Environmentalist (2007) 27:511–517
DOI 10.1007/s10669-007-9069-9

Individual changes in human EEG caused by 450 MHz microwave modulated at 40 and 70 Hz

Maie Bachmann · Ruth Tomson · Jaan Kalda · Maksim Säkki · Jaanus Lass · Viiu Tuulik · Hiie Hinrikus

Published online: 4 July 2007

Abstract This study was aimed to investigate the changes in the human electroencephalographic (EEG) signal caused by modulated low-level microwaves. The 450 MHz microwave exposure modulated at 40 Hz and 70 Hz frequencies was applied to a group of 15 volunteers. The field power density at the scalp was 0.16 mW/cm^2. Ten cycles of the exposure (1 min on and 1 min off) at both modulation frequencies were applied. Analysis of the EEG signal was performed using three different methods: nonlinear method of scaling analysis for length distribution of low variability periods (LDLVP), relative changes in EEG energy (*S*-parameter) and beta ratio (*H*-parameter). The analysis revealed significant changes caused by microwave for the whole group (*H*-parameter method). The exposure caused increase of the EEG beta power (*S*-parameter method). Statistically significant changes in EEG were detected for four subjects (26.7%) at 40 Hz modulation frequency (LDLVP method).

Keywords EMF effects · Time variability · Scaling analysis · Quantitative EEG · Spectral analysis

M. Bachmann (✉) · R. Tomson · J. Lass ·
V. Tuulik · H. Hinrikus
Department of Biomedical Engineering, Technomedicum of Tallinn University of Technology, 5 Ehitajate Rd, Tallinn 19086, Estonia
e-mail: maie@cb.ttu.ee

J. Kalda · M. Säkki
Institute of Cybernetics, Tallinn University of Technology, 21 Academy Rd, Tallinn 12618, Estonia

1 Introduction

The nervous system has been thought to be most sensitive to external electromagnetic fields (EMF) since there is a tremendous electrical activity in neural processes. Information processing and transmission in nervous system is based on bioelectromagnetic phenomena. Therefore, it can be expected that EMF effects appear most likely in nervous system.

Modulated microwave radiation at non-thermal level of field power density can affect human central nervous system in a sensible way. However, the effect is weak and difficult-to-detect. Several investigators have reported that low-level exposure produces alterations in the EEG signal and brain behavior (Mann and Roschke 1996; Borbely et al. 1999; Huber et al. 2000; Krause et al. 2000; Lass et al. 2002; Hinrikus et al. 2004; Curcio et al. 2005), while others conclude that exposure to electromagnetic field does not alter resting EEG (Hietanen et al. 2000; Krause et al. 2000). Reports of possible non-thermal EMF effects are often contradictory and the difficulties in independent repeating of the experimental results cause doubts. Mechanisms behind the effects are still unclear.

In our previous studies the relative changes in the EEG rhythms energy caused by microwave radiation modulated inside the EEG physiological spectrum at frequencies 7 Hz, 14 Hz and 21 Hz were investigated (Hinrikus et al. 2004, 2005). The conclusion was that the effect produced by microwave radiation has a clear frequency dependence and increases with modulation frequency. The influence of microwave with modulation frequency 217 Hz—technical frequency much higher than the EEG rhythms—has been also reported to produce statistically significant changes in time variability and intensity of the EEG signal for 10–20% of healthy subjects (Bachmann et al. 2004).

This study was aimed to evaluate the effect of microwave modulated with intermediate frequencies 40 Hz and 70 Hz. The same exposure conditions utilized in our previous studies were applied (Hinrikus et al. 2004, 2005; Bachmann et al. 2004). The mechanism of low-level microwave effect on biological tissues is still not clear. Therefore, it is not possible to predict the character of changes in brain bioelectrical activity: the effect could be related to stimulation or depression of the brain activity, which leads to changes in intensity of the EEG signal. The effect could be also related to changes on neurons spiking frequency or processes in synapses, which leads to changes in time variability of the EEG signal. Therefore three methods were selected for EEG analysis: scaling analysis of length distribution of low variability periods (LDLVP) as sensitive to signal time variability (Bachmann et al. 2005a), relative change in the EEG energy (Hinrikus et al. 2004) as sensitive to energy variations and beta ratio as sensitive to energy distribution inside the EEG spectrum. The hypothesis was that measures calculated with these methods differ for EEG signals recorded with and without microwave exposure.

2 Method and equipment

2.1 Subjects

Our experiments were carried out on a group of healthy volunteers, consisting of 15 young persons (aged 21–24): eight male and seven female. A questionnaire and a clinical interview were used to evaluate their physical and mental condition (tiredness, sleepiness) before the experiment. All the subjects selected had no medical or psychiatric disorders and tired or sleepy persons were excluded. After the recordings, they were asked to describe how they were feeling during the experiment. The subjects reported neither alertness nor any strain experienced during the recordings. The experiments were conducted with understanding and written consent of each participant.

During the experiments, the experimenter and the subjects were in the same laboratory room. The room was dark and the subjects were lying in a relaxed position, eyes closed and ears blocked during the experiments.

All the subjects passed two recording sessions—with microwave exposure and sham exposure. For each recording session, the exposure condition was randomly assigned. The subjects were not informed of their exposure during a session, however, they were aware of the possibility of being exposed. Only one experimental EEG recording session was performed for a subject during a day between the time interval of 9 a.m. to noon.

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

2.2 Microwave exposure

Microwave exposure at the non-thermal level of field power density was selected identical to that in our previous studies except modulation frequencies (Lass et al. 2002; Hinrikus et al. 2004, 2005; Bachmann et al. 2004; Bachmann et al. 2005a). Exposure conditions were the same for all subjects.

450 MHz microwave radiation was 100% pulse-modulated at 40 and 70 Hz frequency (duty cycle 50%). The output power of 1 W electromagnetic radiation was guided by a coaxial lead to the 13 cm quarter-wave antenna located 10 cm from skin on the left side of head.

Estimated field power density at skin was 0.16 mW/cm^2 and SAR value 0.35 W/kg (Hinrikus et al. 2004).

2.3 Recording protocols and equipment

Our experimental study was performed according to recording protocol identical for all subjects. All subjects passed two recording protocols with microwave exposure and sham.

The protocol with exposure lasted 40 min, during which the resting eyes closed EEG was continuously recorded. For the duration of every even minute of the recording the subject was exposed to microwave at modulation frequency 40 or 70 Hz. The pair of successive reference minute followed by exposed minute was an exposure cycle. Twenty exposure cycles were applied during a recording: first ten exposure cycles were performed at first and ten last at second modulation frequency. Selection of 40 or 70 Hz as first or second modulation frequency was randomly assigned.

Sham recording session used the same protocol, except that the microwave power was switched off. For each recording session, the exposure conditions were randomly assigned between subjects.

Cadwell Easy II EEG measurement equipment was used for the EEG recordings. The EEG was recorded using 19 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 on a computer at a 400 Hz sampling frequency.

The pre-processing of the signals was performed in the LabVIEW programming and signal-processing environment.

The EEG spectrum 0.5–39 Hz was selected for the analysis.

2.4 Analysis of the EEG based on the LDLVP method

Initially, all the EEG recordings were divided into two sub-signals: the first sub-signal contained all odd minutes from the initial EEG recording (1 min periods without microwave exposure), and the second sub-signal contained all even minutes of the initial EEG recording with microwave exposure. Odd and even minutes from sham recordings were divided similarly.

The scaling analysis utilizing LDLVP method was applied for two sub-signals.

The LDLVP method has been used and described in details in our previous studies (Bachmann et al. 2005a; Kalda et al. 2001; Säkki et al. 2004). Here we provide a brief summary of this method.

First, we define the local variability as the deviation of the current value of the signal from the local average

$$\delta V(t) = V(t) - T^{-1} \int_{-T/2}^{T/2} V(t+\tau)d\tau, \quad (1)$$

where $V(t)$ is the recorded voltage, and the time-window width T is a free (adjustable) parameter. For EEG signals, a reasonable value is provided by $T = 60$ ms (Bachmann et al. 2005a).

Secondly, low-variability periods are defined as continuous intervals with

$$\delta V(t) < \delta_0. \quad (2)$$

Finally, the number of low-variability periods N exceeding length T_0 is plotted against length T_0, see Fig. 1.

The value of δ_0 was adjusted for each recording individually, reaching a minimum value so that, for both sub-signals, the length of the longest low-variability period was at least 3,750 ms.

The hypothesis of this work was that microwave exposure increases EEG variability. Owing to higher variability, there are fewer long low-variability periods. Therefore it is expected that microwave exposure decreases the area of the $T_0(N)$-curve (see Fig. 1), due to faster cut-off at large values of T_0. According to this assumption, the weighted area

$$S_W = \sum_{N=1}^{128} \ln\left(\frac{N}{\max(N-1, 1/4)}\right) \ln(T_0) N^{1/2} \quad (3)$$

of the function $T_0 = T_0(N)$ was selected as the non-linear quantitative measure.

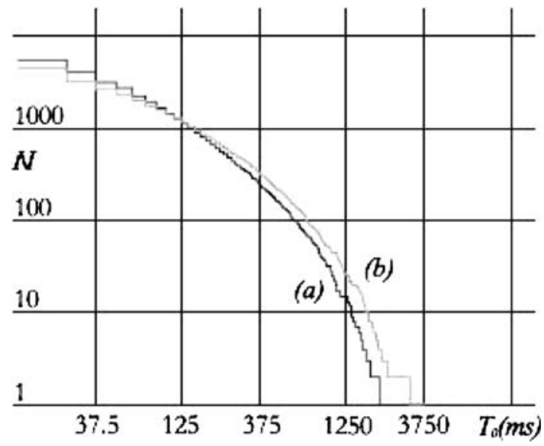

Fig. 1 The number of low-variability periods N exceeding the length T_0 for a significant subject: black line (**a**)—second sub-signal of exposed recording (intervals with microwave); grey line (**b**)—first sub-signal of exposed recording (intervals without microwave)

2.5 Analysis of the EEG based on the S-parameter method

Relative changes in the EEG energy between segments with and without exposure were selected as a measure for detection of the microwave effect on signal intensity.

The analysis method was applied in our previous study (Hinrikus et al. 2005), except for different comparison segments. The energies of the different EEG rhythms were analyzed separately. Therefore, at first, the energies of the four basic EEG rhythm frequencies, theta (4–7 Hz), alpha (8–13 Hz), beta1 (15–20 Hz) and beta2 (22–38 Hz), were extracted from the total EEG signal (0.5–39 Hz) by filtering.

Next, the average energies for segments with and without stimulation were compared. Comparison segments for the S-parameter were selected as the first 30 sec from the reference (unexposed) minute and first 30 s from the exposed minute in an exposure cycle.

The average energy of an arbitrary comparison segment was calculated as follows:

$$s_i = \frac{1}{N}\sum_{r=1}^{N} [x(r)]^2, \quad (4)$$

where x is the amplitude of the recorded signal and N is the number of samples, during 30 sec $N = 12,000$. The relative change in the energy of the recording segments with and without stimulation was selected for further analysis. Finally, parameter S was calculated as follows:

$$S = \left(\frac{s_2}{s_1} - 1\right) \times 100\%, \quad (5)$$

where s_1 and s_2 were the average energies inside the comparison segments without and with stimulation, respectively. For sham recordings the same parameter was calculated for comparison segments as first 30 s of even and first 30 s of odd minutes of the recordings.

2.6 Analysis of the EEG based on the H-parameter method

The relative difference in power distribution between beta and theta rhythms inside EEG spectrum was selected as the third measure for estimation of the effect of microwaves.

For this method the subsignals were created using the method formerly described with a small exception: every recording was divided into two subsignals utilizing only the first 30 s of every recorded minute.

Next, the power spectral density (PSD) was estimated by means of Welch's averaged periodogram method. A subsignal was divided into overlapping sections (50%), with the length of 2,048 points and windowed by the Hanning window. Afterwards, the power on the theta (W_{tmn}) and beta band (W_{bmn}) was computed for each subject (indexed by $n \in [1, 15]$) and subsignal (indexed by $m = 1, 2$) as the area under the spectrum for the corresponding frequency band (integral of the band).

The relative difference of the beta and theta rhythms power was selected for further analysis. Finally, parameter H for a subject was calculated as follows:

$$H = \frac{W_{\mathrm{b}} - W_{\mathrm{t}}}{W_{\mathrm{b}} + W_{\mathrm{t}}}, \qquad (6)$$

where W_{b} and W_{t} are the beta and theta rhythms power respectively.

The values of the parameter H for P channels for the individual subjects and for all recordings' subsignals were calculated.

Signal processing and calculation of the parameters were performed in the MatLab and LabVIEW programming and signal processing environment.

2.7 Statistical analysis

For sham recordings, sub-signals were completely equivalent. The mathematical expectation of the difference in the calculated EEG parameters is zero, and natural variability of the parameter could be obtained as the standard deviation σ_{sh} for sham recordings.

The ratio of the difference of the computed parameters for exposed and reference signals to the standard deviation of the sham recordings was used for evaluation and respective p-values are obtained by means of the cumulative f-distribution:

$$p = F_{1,15}\left[(P_{2n} - P_{1n})^2 \sigma_{\mathrm{sh}}^{-2}\right], \qquad (6)$$

where P_{1n} and P_{2n} are values of a parameter for non-exposed and exposed signals for a subject. For post hoc analysis the modified Bonferroni correction was applied according to which the smallest p-value is to be multiplied by the number of data points 15, the second smallest is to be multiplied by 15/2 = 7.5 etc.

Two-tailed paired Student t-test was performed for statistical analysis of results for a group.

3 Results

The results of LDLVP analysis for a subject are presented in Fig. 1. As can be seen, microwave exposure lowers the curve at the right-hand part of the graph (large values of T_0). Such a change in curve indicates that microwave exposure increases variability of the EEG signal: owing to higher variability there are fewer long low variability periods.

The results of the S-parameter analysis for the whole group are presented in Fig. 2. The graph illustrates the effect of microwave exposure—changes between exposed and not exposed segments of the recordings on different EEG rhythms and for sham, 40 Hz and 70 Hz modulation frequency. As can be seen, microwave exposure causes increase in energy of the EEG beta1 and beta2 rhythms.

The results of analysis using relative difference in power distribution between beta and theta rhythms inside EEG (H-parameter) are presented in the Fig. 3. The largest difference between exposed and reference sub-signals can be seen at modulation frequency 40 Hz. It is also noticeable that parameter H is less negative for subsignals in the case

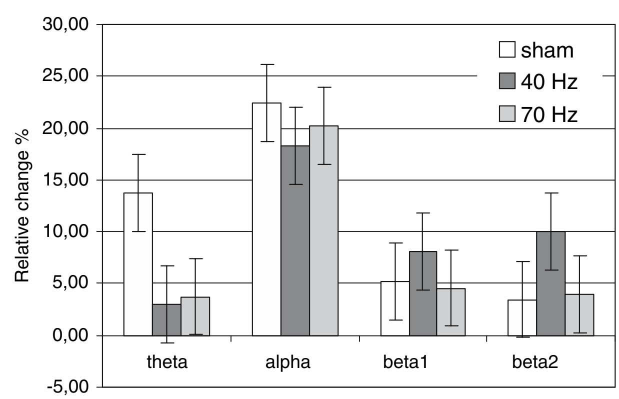

Fig. 2 The relative average changes in % (S-parameter) of the EEG rhythms energy of the recording segments with and without microwave exposure in P-channels for the whole group

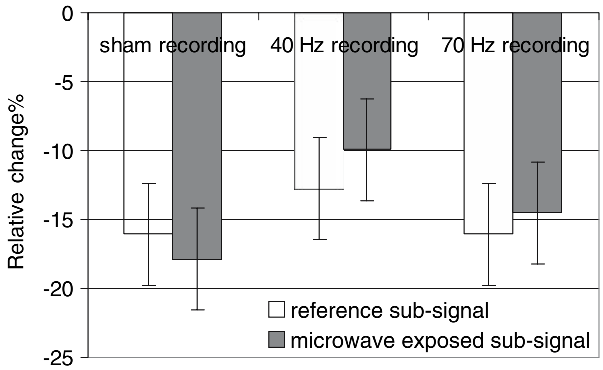

Fig. 3 Average values of the beta-ratio in % (*H*-parameter) for reference and microwave exposed sub-signals in the case of sham recordings, microwave exposed recordings at modulation frequency 40 Hz and 70 Hz in P-channels for a group

of 40 Hz modulation frequency compared to sham recordings and recordings at modulation frequency 70 Hz.

Statistical evaluation performed for the whole group did not reveal significant difference between exposed and reference EEG except *H*-parameter analysis. For a group, there are statistically significant differences between calculated *H*-parameters for reference and microwave exposed sub-signals at modulation frequency 40 Hz ($p = 0.036$).

The results of statistical analysis of the LDLVP quantitative measures and of the *S*-parameter for beta2 rhythm at modulation frequency 40 and 70 Hz recordings, calculated for each subject, are presented in Table 1. Statistically significant results occur only at modulation frequency 40 Hz. As can be seen in Table 1, after Bonferroni correction the analysis resulted in *p*-values lower than 0.05 for four subjects in the case of LDLVP method and two subjects in the case of *S*-parameter method at modulation frequency 40 Hz. The outcome of statistical analysis of the parameter *H* for modulation frequencies 40 and 70 Hz, calculated for each subject, did not produce any significant result.

4 Discussion

As Table 1 illustrates, the LDLVP presents the best outcome at modulation frequency 40 Hz, resulting in significant results for four subjects. Accordingly, significant effect of exposure to the EEG signal was detected for 26.7 % of subjects.

Considering the direction of influence at modulation frequency 40 Hz, for two subjects under the exposure the computed LDLVP weighted area increased, and for two it decreased. For all subjects, the departure from the sham behavior is statistically reliable. This is somewhat different from what has been observed for the modulation frequency 7 Hz, when the sign of the departure was always negative (corresponding to increased variability) (Bachmann et al. 2005a). However, the outcome of a study at modulation frequency 217 Hz, in which for half of the subjects the computed LDLVP weighted area decreased and for another half it decreased (Bachmann et al. 2005b), coincides with current results at 40 Hz.

Table 1 Normalised differences in P-channels for LDLVP parameters (EEG frequency band 0.5–39 Hz) and *S*-parameters (EEG beta2 frequency band) between microwave exposed and reference sub-signals for recordings at modulation frequency 40 Hz and 70 Hz, calculated for a subject *n* as $D_n = (P_{2n} - P_{1n})/\sigma_{sh}$; index 1 as reference sub-signal, index 2 as microwave exposed sub-signal; concurrent *p*-values as a result of Bonferroni correction

Microwave exposure	40 Hz				70 Hz			
Method	LDLVP		*S*-parameter		LDLVP		*S*-parameter	
Subject	*D*	*p*-value	*D*	*p*-value	*D*	*p*-value	*D*	*p*-value
1	0.95	0.59	0.80	1.00	1.93	0.34	0.51	1.00
2	–3.02	0.03	5.96	3.95 E-04	–0.77	0.84	3.45	0.05
3	1.30	0.39	1.09	0.88	–0.60	0.84	–1.41	0.67
4	–0.21	0.84	–0.01	1.00	–0.60	0.76	0.30	0.83
5	–0.39	0.81	0.60	1.00	1.68	0.40	–0.86	0.67
6	–0.28	0.84	–0.67	1.00	–0.04	0.97	–1.19	0.54
7	–0.63	0.80	0.58	1.00	–0.98	0.72	–1.25	0.58
8	–1.51	0.32	0.45	1.00	–0.11	0.98	1.00	0.62
9	3.69	0.02	1.16	0.99	0.35	0.91	1.37	0.57
10	2.49	0.07	1.65	0.60	–0.21	0.96	0.51	0.72
11	0.46	0.82	–0.04	1.00	2.14	0.34	0.60	0.84
12	3.09	0.03	0.15	1.00	–2.74	0.19	0.54	0.82
13	1.93	0.17	–0.16	1.00	1.16	0.78	0.01	0.99
14	–3.69	0.01	4.50	3.19 E-03	0.77	0.75	1.57	0.69
15	0.49	0.86	0.45	1.00	–1.05	0.76	1.67	0.87

The *S*-parameter measures exceeded the limit of significant deviation from zero hypothesis also at modulation frequency 40 Hz in beta2 frequency band (Table 1), providing two significant cases out of 15, that is 13.3%. There were no significant results at modulation frequency 70 Hz.

The LDLVP and *S*-parameter measures didn't detect significant effect of microwave for the whole group. The reason can be high variability of the parameters between subjects as well as different individual sensitivity to microwave. The parameter *H* is consistent with the results of the above discussed parameters revealing the group effect at modulation frequency 40 Hz and indicating no significant differences between sham subsignals and subsignals from the recordings at modulation frequency 70 Hz.

As with all methods, modulation at frequency 70 Hz is not as effective as at 40 Hz. Possible reason is that 40 Hz is quite close to the EEG physiological frequencies and the switching with brain oscillations is more effective.

From those results it is difficult to conclude which measure, LDLVP, *S*-parameter or *H*-parameter, is more effective and whether the effect of modulation frequency 40 Hz appear rather in intensity (*S*- and *H*-parameter) or time variability (LDLVP) of the EEG signals. The results reported in our previous study with 7 Hz modulated microwave lead to the conclusion that the effect appears in time variability (Bachmann et al. 2005a), while the next study concerning modulation frequency 217 Hz concluded that the effect is rather in intensity (Bachmann et al. 2005b).

From Table 1, it can be seen that the subjects having significant results with different methods overlap. The LDLVP method gave four significant results compared to two with the *S*-parameter. Furthermore, the *H*-parameter gives significant results for a group. This indicates that microwave stimulation causes different effects for different subjects and there is a need for various methods to detect those effects.

The analysis by the LDLVP method detected the effect of exposure at modulation frequency 40 Hz for 26.7% of subjects. For instance, the rate of multiple chemical sensitivity (MCS) occurrence is estimated to be between 2 and 10% in the general population (Cullen 1987). Taking this into consideration, LDLVP method, *S*-parameter and *H*-parameter demonstrated good sensitivity detecting the effects of microwave stimulation at modulation frequency 40 Hz.

Main trend of changes caused by microwave exposure modulation frequencies was increase of the EEG energy in beta rhythm. Increased beta absolute power was also observed in alcohol-dependent subjects (Rangaswamy et al. 2002).

5 Conclusion

450 MHz microwave exposure modulated at 40 Hz caused statistically significant changes in the EEG time variability (26.7% of subjects) and energy variations (13.3% of subjects). Changes in energy spectral distribution were statistically significant for the whole group. The main trend of changes was the increase in the EEG beta rhythm energy and the effect was more evident at the modulation frequency closer to the physiological EEG rhythms (40 Hz).

Acknowledgements This study has been supported by the Estonian Science Foundation grants No 6632 and 6121.

References

Bachmann, M., Kalda, J., Lass, J., Tuulik, V., & Hinrikus, H. (2004). Power spectrum distinguishes the effect of microwave stimulation on human EEG at rest, Biological Effects of EMFs 3rd International Workshop, pp. 75–81, Kos, Greece, 4–8 October 2004.

Bachmann, M., Kalda, J., Lass, J., Tuulik, V., Säkki, M., & Hinrikus, H. (2005a). Non-linear analysis of the electroencephalogram for detecting effects of low-level electromagnetic fields. *Medical & Biological Engineering & Computing, 43*, 142–149.

Bachmann, M., Säkki, M., Kalda, J., Lass, J., Tuulik, V., & Hinrikus, H. (2005b). Effect of 450 MHz microwave modulated with 217 Hz on human EEG in rest. *The Environmentalist, 25*, 165–171.

Borbely, A. A., Huber, R., Graf, T., Fuchs, B., Gallmann, E., & Acherman, P. (1999). Pulsed high—frequency electromagnetic field affects human sleep and sleep electroencephalogram. *Neuroscience Letters, 275*, 207– 210.

Cullen, M. R. (1987). *Workers with multiple chemical sensitivities occupational medicine: State of the art Reviews* (Vol. 2). Philadelphia: Hanley & Belfus, Inc., pp. 655–661.

Curcio, G., Ferrara, M., Moroni, F., D'Inzeo, G., Bertini, M., & De Gennaro, L. (2005). Is the brain influenced by a phone call? An EEG study of resting wakefulness. *Neuroscience Research, 53*, 265–270.

Hietanen, M., Kovala, T., & Hamalainen, A. M. (2000). Human brain activity during exposure to radiofrequency fields emitted by cellular phones. *Scandinavian Journal of Work, Environment & Health, 26*, 87–92.

Hinrikus, H., Bachmann, M., Tomson, R., & Lass, J. (2005). Non-thermal effect of microwave radiation on human brain. *The Environmentalist, 25*, 187–194.

Hinrikus, H., Parts, M., Lass, J., & Tuulik, V. (2004). Changes in human EEG caused by low—level modulated microwave stimulation. *Bioelectromagnetics, 25*, 431–440.

Huber, R., Graf, T., Cote, K.A., Wittmann, L., Gallmann, E., Matter, D., Schuderer, J., Kuster, N., Borbely, A. A., & Achermann, P. (2000). Exposure to pulsed high-frequency electromagnetic field during waking affects human sleep EEG. *Neuroreport, 11*, 3321–3325.

Kalda, J., Säkki, M., Vainu, M., & Laan, M. (2001). Zipf's law in human heartbeat dynamics. Available: http://arxiv.org/abs/physics/0110075.

Krause, C. M., Sillanmäki, L., Koivisto, M., Häggqvist, A., Saarela, C., Revonsuo, A., Laine, M., & Hämäläinen, H. (2000). Effects of electromagnetic field emitted by cellular phones on the EEG during a memory task. *Neuroreport, 11*, 761–764.

Krause, C. M., Sillanmäki, L., Koivisto, M., Häggqvist, A., Saarela, C., Revonsuo, A., Laine, M., & Hämäläinen, H. (2000). Effects of electromagnetic fields emitted by cellular phones on the electroencephalogram during a visual working memory task. *International Journal of Radiation Biology, 76*, 1659–1667.

Lass, J., Tuulik, V., Ferenets, R., Riisalo, R., & Hinrikus, H. (2002). Effects of 7 Hz-modulated 450 MHz electromagnetic radiation on human performance in visual memory tasks. *International Journal of Radiation Biology, 78*, 937–944.

Mann, K., & Roschke, J. (1996). Effects of pulsed high-frequency electromagnetic fields on human sleep. *Neuropsychobiology, 33*, 41–47.

Rangaswamy, M., Porjesz, B., Chorlian, D. B., Wang, K., Jones, K. A., Bauer, L. O., Rohrbaugh, J., O'Connor, S. J., KuperKuperman, S., Reich, T., & Begleiter, H. (2002). Beta power in the EEG of alcoholics. *Biological Psychiatry, 52*(8), 831–842.

Säkki, M., Kalda, J., Vainu, M., & Laan, M. (2004). The distribution of low-variability periods in human heartbeat dynamics. *Physica A, 338*, 255–260.