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ORIGINAL ARTICLE

After-effect induced by microwave radiation in human electroencephalographic signal: a feasibility study

Maie Bachmann[a], Laura Päeske[a], Andreas A. Ioannides[b], Jaanus Lass[a] and Hiie Hinrikus[a]

[a]Centre for Biomedical Engineering, Department of Health Technologies, Tallinn University of Technology, Tallinn, Estonia; [b]Laboratory for Human Brain Dynamics, AAI Scientific Cultural Services Ltd, Nicosia, Cyprus

ABSTRACT

Purpose: This feasibility study is aimed to clarify the possibility of detection of microwave radiation (MWR)-induced event related potential (ERP) in electroencephalographic (EEG) signal.

Methods: To trigger onset and offset effects in EEG, repetitive MWR stimuli were used. Four 30-channel EEG recordings on a single subject were performed, each about one month apart. The subject was exposed to 450 MHz MWR modulated at 40 Hz at the 1 g peak spatial average specific absorption rate of 0.3 W/kg. During a recording, 40 cycles of 30 s on–off MWR exposure were used. The artifact-free responses to 126 MWR-ON stimuli and 134 MWR-OFF stimuli were averaged over stimuli and channels.

Results: Regarding EEG signals locked to MWR-OFF stimulus, the enhanced signal level at alpha frequency band and about twice higher signal to noise ratio at 200 to 440 ms after the stimulus have been detected. No remarkable response in EEG signals locked to MWR-ON stimulus.

Conclusions: The detection of offset effect confirms that there should be an imprint generated by MWR in brain. The results of this preliminary study provide evidence for the detection of MWR-induced ERP in EEG signal and encourage further research in this direction.

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KEYWORDS
Event related potential; microwave radiation; EEG; resting potential

Introduction

The effect of microwave radiation (MWR) in brain bioelectrical activity is weak and therefore difficult to detect. Reports on possible low-level MWR effects are often contradictory. Several studies have reported low-level MWR effects on human behavior and nervous system (Valentini et al. 2007; Juutilainen et al. 2011; Kwon and Hämäläinen 2011). The effects of low-level MWR on the power of human resting electroencephalographic (EEG) signal have been detected by some authors (Huber et al. 2002; Curcio et al. 2005; Hinrikus et al. 2008a). A possible mechanism of excitation of brain oscillations by modulated MWR has been proposed and supported by the related enhancement of EEG signal indicated in experiments (Hinrikus et al. 2011). Effects of MWR on cognitive performance have also been reported by some authors. However, the changes in EEG recorded during cognitive tasks have not been convincingly replicated (Krause et al. 2000, 2004; Haarala et al. 2003, 2004.

Only few attempts to detect MWR-induced event related potentials (ERP) in EEG have been reported. The 3G smart phone exposure, at SAR 0.69 W/kg, has been explored by analyzing the EEG signals recorded during switched on mobile phones, while applying 60 stimuli for each of the 31 participants (Roggeveen et al. 2015). The time course of the presented evoked potentials follows the curves of mean radiation intensity. Therefore, it is difficult to exclude the possibility that the presented evoked potentials, recoded during switched on mobile phone, could be an artefact caused by direct interference due to direct impact of radiation in EEG device. Instead of MWR, the electric field pulses of 0.7 ms and of about 100 V/m have been applied in another study to trigger evoked potentials (Carrubba et al. 2010). There are no publications convincingly reporting the MWR-induced ERP.

The EEG signal has chaotic nature and characteristic changes related to a stressor are hidden in natural variability of the signal. The changes in resting EEG power or linear or nonlinear behaviors related to neurological or mental disorders can be detected directly in a recorded signal using advanced signal analysis. To detect ERP, multiple trials time-locked to the event are averaged and a detectable response can be achieved by averaging about 2 to 3 hundreds of trials (Luck 2005). While averaging the trials, it is presumed that the ERP is in phase and time-locked to the event, while background EEG is not correlated to the event and therefore, the background EEG is expected to decrease close to zero as random noise.

The changes created by modulated microwave radiation in resting EEG power have been detected in EEG signals (Huber et al. 2002). More detailed studies have used to exposure cycles (one minute MWR-ON, one minute MWR-OFF) to better distinguish the MWR effect (Hinrikus et al. 2008a, 2011). Keeping in mind the multiple repetitive methods required for detection of ERP signals, created by visual or auditory sensing of an event, the detection of microwave-induced ERP signals not related to any sensing organ is

CONTACT Maie Bachmann maie@cb.ttu.ee Department of Health Technologies, Centre for Biomedical Engineering, Tallinn University of Technology, 5 Ehitajate Rd, EE19086 Tallinn, Estonia

a challenge. There is still no study reporting reliable detection of MWR-induced ERP.

High amplitude artifacts, generated by repeated electromagnetic stimuli, presents an additional complication in detection of MWR-induced ERP. We hypothesized that for any electromagnetic change in the environment detected by the brain there will be an onset and offset response elicited by the start and end of the stimulation. We, therefore, expect that an evoked potential will be generated in response to the stimulus onset and offset irrespective of whether or not this is consciously perceived. In the case of MWR, there can be no perception as humans do not have an organ to sense MWR. The unambiguous detection of offset effect is significant without any reference to the offset effects from stimuli that are perceived. In this study, we avoided the complications of direct interference of MWR to the EEG sensors by focusing on the detection of an offset effect. The demonstration of offset effects confirms that the presence of MWR induces a change in the brain and that the return to an earlier state after the cessation of MWR leaves a measurable imprint in the EEG record.

The aim of this feasibility study is to provide evidence of detection of MWR-induced ERP in EEG signal. For this purpose, we used repetitive low-level modulated MWR stimuli to trigger onset and offset effects in human EEG. To avoid variability between subjects, four EEG recordings on a single subject have been performed and analyzed.

Possible mechanism of microwave-induced ERP

Low-level microwave radiation, rotating dipolar water molecules, can reduce hydrogen bonds, decrease viscosity and increase diffusion (Hinrikus et al. 2018). Neuronal resting conditions are determined by balance between diffusion driven j_D and electric field driven j_E ions currents density through a cell membrane (Malmivuo and Plonsey 1995)

$$j_D + j_E = -D\nabla c - cqE = 0,$$

where D is diffusion coefficient, ∇c is ions concentration gradient, c is ions concentration, q is an ion charge and E is electric field strength. The resting potential U or Nernst potential can be determined from the equation above (Malmivuo and Plonsey 1995)

$$U = -\frac{D}{q}\ln\frac{c_i}{c_o}$$

where c_i is intracellular and c_o is extracellular ions concentration.

Increased diffusion upsets the balance of the currents through neuron membrane and alters the resting potential U. The altered resting potential can be considered as an action potential and interpreted as MWR-induced ERP.

Methods

Experimental procedure and equipment

The experiments were carried out on a single healthy female volunteer (age 37). Four EEG recordings were performed on different days about one month apart starting at around 11 o'clock. The room of experiments was dark and the subject was lying in a relaxed position, eyes closed during the experiments. One month before and during the project period, the subject did not consume any alcohol, caffeinated drinks, tobacco nor psychotropic substances. Before each EEG recording, the subject had at least 8 h of sleep.

The resting eyes closed EEG was continuously recorded during 42 min. The computer switched the microwave radiation on for the first time 2 min after the start of the recording. The microwave exposure was switched on and off 40 times while the time period for on and off cycles was 30 s. Therefore, the whole recording consisted 40 microwave exposed cycles with the length of 30 s and 40 non-exposed cycles, again with the length of 30 s.

The EEG signals were recorded using Neuroscan Synamps2 acquisition system (Compumedics, NC). Thirty EEG channels were placed according to the International 10/20 extended system. The average of mastoids (M1, M2) was selected as reference and horizontal and vertical electro-oculograms (EOG) were recorded. Raw EEG signals were recorded with a frequency band of 0.3–200 Hz at a sampling rate of 1000 Hz. The impedance of recording electrodes was below 10 kΩ. MATLAB software (The MathWorks, Inc., Natick, MA) was used for EEG signal processing.

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

Microwave radiation at the non-thermal level of field power density was selected to be identical to that in our previous studies (Hinrikus et al. 2008b, 2011). The 450 MHz electromagnetic radiation was generated by the Rohde & Swartz signal generator model SML02 and was 100% pulse-modulated at 40 Hz frequency, duty cycle 50%. The amplified by the Dage Corporation power amplifier model MSD-2597601 electromagnetic radiation 1 W output power was guided by a coaxial lead to the quarter-wave antenna NMT450 RA3206 by Allgon Mobile Communication AB, located close to ear 10 cm from the skin on the left side of the head. The Central Physical Laboratory of the Estonian Health Board measured the spatial distribution of the electromagnetic radiation power density by the Chauvin Arnoux Fieldmeter CA 43 field strength meter. The average field power density of the modulated microwave at the skin from the left side of the head was 0.16 mW/cm^2. SEMCAD (Schmid & Partner Engineering AG, Zurich, Switzerland) software was used for calculation of the specific absorption rate (SAR). The finite difference time domain (FDTD) computing method with specific anthropomorphic mannequin (SAM) specified in IEEE Standard 1528 was applied. The calculated spatial distribution of SAR is present in Figure 1. The calculated 1 g peak spatial average SAR has the maximum value of 0.303 W/kg near the left ear. During the experiments, the stability of the electromagnetic radiation level was monitored by the IC Engineering Digi Field C field strength meter.

EEG analysis

Any process of filtering can have an effect on microwave exposure transition moments, therefore the raw data of the microwave transition trials were analyzed. Those trials were selected starting at 2 s before the microwave transition moment ending at 2 s after the transition moment. After segmenting the data there were 40×4 transition trials MWR-ON and 40×4 transition trials MWR-OFF. From those trials, trials with artifacts and/or with clear signs of drowsiness were removed. This ended up with 126 MWR-ON trials (1st recording – 37 trials; 2nd recording – 32 trials; 3rd recording – 19 trials; 4th recording – 38 trials) and 134 MWR-OFF trials (1st recording – 38 trials; 2nd recording – 33 trials; 3rd recording – 25 trials; 4th recording – 38 trials).

The responses to 126 MWR-ON stimuli and 134 MWR-OFF stimuli were averaged over stimuli and channels. The signal to noise ratio (SNR) served to facilitate the identification of the ERP. For that a fixed reference window $n(t)$ was chosen 100 ms before the event, while a sliding window $s_i(t)$ with a length of also 100 ms was moved from the beginning ($i = 1$) to the end ($i = 3900$) of the averaged transition segment with a step of 1 sample (1 ms) and a SNR value for every sliding window was calculated for MW-ON and MW-OFF transition segments as

$$\mathrm{SNR}_i = \frac{\mathrm{var}\{s_i(t)\}}{\mathrm{var}\{n(t)\}}.$$

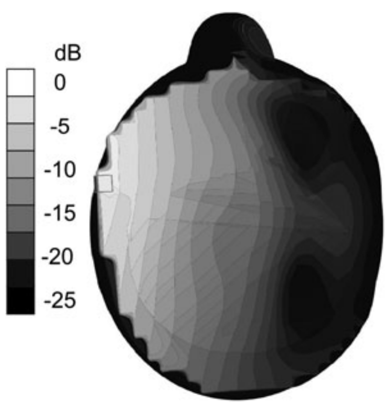

Figure 1. Spatial distribution of SAR calculated in the specific anthropomorphic mannequin (SAM); 0 dB corresponds to 1 g peak spatial average SAR 0.303 W/kg for 1 W antenna input power.

The power spectral density of the recorded EEG signals was calculated by means of Welch's averaged periodogram method and averaged over all MWR-ON trials and MWR-OFF trials for comparison.

Results

The EEG power spectral density for trials with and without MWR were similar, no changes in alpha peak nor components at fixed frequencies were detected. For the subject, the high alpha peak occure at 10 Hz frequency.

The responses averaged over MWR-ON trials and channels are present in Figure 2. The level of ERP is about of 0.1 of the recorded EEG signal. The bold solid line indicates the grand average response to the MWR-ON stimuli. The thin solid line presents the average response to MWR-ON stimuli using the trials from first and second EEG recording and the thin dotted line represents the average response to MWR-ON stimuli using the trials from the third and fourth EEG recording. The noise level is much higher while only half the stimuli are in use – thin solid and thin dotted lines. In addition, there is no uniform behavior that could be interpreted as an evoked response. No response components at fixed frequencies are evident.

The responses averaged over MWR-OFF trials and channels are present in Figure 3. The level of the responses is about 0.1 of the recorded EEG signals. Looking at the responses around 300 ms after the stimulus (stimulus marked with a vertical solid line), an uniform behavior was detected. In the time interval about 150–450 ms the rise of response is observable. This behavior exist not only in the grand average (bold solid line) but also while the trials are split in half (thin solid line and thin dotted line), raising the confidence of the result. The signal component at 10 Hz frequency, equal to the alpha peak frequency of the subject, is clearly evident.

Still, to evaluate more precisely the existence and location of the response to the stimuli a SNR for MWR-ON and MWR-OFF trials are present in Figure 4.

While the SNR values do not reveal any remarkable response for MWR-ON stimuli, the SNR values are about twice higher in 200–340 ms post-stimulus interval for MWR-OFF stimuli. As the length of the sliding window (100 ms) has to

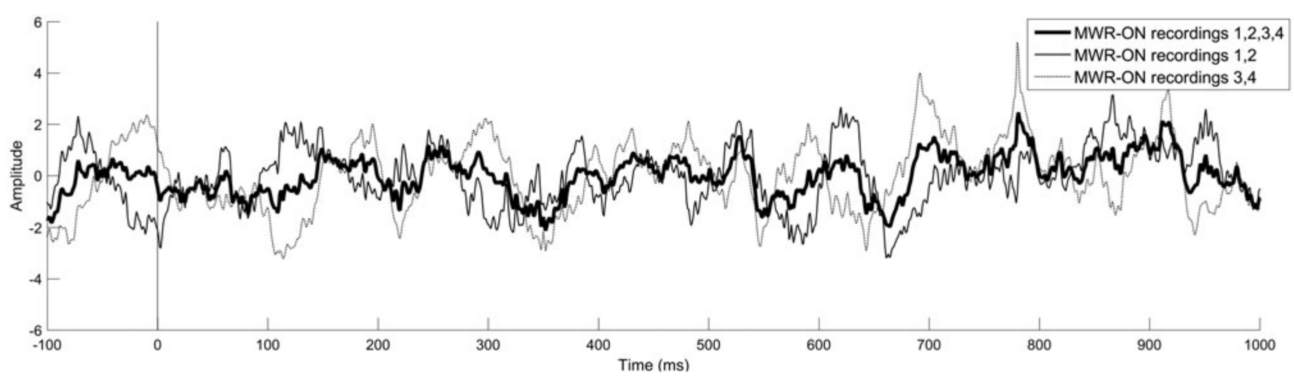

Figure 2. The responses averaged over MWR-ON trials and channels. Bold solid line – grand average response to all MWR-ON stimuli. Thin solid line – average response to MWR-ON stimuli using the trials from first and second EEG recording. Thin dotted line – average response to MWR-ON stimuli using the trials from the third and fourth EEG recording. Solid vertical line represents the onset of MWR.

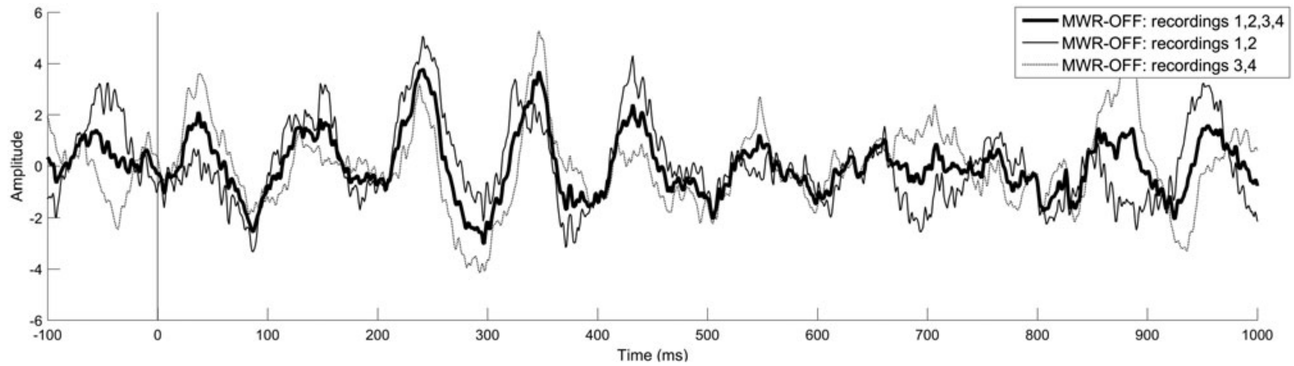

Figure 3. The responses averaged over MWR-OFF trials and channels. Bold solid line – grand average response to all MWR-OFF stimuli. Thin solid line – average response to MWR-OFF stimuli using the trials from first and second EEG recording. Thin dotted line – average response to MWR-OFF stimuli using the trials from the third and fourth EEG recording. Solid vertical line represents the end of MWR.

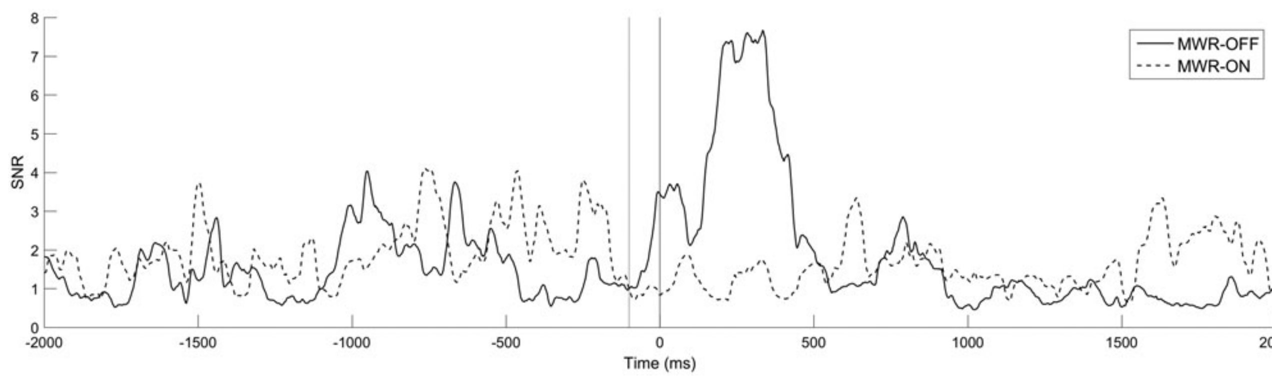

Figure 4. Signal to noise ratio calculated in 100 ms sliding window (step size 1 ms) for MWR-ON (solid line) and MWR-OFF (dashed line) trials. Vertical solid line at time 0 ms represents the onset of stimulation (either ON or OFF). Vertical dotted line represents the time when sliding window started to use post-stimulus data. Reference window with a length of 100 ms was selected as the pre-stimulus interval (−100 to −1 ms).

be taken into account, the response was revealed in 200–440 ms post-stimulus interval.

Discussion

The low-level modulated MWR repetitive stimulation on a single female subject results in changes from baseline EEG time locked with the end of the MWR stimuli. The delay 200–440 ms from a stimulus is characteristic for ERP as well as after-effect (Luck 2005; Huang et al. 2008). However, no comparable changes appeared time locked with the start of MWR stimuli. The undetectable onset response in this study can be explained by the character of applied MWR. The pulses of modulation frequency, that play important role in MWR effects (Juutilainen et al. 2011), are non-synchronized with MWR-ON stimulus. Despite that the onset effect can occur with modulation pulses, the effect is not locked to MWR-ON event and therefore not detectable as ERP response.

As the changes appeared more than 200 ms after the offset of MWR stimulation, the change from baseline EEG cannot be explained by a possible MWR interference nor different filters applied before the digital-analog conversion. No digital filters were in use. The effect appearing later than on–off switching in time, could only be related to the ERP created in brain.

While considering the brain response to MWR-OFF stimuli, it can be seen that around 200 ms after the MWR-OFF stimuli the response component at alpha frequency becomes evident. The presence of alpha rhythms in ERP has been mentioned also by other researchers (Vanderperren et al. 2008). In neurophysiology, it is well known that alpha peak emerges in EEG with eye closure and disappears with eyes opening as the brain becomes loaded by much larger amount of information. Keeping in mind the oscillating character of brain neuronal activity (Steriade and Timofeev 2003; Buzsáki and Draguhn 2004), the high peak of alpha in resting EEG can be explained by stronger synchronization of oscillations in unloaded brain compared to larger loading with increased information processing in eyes open condition. The appearance of more remarkable alpha frequency component in response with MWR-OFF stimulus may be a marker of raised synchronization of neuronal oscillations in brain without MWR. Much less alpha component in segments with MWR may be interpreted as a result of additional loading of brain by information processing related to MWR.

The fact that the recordings were performed on four different days, each of which about 1 month apart, give additional confidence to the results. The same brain response was revealed while using just first two recordings or the last two recordings, indicating that the response was not an one-time event.

Considering the results, one has to bear in mind the limitations of the study. First of all, those preliminary results were gained on a single subject and should be repeated on a larger group. As our previous studies on MWR effects have showed, about 30% of the subjects indicate MWR effect (Hinrikus et al. 2008b), it can be expected that at least the same percentage of subjects express also MWR transition effect. Still, as brain has the ability to adapt, even larger percentage of subjects can indicate MWR transition effect. Most probably also the timing of the MWR transition effect varies between subjects. Therefore, a simple grand average might not be the best method to reveal the effect and more sophisticated methods are needed.

The experiments at different modulation parameters of MWR are recommended to provide better synchronization with MWR-ON transition.

It can be considered whether increasing the number of stimulations, limited in this case with drowsiness, could better reveal the effect. The current study did not indicate whether the 30 s exposure before the MWR OFF transition was necessary to reveal the brain response. In future, the influence of the length of MWR exposure to brain response should be studied. In case the effect reveals already with shorter exposure lengths, the whole recording can be shortened or the number of stimulations enlarged. This would also give valuable information about the MW effect.

Conclusion

Current study analyzed four EEG recordings of one subject recorded on different days about one month apart. The subject was exposed to 450 MHz MWR modulated at 40 Hz at the 1 g peak spatial average SAR of 0.3 W/kg. The preliminary results indicate increased signal-to-noise ratio of the EEG signal with power mainly in the alpha frequency band; this increase in SNR is time-locked to the offset of MWR and peaks between 200 and 440 ms after the stimulus. The detection of offset effect implies that there should be a change in the brain activity generated by the MWR onset; the absence of a clear signature of this effect in the SNR traces implies that the brain response is not as sharply defined in time as the offset effect. The results of this study confirm the possibility of detection of MWR-induced ERP in EEG signal and encourage further research in this direction.

Disclosure statement

No potential conflict of interest was reported by the authors.

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Notes on contributors

Maie Bachmann, PhD, is Professor of Biosignals Processing.

Laura Päeske, PhD student, has experience in recording and processing EEG signals.

Andreas A. Ioannides, PhD, Professor, has experience in physics and neuroscience, Director of the Laboratory of Human Brain Dynamics, AAI Scientific Cultural Services Ltd, Cyprus.

Jaanus Lass, PhD, senior research fellow, is experienced in biomedical engineering.

Hiie Hinrikus, PhD, DSc, Professor Emeritus, has experience in radio physics, microwave and biomedical engineering.

ORCID

Hiie Hinrikus http://orcid.org/0000-0002-3737-5573

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