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Alterations in Human EEG Activity Caused by Extremely Low Frequency Electromagnetic Fields

D. Cvetkovic, E. Jovanov, *Senior Member*, and I. Cosic, *Senior Member*

Abstract—**This study has investigated whether extremely low frequency (ELF) electromagnetic fields (EMFs) can alter human brain activity. Linearly polarised magnetic flux density of 20µT (rms) was generated using a standard double Helmholtz coils and applied to the human head over a sequence of 1 minute stimulations followed by one minute without stimulation in the following order of frequencies 50, 16.66, 13, 10, 8.33 and 4Hz. We collected recordings on 33 human volunteers under double-blind counter-balanced conditions. Each stimulation lasted for two minutes followed by one minute post-stimulation EEG recording. The same procedure was repeated for the EMF control sessions, where the order of control and exposure sessions was determined randomly according to the subject's ID number. The rest period between two conditions (exposure and control) was 30 minutes. The results indicate that there was a significant increase in Alpha1, Alpha2, and Beta1 at the frontal brain region, and a significant decrease in Alpha2 band in parietal and occipital region due to EMF exposure.**

I. INTRODUCTION

Several studies have been conducted to asses whether electromagnetic field (EMF) exposures at characteristic frequencies of brain electrical activity could influence alterations in the EEG and other physiological parameters. Studies on 16.66 Hz and 50 Hz have reported adverse effects on humans and animals [1]-[4]. A single-blind study on 61 volunteers exposed to alternating 3Hz magnetic field of 0.1mT for 20 minutes caused relative spectral power increase at theta and alpha EEG bands and decrease in beta EEG band at the occipital head regions [5]. It was previously reported that applications of electromagnetic fields (EMFs) in the range 0-60Hz and intensity 20 – 100 µT, altered EEG activity in animals and human subjects during 2-second exposure epochs [6]. It was concluded that a weak EMF applied continuously to human subjects for 10 minutes resulted in a reduction in brain electrical activity at the frequency of the EMF during the 1-minute interval following termination of the field. A similar study reported on the effects of 1.5 and 10 Hz EMFs, 20- 40µT, and the results indicated altered brain EEG activity [7]. A recent double blind study on 20 subjects suggested that exposure to ELF magnetic fields altered human EEG activity, specifically within the alpha frequency band (8-13Hz) [8]. The findings indicated that alpha activity was significantly higher over the occipital electrodes and marginally higher over the parietal electrodes at post-exposure.

The purpose of this study was to investigate whether combined extremely low frequencies EMFs (50, 16.66, 13, 10, 8.33 and 4Hz, in that order) which have previously been investigated in literature only as individual frequencies, could cause changes in the EEG activity under double-blind and counter-balanced conditions.

II. MATERIALS AND METHODS

A. *Design of Helmholtz Coil Magnetic Field Exposure Apparatus*

The preliminary [9],[10] and final studies investigated whether multiple sinusoidal extremely low frequency (ELF) (50, 16.66, 13, 10, 8.33 and 4Hz) linearly polarised magnetic flux density of 20±0.57µT (rms) applied to the human head over a non-continuous period of 12 minute, could causes alterations in the EEG rhythms on 33 human volunteers [11]. Standard circular Helmholtz pair of coils have been designed to pass the current of approximately 140mA. The total coil impedance was 71 Ω, designed with average radii of 65cm, copper wire of 0.8mm in diameter and 250 turns each. A signal generator effective in producing high quality sine waveforms of high stability/accuracy ELF signals was designed and developed using EXAR XR-2206 monolithic IC. Also, an audio amplifier was designed and constructed with the approximate gain of 10 to deliver sufficient current to the coils. The magnetic flux density was verified by direct measurement using "Wandel and Goltermann" EFA-200 EMF Analyser. The linearly polarized filed was perpendicular to the Earth's North-South magnetic field.

B. *Subjects and EEG Montages and Procedures*

The final experiments were conducted on 33 healthy subjects, 24 male and 9 female, with mean age of 30 years, SD 11 years, range 20-59 years. The RMIT ethics committee approved the study and all subjects gave written informed

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D. Cvetkovic (corresponding author) is with Australian Centre for Radiofrequency Bioeffects Research (ACRBR) and RMIT University, School of Electrical and Computer Engineering, GPO Box 2476V, Melbourne, VIC 3001, Australia, tel: +613 9925 9641, fax: +613 9925 2007, e-mail: dean.cvetkovic@ rmit.edu.au.

E. Jovanov is with Electrical and Computer Engineering Dept, University of Alabama in Huntsville, Huntsville, Alabama 35899, U.S.A. tel: +1 (256) 824 5094, fax: +1 (256) 824 6803, e-mail: jovanov@ece.uah.edu.

I. Cosic is with Australian Centre for Radiofrequency Bioeffects Research (ACRBR) and RMIT University, School of Electrical and Computer Engineering, GPO Box 2476V, Melbourne, VIC 3001, Australia, tel: +613 9925 1971, fax: +613 9925 2007, e-mail: irena.cosic@ rmit.edu.au.

consent prior to the experiment. During the EEG recording sessions, subjects were asked to lie down between the coils in saggital plane direction perpendicular to the coil axis and in the supine position. The entire experiment was performed in a darkened and sound proof RF anechoic chamber to prevent erroneous recordings due to the standing waves and power line interference.

C. EEG Recording and Experimental Protocol

The EEG equipment used throughout testing was the Mindset MS-1000 recording system. Neuroscan 19 Channel Caps electrodes were used with referential montage of 16 channels. The left brain hemisphere electrodes: Fp1, F7, F3, T7, C3, P7, P3 and O1 were all referenced to M1 (left mastoid), while the right brain hemisphere electrodes: Fp2, F8, F4, T8, C4, P8, P4 and O2 were referenced to right mastoid M2. The baseline EEG was recorded prior to any stimulation for one minute. Each stimulation (50, 16.66, 13, 10, 8.33 and 4Hz) lasted for two minutes followed by one minute post-stimulation EEG recording. Therefore, total length of an experiment was 19 minutes. The same procedure was repeated for the EMF control sessions. The order of control and exposure sessions was determined randomly according to the subject's ID number. Subjects with odd ID numbers were first tested with control condition (no EMF exposure) followed by EMF stimulation after 30 minute break. Double-blind counterbalanced condition was exercised. The two EMF sessions were highly considered in the analysis as a factor that might reveal that if the 1st session was EMF exposure, the EEG activity results during the 2nd EMF control session could still be influenced or dependent on the results of the 1st EMF exposure session.

III. Signal Processing and Statistical Method

All the collected EEG data was processed using Matlab tool. The main Matlab script was written to process all 16 channel EEG data of all subjects and generate valuable parameters that would be used in the further statistical analysis, such as Total spectral power of each stimulation EEG data (i.e. before, 50Hz, 16.66Hz, 13Hz, 10Hz, 8.33Hz and 4Hz); Spectral power in the stimulated band, before/after; Central band frequency before/after and Relative difference "ratio" between the individual band and total spectral power before/after. Spectral function was written to compute the windowed discrete-time Fourier transform of a signal using a sliding window. The EEG band intervals were as Theta (3-5Hz), Alpha1 (7.5-9.5Hz), Alpha2 (9-11Hz), Beta1 (12-14Hz), Beta2 (15.5-17.5Hz) and Gamma (49-51Hz). Delta and Gamma band data was excluded from this particular analysis. We compared the EEG activity "before" and "after" stimulation for each frequency stimulation and band. Throughout this method, "before" stimulation EEG data was regarded for every next recording of the "after". For example, if 1st recording was before any stimulation, 2nd was 50Hz stimulation (gamma band), 3rd was 16.66Hz stimulation (beta2 band). The script used for this signal processing computed all the parameters mentioned above as 1 second epochs, maximum of 60 epochs per recording. Throughout this investigation, only the relative difference (ratio) parameter between the individual bands and total spectral power (before and after) was used for the statistical analysis.

IV. Results

Multiple paired samples 2-tailed t-tests and ANOVA's 3-way mixed design for within and between-subject measures were employed. The factors considered were the "before and after", "exposure and control" and "first and second session." The first test conducted was for the first session of EMF exposure and there were 16 subjects used for this session. The second test was the second session EMF control (*df=15*), the third test was the first session EMF control (*df=16*) and the fourth test was the second session EMF exposure (*df=16*).

A. EMF Exposure followed by EMF Control Results

In Alpha1 band and 8.33Hz stimulation under EMF control (2nd session), *t*-test results revealed a significant relative difference increase from before to after at T7 ($t(15)= -2.397$, $p<0.030$). ANOVA test revealed a significant difference for the interaction between exposure/control and sessions factors (T7) ($F(1,31)= 5.992$, $p<0.020$). In Alpha2 band after 10Hz stimulation, 2nd control session, the relative difference has decreased, highlighted by a high difference observed in parietal and occipital regions, P3, that the relative difference at before (M=0.1789, SE=0.0201) was significantly higher than after (M=0.1573, SE=0.0140), $t(15)= 3.081$, $p<0.008$. At P4, the relative difference before (M=0.1861, SE=0.0223) was significantly higher than after (M=0.1510, SE=0.0134), $t(15)= 2.812$, $p<0.013$. The occipital regions, O1 before (M=0.1399, SE=0.0156) and after (M=0.1243, SE=0.0111), $t(15)= 2.256$, $p<0.039$; and O2 before (M=0.1383, SE=0.0137) and after (M=0.1203, SE=0.0104), $t(15)= 3.283$, $p<0.005$, as shown in Figure 1. There was a largest decrease in relative difference from before to after by 12% (P3), 18.4% (P4), 11.2% (O1), and 13% (O2) than at any other electrode and stimulation. The 3-way ANOVA revealed a significant difference at the interaction between exposure/control and sessions (P3) $F(1,31)= 11.918$, $p<0.002$ and the main factor before/ after $F(1,31)= 5.230$, $p<0.029$. At P4 electrode, a significant difference between exposure/control and sessions was $F(1,31)= 14.827$, $p<0.001$ and before/after $F(1,31)= 4.406$, $p<0.044$; O1 revealed $F(1,31)=9.346$, $p<0.005$ (exposure/control and sessions); and O2 $F(1,31)= 13.071$, $p<0.001$. The t-test results for 13Hz stimulation in Beta1 band revealed no significant differences at any electrode, as shown in Figure 2.

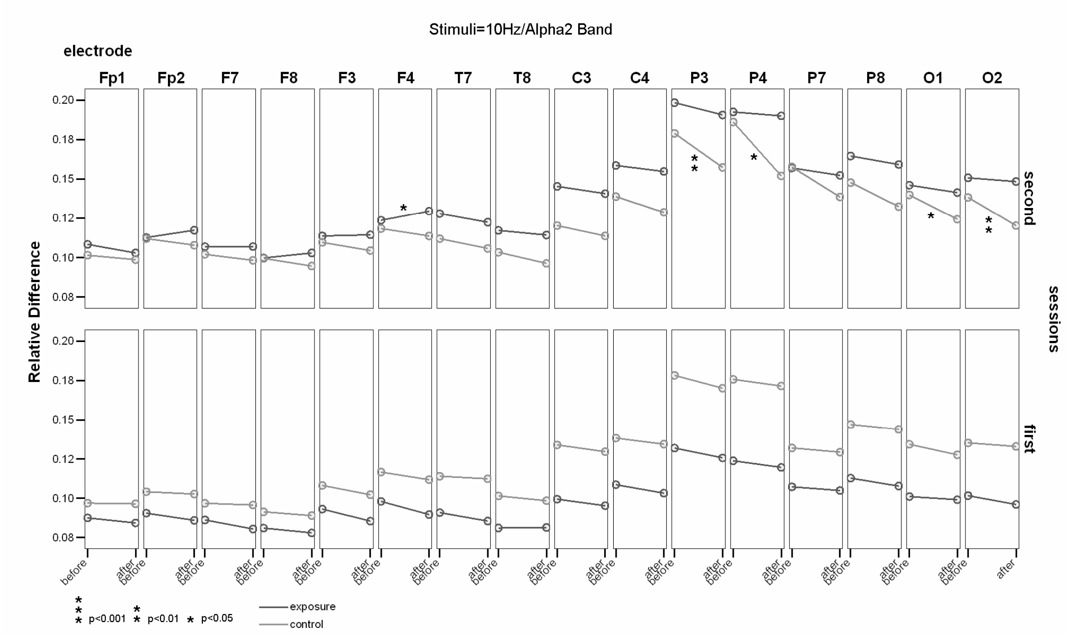

Figure 1. The Relative Differences Versus "Before" and "After" Results Represented at 10Hz Stimulation in a Alpha2 band for EMF Exposure/Control and First/Second Session Conditions.

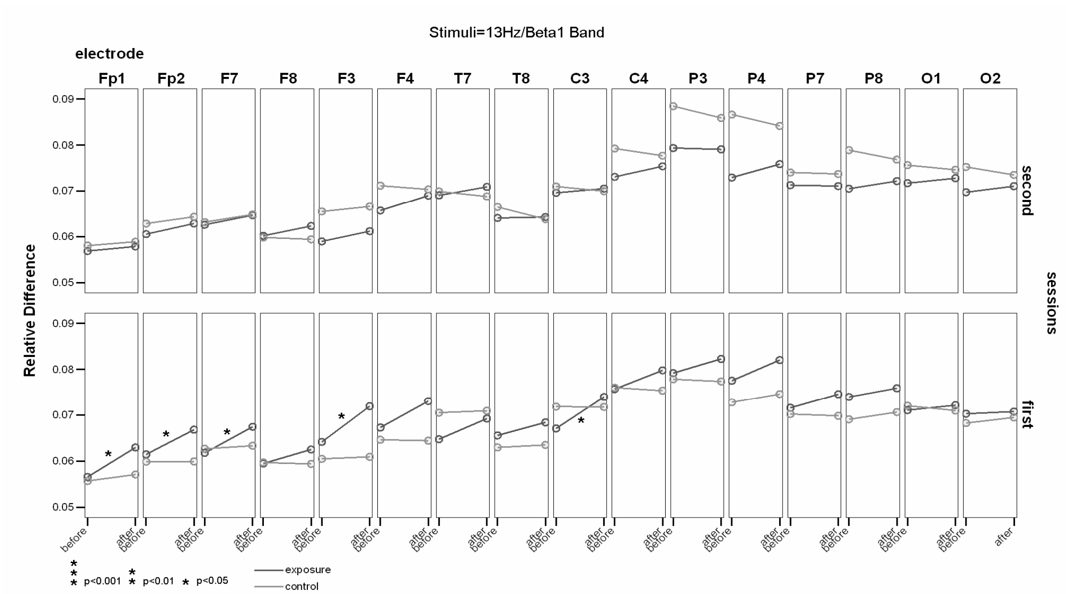

Figure 2. The Relative Differences Versus "Before" and "After" Results Represented at 13Hz Stimulation in a Beta1 band for EMF Exposure/Control and First/Second Session Conditions.

For the 1st EMF exposure session, the t-test results revealed a significant increase at Fp1, Fp2, F7, F3 and C3 for 13Hz stimulation in Beta1 band. At F7 before, $t(1,15)= -2.798$, $p<0.014$; F3 before $t(1,15)= -2.659$, $p<0.018$; and C3 before $t(1,15)= -2.391$, $p<0.030$. There was an increase in relative difference from before to after by 10.1% (Fp1), 8% (Fp2), 8.4% (F7), 10.8% (F3) and 9.3% (C3). The ANOVA results revealed a significant differences between before and after main factors at Fp1 $F(1,31)= 12.852$, $p<0.001$; Fp2 $F(1,31)= 7.058$, $p<0.012$; F7 $F(1,31)= 15.730$, $p<0.0001$; and C3 (NS). In 1st EMF exposure Beta1 band (13Hz), ANOVA's significant results for before and after main factor, were very similar with the t-test's results.

B. EMF Control followed by EMF Exposure Results

For the 2nd EMF exposure session, the t-tests were conducted for 8.33Hz stimulation in Alpha1 band, that relative difference at electrodes Fp1, F7, F3, F4 and C4 was significantly higher before than after stimulation. The results of t-tests were: F7 before $t(1,16)= 2.120$, $p<0.050$; F3 before $t(1,16)= 2.862$, $p<0.011$; F4 before $t(1,16)= 2.682$, $p<0.016$; and C4 before $t(1,16)= 2.872$, $p<0.011$. There was a decrease in relative difference from before to after by 11.1% (Fp1), 11.3% (F7), 10% (F3), 9.8% (F4) and 8.8% (C4). The ANOVA results indicated a significant difference at: F7 $F(1,31) = 6.485$, $p<0.016$ (exposure/control and sessions) and $F(1,31) = 4.485$, $p<0.042$ (before/after and sessions); F3 $F(1,31) = 4.524$, $p<0.041$ (exposure/control and sessions) and $F(1,31) = 4.297$, $p<0.047$ (before/after and sessions); F4 $F(1,31) = 11.554$, $p<0.002$ (exposure/control and sessions); and C4 $F(1,31) = 5.121$, $p<0.031$ (exposure/control and sessions) and $F(1,31) = 6.035$, $p<0.020$ (before/after and sessions). Under the 2nd EMF exposure session, the t-test revealed a significant difference between before and after stimulation of 10Hz in Alpha2 band at F4, where a relative difference was higher before than after the 10Hz stimulation $t(16) = -2.130$, $p<0.049$, as shown in Figure 1. ANOVA revealed a significant difference for the interaction between exposure/control and session's factor, $F(1,31) = 11.043$, $p<0.002$. For 13Hz stimulation, there was no significant difference.

V. Discussion

The statistical EMF exposure/control tests have been conducted and the summary of its entire hypothesis tested have been illustrated in Figure 3.

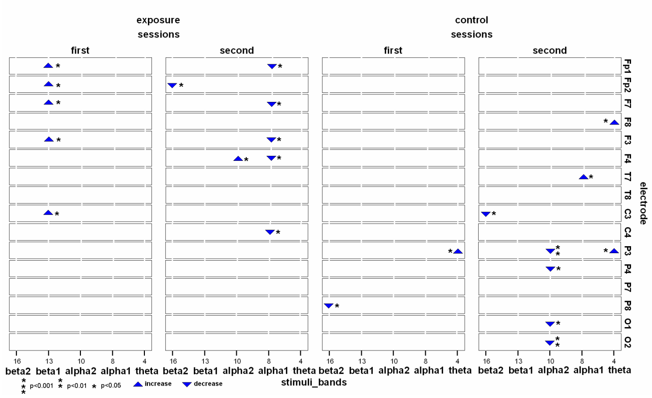

Figure 3. Summary of All the T-test Significant Relative Increase/Decrease for the Standard EMF Exposure/Control and First/Second Session Conditions at Individual Bands/Stimuli and Electrodes.

The alternative hypothesis test for EMF Exposure 1st and Control 2nd session results signify a possibility that the EEG activity could remain altered for at least 50 minutes after the exposure (30 minutes break between the exposure and control conditions with additional 20 minutes for EMF control EEG recordings and stimulations). For the corrected alpha rate value of multiple tests, Bonferroni test was used with the new modified alpha rate of $p<0.0025$. No significant differences were observed as a result of this correction. However, the final analysis results suggest that EEG activity in Alpha1, Alpha2 and Beta1 band could be altered due to EMF exposures, which are mainly associated with stimulation frequencies of 8.33, 10 and 13Hz.

VI. Conclusion

The results from the EEG study on 33 subjects have indicated that under the first EMF exposure there was a shift from a significant increase in Beta1 band at frontal region of the brain to a significant decrease in Alpha2 band at the back region (parietal and occipital) under the post-EMF exposure. However, when the subjects were exposed to EMF after 60 minutes of rest, they exhibited a decrease in Alpha1 band.

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