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# Resting EEG Is Affected by Exposure to a Pulsed ELF Magnetic Field

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An increasing number of reports have demonstrated a significant effect of extremely low frequency magnetic fields (ELF MFs) on aspects of animal and human behavior. Recent studies suggest that exposure to ELF MFs affects human brain electrical activity as measured by electroencephalography (EEG), specifically within the alpha frequency (8–13 Hz). Here we report that exposure to a pulsed ELF MF with most power at frequencies between 0 and 500 Hz, known to affect aspects of analgesia and standing balance, also affects the human EEG. Twenty subjects (10 males; 10 females) received both a magnetic field (MF) and a sham session in a counterbalanced design for 15 min. Analysis of variance (ANOVA) revealed that alpha activity was significantly higher over the occipital electrodes (O1, Oz, O2) [$F_{1,16} = 6.858$; $P = .019$, $eta^2 = 0.30$] and marginally higher over the parietal electrodes (P3, Pz, P4) [$F_{1,16} = 4.251$; $P = .056$, $eta^2 = 0.21$] post MF exposure. This enhancement of alpha activity was transient, as it marginally decreased over occipital [$F_{1,16} = 4.417$; $P = .052$; $eta^2 = 0.216$] and parietal electrodes [$F_{1,16} = 4.244$; $P = .056$; $eta^2 = 0.21$] approximately 7 min after MF exposure compared to the sham exposure. Significantly higher occipital alpha activity is consistent with other experiments examining EEG responses to ELF MFs and ELF modulated radiofrequency fields associated with mobile phones. Hence, we suggest that this result may be a nonspecific physiological response to the pulsed MFs. Bioelectromagnetics 25:196–203, 2004. 

**Key words: alpha waves; electromagnetic field; occipital; parietal**

## INTRODUCTION

There have been a number of publications over the last 20 years indicating that weak (<200 μT), extremely low frequency (<300 Hz) magnetic fields (ELF MFs) can strongly influence opioid-like behavior in animals as diverse as rodents, pigeons, and snails [Kavaliers et al., 1994] and perhaps humans [Papi et al., 1995; Sartucci et al., 1997]. We have previously studied the effects of weak, pulsed ELF MFs on pain processing in snails [Thomas et al., 1997a,b, 1998a], mice [Thomas et al., 1998b], and humans [Rollman et al., 2002]. We have also demonstrated that a non-conscious behavior, normal human standing balance, can be perturbed by exposure to a pulsed ELF MF [Thomas et al., 2001a] and that the direction of the effect is light dependent [Prato et al., 2001].

Recent publications reviewing the effects of ex posure to weak ELF MFs and ELF modulated radiofrequency fields [Cook et al., 2002; Hamblin and Wood, 2002] upon human electrophysiology and cognitive processing suggests that brief ELF MF exposures influence human brain electrical activity as measured by electroencephalography (EEG). One of the more conspicuous results is higher resting and evoked EEG alpha (8–13 Hz) activity subsequent to both ELF MF [Bell et al., 1991; Bell et al., 1994a; Lyskov et al., 1993a,b] and ELF modulated RF exposure associated with mobile phones [Huber et al., 2000, 2002; Krause et al., 2000a,b; Lebedeva et al., 2001; Croft et al., 2002]. Oscillatory activity within the EEG alpha band has many functional correlates associated with memory processing and attention [Başar, 1998]. However, the increase in resting posterior alpha activity upon subject's eyes closing, while a relatively stable effect, still lacks any definite functional significance, except denoting it as a state of relaxed wakefulness [Niedermeyer, 1999]. This rest state has recently been

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studied and is fairly well delineated in terms of functional anatomy by fMRI and PET studies [Gusnard and Raichle, 2001; Raichle et al., 2001]. We have decided to study this state and are hypothesizing that 8–13 Hz alpha activity in the resting EEG will be affected by a brief exposure to pulsed extremely low frequency magnetic fields (ELF MFs).

## METHODS

### Subjects

Subjects (ages 20–32; 10 males/10 females) were recruited from staff and students at Lawson Health Research Institute (London, Ont.). The research protocol was approved by the University of Western Ontario Review Board for Health Sciences Research Involving Human Subjects (London, Ont., Canada).

### Procedure

All subjects were informed that participation consisted of two sessions, one consisting of a 15 min exposure to a specific pulsed ±200 μT MF, with the other session consisting of 15 min sham exposure, counterbalanced across subjects for order, randomly presented (sham-MF, n = 10; MF-sham, n = 10). Using a standard cross-over design, subjects were run approximately 1 week apart between sessions. We took measures to ensure that the time of day remained constant for all subjects with all experiments taking place in the afternoon (12 pm–5 pm, EST), while attempting to control for other factors that could affect test–retest comparisons between EEG sessions, e.g., eating meals, nicotine, and alcohol intake. Ambient florescent white light levels in the exposure room were 0.51 W/m$^2$ (350 lux; LightSpex, McMahan Research Laboratories, Chapel Hill, NC).

Subjects were fitted with the EEG recording apparatus (QuikCap, Sterling VA) and seated within the exposure device [Thomas et al., 2001b]. Subjects were told that the session would begin recordings with eyes open, followed by eyes closed for the duration of the experiment until instructed to open their eyes (see Table 1). They were instructed to relax, but to not fall asleep. The experiment consisted of 5 min of pre-exposure baseline EEG (2.5 min eyes open and then 2.5 min eyes closed) followed by either 15 min of MF or sham exposure.

Due to the interference of the pulsed magnetic field (MF) with the recording, EEG was sampled approximately 7 s after the end of the MF or sham condition. The 7 s interval was selected to ensure the recording was free from any interference after the cessation of the MF. This 5 min period after the MF/sham exposure was designated a 'sampling' period, where the first 1 min after exposure and also the last 1 min (minute 5) from the sampling period were collected. At the end of the 'sampling period,' subjects were informed that the experimenter would alert them that there would be a few more minutes of eyes closed recording and they would be alerted shortly to 'open their eyes.' Following the warning was a final 5 min post-exposure baseline (2.5 min eyes closed and 2.5 min eyes open). Table 1 shows the structure of each session.

### Exposure Apparatus

The MF exposure system consists of three orthogonal square Helmholtz-like coils with 2, 1.75, and 1.5 m sides (10 turns of 8-gauge stranded conductor per coil with an incorporated high temperature, non-conductive cooling/heating tube wound on Lexan® frames). Each of the three coil pairs were driven by a constant current amplifier via a digital to analog converter [Thomas et al., 2001b]. Only the vertical coil pair was powered during exposure; all other coils were unpowered. With respect to the production of any auditory artifacts, the apparatus showed no acoustic noise production above ambient (<64 db ambient, 20 Hz–18 kHz) during pulsed MF exposure (±200 μT).

There was minimal possibility of olfactory artifacts due to amplifier heating, as neither the coils or the constant current amplifiers used for the production of the MFs are being driven near to capacity [Thomas et al., 2001b]. Furthermore, the exposure room where the coils are present is separate from the room containing the amplifiers and power supplies. All air is vented from an institution common air supply into the exposure room, then into the amplifier room and then directly outside the facility, so any possible odor, however unlikely, would also be vented. This was established primarily for rodent odor clearance, but is also useful

**TABLE 1. Overview of the Procedure: There was 5 min of Pre/Post Exposure Baseline Eyes Open/Closed at the Beginning and End of the Experiment**

| Pre-exposure eyes open baseline | Pre-exposure eyes closed baseline | Magnetic field/ sham | EEG sampling period | Post-exposure eyes closed baseline | Post-exposure eyes open baseline |
|---|---|---|---|---|---|
| 2.5 min | 2.5 min | 15 min | 5 min | 2.5 min | 2.5 min |

MF/sham condition was applied continuously for 15 min. The EEG sampling period was the 5 min period after the magnetic field/sham, during which the 1 min after and the final minute of the 5 min period was sampled.

for maintaining a constant and stable temperature and noise barrier for the exposure facility. [Thomas et al., 2001b].

The specific pulsed MF (see Fig. 1) was monitored with a 3-D fluxgate magnetometer (Bartington Instruments Ltd., Oxford, England) through an analog to digital converter. The amplifiers were on but there was no signal during sham exposure; ambient sham values were 14.7 μT horizontal, 43.3 μT vertical with 60 Hz < 0.2 $\mu T_{rms}$.

## Pulsed Magnetic Field Design

The pulsed MF used in the current study (U.S. Patent #6,234,953) has been utilized in a number of previous studies and was designed to examine the 'coupling' mechanism of MF characteristic to biological behavior. Here, we use the term 'coupling' as the cascade of events from the initial detection to final physiological/behavioral response. Walleczek [1995] postulated that coupling could be enhanced by intermittent exposure linked to the underlying physiology to be altered as compared to using a constant exposure. Figure 1 is an example of the pulsed waveform.

The experimental results found in Thomas et al. [1997a,b, 1998a,b] from the pulsed fields were significantly greater than those from a pure sinusoidal field. This suggests that besides the initial detection mechanism, the coupling of detection to the behavioral response may be dependent on the higher order frequencies and waveforms in the ELF MF exposure. Here we postulated that pulsed MFs might be more specific in generating physiological/behavioral responses than the application of a constant sinusoidal field. The assumption is that endogenous frequencies may be specific for certain tasks and that a specific pulsed field can match or entrain such a specific endogenous frequency. The selection of intensity was chosen to match the intensity used in our previous studies assessing pulsed MF exposure on human standing balance. The power content is extremely low above 500 Hz with most of the power content below 300 Hz.

## Electrophysiological Measures

EEG was recorded from 12 Ag/AgCl electrodes (F3, F4, Fz, C3, C4, Cz, P3, P4, Pz, Oz, O1, O2) on the scalp with a Quik-cap (Neuroscan Labs, Sterling, VA).

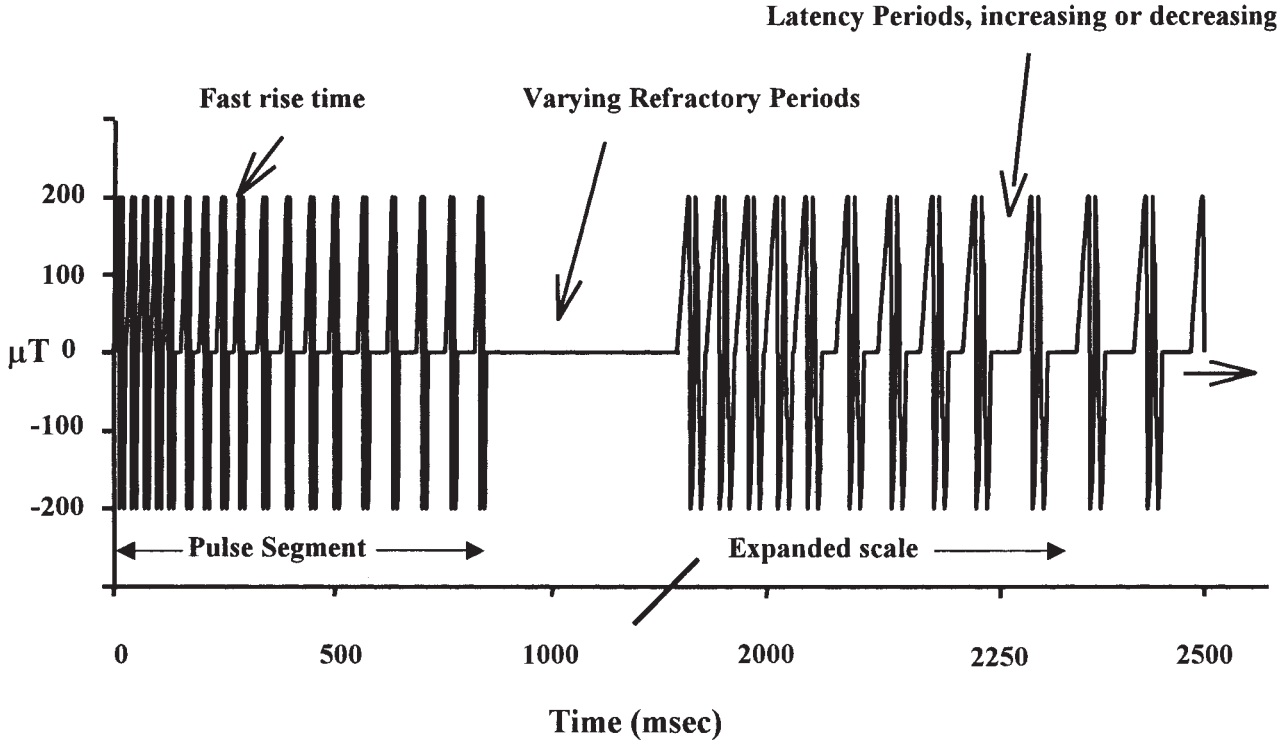


Fig. 1. The pulsed magnetic field (MF) design used in the current study. The design is made of individual pulses, each of which are doublet, combined in an 853 ms segment which includes 18 pulses. Each pulse has a maximum rise time of 1 ms resulting in a maximum time changing MF of 0.4 T/s. In between segments are varying refractory periods of 110, 220, 330 ms followed by a longer fourth refractory period of 1200 m which begins another pulse segment (853 ms). This pattern was repeated for 15 min.

Reference was to linked ears and also included a forehead ground (AFz). Vertical electrooculogram (EOG) was recorded to control for eye movement artifacts. Data acquisition was provided by a Scan 4.2 Workstation through Grass Model 12 Neurodata Acquisition System (Astro-Med, West Warwick, RI), continuously sampled at 1024 Hz (i.e., 1024 samples per second) and bandpass filtered from 0.1–300 Hz with a 60 Hz notch filter. Data was stored and analyzed offline. Electrode impedances were not measured directly in the study, however, high pass filtering and baseline correction would have removed any possible interferences. Recent data suggests that even with severely high impedance levels, EEG data quality is not affected [Ferree et al., 2001].

### Resting EEG

One minute of artifact-free EEG data (lacking obvious muscle/movement artifacts) was sampled from each of the four baseline periods (eyes open/closed, pre/post exposure), with 1 min sampled from the beginning of the data period immediately post-MF/sham exposure, and a second minute taken from the end of the 5 min sampling period. The eyes open/eyes closed paradigm was chosen for internal consistency, both within sessions and between sessions. The 1 min periods were subjected to ocular artifact rejection (vertical eye movements) and then epoched into 2 s periods. After baseline and artifact correction (rejection criteria, $\pm 100\ \mu V$), the 2 s bins were spline fit into 2048 data points and averaged in the frequency domain (Fast Fourier Transform; Hanning window; 10%). The EEG was evaluated over the spectrum 4–80 Hz for changes within the EEG frequency bands: theta (4–7 Hz), alpha (8–13 Hz), beta (14–35 Hz), and gamma (35–80 Hz).

## STATISTICAL ANALYSES

Amplitude-frequency values were subjected to statistical analyses using analysis of variance (ANOVA) with a significance level set at 0.05 (SPSS, Statistical Packages for Social Sciences) [SPSS version 10, SPSS, Inc., Chicago, IL]. Decided a priori, separate ANOVAs (Bonferonni-corrected, mixed design with one level repeated) were performed, examining the individual frequency (theta, alpha, beta, gamma) at each set of electrodes (O1, O2, Oz; P3, P4, Pz; C3, C4, Cz; F3, F4, Fz) from each epoch (eyes open/closed pre-exposure; 1 min post MF and sham exposure; eyes open/closed post-exposure) by sex (male and female) and by order of presentation (sham-MF or MF-sham). For example, in a single ANOVA we would examine the alpha frequency at the occipital electrodes 1 min after the MF compared to the sham exposure for males/females and order of presentation.

In reporting the ANOVA, the F-value is calculated by the ratio of the mean squares (dividing the between and within group sums of squares by their degrees of freedom, noted respectively as subscripts of the F value, e.g., $F_{1,16}$). Also stated are the effects sizes, the proportion of the variance in the dependent variable (e.g., alpha activity) that can be attributed to the independent variable (e.g., sham/MF exposure) [Norman and Streiner, 1998]. Where appropriate, corrected post-hoc analyses using *t*-tests (for independent or related samples) were selected within SPSS to assess within subject or between subjects effects.

## RESULTS

When comparing resting alpha activity after the MF and sham conditions to the pre-exposure, eyes closed baseline, large decreases in alpha activity (8–13 Hz) were noted. ANOVA revealed that compared to the pre-exposure baseline, there was significantly less alpha activity after MF exposure at the occipital [$F_{1,16} = 21.83$; $P < .0001$; $eta^2 = 0.577$] and parietal electrodes [$F_{1,16} = 19.88$; $P < .0001$; $eta^2 = 0.554$]. There was also less alpha activity after the sham exposure for occipital [$F_{1,16} = 50.11$; $P < .0001$; $eta^2 = 0.758$] and parietal electrodes [$F_{1,16} = 47.27$; $P < .0001$; $eta^2 = 0.747$]. ANOVA revealed significantly higher resting EEG alpha activity over the occipital electrodes (O1, Oz, O2) [$F_{1,16} = 6.858$; $P = .019$, $eta^2 = 0.30$] and a marginally higher amount over the parietal electrodes (P3, Pz, P4) [$F_{1,16} = 4.251$; $P = .056$, $eta^2 = 0.21$] 1 min after the MF condition compared to the sham condition (for means and standard errors, see Table 2). Figure 2 displays the mean and standard error of the mean [n = 20] for resting EEG alpha activity 1 min after the MF and sham conditions. Figure 3 displays the grand averaged frequency data for the occipital electrodes (O1, Oz, O2).

There were no significant differences in alpha activity over the remaining frontal or central electrodes or any significant effects within the theta, beta, or gamma bands 1 min after the MF or sham condition. Examining the last minute from the sampling period after the MF and sham condition (approximately 4 min post MF/sham), there was a significantly lower amount of alpha activity over the frontal electrodes (F3, Fz, F4), after the MF condition compared to the sham condition [$F_{1,16} = 5.356$; $P = .03$, $eta^2 = 0.252$]. This was the only significant effect at this time period for electrode or frequency. An examination of the last post-exposure eyes closed baseline (approximately 7 min post MF/sham) revealed a marginally lower amount of alpha

**TABLE 2. Mean, Standard Errors, and Confidence Intervals for Alpha Activity Over the Occiptal Electrodes O1, O2, and Oz for MF and Sham Conditions**

| Exposure condition | Electrodes | Mean of alpha activity | Standard error of alpha activity | 95% confidence interval lower bound | 95% confidence interval upper bound |
|---|---|---|---|---|---|
| MF | O1 | 22.394 | 2.359 | 17.392 | 27.395 |
| | Oz | 23.052 | 2.378 | 18.010 | 28.093 |
| | O2 | 20.453 | 2.501 | 15.151 | 25.756 |
| Total alpha MF | | 21.966 | 2.360 | 16.964 | 26.969 |
| Sham | O1 | 17.836 | 1.425 | 14.816 | 20.856 |
| | Oz | 18.314 | 1.455 | 15.230 | 21.397 |
| | O2 | 16.306 | 1.228 | 13.703 | 18.909 |
| Total alpha sham | | 17.485 | 1.342 | 14.641 | 20.330 |

activity after the MF condition compared to the sham condition at the occipital (O1, Oz, O2) [$F_{1,16} = 4.417$; $P = .052$; $eta^2 = 0.216$] and parietal (P3, Pz, P4) electrodes [$F_{1,16} = 4.244$; $P = .056$; $eta^2 = 0.21$]. There were no other significant effects found at this time point. There were no significant differences for frequency or electrode for the either of the pre- or post-exposure 'eyes open' baselines or the first pre-exposure 'eyes closed' baseline.

## DISCUSSION

This study further demonstrates that the pulsed MF design utilized in previous studies to affect aspects of animal and human behavior [Thomas et al., 1997a, 2001a] also has an effect upon the resting human EEG. This study found that alpha activity was significantly higher over the occipital region after a 15 min MF exposure compared to the sham exposure. Approximately 30% of the variation in alpha activity could be explained by pulsed MF exposure. This result is very consistent with previous literature, where occipital alpha has been found to be higher after ELF MF [Lyskov et al., 1993a,b] as well as after ELF modulated RF associated with mobile phones [Huber et al., 2000; Krause et al., 2000a,b; Croft et al., 2002; Huber et al., 2002; Schuderer et al., 2002].

We also found that this high degree of alpha activity over the occipital region was no longer

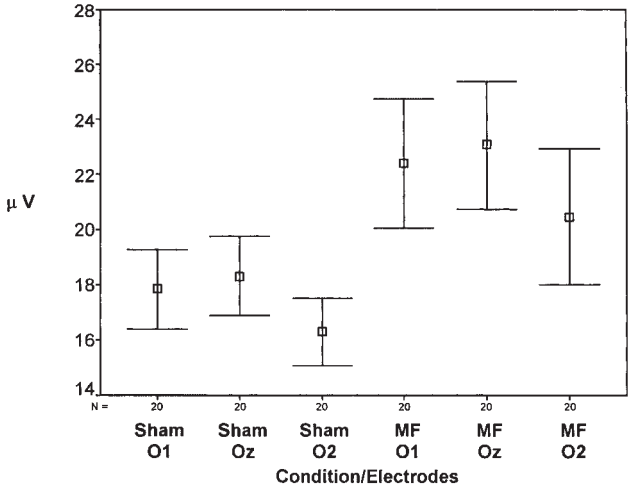


Fig. 2. A significant main effect for MF exposure ($F_{1,16} = 6.858$; $P = .019$, $eta^2 = 0.30$) was found for alpha activity over the occipital electrodes, with a higher degree of alpha activity one minute after the pulsed MF compared to 1 min after sham condition.

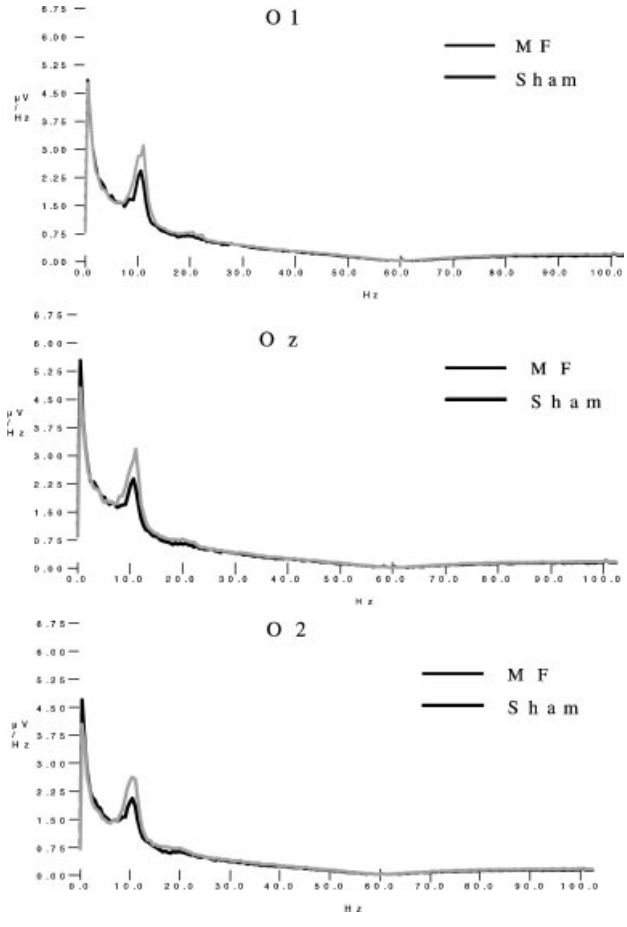


Fig. 3. Frequency spectra of activity over the occipital electrodes (O1, Oz, O2) with a significant peak in 8–13 Hz alpha activity 1 min after MF exposure compared to sham exposure.

significantly different from sham exposure approximately 3 min later and that at this time point, the alpha activity over the frontal regions was significantly lower after MF exposure compared to the sham exposure. Examining a further time point approximately 7 min after MF exposure, alpha activity over the occipital electrodes was now lower post-MF exposure compared to the sham exposure; however, this was a marginally significant result. This finding is a similar result to the Huber et al. [2000] study where alpha activity was higher in the first 30 min of non-REM sleep in the MF condition, but had decreased below sham exposure levels within the last 30 min.

The use of a two session design for the sham and MF exposure may be a better alternative than using a single session, since it could allow for the assessment of perseveration or 'washout' of any effects. Lyskov et al. [1993a,b] and Huber et al. [2000] utilized both a sham and a MF exposure over two sessions and found results comparable to our study. Studies reporting lower amounts of resting alpha, post MF exposure in a single session design such as Bell et al. [1994b], did not use a separate sham session; and the reported decline in alpha may simply be due to decreasing arousal [Cantero et al., 2002]. This decline was also noted in our current study, as alpha activity was found to decrease significantly from the pre-exposure baseline in both the sham and MF conditions. However, when we compared the similar time points, 1 min after both the sham and MF, it was clear that at this time point, alpha activity was higher post-MF compared to sham. It may be worth considering that MF exposure interferes with the normal decrease in posterior alpha activity. It is also worth noting that there were no pre-exposure baseline differences between sham and MF sessions in any EEG frequency with subject's eyes open or eyes closed, suggesting that there was good consistency between sessions.

What is the possible significance of the higher amount of alpha activity subsequent to MF exposure? Although the alpha activity recorded over the posterior region with eyes closed was one of the first phenomenon noted within the scalp-recorded EEG, the source and functional correlates remain largely unknown and it has most often been associated with a state of 'relaxed wakefulness' [Niedermeyer, 1999]. This activity may be related in part to the 'default' state of the brain [Gusnard and Raichle, 2001; Raichle et al., 2001] as the state itself is one of motor inactivity and low sensory stimulation where attention is directed inward. With respect to the lower degree of frontal alpha activity, anterior brain electrical asymmetries in response to reward and punishment have been found over frontal electrodes, with less left frontal alpha power during reward than during punishment trials [Sobotka et al., 1992]. The MF design used in this study has been found to affect opioid-based analgesic processes [Thomas et al., 1997a,b, 1998a,b], which may be related to 'reward' properties. Future studies will address this hypothesis.

It is currently thought that alpha activity is elicited by a set of distributed generators throughout the brain with the posterior alpha activity likely coming from cortical regions such as the occipital cortex, calcarine fissure, parietal-occipital sulcus [Başar, 1998; Cantero et al., 2002]. Why exactly these generators should respond to the pulsed MF remains unclear. One possibility is that the higher degree of alpha post-MF exposure may be due to habituation or conditioning to a repeated stimulus. The pulsed field design in our study consists of a series of pulses separated by refractory periods of various temporal intervals (see Fig. 1). Similarly, experiments by Lyskov et al. [1993a] using an intermittent 45 Hz MF (1 s on, 1 s off) for 15 min and 1 h [Lyskov et al., 1993b], also found higher occipital alpha activity. The latter study also employed a continuous exposure to a 45 Hz MF and found no significant changes in the EEG compared to sham, while the intermittent exposure caused higher alpha activity. The use of an intermittent presentation of the MF was also used by Bell et al. [1991, 1994a], who also noted higher occipital alpha activity. In experiments examining the EEG responses to mobile phones, particularly the GSM variety, the RF MF is pulsed on/off at a frequency of 217 Hz. However, additional frequencies are introduced due to the modulation scheme, such as the frequency of 8.34 Hz [Hamblin and Wood, 2002], which falls within the alpha band.

One conclusion that could be drawn from the current study and from past experiments is that the alpha response subsequent to exposure may be a non-specific central nervous system response. According to Salansky et al. [1998], the central nervous system (CNS) reacts to external stimulation through a complex series of specific and non-specific responses. The specific responses are determined by the physical nature of the stimulation, while the non-specific responses depend upon the intrinsic features of the organism and are to a large extent determined by the common mechanisms of the CNS adaptation to any stimulation. Biological systems are sensitive in varying degrees to rhythmic stimulation independent of modality, and interrupted or chronically repeated stimuli may lead to enhanced effects [Salansky et al., 1998]. This is very similar to the phenomenon of 'emitted alphas' noted by Başar [1998], where trained subjects were found to emit coherent alpha oscillations to expected or predicted stimuli from a series. When an expected stimulus from a train was absent, a degree of alpha activity was

'emitted' in its place [Maltseva et al., 2000]. The presentation of a rhythmic stimulus such as an intermittently presented ELF MF for a short duration (15 min) may have allowed the brain to habituate to its presence and then respond to the absence or offset of the MF. Furthermore, the results of this study also suggest that the ELF component of mobile phone radiation may be an important factor in EEG responses to mobile phones, as also suggested by Hamblin and Wood [2002].

## CONCLUSION

Exposure to a specific pulsed ELF MF was found to result in higher resting EEG alpha activity (8–13 Hz) compared to a sham exposure. Reviews of the literature indicate that this is a consistent result subsequent to electromagnetic field exposure of different frequencies and intensities. We suggest that this result may be a non-specific effect related to the pulsed or intermittent stimulus presentation of the electromagnetic fields. This current study was the first from our laboratory to examine the effects of a pulsed MF upon the human EEG and is not without its drawbacks. Due to the profound interference from the MF, we were unable to record EEG while the MF was on, limiting the important question of 'when' this effect may have occurred. The current results indicate that after a 15 min exposure, there is significantly higher occipital alpha activity, yet this effect may have occurred earlier in the exposure and was obscured due to the interference. Future experiments will test this hypothesis.

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