Pulsed radio frequency radiation affects cognitive performance and the waking electroencephalogram

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Received 15 December 2006; accepted 26 January 2007

We investigated the effects of radio frequency electromagnetic fields on brain physiology. Twenty-four healthy young men were exposed for 30 min to pulse-modulated or continuous-wave radio frequency electromagnetic fields (900 MHz; peak specific absorption rate 1 W/kg), or sham exposed. During exposure, participants performed cognitive tasks. Waking electroencephalogram was recorded during baseline, immediately after, and 30 and 60 min after exposure. Pulse-modulated radio frequency electromagnetic field exposure reduced reaction speed and increased accuracy in a working-memory task. It also increased spectral power in the waking electroencephalogram in the 10.5–11 Hz range 30 min after exposure. No effects were observed for continuous-wave radio frequency electromagnetic fields. These findings provide further evidence for a nonthermal biological effect of pulsed radio frequency electromagnetic fields. *NeuroReport* 18:803–807 © 2007 Lippincott Williams & Wilkins.

Keywords: cognitive function, EEG, electromagnetic fields, human exposure, mobile phones, pulse modulation

Introduction

The effects of radio frequency electromagnetic fields (RF EMF) on cognitive–behavioral outcomes and the waking electroencephalogram (EEG) are inconsistent and somewhat controversial. RF EMF were reported to influence cognitive functions such as working memory and attention during exposure (e.g. [1,2]). The effects include both increases and decreases in performance speed, and accuracy in simple and complex motor, attention, vigilance, and working-memory tasks (e.g. [3,4]). Except in Preece *et al.* [2], the effects were observed in response to pulsed fields. In several studies, no performance changes were observed, or effects reported earlier could not be replicated (e.g. [5,6]).

Pulsed RF EMFs were also found to affect the waking EEG. Although Röschke and Mann [7] detected no changes in spectral power during a short exposure interval, Curcio *et al.* [8] observed an increase of alpha power during and after exposure. We found that the EEG power in the alpha and sigma range of the waking and sleep EEG was increased after pulse-modulated (PM), but not after continuous-wave (CW) RF EMF exposure [9].

We aimed to further investigate the effects of RF EMF on the brain and to clarify the role of pulse modulation in mediating those effects, as advanced telecommunication systems like the global system for mobile communication (GSM) include such pulse-modulation components. We compared effects of a PM and a CW RF EMF on cognitive performance and the waking EEG. On the basis of earlier studies [1,2,10], we expected shortened reaction times in the cognitive tasks during exposure to both RF EMF conditions. We hypothesized that EEG alpha activity (8–12 Hz) would increase after exposure to the PM signal, but not after exposure to the CW RF EMF [9].

Methods

Participants

Right-handed healthy male nonsmoking students [n=24, 19–25 years, mean 22.1±0.4 (±SEM)] with moderate alcohol (≤5 drinks/week) and caffeine (≤3 cups coffee/day) consumption participated in the experiment. They were recruited from the student population of the University of Zürich and ETH Zürich and were paid for participation. The local ethics committee for research on human participants approved the protocol. The participants gave written informed consent. They reported good health, no history of neurologic and psychiatric disease, and no use of medication or illicit drugs. Eighteen participants owned a cell phone and reported that they used it less than 1 h/week (mean use 36.7±3.0 min/week). On the 3 days before each experimental block, participants were asked to abstain from caffeine, alcohol, and medication and to adhere to a regular sleep–wake schedule (8 h of nighttime sleep, 23:00–07:00 h $\pm$1 h with respect to bedtime; no daytime naps). Compliance was verified with wrist-worn actimeters and sleep logs. Cell phones had to be switched off on the night before each experimental block and no calls were allowed until the block was completed.

Design

Three experimental conditions were applied at weekly intervals in a double-blind, randomized, and counterbalanced crossover design: exposure to a PM RF EMF (see below), a CW RF EMF (not modulated), and a sham exposure (no field). After a baseline (BL) EEG recording, participants were exposed for 30 min while performing two series of cognitive tasks. To investigate the time-course of RF EMF-induced effects on brain functioning, the waking EEG was recorded immediately after, and 30 min and 60 min after exposure. The experimental sessions were scheduled in the afternoon (14:45–18:00 h), always at the same time of day for each participant.

Exposure

Each participant's head was positioned between two planar patch antennas. The center of the antenna was placed 42 mm vertically above the ear canal at a distance of 115 mm from the head [11]. Pairs of participants were exposed unilaterally (left hemisphere) for 30 min. The two active exposure conditions consisted of the same carrier frequency of 900 MHz and the same time-averaged power equivalent to a peak spatial specific absorption rate (psSAR) of 1 W/kg averaged over 10 g of tissue (exposure limit: 2 W/kg). The PM signal simulated exposure from a GSM handset (GSM frame structure; basic frame of 4.6 ms is composed of eight slots of 0.577 ms duration; one of these eight slots being active; and modulation components consisting of 2, 8, 217, 1733 Hz and higher harmonics [12]). Electrode leads were horizontally oriented to minimize interference with the RF EMF in active exposure conditions [11].

Cognitive tasks

To investigate the effects on cognitive functioning, we used three tasks employed in earlier studies. In the 'simple reaction time task' (SRT, [10]), participants had to press the '0' button when a '0' appeared on the screen. In the '2-choice reaction time task' (CRT [13]), participants had to press the 'J' or the 'N'-button when the word 'JA' (yes) or 'NEIN' (no) appeared on the screen. In the 'N-back task' [1], consonants were randomly presented on the screen. Participants had to compare the current letter with any letter presented 1 trial, 2 trials, or 3 trials back. In case of a match, they had to press the 'J' button, otherwise the 'N' button. Participants were instructed to respond as quickly and as accurately as possible by pressing the corresponding button on a response box. To assess changes during the 30-min exposure, each task was presented twice in a fixed order (SRT, CRT, 1-back, 2-back, and 3-back). Completion of one series of tasks took 13–14 min. To minimize practice effects, participants completed a training session 7 days before the study.

Waking electroencephalogram

The EEG (derivation C3A2), the electromyogram, the electrooculogram (differential recording), and the electrocardiogram were recorded by a polygraphic amplifier (PSA24, Braintronics Inc., Almere, The Netherlands), digitized, and stored with a resolution of 128 Hz [14]. Waking EEGs were recorded for 6 min (3 min eyes closed, 3 min eyes open). Participants were instructed to sit on a chair, to position their head on a chin support, and to move as little as possible. To minimize eye movements, participants were instructed to slightly touch the closed eyelids (eyes closed) and to fixate a black dot on the opposite wall (eyes open). Vigilance was ensured by continuous online visual inspection of the recordings.

Data analysis

Cognitive tasks

Reaction times $\leq$50 ms and outliers were excluded. The outliers over all the sessions were determined with a robust rejection procedure (4 $\times$ median deviation [15]). This procedure did not alter accuracy. Reciprocal values of reaction times were expressed as speed (1/s; CRT, and N-back: correct responses). Statistical analyses were carried out using linear mixed models (SAS 8.2, SAS Institute Inc., Cary, North Carolina, USA). The model included the factors 'week' (1, 2, 3), 'condition' (sham, CW, PM), and 'session' (first and second half of exposure), and the corresponding interaction effects. 'Condition' was modeled as a categorical variable.

The percentage of correct answers in the CRT and the N-back tasks served as a measure of accuracy. Residuals were not normally distributed in the CRT and the 1-back and 2-back tasks. Thus, nonparametric Wilcoxon signed-rank tests were applied. Comparisons of CW vs. sham and PM vs. sham were performed for (i) session 1, (ii) session 2 and (iii) the difference between the two sessions (Δ). Significance levels were adjusted for multiple testing (six tests) according to Bonferroni–Holm [16]. Residuals in the 3-back task approached a normal distribution and the data were analyzed with linear mixed models (see speed analysis). Δ-values were analyzed in an overall model including the factors 'condition' (sham, CW, PM), 'load' (1-back, 2-back, and 3-back) and the 'condition $\times$ load' interaction. To control for multiple testing, a multiple endpoint adjustment was performed for the cognitive outcomes [17].

Waking electroencephalogram

Waking EEG was visually inspected for artifacts. Artifact-free epochs of 2 s (at least 30 2-s epochs per recording) were subjected to spectral analysis (Hanning window; frequency resolution 0.5 Hz). Owing to the high interindividual variation of the position and size of the alpha peak, relative spectra were evaluated. For each participant, the position of the alpha-peak frequency was determined in the BL spectra averaged over the three experimental conditions (sham, CW, PM). Spectra at 0, 30, and 60 min after exposure were centered at the alpha peak frequency of mean BL (9.7 $\pm$ 0.19 Hz) and expressed relative to the BL of the corresponding condition. Log-transformed relative spectra ($\pm$5 Hz around the alpha-peak) were analyzed with linear mixed models. Two recordings were lost owing to computer problems (30 and 60 min after exposure, different participants). The model included the factors 'week' (1, 2, 3), 'condition' (sham, CW, PM), 'time' (0, 30, 60 min after exposure) and the 'condition $\times$ time' interaction. Posthoc analyses comprised two-tailed paired *t*-tests.

Results

Cognitive tasks

In the course of the study, the participants became slower in the SRT (week: $P<0.04$) and became faster in the N-back tasks (1-back, 2-back, 3-back, $P<0.0001$). No changes in speed over time occurred in the CRT.

Whereas no RF EMF-induced effect on speed was found in the SRT and the CRT, significant 'condition' effects were observed in the 2-back and 3-back tasks ($P<0.002$; 2-back: 1.95 ± 0.11 1/s [sham], 1.87 ± 0.09 1/s [CW], 1.81 ± 0.08 1/s [PM]; 3-back: 1.70 ± 0.11 1/s [sham], 1.70 ± 0.09 1/s [CW], 1.58 ± 0.08 1/s [PM]).

Accuracy was affected in the 3-back task only (Fig. 1a; 'condition $\times$ session' interaction, $P<0.004$). An analysis of differences between the sessions (Fig. 1b) revealed a 'condition' effect ($P<0.001$) and a 'condition $\times$ load' interaction ($P<0.02$). Thus, RF EMF-dependent changes in accuracy were dependent on the cognitive workload, reaching significance in the 3-back task. After adjusting for multiple endpoints (α=0.05; number of tests=18; overall correlation among cognitive outcomes=0.45), all observed 'condition' effects and the 'condition $\times$ session' interaction remained significant at the adjusted P-level of 0.01 [17], but not the 'condition $\times$ load' interaction.

Waking electroencephalogram

Exposure to PM RF EMF enhanced alpha power in the waking EEG (eyes closed) 30 min after exposure (Fig. 2). Statistical analysis revealed significant main effects of 'condition' ($P<0.05$) and 'time' ($P<0.05$) between 10 and 11 Hz and at 12 Hz. Post-hoc paired t-test revealed higher power in the 10.5 and 11 Hz bins, 30 min after PM EMF exposure ($P<0.01$) and lower power at 12 Hz, 60 min after PM EMF exposure ($P<0.03$), compared with sham control. No order effect was observed. The EEG of the eyes-open condition was not consistently altered by RF EMF exposure.

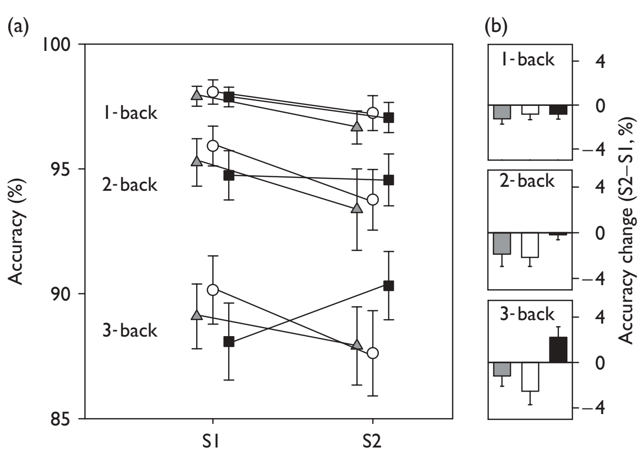

Fig. 1 Effect of RF EMF exposure on accuracy in the 1-back, 2-back, and 3-back tasks (mean $\pm$ SEM; n=24). Three exposure conditions were applied: sham (▲) exposure, continuous-wave (○), and pulse-modulated (■) RF EMF exposure. (a) Accuracy in the first (S1) and the second (S2) half of exposure (session). A linear mixed-model ANOVA, revealed a significant 'condition $\times$ session' interaction ($P<0.004$) in the 3-back task. (b) Accuracy changes from session 1 to session 2 (Δ). A linear mixed-model ANOVA, revealed a significant main effect for 'condition'($P<0.001$) and a significant 'condition $\times$ load' interaction ($P<0.02$). Gray bar, sham; white bar, continuous-wave; black bar, pulse-modulated RF EMF exposure; ANOVA, analysis of variance; RF EMF, radio frequency electromagnetic fields.

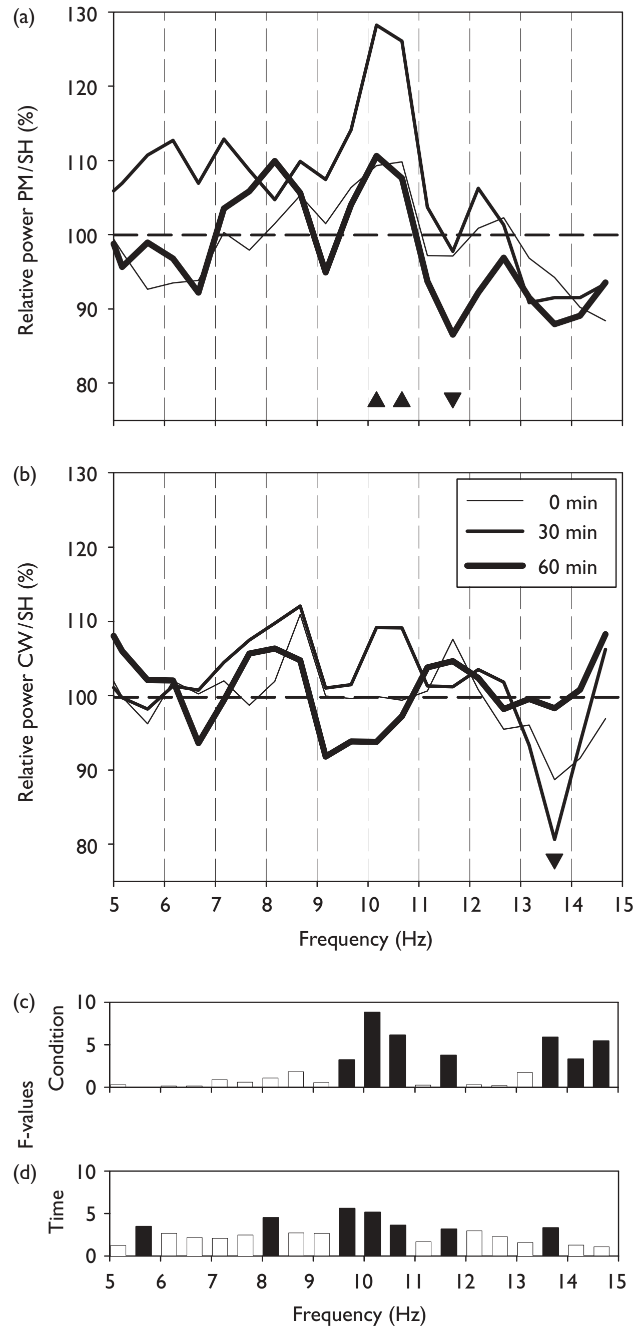

Fig. 2 RF EMF induced changes in the power spectra of the waking EEG (C3A2 derivation, eyes closed; n=24) 0, 30 and 60 min after exposure. Power spectra were centered $\pm$5 Hz around the alpha peak frequency in baseline (9.7 ± 0.19 Hz). Spectra in each condition were first expressed relative to the corresponding baseline and, subsequently, relative to the sham control condition (=100%). Relative power spectra (geometric mean) (a) PM vs. SH; (b) CW vs. SH; (c) F-values of linear mixed-model ANOVA for the factor 'condition' and (d) the factor 'time'. Significant values ($P<0.05$) are indicated by black bars. Concomitant 'condition' and 'time' effects were post-hoc evaluated with two-tailed paired t-tests: (▲) $P<0.01$, PM vs. SH (30 min); (▼) $P<0.03$, PM vs. SH (60 min); and $P<0.01$, CW vs. SH (30 min). ANOVA, analysis of variance; CW, continuous-wave RF EMF; EEG, electroencephalogram; PM, pulse-modulated RF EMF; RF EMF, radio frequency electromagnetic fields; SH, sham control condition.

Discussion

Our results indicate that pulse-modulated RF EMF, similar to those emitted by mobile phones, affect cognitive performance and the waking EEG at a psSAR of 1 W/kg. We observed a significant 'condition' effect on speed in the 2-back and 3-back tasks. In the 3-back task, accuracy was affected with increasing exposure duration, indicating that either an increased cognitive load or a certain exposure time is needed to induce an effect. Furthermore, the increase in alpha power was not observed immediately after exposure, but after a 30-min delay, indicating that these changes may outlast the exposure period.

Currently, no validated and reliable tool exists to assess the cognitive effects of RF EMF exposure. The cognitive tasks applied in this study were chosen on the basis of recently published work [1,2,10]. Existing evidence indicates that RF EMF-induced changes in cognitive performance are small and that not all cognitive tasks are suitable or sensitive enough to reliably detect slight alterations in performance (see [18]). The effect on accuracy with increasing cognitive workload in the N-back task during PM EMF exposure suggests that RF EMF effects are only observed under a certain cognitive demand. This is consistent with the finding of Koivisto *et al.* [1], who reported improved performance in the high-memory-load portion of the N-back task only. In addition, not only the difficulty of a task but also the exposure duration before task performance may be relevant to observe an effect. In our experiment, tasks were performed in two sessions and in a fixed order. Accuracy was affected in the second session of the N-back task only, whereas no effects were observed in the first session. As this task was always the last in the sequence, the exposure duration was the longest for this task. In contrast to our hypothesis, we observed the changes in cognitive performance during PM, but not during CW exposure, supporting the relevance of PM in mediating RF EMF effects.

Increasing evidence indicates that pulsed RF EMF exposure affects alpha activity in the waking EEG [8,9,19–21]. RF EMF effects on alpha activity have been reported to occur during exposure as well as immediately after exposure (e.g. [8,20,21]). The current findings confirmed our hypothesis that PM, and not CW, exposure affects alpha activity in the waking EEG, corroborating the notion that pulse modulation is crucial for EMF-induced alterations in brain physiology. Alpha activity was significantly increased 30 min after the end of PM RF EMF exposure, but not immediately after, or 60 min after exposure, indicating that the effect appeared and disappeared within this time window. This finding is in line with Croft *et al.* [19], who reported increased 8–12 Hz activity as a function of exposure duration. In general, the alpha rhythm dominates the human waking EEG in relaxed wakefulness under eyes-closed conditions. High alpha power is assumed to reflect an idle brain state, which can be blocked by eye opening or mental activity [22]. Alpha-generating mechanisms involve both thalamic and nonthalamic sources [23,24]. As hypothesized for sleep [11], subcortical regions (including the thalamus) may contain the structures most sensitive to RF EMF. Alternatively, altered cortical neuronal activity due to RF EMF exposure may have modified the cortico-thalamo-cortical loops [9]. Thus, the increase in spontaneous alpha activity may result from the interference of RF EMF with the electrophysiological properties of the brain, as suggested by recent findings of altered intracortical excitability after GSM exposure [25].

Conclusion

Our results provide further evidence for a nonthermal biological effect of pulsed RF EMF, as pulse modulation is an important factor for inducing biological changes. The observed effects of pulse-modulated RF EMF on cognitive performance and brain activity, however, were subtle and the underlying physiological mechanisms remain unknown. Thus, the effects have to be interpreted cautiously, in particular, with respect to possible health consequences of RF EMF exposure.

Acknowledgements

All authors declare no conflict of interest. They thank Sven Ebert for support with exposure equipment, Dr Roland Dürr and Karl Wüthrich for technical support, and Prof Alexander Borbély for comments on the manuscript. The study was supported by the Swiss National Science Foundation and the Federal Office of Public Health.

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