Estonian Journal of Engineering, 2008, **14**, 2, 91–106 doi: 10.3176/eng.2008.2.01

Effect of modulated microwave radiation on electroencephalographic rhythms and cognitive processes

Hiie Hinrikus, Maie Bachmann, Jaanus Lass and Viiu Tuulik

Department of Biomedical Engineering, Technomedicum of the Tallinn University of Technology, Ehitajate tee 5, 19086 Tallinn, Estonia; hiie@cb.ttu.ee

Received 8 January 2008, in revised form 5 March 2008

Abstract. This paper is a review of the studies performed on microwave effects on resting electroencephalography (EEG) and visual memory and information processing during the last ten years. Some earlier results, obtained at the Biomedical Engineering Centre of the Tallinn University of Technology are reevaluated and generalized. Microwave radiation of 450 MHz, modulated at 7, 14, 21, 40, 70, 217 and 1000 Hz was applied. The calculated spatial peak SAR, averaged over 1 g, was 0.303 W/kg. The developed new methods of EEG analysis can detect small changes in the EEG signals caused by microwave exposure. Microwave exposure causes most remarkable increase in the EEG alpha power (reported also by other authors) and smaller increase in the beta power, detected by sensitive methods. The obtained results showed that the effect of microwave radiation depends on the modulation frequency and, consequently, has non-thermal origin. Sensitivity to microwave esposure is individual, the rate of the subjects significantly affected was 13–30% for different groups. The physiological adaptation of the brain compensates and even overcompensates the effect of the microwave exposure. The results confirm that the microwave effect is not linearly related to the intensity of the applied field. The changes in human performance of visual memory tasks and visual information processing are small, but statistically significant ($p < 0.05$).

Key words: electromagnetic field, modulated microwaves, EEG rhythms, memory, attention, adaptation.

1. INTRODUCTION

Effect of the microwave radiation on the bioelectrical activity of the human brain has become of major interest with increasing application of telecommunication devices. On the other hand, successful application of transcranial electric and magnetic stimulation in brain research and neurotherapy have initiated interest in the possible influence of electromagnetic fields of different frequencies. During the recent decade, discussions have been focused on the effects of low-level microwave radiation on the human EEG signal and on the cognitive effects [1]. Several investigators have reported that exposure to low-level microwaves produces alterations in the resting or sleep EEG signal and brain behaviour [2–10]. Pulse-modulated EMF exposure enhanced EEG power in the alpha frequency range [9,10]. Exposure to EMF without pulse modulation did not enhance waking or sleep EEG power [10]. The exposure to EMF modulates the response of the EEG oscillatory activity in the 6–8 and 8–10 Hz frequency bands differently during cognitive processes [11]. However, some authors were unable to confirm their previous findings in their later studies [12,13]. In [11,14] it has been found that the exposure to microwaves does not alter the resting EEG. In [15] the authors conclude that microwaves, emitted by mobile phones, have effect on brain oscillatory responses during cognitive processing in children. Several authors have demonstrated that exposure to pulse-modulated microwaves alters not only the EEG but also regional cerebral blood flow [10,16]. However, difficulties experienced in independent repetition of these experiments have caused doubts concerning these effects; moreover, mechanisms behind the effects are still unclear.

In experiments with human volunteers, microwave exposure has been reported to correspond to that of an average GSM cellular phone [4–6,9,12,16,17]. Such a pulse-modulated radio frequency exposure consists of 900 MHz carrier radio frequency and includes low-frequency modulation components of 2, 8, 217 and 1736 Hz and corresponding harmonics [10]. Application of cellular phones as sources of radiation provides no possibility to evaluate such important characteristics of the effect as dependence on the modulation frequency and on the level of radiation power density, etc.

There are different reasons for difficulties by identification of microwave effects on EEG and cognitive processes, some of which are listed below.

1. Microwave exposure as a weak physical stressor causes only small changes in EEG and the effect is hidden in natural variability of the EEG signal.
2. Mechanism of the microwave effect is still unclear and therefore its interpretation is complicated.
3. Cellular phone, used as a source of radiation in most of experiments, has a complicated frequency spectrum. Therefore, clarification of the role and effect of each modulation frequency is impossible.
4. Effect of the microwave exposure is individual. Therefore it is difficult to get statistically significant result for a group of individuals.
5. The brain has the ability of physiological adaptation to an external stressor. This brain behaviour decreases or even compensates the effect of the stressor.
6. Variations in the microwave power density inside the brain tissues may be important.
7. Variability of the physiological states of the brain causes significant differences in the sensitivity to an external stressor.

In this paper we present an overview and analysis of the main results of papers [7,8,18–31]. Investigations were aimed first of all to the selection and development of methods, sensitive to small hidden changes in the EEG signal. We decided to evaluate the effect of a microwave radiation, modulated at certain fixed frequencies, and not to apply the GSM signal with a complex spectrum. Modulation frequencies within the EEG spectrum of 7, 14, 21 and 40 Hz as well as of 70, 217 and 1000 Hz were used. Such a spectrum provides more information for the interpretation of possible mechanisms of the effect. We took into account individual sensitivity of subjects and performed statistical analysis not only for groups but also for individuals. In parallel we tried to evaluate physiological adaptation of the brain to microwave exposure and to investigate changes in the effect at different levels of the microwave power. Under the same exposure conditions we evaluated changes in human performance in visual memory tasks and in processing of visual information.

2. METHODS

2.1. Subjects

The experiments on resting EEG were carried out on five different groups of young healthy volunteers. The first group, exposed at 7 Hz modulation, consisted of 23 persons (aged 21–24 years) 12 male and 11 female; the second group, exposed at 7, 14 and 21 Hz modulation, consisted of 13 persons (aged 21–30), 4 male and 9 female; the third group, exposed at 40 and 70 Hz modulation, consisted of 15 persons (aged 21–24), 8 male and 7 female; the fourth group, exposed at 217 and 1000 Hz, consisted of 19 persons (aged 21–24), 8 male and 11 female and the fifth group, exposed at 40 and 1000 Hz modulation, consisted of 7 persons (aged 19–21), 3 male and 4 female.

The laboratory room was dark and during experiments the subjects were lying in a relaxed position, eyes closed and ears blocked. The subjects reported neither alertness nor any strain, experienced during the recordings. All subjects passed the experimental protocols with exposure and sham. The subjects were not informed about their exposure during the experiment, however, they were aware of the possibility of being exposed. Only one experimental EEG recording was performed for a subject during a day.

The experiment on visual memory was performed on a group of 100 subjects (aged 18–25), 63 male and 37 female, at the modulation frequency of 7 Hz. In the study with the method of face masking were involved 10 subjects (aged 19–32), 4 male and 6 female, at modulation frequency of 7 Hz.

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

2.2. Microwave exposure

Microwave exposure had the same frequency of radiation and field power density in all the studies, only the modulation frequency was varied: 7 Hz for the first, 7, 14 and 21 Hz for the second, 40 and 70 Hz for the third, 217 and 1000 Hz for the fourth and 40 and 1000 Hz for the fifth group of subjects in experiments on resting EEG. Exposure conditions were the same for all subjects in the group.

The 450 MHz electromagnetic radiation was generated by the Rhode & Swartz signal generator model SML02. The RF signal was 100% pulse-modulated by the pulse modulator SML-B3, duty cycle 50%. Such a selection of modulation provided stability of the average energy at all modulation frequencies. The signal from the generator was amplified by the Dage Corporation power amplifier model MSD-2597601. The 1 W (10 W for the fifth group) electromagnetic radiation output power was guided by a coaxial lead to the 13 cm quarter-wave antenna NMT450 RA3206, located at 10 cm from the skin on the left side of the head.

The spatial distribution of the electromagnetic radiation power density was measured with the Fieldmeter C.A 43 field strength meter. The measurements were performed by the Central Physical Laboratory of the Estonian Health Protection Inspection. During the experiments, the stability of the electromagnetic radiation level was monitored by the IC Engineering Digi Field C field strength meter. Estimated from the measured calibration curves, the average field power density of the modulated microwave on the skin of the left side of the head was 0.16 mW/cm^2 (1.6 mW/cm^2 for one recording protocol). The specific absorption rate (SAR) was calculated using software SEMCAD. 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 [30].

2.3. Resting EEG: recording protocol and equipment

The experimental studies on resting EEG were performed according to the recording protocol, identical for all subjects. All subjects completed the sessions with microwave and sham exposure, during which the resting, eyes-closed EEG was continuously recorded.

The subject was exposed to the microwave at the fixed modulation frequency during every even minute of the recording. The pair of a reference minute followed by the exposed minute constituted an exposure cycle. Ten cycles at the fixed modulation frequency were performed for each modulation frequency (Fig. 1). The first ten exposure cycles were performed at the first and the next ten cycles at the second modulation frequency. A computer randomly assigned the succession of modulation frequencies during recordings. Selection of 40 or 70 Hz and 217 or 1000 Hz as the first and second modulation frequencies was also randomly assigned. Ten exposure cycles were applied for the first group, where

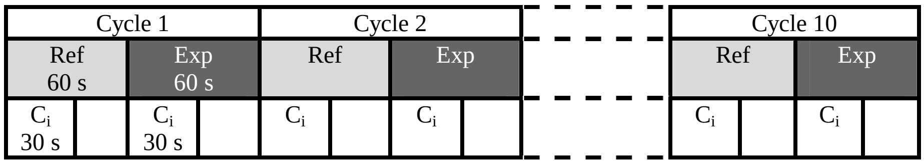

Fig. 1. The recording protocol: Ref and Exp denote segments of an exposure cycle without and with the microwave radiation, C_i denotes the comparison interval for the analysis.

only the 7 Hz modulation frequency was applied after the short-term (20 s) photic modulation. At modulation frequencies of 7, 14 and 21 Hz, two exposed recording sessions were performed, five cycles of exposure at every frequency during each session.

Sham recording session used the same protocol, except that the microwave power was switched off.

The Cadwell Easy II EEG measurement equipment was used for the EEG recordings. The EEG was recorded using 9 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. The EEG recordings were stored in a computer with a 400 Hz sampling frequency.

2.4. Resting EEG: preprocessing

The powers of four basic EEG frequency bands, theta (4–6.8 Hz), alpha (8–13 Hz), beta1 (15–20 Hz) and beta2 (22–38 Hz), were extracted from the total EEG (0.5–48 Hz) by filtering. Elliptic bandstop filters with an attenuation of 50 dB in the stopband were used. Such a selection of the EEG frequency bands excluded the frequencies of 7, 14, 21 and 40 Hz and also possible related artifacts from the analysis. The pre-processing of the signals was performed in the LabVIEW programming and signal-processing environment. The energies of different EEG rhythms were analysed separately.

2.5. Resting EEG: methods of EEG analysis

Microwave exposure as a weak physical stressor causes only small changes in the EEG and the effect is hidden in the natural variability of the EEG signal. Quantitative analysis of the changes in the dynamics of the EEG is complicated due to the irregular nature of the EEG signal.

Our attempts to detect the effect of microwave radiation on human EEG showed that some traditional methods of the EEG analysis, such as quantitative EEG and bispectrum or fractal dimension, did not provide reliable distinction of the microwave effect. Two original methods, sensitive to small changes in the EEG signal, were developed and proved most effective [18–20].

The method of integration of differences (ID) uses modulation with following integration of the energy of the recorded signal of EEG segments with and without stressor [18,20]. The method consists of several steps. Firstly, the average energy of the signal inside a selected comparison segment in a time-window T is calculated. Secondly, relative differences in the average energies in comparison segments without and with exposure for every cycle, are calculated. Thirdly, integration of the differences over ten cycles of exposure for a subject n is applied and characteristic parameter S_n at the fixed modulation frequency calculated.

Multifractal method of scaling analysis, based on the length distribution of low variability periods (LDLVP), was adopted for EEG analysis. The LDLVP method provides a simple way for detecting the multifractal characteristics of a time-series and yields better temporal resolution than the traditional multifractal analysis [19]. Firstly, we define the local average of the signal in the time-window T. Secondly, we define the local variability as the deviation of the current value of the signal from the local average $\delta V(t)$. Thirdly, the low-variability periods are defined as continuous intervals with variability within limits δ_0, $\delta V(t) < \delta_0$. Finally, the number of low-variability periods N, exceeding the length of low-variability periods T_0, is plotted versus the length T_0. The weighted area under the curve of the function $T_0 = T_0(N)$ was selected as the non-linear quantitative measure.

2.6. Resting EEG: calculation of adaptation

Adaptation parameter as the relative change in the EEG energy between the reference segment and the segment with exposure was selected as a measure of the brain adaptation to microwave exposure. Segments for comparison were selected as the first 20 s from the mean of 2 reference minutes and the first 20 s from the exposed minute [21]. For the following comparisons, the reference segment remained constant and the exposed segment was shifted in time with a step of 4 s up to the end of exposed minute. As a result, for each exposed minute there were 11 pairs of comparison segments. The results of calculations were averaged over ten exposure minutes. The same calculations were performed for recovery segments of the exposed recordings and for odd and even minutes of the sham sessions.

2.7. Visual memory tasks

In the experiment on human performance in visual memory tasks, a set of three different tests concerning attention and short-term memory was used [7]. Task 1 (the trail-making test) involved selecting alternately black digits from 1 to 25 in ascending and white digits from 24 to 1 in descending order. The time spent on the task and the number of errors were recorded and analysed. Task 2 involved viewing a picture of 12 objects during 3 s, followed by a list of 24 words. The subjects were required to select words, representing previously presented objects. In the task 3 (correction test), an array of letters in 10 rows (60 in each row) was presented, and the subject was required to identify all examples of a particular two-letter combination. Special software was elaborated to present the tasks and to register right and wrong answers.

2.8. Visual masking

In the experiment on face masking the subjects were presented two photos of an unfamiliar young male face one after another (visual stimuli during 40 and 20 ms) and the task was to identify the pictures from a group of six photos [22]. The phenomenon of visual masking is revealed as anamorphosis in subject's perception of two instantaneous visual stimuli, presented within a short time interval. The responses were grouped into eight categories, regarding correct identification of the faces and the order of their presentation. The tests for a subject were performed in 16 sessions, using the pseudo-random distribution of the sessions with the microwave and the sham exposure, so that finally each subject made 8 sessions with exposure and 8 sessions without exposure (sham exposure). Each set consisted of 50 trials, altogether one subject made 800 trials, 400 with and 400 without the microwave exposure. Special software was elaborated to present two human face photos as visual stimuli and to register subject's ability to identify the images afterwards.

3. RESULTS AND DISCUSSION

3.1. Modulation frequency 7 Hz

Resting EEG, visual memory and masking tasks were performed at the modulation frequency of 7 Hz. Application of short-term photic simulation and ten cycles of the microwave stimulation resulted in obvious changes in the EEG, caused by both, photic and microwave exposure in comparison with sham: averaged over whole group bars differed in all EEG channels (Fig. 2) [8]. Nevertheless, no statistically significant changes caused by photic or microwave exposure were detected in the average EEG energy for the group. Microwave exposure caused statistically significant increase in the standard deviation of the EEG energy. The changes, caused by the microwave exposure, were statistically significant for three subjects.

The results of the visual memory and attention task 1 (trail-making test) indicated an increase of wrong answers in the exposed group (Fig. 3) [7]. However, the results of tasks indicated no significant differences in the means of the exposed and sham-exposed groups, but the variances of errors differed significantly. Tasks 1 and 3 (correction) showed a significant increase in the variances of errors ($p < 0.05$) in the exposed group in comparison with the sham-exposed group. The results of the task 2 indicated significant decrease in errors

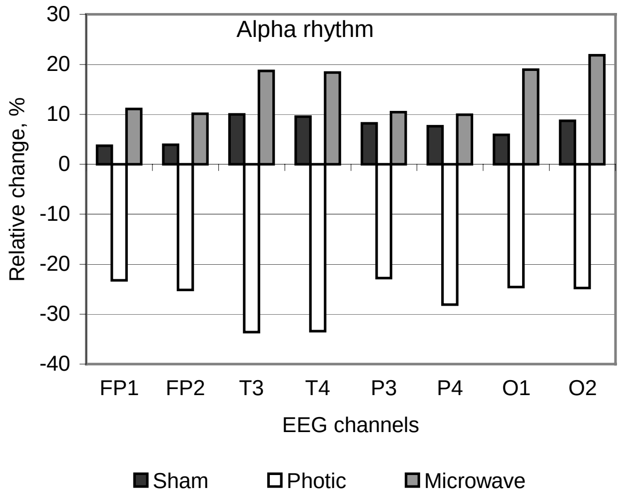

Fig. 2. Influence of the photic and microwave exposure on the EEG alpha rhythm power in different EEG channels at 7 Hz modulation frequency (first group).

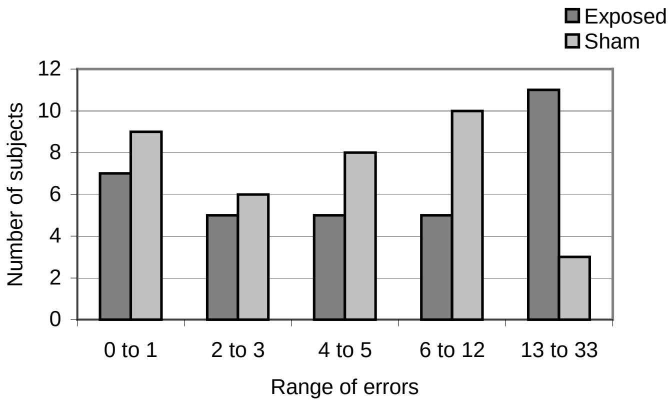

Fig. 3. Histogram of errors made during task 1 (trail-making test) with and without (sham) microwave exposure.

($p < 0.05$) in the exposed group. From these results we can conclude that the effect of microwave exposure depends on the level of complexity of the tasks and is more remarkable in more complicated tasks.

The face-masking task demonstrated that recognition of both stimuli in a pair was better ($p < 0.05$) under the sham-exposure conditions, but the actual difference in comparison with answers in exposed conditions was only 5% [22].

3.2. Modulation frequencies 7, 14 and 21 Hz

Dependence of the microwave effect on the modulation frequency was evaluated at modulation frequencies within the EEG spectrum [23,24]. Values of relative changes of the effect, caused by modulated at 7, 14 and 21 Hz microwave exposure in the EEG theta, alpha, beta1 and beta2 power, averaged over the whole group, are presented in Fig. 4. The microwave exposure caused significant enhancement of the average EEG power in the alpha and beta frequencies. Changes in the alpha power were about twice higher than in the beta power. The effect was statistically significant. No effect was observed at the theta band frequencies.

The effect of the microwave modulated at fixed low frequency differs at different modulation frequencies. Whereas duty cycle of the pulse modulation is 50%, the energy of microwave radiation is constant at all modulation frequencies. Therefore the origin of the effect should be different from heating. An explanation of the quasithermal mechanism of the microwave effect was given in [25–27]. The microwave field (electric field of 1 V/cm) can introduce a disturbance of the thermal equilibrium inside tissues, which is equivalent to the temperature rise of 1 K on the cell of 10 mm radius [26].

Increase in the EEG power became evident at the EEG band frequencies lower than the modulation frequency or close to it. The results show that the EEG alpha and beta1 power levels increase at 14 Hz and the EEG alpha, beta1 and beta2 power levels increase at modulation frequencies 21 Hz. This finding indicates the possibility of parametric excitation of the oscillations in the brain by the external periodic stimulation. No significant changes in the EEG were detected at the 7 Hz modulation frequency. According to the above hypothesis, only the EEG theta band can be affected by microwaves at the 7 Hz modulation frequency. Experimental data indicated no significant changes in the EEG theta

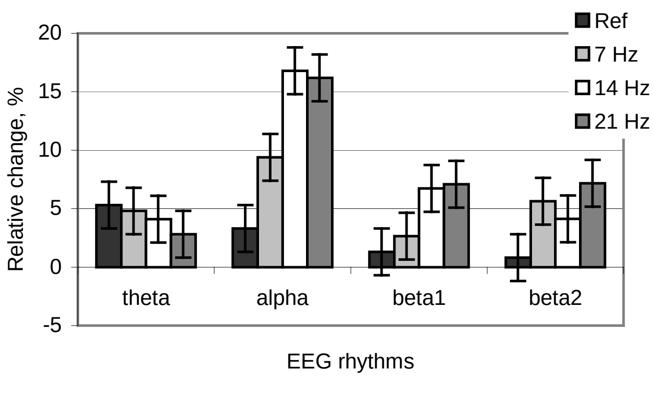

Fig. 4. Percentage of relative change in the EEG theta, alpha, beta1 and beta2 power at a fixed modulation frequency averaged over 10 cycles; all subjects and EEG channels for the four different exposure conditions (reference, 7, 14 and 21 Hz) in exposed and sham recordings (second group).

band at all. A possible explanation is that sources of the EEG theta rhythms are located in deeper brain layers and are therefore more shielded from the external fields.

The changes were more obvious at the beginning of the exposure segments [[23]]. The decrease of the changes within an exposure time (1 min) can be explained by the physiological adaptation of the brain to the weak external stressor.

3.3. Individual sensitivity at 7, 14, 21, 40, 70, 217 and 1000 Hz modulation

The changes caused by microwave exposure in the EEG differed for different subjects in all groups and at all modulation frequencies [[8,19,28–30]]. However, in the case of significantly affected subjects the microwave exposure always enhanced the EEG power. An example of different sensitivity of subjects to microwave exposure is presented in Fig. 5.

Statistical evaluation of individual sensitivity to microwave exposure for a subject was performed by comparison of the changes, caused by the exposure in the EEG of the subject, with the standard deviation of the changes in sham recordings for a group.

Numbers of subjects with statistically significant changes ($p < 0.05$) in the EEG, analysed by the LDLVP and ID methods, are presented in Table 1. Within some groups the EEG signals of the subjects were analysed by both LDLVP and ID methods. The subjects for whom the changes in the EEG were significant in the analysis by the ID method were detected as significantly affected also by the LDLVP method. The rate of persons, sensitive to modulated microwaves, 13–26%, is even higher than the rate of persons of multiple chemical sensitivity, estimated to be between 2 and 10% in the general population [[32]].

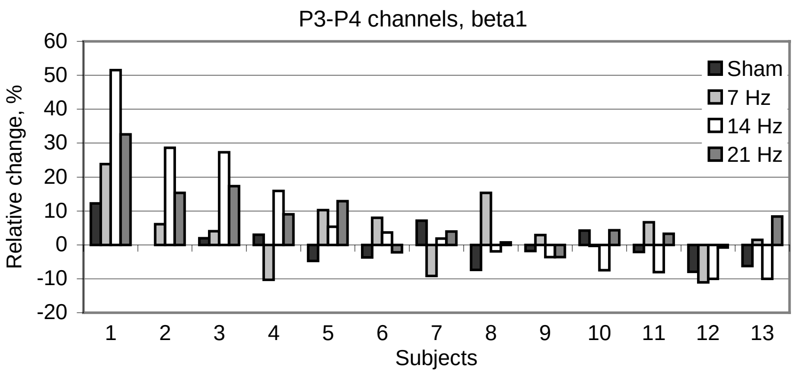

Fig. 5. Relative change in the EEG power at modulation frequencies of 7, 14 and 21 Hz for individual subjects averaged over 10 cycles in P3-P4 channels (second group).

Table 1. Number of subjects, significantly affected by microwave exposure at different modulation frequencies

ID method				LDLVP method		
Modulation frequency, Hz	Total number of subjects	No of affected subjects	Rate of affected subjects, %	Modulation frequency, Hz	No of affected subjects	Rate of affected subjects, %
7	23	3	13	7	6	26
7	13	0	0	*	*	*
14	13	4	31	*	*	*
21	13	3	23	*	*	*
40	15	3	20	40	4	27
70	15	2	13	70	2	13
217	19	3	16	217	5	26
1000	19	0	0	1000	0	0

Sensitivity of some subjects to the exposure of microwaves is most likely related not to hypersensitivity of these individuals but to the variability of the physiological state of the brain. Human brain is a highly complicated chaotic system and is simultaneously affected by hundreds of physical, chemical, psychological etc. stressors. Microwave exposure is one of these. Effect of microwave exposure as a weak stressor depends on the combination of other stressors and state of the brain. This idea was supported by our results on two groups at 7 Hz modulation. The first group was subjected to photic stimulation before the microwave exposure and 6 subjects were significantly affected by the microwave exposure [19]. The second group was not subjected to photic stimulation and none of the subjects was significantly affected by the microwave exposure at 7 Hz modulation [23].

The effect of the exposure on a subject depends on its physical condition and may vary from day to day. The rate of subjects, affected during an experimental session, depends on the physiological states of their brains at this time. Repeatability of the effect is not high due to the variation of many coexisting factors. Similar situation takes place in the case of the effects caused by alcohol. An increased EEG beta power has also been observed in alcohol-dependent subjects [33].

3.4. Adaptation at 40 Hz modulation

The adaptation curves were different for exposed and not exposed subjects [21]. As expected, alpha and beta powers do not change much compared to the reference level during the sham recordings and the average values of the adaptation parameters stay near the zero level for even and uneven minutes.

The results of calculations of the adaptation parameter at the 40 Hz modulation frequency, averaged over the group of 14 subjects, indicated an increase in the alpha power with some delay in the beginning and a decrease after the exposure period (recovery onset). However, relative values of the changes are comparable with those for the sham signals.

The most evident specific changes in adaptation curves emerge in the beta power (Fig. 6). The beta power increases considerably in the first half of the exposure period, after that it decreases crossing the zero level and becomes even less than the reference value. Such a curve demonstrates ability of the brain to adapt to the weak stressor and to compensate and even overcompensate the initial effect.

Calculated average values of the changes of the adaption parameter and results of statistical evaluation are presented in Table 2. Two-tailed paired Student t-test was performed to evaluate the adaptation parameter differences between the exposed and recovery or even and uneven minutes of the exposed and sham recordings.

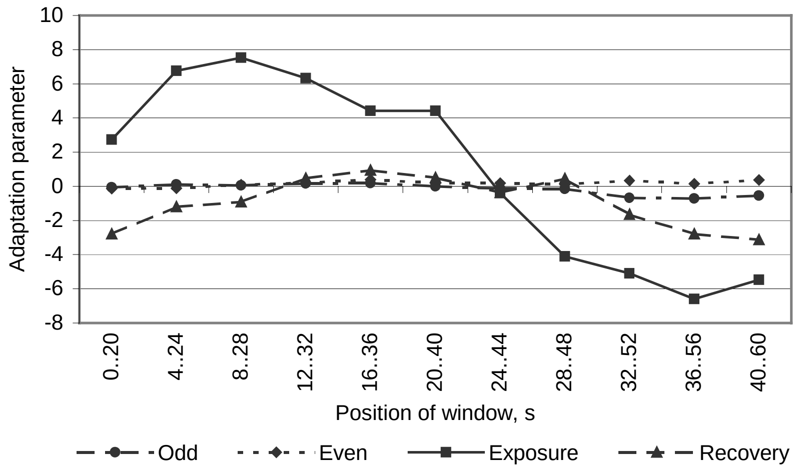

Fig. 6. Mean values of the adaptation parameter in the beta rhythm, calculated for time-shifted windows for a group of 14 subjects for exposed and recovery minutes of the recordings with microwave exposure at 40 Hz modulation frequency and odd and even minutes of the recordings with sham exposure.

Table 2. Average values of differences between adaptation parameters for the exposed and recovery minutes in recordings with microwave exposure (MW) and even and uneven minutes in recordings with sham exposure for a group of 14 subjects (7 male and 7 female); modulation frequency 40 Hz

	Change		*p*
	MW	Sham	
Alpha	0.71	0.27	0.0026
Beta	4.48	0.38	0.0004

The results show that adaptation effect of human brain to low-level microwave exposure is evident. The initial increase of the EEG power was compensated and even overcompensated. The adaptation phenomena were obvious in EEG alpha and beta rhythms.

3.5. Higher power density at 40 and 1000 Hz modulation

The experiments were performed on the fifth group of subjects (7 persons), exposed to the microwave (power density of 1.6 mW/cm^2) [32]. The subjects from the third (40 Hz modulation) and fourth (1000 Hz modulation) group, exposed to the 0.16 mW/cm^2 microwave power density, were used for comparison.

Average values of the relative changes of the EEG in T3 and T4 channels are shown in Fig. 7. Main trend is the decrease of the EEG energy with microwave exposure in theta and increase in alpha, beta1 and beta2 rhythm frequencies. Maximal increase reaches 17% at the lower and 12% at the higher power density. Statistical analysis for the groups did not reveal significant differences between sham and exposed results. Results of statistical analysis for individual subjects showed that three subjects at lower and one subject at higher power density were affected by microwave exposure at 40 Hz modulation. Only one subject was affected significantly at 1000 Hz modulation and higher power density. Most of statistically significant changes took place in the EEG beta rhythms. Absence of statistically significant differences between calculated measures for individuals in the case of sham recordings confirm that the changes are really introduced by the microwave.

Experimental data showed that the 450 MHz microwave, modulated at 40 and 1000 Hz, caused comparable changes in the EEG at levels of the field power densities lower and higher than the thermal limit. Increase in the applied microwave power did not result in an increase of the effect or the number of affected individuals. Microwave caused statistically significant changes in the EEG rhythms energy of 20% of subjects at the lower and of 14% of subjects at the higher field level. Results of our experimental study do not confirm the hypothesis about stronger microwave effect at higher field power density.

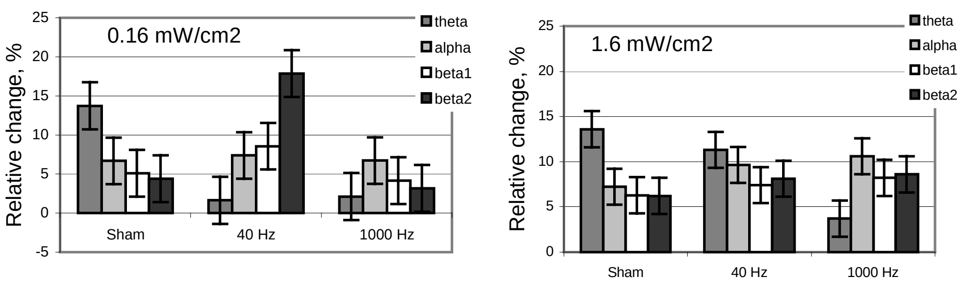

Fig. 7. Relative change in the EEG theta, alpha, beta1 and beta2 rhythms power, caused by microwave exposure averaged over 10 exposure cycles and all subjects within a group in the EEG T3-T4 channels for microwave exposures of 0.16 (14 subjects) and 1.6 W/cm^2 (7 subjects).

4. CONCLUSIONS

The above adds knowledge to the understanding of microwave effects on EEG and cognitive processes.

1. The results show that ID and LDLVP methods can detect small changes in EEG signals caused by microwave exposure. Microwave exposure causes most remarkable increase in the EEG alpha power and less increase in the beta power.
2. The effect of microwave radiation on the EEG rhythms depends on the modulation frequency and has non-thermal origin. The effect is stronger at modulation frequencies higher or close to the EEG rhythms frequencies.
3. Sensitivity to microwave exposure is individual, the rate of the subjects significantly affected was 13–30%.
4. Physiological adaptation of the brain compensates and even overcompensates the effect of the microwave exposure.
5. The microwave effect is not linearly related to the applied field power density.
6. The changes in human performance, due to microwave exposure, in visual memory tasks and visual information processing are small but statistically significant.

ACKNOWLEDGEMENT

Studies of microwave effects have during the years been supported by Estonian Science Foundation (grants Nos 4871, 5143, 6173 and 6632).

REFERENCES

1. Cook, C. M., Saucier, D. M., Thomas, A. W. and Prato, F. S. Exposure to ELF magnetic and ELF-modulated radiofrequency fields: the time course of physiological and cognitive effects observed in recent studies (2001–2005). *Bioelectromagnetics*, 2006, **27**, 613–627.
2. Reiser, H., Dimpfel, W. and Schober, F. The influence of electromagnetic fields on human brain activity. *Eur. J. Med. Res.*, 1995, **1**, 27–32.
3. Mann, K. and Roschke, J. Effects of pulsed high-frequency electromagnetic fields on human sleep. *Neuropsychobiology*, 1996, **33**, 41–47.
4. Borbely, A. A., Huber, R., Graf, T., Fuchs, B., Gallmann, E. and Achermann, P. Pulsed high-frequency electromagnetic field affects human sleep and sleep electroencephalogram. *Neurosci. Lett.*, 1999, **275**, 207–210.
5. Huber, R., Graf, T., Cote, K. A., Wittmann, L., Gallmann, E., Matter, D., Schuderer, J., Kuster, N., Borbely, A. A. and Achermann, P. Exposure to pulsed high-frequency electromagnetic field during waking affects human sleep EEG. *NeuroReport*, 2000, **11**, 3321–3325.
6. Krause, C. M., Sillanmäki, L., Koivisto, M., Häggqvist, A., Saarela, C., Revonsuo, A., Laine, M. and Hämäläinen, H. Effects of electromagnetic field emitted by cellular phones on the EEG during a memory task. *NeuroReport*, 2000, **11**, 761–764.
7. Lass, J., Tuulik, V., Ferenets, R., Riisalo, R. and Hinrikus, H. Effects of 7 Hz-modulated 450 MHz electromagnetic radiation on human performance in visual memory tasks. *Int. J. Radiation Biol.*, 2002, **78**, 937–944.

8. Hinrikus, H., Parts, M., Lass, J. and Tuulik, V. Changes in human EEG caused by low-level modulated electromagnetic radiation stimulation. *Bioelectromagnetics*, 2004, **25**, 431–440.
9. Curcio, G., Ferrara, M., Moroni, F., D'Inzeo, G., Bertini, M. and De Gennaro, L. Is the brain influenced by a phone call? An EEG study of resting wakefulness. *Neurosci. Res.*, 2005, **53**, 265–270.
10. Huber, R., Treyer, V., Borbely, A. A., Schuderer, J., Gottselig, J. M., Landolt, H. P., Werth, E., Berthold, T., Kuster, N., Buck, A. and Achermann, P. Electromagnetic fields, such as those from mobile phones, alter regional cerebral blood flow and sleep and waking EEG. *J. Sleep Res.*, 2002, **11**, 289–295.
11. Krause, C. M., Sillanmäki, L., Koivisto, M., Häggqvist, A., Saarela, C, Revonsuo, A., Laine, M. and Hämäläinen, H. Effects of electromagnetic fields emitted by cellular phones on the electroencephalogram during a visual working memory task. *Int. J. Radiation Biol.*, 2000, **76**, 1659–1667.
12. Krause, C. M., Haarala, C., Sillanmaki, L., Koivisto, M., Alanko, K., Revonsuo, A., Laine, M. and Hamalainen, H. Effects of electromagnetic field emitted by cellular phones on the EEG during an auditory memory task: a double blind replication study. *Bioelectromagnetics*, 2004, **25**, 33–40.
13. Wagner, P., Roschke, J., Mann, K., Hiller, W. and Frank, C. Human sleep under the influence of pulsed radiofrequency electromagnetic fields: a polysomnographic study using standardized conditions. *Bioelectromagnetics*, 1998, **19**, 199–202.
14. Hietanen, M., Kovala, T. and Hamalainen, A. M. Human brain activity during exposure to radiofrequency fields emitted by cellular phones. *Scand. J. Work Environm. Health*, 2000, **26**, 87–92.
15. Krause, C. M., Bjornberg, C. H., Pesonen, M., Hulten, A., Liesivuori, T., Koivisto, M., Revonsuo, A., Laine, M. and Hamalainen, H. Mobile phone effects on children's event-related oscillatory EEG during an auditory memory task. *Int. J. Radiation Biol.*, 2006, **82**, 443–450.
16. Huber, R., Treyer, V., Schuderer, J., Berthold, T., Buck, A., Kuster, N., Landolt, H. P. and Achermann, P. Exposure to pulse-modulated radio frequency electromagnetic fields affects regional cerebral blood flow. *Europ. J. Neurosci.*, 2005, **21**, 1000–1006.
17. Loughran, S. P., Wood, A. W., Barton, J. M., Croft, R. J., Thompson, B. and Stough, C. The effect of electromagnetic fields emitted by mobile phones on human sleep. *NeuroReport*, 2005, **28**,1973–1976.
18. Hinrikus, H., Bachmann, M., Kalda, J., Sakki, M., Lass, J. and Tomson, R. Methods of electroencephalographic signal analysis for detection of small hidden changes. *Nonlinear Biomed. Physics*, 2007, **1**(9), 28 July 2007. http://www.nonlinearbiomedphys.com/ content/1/1/9
19. Bachmann, M., Kalda, J., Lass, J., Tuulik, V., Sakki, M. and Hinrikus, H. Non-linear analysis of the electroencephalogram for detecting effects of low-level electromagnetic fields. *Med. Biol. Eng. Comput.*, 2005, **43**, 142–149.
20. Bachmann, M., Lass, J., Kalda, J., Säkki, M., Tomson, R., Tuulik, V. and Hinrikus, H. Integration of differences in EEG analysis reveals changes in human EEG caused by microwave. In *Proc. 28th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*. New York, 2006, 1597–1600.
21. Rubljova, J., Bachmann, M., Lass, J., Tomson, R., Tuulik, V. and Hinrikus, H. Adaptation of human brain bioelectrical activity to modulated 450 MHz microwave. In *Proc. 29th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*. Lyon, 2007, 4747–4750.
22. Rodina, A., Lass, J., Riipulk, J., Bachmann, T. and Hinrikus, H. Study of effects of low microwave field by method of face masking. *Bioelectromagnetics*, 2005, **26**, 571–577.
23. Hinrikus, H., Bachmann, M., Lass, J., Tomson, R. and.Tuulik, V. Effect of 7, 14 and 21 Hz modulated 450 MHz microwave radiation on human electroencephalographic rhythms. *Int. J. Radiation Biol.*, 2008, **84**, 69–79.
24. Lass, J., Hinrikus, H., Bachmann, M. and Tuulik, V. Microwave radiation has modulation frequency dependent stimulating effect on human EEG rhythms. In *Proc. 26th Annual*

International Conference of the IEEE Engineering in Medicine and Biology Society. San Francisco, 2004, 4225–4228.
25. Hinrikus, H., Lass, J. and Tuulik, V. Interaction of low-level microwave radiation with nervous system – a quasi-thermal effect? *Proc. Estonian Acad. Sci. Eng.*, 2004, **10**, 82–94.
26. Hinrikus, H., Bachmann, M., Tomson, R. and Lass, J. Non-thermal effect of microwave radiation on human brain. *Environmentalist*, 2005, **25**, 187–194.
27. Lass, J., Riipulk, J. and Hinrikus, H. The sensitivity of living tissue to microwave field. In *Proc. 20th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*. Hong Kong, 1998, vol. 20, 3249–3252.
28. Bachmann, M., Säkki, M., Kalda, J., Lass, J., Tuulik, V. and Hinrikus, H. Effect of 450 MHz microwave modulated with 217 Hz on human EEG in rest. *Environmentalist*, 2005, **25**, 165–171.
29. Bachmann, M., Kalda, J., Säkki, M., Tomson, R., Lass, J., Tuulik, V. and Hinrikus, H. Individual changes in human EEG caused by 450 MHz microwave modulated at 40 and 70 Hz. *Environmentalist*, 2007, **27**, 511–517.
30. Hinrikus, H., Bachmann, M., Lass, J., Karai, D. and Tuulik, V. Effect of low frequency modulated microwave exposure on human EEG: individual sensitivity, *Bioelectromagnetics*. Forthcoming.
31. Tomson, R., Hinrikus, H., Bachmann, M., Lass, J. and Tuulik, V. Effect of modulated 450 MHz microwave on human EEG at different field power densities. *IFMBE Proc.*, 2007, **16**, 210–213.
32. Cullen, M. R. The workers with multiple chemical sensitivities: an overview. *Occupat. Medicine*, 1987, **2**, 655–661.
33. Rangaswamy, M., Porjesz, B., Chorlian, D. B., Wang, K., Jones, K. A., Bauer, L. O., Rohrbaugh, J., O'Connor, S. J., Kuperman, S., Reich, T. and Begleiter, H. Beta power in the EEG of alcoholics. *Biol. Psychiatry*, 2002, **52**, 831–842.

Moduleeritud mikrolainekiirguse mõju aju rütmidele ja kognitiivsetele protsessidele

Hiie Hinrikus, Maie Bachmann, Jaanus Lass ja Viiu Tuulik

On esitatud ülevaade viimase kümmekonna aasta jooksul Tallinna Tehnikaülikooli biomeditsiinitehnika keskuses tehtud uuringutest mikrolainekiirguse mõjust puhkeoleku elektroentsefalograafilisele (EEG) signaalile ja visuaalsele mälule ning visuaalse informatsiooni töötlemisele. On kirjeldatud kasutatud meetodeid ja analüüsitud peamisi tulemusi. Väljatöötatud EEG-signaali analüüsi meetodid on võimelised eristama mikrolainekiirguse poolt tekitatavaid väikesi muutusi EEG-signaalis. Kiirgus suurendab kõige rohkem EEG-alfarütmide võimsust ja kutsub esile väiksema tõusu EEG-beetarütmide võimsuses. Saadud tulemused tõestavad, et mikrolainekiirguse mõju EEG-rütmidele sõltub kiirguse modulatsioonisagedusest ja on seega mittesoojusliku päritoluga. Tundlikkus mikrolainekiirgusele on individuaalne: oluliselt mõjutatute osakaal on 13–30%. Aju füsioloogiline adaptatsioon kompenseerib ja isegi ülekompenseerib mikrolainekiirguse mõjul tekkinud muutusi EEG-signaalis. Saadud tulemused kinnitavad ka seda, et mikrolainekiirguse mõju ei sõltu lineaarselt kiirguse võimsusest. Kiirguse poolt tekitatud muutused inimese võimetes visuaalse mälu ja visuaalse informatsiooni töötlemise ülesannete täitmisel on väikesed, kuid statistiliselt olulised.