a zone number (Tso and Caughey, 1965). Considering human brain as an excitable system, f_0 corresponds to the frequency of brain neuronal oscillations.

Parametric resonance is possible not only at the fixed resonance frequencies, but also inside the zones of instability at frequencies lying on either side of their resonance values. The width of the zones of instability and the strength of excitation decreases with the zone number. The damping factor is inversely proportional to the quality factor of the system (Butikov, 2004; Tso and Caughey, 1965). The unperturbed brain is a complex system of numerous self-governed oscillations; the properties of neuronal oscillators system are the result of the physical architecture of neuronal networks, depending on the coupling strength between oscillators and the limited speed of neuronal communication due to axon conduction and synaptic delays (Buzsáki and Draguhn, 2004; Nunez, 1995; Steriade and Timofeev, 2003). The periodic alterations of two parameters of the complex neuronal oscillators system is expected to result in parametric excitation of brain oscillators in the frequency band rather wider than the width of the zones of instability predicted by theory.

Experimental validation of the proposed mechanism employing direct measurement of the parameters of nervous system affected by microwave radiation is not possible without strong perturbation of the system. However, the outcome of the proposed mechanism as the impact of periodic excitation of the parameters on the oscillations in the nervous system can be detected

recording the EEG signal generated by the brain bioelectrical oscillations.

Experimental methods and equipment

Subjects

The experiments were carried out on a group of healthy volunteers, consisting of 15 young persons (aged 21–24): 8 males and 7 females. A questionnaire and a clinical interview were used to evaluate their physical and mental condition (tiredness, sleepiness) before the experiment. The selected subjects reported no medical or psychiatric disorders. All tired or sleepy persons were excluded. After the recordings, they were asked to describe their feeling during the experiment. The subjects reported neither alertness nor any strain experienced during the recordings.

The experiments were performed in a special acoustically and electrically shielded laboratory room. The subjects were lying in a relaxed position, eyes closed and ears blocked during the experiments. The subjects were subjected to only one experimental EEG recording session daily between the times of 9 am and noon.

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 Tallinn Medical Research Ethics Committee.

Microwave radiation

Microwave radiation applied in this study was selected identical to that in our previous studies except combination of modulation frequencies (Hinrikus et al., 2008a, 2011). Modulation frequencies in this study 7, 40 and 1000 Hz were selected in the lower (7 Hz) and higher (40 Hz) band of EEG spectrum and much higher (1000 Hz) than the EEG frequencies.

Microwave radiation of 450 MHz was generated by a signal generator (model SML02, Rohde & Schwartz, Munich, Germany). The radio-frequency signal was 100% pulse-modulated using a modulator (SML-B3, Rohde & Schwartz, Munich, Germany) at frequencies of 7, 40 or 1000 Hz (duty cycle 50%). Such meander-like on-off modulation provides the independence of SAR from modulation frequency because the level and duration (during half-period switched on, half-period switched off) of radiation stay constant at any modulation frequency. Higher harmonics were depressed more than 25 dB at all modulation frequencies. The signal from the generator was amplified by a power amplifier (model MSD-2597601, Dage Corporation, Stamford, CT, USA). The generator and the amplifier were carefully shielded. The output power of 1 W electromagnetic radiation was guided by a coaxial lead to the 13-cm rod antenna (NMT450 RA3206, Allgon Mobile Communication AB, Stockholm, Sweden) located 10 cm from the skin on the left side of head. The antenna was fixed in a dielectric holder mounted to the bed construction where a subject was lying. The subjects head position on the pillow was fixed and the antenna was oriented under 45° to the central axis of the head.

The SAR was calculated using SEMCAD (Schmid & Partner Engineering AG, Zurich, Switzerland) software, models and database. The distribution of SAR in a specific anthropomorphic mannequin of human head was calculated using the Finite Difference Time Domain computing method. The calculated spatial peak SAR averaged over 1 g was 0.303 W/kg.

The spatial distribution of the microwave power density radiated by antenna was measured using a field-strength meter (Fieldmeter C.A 43, Chauvin Arnoux, Paris, France). The measurements were done by the Central Physical Laboratory of the Estonian Health Board (Tallinn, Estonia) in accordance to the approved methodology and using a calibrated device. The reference curves of the dependence of field power density on the distance from the radiating antenna were obtained from these measurements, performed under real experimental conditions. During the experiments, a Digi Field C field strength meter (Thousand Oaks, CA, USA) was used to monitor the stability of the electromagnetic radiation level. The average field power density of the modulated microwave at the skin on the left side of head was 0.16 mW/cm^2 estimated from the measured reference curves.

Recording protocol and equipment

The recording protocol was selected similar to that used in our previous studies (Hinrikus et al., 2008a; Suhhova et al., 2013). Repetitive on-off cycles of radiation during the same EEG recording were applied for better distinguishing between the alterations related to microwave radiation and natural variability of the EEG signal.

The protocol of a recording session with microwave consisted of three series including five exposure cycles in each series (Figure 2). An exposure cycle consisted of 1-min segment without radiation and 1-min segment with radiation. Each series was conducted with microwave radiation at a fixed modulation frequency of 7, 40 or 1000 Hz. The order of modulation frequencies was

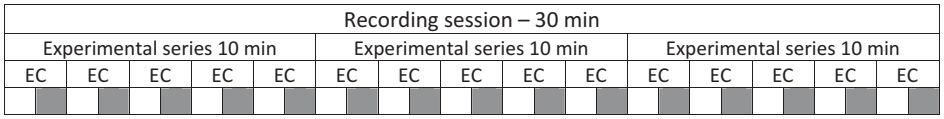

Figure 2. Schedule of a recording session: three experimental series at a constant modulation frequency; five 2-min exposure cycles (EC) in a series; one 1-min reference segment in a cycle without radiation (white) and one 1-min modulated microwave radiation segment in a cycle (dark).

randomly assigned during a recording session. For each recording session, the exposure conditions were randomly assigned between subjects. Each subject was subjected to 10 on-off cycles at each modulation frequency in total and passed 2 recording sessions with microwave exposure and 1 sham recording. Two recording sessions with five cycles were planned to avoid too long recordings. All recording sessions lasted for 30 min, during which the resting eyes closed EEG was continuously recorded.

The EEG signals were recorded by Cadwell Easy II EEG measuring equipment (Kennewick, WA, USA). A standard EEG device was used without modification of leads. Recently published study on EEG electrode artifacts offer no support to concerns for enhanced induced fields or temperature increase around the electrodes in human EMF studies (Murbach et al., 2014). To record EEG, nine electrodes were placed on the subject's head according to the international classification system of 10–20-electrode position. Channels were selected to cover the entire head: frontal – FP1, FP2; temporal – T3, T4; parietal – P3, P4; occipital – O1, O2; and the reference electrode Cz. The EEG recordings were stored on a computer at the sampling frequency of 400 Hz.

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 human head (Hinrikus et al., 2008b). The resistances of EEG electrode contacts with phantom shell were close to these in the case of real head. The recordings on phantom were conducted in accordance with the procedure of the study. Multichannel recordings in frequency band 0.5–48 Hz detected spectral components at 7, 40 Hz (modulation frequencies) and 21 Hz (third harmonics of 7 Hz) in some of the channels. Spectral component at the third harmonics of the modulation frequencies was suppressed over −30 dB. No other spectral components were detected. The modulation frequencies and third harmonic were removed from the EEG analysis by filtering in preprocessing.

EEG analysis

Initially, the total EEG frequency band 0.5–48 Hz was selected in the EEG recorder. The powers of four EEG frequency bands, theta (4–6.8 Hz), alpha (8–13 Hz), beta1 (15–20 Hz) and beta2 (22–38 Hz), were selected for further analysis and extracted from the total EEG by filtering. Elliptic bandpass filters with an attenuation of 50 dB in the stopband were used.

Relative changes in the recorded EEG signal power between the cycle segments with and without radiation were selected as a measure for detection of the microwave effect (Hinrikus et al., 2008a; Hinrikus et al., 2008b). Parameter S_c as a relative change of the EEG power between the segments with and without microwave radiation of an arbitrary exposure cycle c was calculated as:

$$S_c = \frac{s_{s2} - s_{s1}}{s_{s1}} \times 100\% \tag{8}$$

where s_{s1} and s_{s2} are the average EEG powers within the exposure cycle segments without and with radiation, respectively. In sham recording, s_{s1} and s_{s2} are average EEG powers within odd and even minutes of the recorded signal. The average value of the EEG power s_{si} of an arbitrary 60-s EEG segment i was calculated as

$$s_{si} = \frac{1}{n}\sum_{r=1}^{24000} [v(r)]^2 \tag{9}$$

where $v(r)$ is the amplitude of the recorded signal in a sample r and 24000 is the number of samples in a 60-s segment. Relative changes in the recorded EEG signal power related to microwave radiation were calculated for each EEG channel e and subject m as averaging the relative change for a cycle S_c over 10 cycles:

$$S_{me} = \frac{1}{10}\sum_{c=1}^{10} S_c \tag{10}$$

Distribution of microwave effect in the head was calculated using the S_{me} values averaged over all subjects (m = 15) 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.

Signal processing and parameter calculations were performed in the LabVIEW (National Instruments, Austin, TX, USA) programming and signal processing environment.

Statistics

The nonparametric Mann–Whitney *U*-test was used for statistical evaluation of calculated S_{me} (formula 10) values for a group. The differences between the values achieved at various exposure conditions (sham–7 Hz, sham–40 Hz, sham–1000 Hz, 7–40 Hz, 7–1000 Hz and 40–1000 Hz modulation frequencies) were analyzed separately for each EEG frequency band. The Bonferroni correction for multiple comparisons at different exposure conditions and EEG frequency bands was applied and the confidence level 0.05 for corrected values was selected for evaluation.

Results

No alterations were detected in the recorded signal during a recording session on a passive phantom of human head.

Figure 3 presents alterations of power between exposed and nonexposed EEG signal segments caused by microwave radiation modulated at 7, 40 and 1000 Hz frequencies in different EEG frequency bands for a group of subjects. The results of calculation according to formula (8) were averaged over 10 exposure cycles, 8 EEG channels and 15 subjects. Modulated at 7 Hz, radiation causes small statistically insignificant increase of EEG power in alpha frequency band and no remarkable changes in other bands. Modulated at 40 Hz, radiation enhances significantly EEG power in alpha, beta1 and beta2 frequency bands but not in theta band. No obvious trends of alteration are related to modulated at 1000 Hz radiation in any band.

The results of statistical calculations are presented in Table 1. Statistical analysis indicates as significant alterations caused by 40 Hz modulation compared to sham, 7 and 1000 Hz modulation in EEG alpha, beta1 and beta 2 frequency bands. No significant differences between the various exposure conditions are revealed in

Table 1. Results of the Mann–Whitney *U* test with Bonferroni correction for comparisons between the sham, modulated at 7, 40 and 1000 Hz microwave exposed series for a group in the EEG theta, alpha, beta1 and beta2 frequency bands.

	p-Values			
	Sham	7 Hz	40 Hz	1000 Hz
		Theta		
Sham	N/A	1	1	1
7 Hz	1	N/A	1	1
40 Hz	1	1	N/A	1
1000 Hz	1	1	1	N/A
		Alpha		
Sham	N/A	0.18	0.0002	1
7 Hz	0.18	N/A	0.01	1
40 Hz	0.0002	0.01	N/A	0,001
1000 Hz	1	1	0.001	N/A
		Beta1		
Sham	N/A	1	0.001	1
7 Hz	1	N/A	0.003	1
40 Hz	0.001	0.003	N/A	0.001
1000 Hz	1	1	0.001	N/A
		Beta2		
Sham	N/A	1	0.0008	1
7 Hz	1	N/A	0.001	1
40 Hz	0.0008	0.001	N/A	0.0009
1000 Hz	1	1	0.0009	N/A

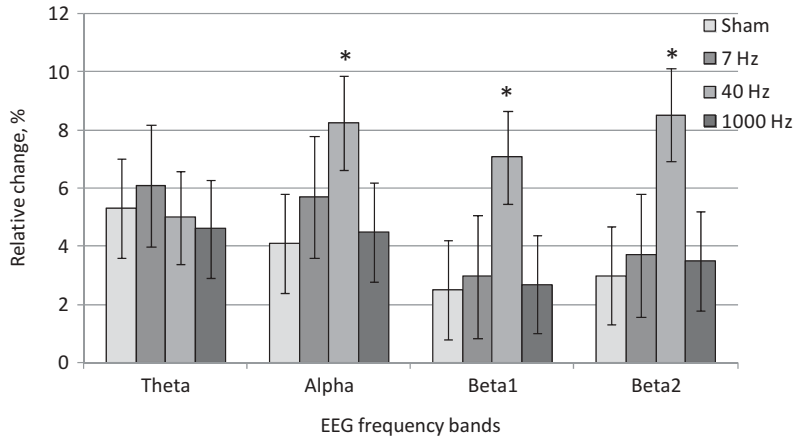

Figure 3. Relative changes in the EEG power as the parameter S_{cme} values calculated for theta, alpha, beta1 and beta2 EEG frequency bands averaged over all exposure cycles $c = 10$, EEG channels $e = 8$ and subjects $m = 15$ at four exposure conditions: sham, modulated at 7, 40 and 1000 Hz microwave radiation. Vertical bars denote standard deviation. Significant difference indicated by Bonferroni corrected $p < 0.05$ marked *.

theta band. No significant differences are indicated between sham and 7 or 1000 Hz modulations as well as between 7 and 1000 Hz modulations in any frequency band.

The effect of excitation by microwave radiation as relative enhancement of EEG power caused by modulated at 7, 40 and 1000 Hz microwave radiation compared to sham level is presented in Figure 4. The effect is maximal with modulated at 40 Hz microwave radiation in EEG beta2 (182%) and beta1 (183%) frequency bands and somewhat less in alpha band (102%). Weak effect of excitation caused by modulated at 7 Hz radiation appears in EEG alpha band (39%). All other bars are lower than 23%. No excitation is revealed with modulated at 1000 Hz radiation.

The plane image of the distribution of the excitation effect on the cortex of human brain caused by modulated at 40 Hz microwave radiation in EEG beta1 band power is presented in Figure 5A. The distribution of SAR in the cross section of specific anthropomorphic mannequin of human head as calculated using SEMCAD software is presented in Figure 5B. Comparison of two pictures demonstrates similarity between distributions of SAR and enhancement of EEG power caused by microwave radiation.

Discussion

According to the theory, modulated at 7 Hz, microwave radiation can cause excitation of EEG power inside the first parametric resonance zones of instability at central frequencies of 1.75, 3.5, 5.25, 7, 8.75, 10.5, 12.25, 14 Hz and higher. Keeping in mind decreasing effectiveness with increasing zone number and EEG signal frequency band selected for analysis (frequencies of 1.75, 3, 5, 7 and 14 Hz are filtered off), the microwave effect is expected at 5.25, 8.75, 10.5, 12.25 Hz, beginning from the third zone of excitation. Therefore, enhancement of

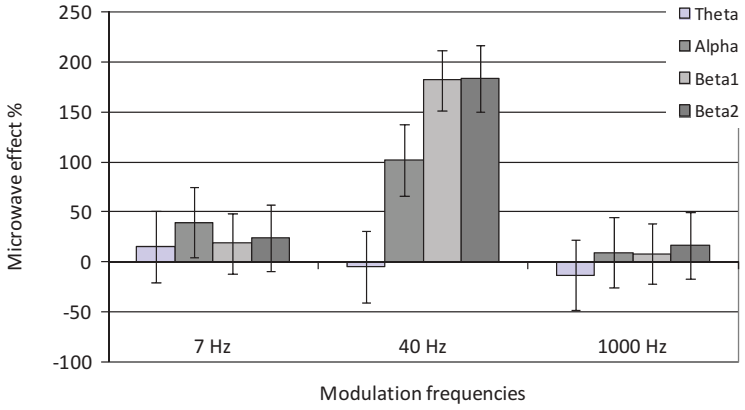

Figure 4. Quantity of the microwave effect as relative difference of changes (parameter S_{me}) between exposed (S_{exp}) and sham (S_{sh}) series calculated as $(S_{exp} - S_{sh})/S_{sh}$ and averaged overall EEG channels and subjects for theta, alpha, beta1 and beta2 EEG frequency bands. Vertical bars denote standard deviation.

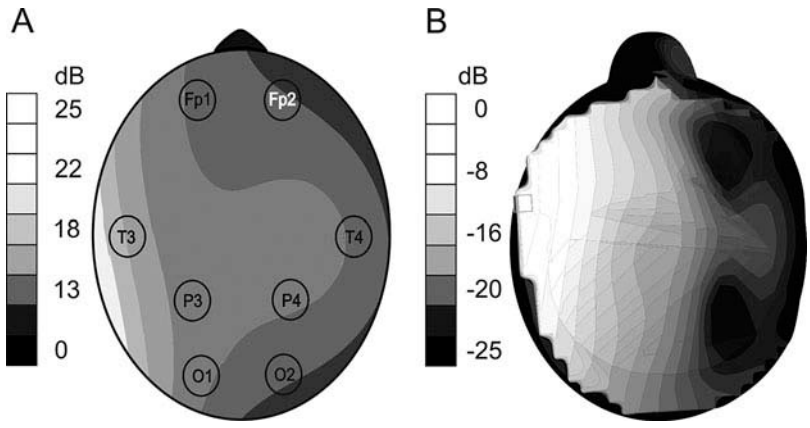

Figure 5. (A) Distribution of microwave effect as relative difference between alterations at 40-Hz modulated microwave exposure and sham conditions in EEG beta1 frequency band averaged over all subjects; and (B) calculated SAR distribution in the SAM cross section. 0 dB corresponds to 0.303 W/kg.

EEG power is possible in EEG theta (5.25 Hz) and alpha (8.75, 10.5, 12.25 Hz) frequency bands. This conclusion is supported by experimental finding: Figures 3 and 4 show that modulated at 7 Hz, microwave radiation causes increase of EEG power in theta and alpha bands. However, due to low intensity of excitation in higher zones of instability, the alterations are not statistically significant in any EEG band even despite that EEG alpha band covers three zones of instability.

Modulated at 40 Hz, microwave radiation can cause excitation of EEG power inside the first parametric resonance zones of instability at central frequencies of 10, 20, 30, 40 Hz and higher. Selection of EEG frequency bands for further analysis excluded 40 Hz by filtering. Therefore, enhancement of power is expected in EEG alpha (10 Hz), beta1 (20 Hz) and beta2 (30 Hz) frequency bands. Experimental findings support this conclusion: Figures 3 and 4 indicate that modulated at 40 Hz, microwave radiation causes increase of EEG power in alpha, beta1 and beta2 frequency bands. The data, related to the first three zones of instability, differ significantly from the sham data and data at 7 and 1000 Hz modulation frequencies.

The theory of parametric excitation predicts resonance zones of instability for microwave radiation modulated at 1000 Hz at central frequencies of 250, 500, 750, 1000 Hz and higher. These frequencies are much higher than EEG spectrum and excitation of EEG power is highly unlikely. Experimental findings support this conclusion: Figures 3 and 4 show no enhancement of EEG power related to microwave radiation modulated at 1000 Hz.

However, the results of the performed EEG experiment support only the final outcome of the proposed mechanism on the neurophysiologic level – the parametric nature of excitation of brain bioelectric oscillations. The validity of foregoing steps of the proposed theoretical network of the mechanism needs additional discussion.

First, microwave radiation really rotates dipolar water molecules and causes polarization of living tissues; the relative permittivity of water is higher than the vacuum permittivity in large diapason of frequencies up to gigahertz (Foster and Schwan, 1996). There are no doubts that low-level microwave radiation causes rotation of dipolar water molecules.

Second, rotation of dipolar molecules obviously disturbs the structure of bonds and causes weakening of hydrogen bonding forces (Figure 1B). Whereas thermal Brownian movement permanently transforms hydrogen bonds, the effect of perturbation by microwave radiation is weak. The suitable for microwave frequencies time constant (1 ps) and the perturbation of hydrogen bonds in external microwave field have been demonstrated using molecular dynamics simulations (Lucar and Chandler, 1996; Solomentsev et al., 2010). There are no frequency limitations for microwave effect on hydrogen bonding up to gigahertz. Consequently, rotation of dipolar water molecules by low-level microwave radiation really can affect hydrogen bonds.

Third, hydrogen bonds are major factor determining viscosity and boiling temperature of water (Petrucci et al., 2007). Weakening of bonding forces, accompanied with decreasing of water viscosity, causes increase of diffusion (Fick's law, formula (1)). Direct measurement of the effect of microwave radiation on diffusion in the brain using fMRI technology is hardly possible because the gradient electric fields, creating much stronger field strengths in the brain, veil the microwave effect. The differences between processes caused by conventional heating and microwave-stimulated heating have been indicated by several authors in various microwave processing technologies and chemistry (Antonio and Deam, 2007; Boon et al., 2007; Bonifas et al., 2008; Galinada and Guiochon, 2007). Microwave chemistry has explored microwave effects on diffusion processes at high temperatures. The enhancement of diffusion in NaCl water solution caused by low-level microwave radiation at constant temperature was demonstrated in our previous experimental study (Hinrikus et al., 2014). Consequently, rotation of dipolar water molecules by low-level microwave radiation enhances diffusion.

The discussion above shows that the main foregoing steps of the mechanism are based on the fundamental knowledge or supported earlier by independent studies.

The important role of diffusion in physiologic and particularly in neurophysiologic processes, e.g. in synaptic transmission, doesn't need additional proof. However, the changes caused by low-level microwave radiation in hydrogen bonds, diffusion and neurophysiologic parameters are weak. Therefore, only modulated microwave radiation, able to cause periodic alterations of the physiologic parameters and "amplification" of the effect by parametric resonance can result in detectable microwave effects. The importance of modulation and dependence of the microwave effect on modulation frequency was reported by Ross Adey team already in classical experiments on calcium efflux (Byus et al., 1984; Lin-Liu and Adey et al., 1982). The crucial role of modulation in microwave effects on cerebral blood flow is underlined in the studies applying the modulation similar to the signals from the global system for mobile communications (GSM)

(Huber et al., 2002, 2005). The experiments with a single-frequency-modulated microwave radiation demonstrated clearly that the effect on EEG depended on modulation frequency (Hinrikus et al., 2008a). The theory of parametric excitation was demonstrated being appropriate for interpretation of the modulated microwave effect on EEG (Hinrikus et al., 2011).

The experimental findings reported by many authors have demonstrated that low-level-modulated microwave radiation induces alterations in the waking and sleep EEG, cognitive performances and brain physiology (Huber et al., 2002, 2005; Krause et al., 2007; Hinrikus et al., 2008a; Lowden et al., 2011; Leung et al., 2011; Lustenberger et al., 2013, 2015; Regel et al., 2007; Veccio et al., 2007, 2010). However, the use of GSM as a source of exposure in many studies makes complicated the evaluation of results in accordance to the mechanism of parametric excitation due to complex structure of modulation frequencies (2, 8, 217, 1736 Hz and the corresponding harmonics). The increase of EEG alpha band power, reported by some authors, can be related to 8 Hz frequency component of GSM signal (expected effect at 4, 8, 12, 16 Hz frequencies). However, an alternative explanation is possible: small microwave effect is more easily detectable in the EEG band of highest power – alpha band. The application of more sensitive method for detection of small alterations in resting EEG, method of integration of differences over 10 cycles of exposure, provided detection of significant enhancement not only in alpha but also in beta band; the stimulation in the EEG frequency bands lower or close to the modulation frequencies of 14 and 21 Hz support the hypothesis of parametric excitation (Hinrikus et al., 2008a). The stimulation of the brain during sleep by modulated at 2 Hz microwave radiation caused increase of the sleep EEG in theta–delta band 1.25–9 Hz but no effect in the EEG spindle activity band 13.75–15.25 Hz (Lustenberger et al., 2013, 2015). Excitation of EEG power in theta–delta band (first expected zones of instability 1, 2, 3, 4 Hz) and no effect in the spindle activity band seems support the proposed mechanism. However, the modulation with short pulses, used in these sleep studies, causes high level of harmonics and creates wide spectrum of the modulation signal limited by 20-Hz low-pass filter (Lustenberger et al., 2015; Schmid et al., 2012). Therefore, the estimation of the detailed structure of the zones of instability is not possible; the excitation is expected inside the whole EEG activity band. On the other hand, the spindles as a very strong neurophysiologic factor can depress a weak microwave effect in 13.75–15.25-Hz band. The studies on sleep EEG, as planned in the cited publications, provide hardly possibility for evaluation of the proposed method. The enhanced brain connectivity related to GSM-like exposure (Veccio et al., 2007, 2010) is supportive to the idea of parametric excitation where synchronous excitation in all brain areas is expected.

The current study supports the results of our previous study (Hinrikus et al., 2011): we are able to predict EEG frequencies which are expected to be excited by modulated microwave radiation – it is a considerable support for the whole mechanism. Once it may be a coincidence or chance, but replication of the experiment at slightly changed conditions (two modulation frequencies, most and less sensitive, tested previously on different groups, are now tested on the same group) and getting similar results is stronger support.

The effect of modulated microwave radiation on nervous activity creates a perspective for noninvasive stimulation of nervous system. Further investigations in this direction are necessary.

The structure of modulation of microwave radiation is important not only in considering neuronal oscillations. Microwave radiation with an arbitrary structure of modulation and even continuous wave radiation can enhance diffusion. The reported by Volkow et al. (2011) increased brain glucose metabolism caused by cell phone radio-frequency signal exposure in the region closest to the antenna can be explained by enhanced diffusion in this brain area. Proposed model of low-level EMF effect is not limited to microwave radiation. Polarization of water molecules and consequently perturbation of hydrogen bonds with related alterations in diffusion and neurophysiologic parameters takes place in large range of EMF frequencies. Therefore, the proposed mechanism can be useful for interpretation of the effect of electrical stimulation on nervous system in wide frequency range of the applied EMF.

The intramolecular bonding like hydrogen bonds can occur not only in inorganic molecules such as water but also in organic molecules like DNA and proteins. The effect of EMF on bonding of bipolar molecules and its physiological consequences need wider investigation.

Conclusions

The proposed mechanism of low-level microwave radiation effect on nervous system bases on the existing knowledge: rotation of water molecules, related to that perturbation of hydrogen bonds and alteration in diffusion. Alterations in diffusion affect neurophysiologic parameters as neurotransmitters transit time and

neuron resting potential. Periodic alteration of the neurophysiologic parameters caused by modulated microwave radiation is expected to result in parametric excitation of brain bioelectric oscillation. Experimental results with a low-level 450-MHz microwave radiation pulse-modulated at 7, 40 and 1000 Hz showed a statistically significant enhancement of the EEG power in alpha, beta1 and beta2 frequency bands at 40 Hz and no significant effect at 7 and 1000 Hz modulation frequencies. The experimental results are in agreement with the nonlinear theory of parametric excitation of the brain bioelectric oscillations inside first zones on instability. The proposed theoretical framework predicts the results of experimental study. The suggested mechanism, free of the restrictions related to field strength or time constant, is the first one providing explanation of low-level microwave radiation effects.

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Declaration of interest

The authors report no conflicts of interest. The authors alone are responsible for the content and writing of the paper.

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