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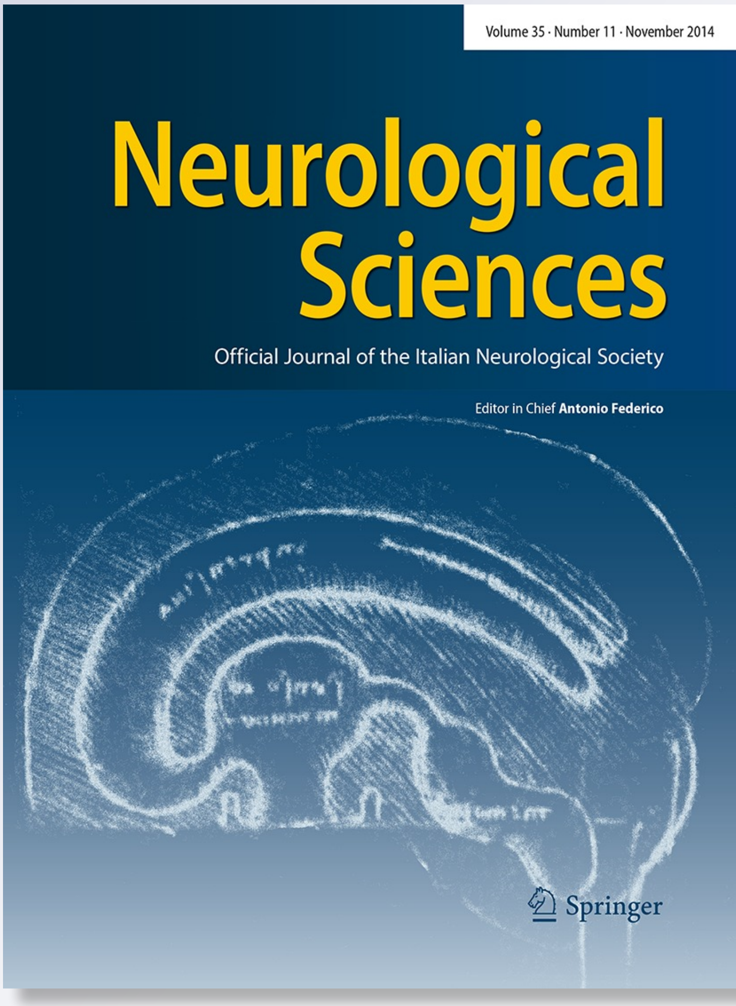

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ORIGINAL ARTICLE

Investigation of EEG changes during exposure to extremely low-frequency magnetic field to conduct brain signals

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Abstract There are evidences that confirm the effect of magnetic fields (MFs) on brain signals and some psychological disorders such as headache, migraine and depression. The aim of the present study was to investigate changes in EEG power spectrum due to localized exposure in different parts of the brain by extremely low-frequency magnetic fields (ELF-MFs) to extract some protocols for treatment of some psychological disorders. In addition, regular effects were investigated by increasing intensity of ELF-MF. Therefore, EEG relative power spectrum was evaluated at T4, T3, F3, F4, and Cz points, when all the points were exposed to MFs with 45, 17, 10, 5, and 3 Hz frequencies, separately. Intensity of MF was 0, 100, 240, or 360 μT in four sessions. Significant changes were observed in different EEG bands caused by locally exposing to ELF-MF in different points of brain ($P < 0.05$). Some exposure to MFs decreased alpha band of frontal and central areas in closed-eyes state. Based on the findings in this study, some protocols can be designed using a combination of various MFs exposures to conduct the brain signals that is necessary to evaluate clinically.

Keywords ELF magnetic fields · EEG · Local exposure · Regular effects · Psychological disorders

Introduction

Recently, there has been increasing scientific evidence that extremely low-frequency magnetic fields (ELF-MFs) can influence the biological systems. The long-term ELF-MFs (50 Hz, 1 mT) may reduce the bone quality by affecting mineralization and collagen integrity [1]. Combination of weak static and ELF-MF affects tumor growth [2]. The magnetic fields (MFs) reduced the human's attention, the perception performance and the recognition accuracy [3, 4]. Also, there are evidences that confirm the effect of MFs on headache, migraine [5] and some psychological disorders such as depression [6, 7].

Some researchers have investigated the effects of pulsed and sinusoidal MFs on the brain activity by analyzing the main frequency bands of the EEG power spectrum [8–16]. These studies usually take the advantage of a uniform field produced by Helmholtz coils, which encompass the head. Therefore, all neurons and EEG sources in the brain are equally exposed to MF. Moreover, they have used a wide variety of experimental designs and exposure conditions. As a result, no regular effects are observed while changing amplitude, frequency, and duration [17]. In the present study, the existence of such a regular effect in the local exposure of different parts of head was investigated by increasing

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intensity of ELF-MF in one group. Moreover, the changes within the EEG frequency bands due to localized exposure to ELF-MFs in different points of the brain were studied for providing some different protocols to treat several symptoms in psychology for future research.

Methods

Subjects

The subjects consisting of 20 males with the mean age of 23.5 ± 2.5 years were students of Tarbiat Modares University (Tehran, Iran). All gave their informed consent. None of them had alcohol drinking and smoking experience. The participants were right-handed and did not have history for epilepsy, chronic pain or psychological disorders leading to take long-term medication. They did not drink coffee or tea at least 3 h before the recording sessions. The research protocol was approved by the Ethical Committee of Tarbiat Modares University.

EEG measurement

Gold-plated surface electrodes (1 cm in diameter) (Thought Technology, Montreal, Canada) were placed on T3, T4, F3, F4, and Cz points (10–20 system). to facilitate quantitative comparisons, all the electrodes were referred to ears, and the ground was on the forehead. Data acquisition sampling rate was 992 Hz and a band-pass filtering was performed from 2 to 50 Hz with a 50 Hz notch filter. The obtained data were stored and analyzed off line.

ELF-MF exposure

MFs were produced using five separate coils (2 cm in diameter, 0.5 cm in height) consisting of 250 turns of copper wire. Each coil was fixed to a C-shape ring of Plexiglas with 3 mm in thickness. The gap on the ring was for crossing of the EEG apparatus electrode wire [18]. Burst alternative current of the coil was produced by a home-made signal generator and driver that its specification was as follows: Frequency range is 0.5–100 Hz, Voltage range of sinusoidal wave is 0–4 V, Current range is 0–1A, and Duty cycle was 10–100 %. Gauss meter (Holaday Industries, Eden Prairie, MN, USA) at 1.5 cm below the Plexiglas ring on the axis of the coil showed the intensity of MF in four sessions as 0, 100, 240, 360 ± 10 μT.

Procedure

Each subject underwent four 120 min sessions to obtain magnetic field intensities 0, 100, 240 or 360 μT with at least 1-day interval. All experiments were performed from 3:00 p.m. to 8:30 p.m. Each participant sat comfortably in a quiet room, instructed to relax but not to fall asleep. They were asked to focus on a fixed area to decrease eye movement. The recordings took place inside a Faraday cage (2 × 1.2 × 1.8 m) constructed of mesh wire (2 × 2 mm) and aluminum frames. Each experiment consisted of the following stages.

After placing the EEG electrodes at each of the five points (T3, T4, F3, F4 and Cz), a recording protocol of 2 min of open-eyes and 2 min of closed-eyes was done to find out the EEG base-line for each participant. Then, the coils were placed on all of the five points by an elastic bandage of the head (surgifix). Next, two subsequent pairs of open- and closed-eyes records were taken, each with 2 min duration with 20 s intervals. Then, two more records were immediately taken concomitant to the exposure of ELF-MF, which is explained in the following subsection. This facilitates the comparison of signals recorded prior to and during the MF exposure. Cook and others did not confirm the existence of a significant persistent effect for more than 7 min after 15 min of ELF exposure [19]. Therefore, the next round of record and exposure was implemented after 10 min in a similar manner with the next frequency to guarantee the absence of persistent effect caused by the first record. Finally, after applying the exposure on the five stages, EEG recording was again taken in the absence of coils, 10 min after the exposure on the fifth stage, similar to the first record (Fig. 1).

The procedure above-mentioned was also implemented for the sham sessions (intensity 0 μT), but the signal generator did not produce any electrical signals. Thus, there was no MF.

MFs design

In each exposure block (2 min), duration of the burst exposure was 5 s [2 s ON and 3 s OFF (Fig. 2)]. In its ON period, regarding stage of exposure in all of the five points (T4, T3, F3, Cz and F4), the frequency of sinusoidal MF was one of the 45, 17, 10, 5 or 3 Hz.

Data analysis

In each record, the 2 s segments during the MF exposure were completely noisy than the 2 s segments, which were selected between the 3 s pauses, were extracted using MATLAB software (MathWorks, Natick, MA, USA) as segments during the MF exposure (Fig. 2). Also, prior to exposure and the sham group that did not receive exposure, 2 s records with 3 s pauses between them were performed similar to the field exposure.

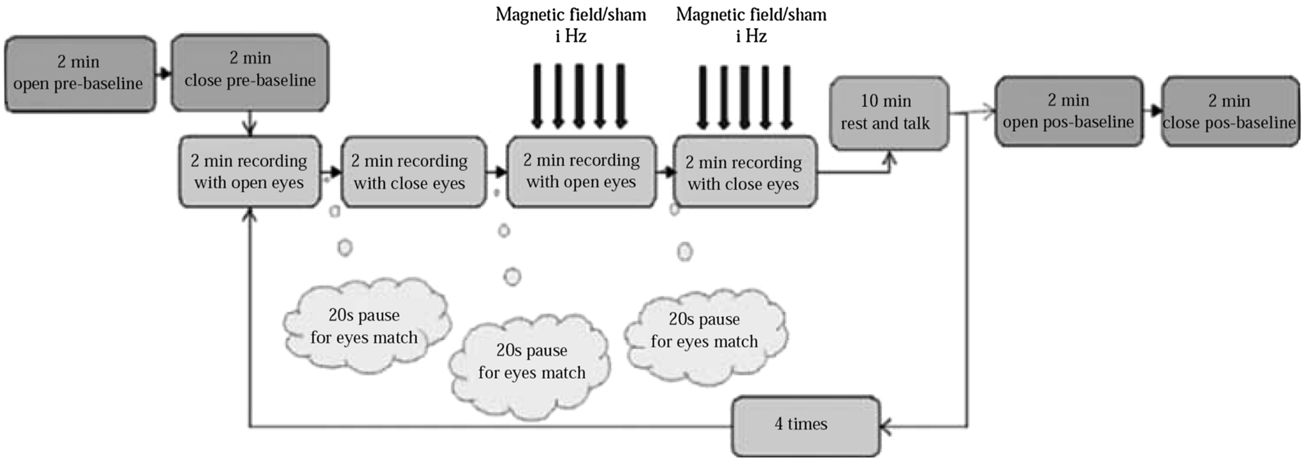
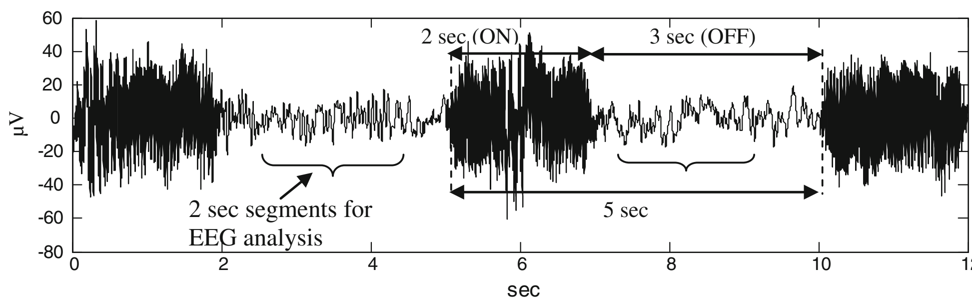


Fig. 1 Each 120 min session consisted of 5 stages plus two base-line recordings prior and subsequent to them. The 2 min recordings were separated with a 20 s pause between them

Fig. 2 A typical EEG recording from the Cz point exposed to 45 Hz and 100 μT ELF-MFs. *Vertical axis* is signal amplitude in (μV) and *horizontal axis* is time (s)



Twenty artifact free segments were selected for each state of open-eyes and closed-eyes as well as prior to and during the exposure. Also, for the control group who did not receive exposure, 2 s records with 3 s pauses between them were performed similar to the field exposure. Frequency analysis of the EEG was subsequently carried out using Fast Fourier Transform (FFT) along with Hanning filter. After averaging of the power spectra of the 20 segments, contribution of each EEG bands and its relative power spectrum was extracted. The analyzed frequency bands included: Delta (2.5–4 Hz), Theta (4.5–7.5 Hz), Alpha (8–12.5 Hz), Beta (13–30.5 Hz), and Gamma (31–47.5 Hz).

Statistical analysis

The relative power spectrums of EEG signals prior to and during the exposure were also compared, using paired *t* test at the significance level of $P < 0.05$.

To study resonance effect (RE), the values of relative power acquired at equivalent frequencies of the radiated field in the power spectrum of participants prior to and during the local MF exposure were extracted separately for the two states of open-eyes and close-eyes. Then they were analyzed with paired *t* test at the significance level of $P < 0.05$.

To compare the effectiveness of MFs intensity, the Repeated Measure ANOVA was used with a significance level set at 0.05.

Finally, the EEG prior to the exposure and the EEG recorded 10 min after the last exposure was compared with paired *t* test at the significance level of $P < 0.05$.

Results

Several EEG bands were changed in each MF exposures that have been showed with Tables 1, 2, 3. In each table, recording points and frequency of exposure as well as the participant's state, i.e., with open-eyes or closed-eyes (with bold letter), are shown. Also, Tables 1, 2, 3 show the results obtained from the paired *t* test comparison of the relative power of spectra prior to and during the exposure, along with the bands with significant changes ($P < 0.05$), using SPSS software.

Upward and downward arrows indicate increase and decrease of the power spectra in a particular band, respectively.

Table 1 The exposure results of the five points by 100 μT ELF-MF

Frequency/ recorded point	F3	F4	Cz	T3	T4
45	Beta↓ (0.045) **Alpha↓ (0.011)**	Beta↓ (0.046) **Alpha↓ (0.032)**	Beta↓ (0.027) **Alpha↓ (0.017)** **Theta↑ (0.004)**	**Alpha↓ (0.041)**	**Delta↑ (0.015)** **Alpha↓ (0.021)**
17	Delta↑ (0.004) Alpha↓ (0.004) **Beta↑ (0.049)**	Alpha↓ (0.023)	Delta↑ (0.001)	Delta↑ (0.017) Theta↑ (0.031)	NS*
10	NS*	NS*	NS*	NS*	Theta↑ (0.014) **Theta↑ (0.042)**
5	Beta↓ (0.045) Theta↑ (0.042)	NS*	**Delta↑ (0.045)**	Alpha↑ (0.005) Theta↑ (0.020)	Delta↑ (0.040)
3	**Alpha↓ (0.029)** **Beta↑ (0.047)** **Theta↑ (0.040)**	**Beta↑ (0.029)**	NS*	NS*	NS*

Significant changes of EEG bands in five measurement points are presented with their *P* values and also closed-eyes state showed with bold letter, ↑ increased power spectra, ↓ decreased power spectra

* Not significant in all defined EEG bands in context

Some exposure to MF decreased alpha band of frontal and central areas in closed-eyes state (Fig. 3).

Sometime decrease in alpha band of frontal and central areas in closed-eyes state have observed during exposure to magnetic fields, especially when intensity of MFs was 240 μT (Table 2). Investigation of the relative power at 45 Hz EEG during the 100, 240 and 360 μT MF exposures with 45 Hz frequency in the five points revealed no significant changes as compared to the state prior to the exposure field, using paired *t* test. Also, the test showed no significant difference for the relative power of 17, 10, 5 and 3 Hz frequencies for the recorded signals at the points F4, Cz, F3, T3 and T4, when these regions were exposed to the MFs with 100, 240 and 360 μT intensities and 17, 10, 5 and 3 Hz frequencies. These results (no significant changes) were observed for both states of open-eyes and closed-eyes.

To investigate the effectiveness of increasing intensity of ELF-MF on the power spectrum of EEG bands, a comparison was performed in the effectiveness of exposure field intensities (0, 100, 240 and 360 μT) with Repeated Measure ANOVA. This comparison had no significant results ($P > 0.05$) that seemed to be for high standard deviation in data.

Discussion

No regular effects were observed when intensity of MF increased from 100 to 360 μT (Tables 1, 2, 3). For example, when all the points were exposed with 10 Hz frequency ELF-MF and intensity of MFs increased from 100 to 360 μT EEG changed in 240 μT, alpha band in F3 point decreased, but in 100 and 360 μT no change was observed. Moreover, exerting 240 μT MF with 17 Hz frequency on the all points in open-eyes and closed-eyes states led to no significant effect while in 360 and 100 μT were different. Similar to exposure in the entire of head that is seen in review article [17] cannot be extended with no regular effect between intensity and frequency of MFs with EEG changing (Tables 1, 2, 3) [20].

Few researchers proposed a resonance effect (RE), in which EEG power alters at the frequency of stimulation [9, 21]. Significant changes in EEG signals similar with frequency of MFs exposure were not observed in open-eyes or closed-eyes states [18, 22]. Even the observation of RE for Delta and Theta waves in the all points, which are supposed to be of cortex origin [23], was not possible. Regarding the fact, the intensities of MF produced by coil at 1.5 cm from the skin surface were 100, 240 or 360 μT, it is rejected that no influence yields as RE with the cortex origin in exposure of MF, because the average distance of cortex layer from the external surface of skin is approximately 1.2 cm [24].

In contrary to findings of Cvetkovic and colleagues [25], the local exposure does not cause the amplification of bands in which the frequency of the applied MF is placed, for example, significant change in alpha band in open-eyes state after exposure of 10 Hz ELF-MF have not be observed (Tables 1 and 3).

Several studies have shown a correlation between alpha rhythm and cognitive performance [26, 27]. The idea, the high frequency electromagnetic fields [especially Mobile phones (MP)] can influence on the activity of the normal alpha wave on brain functioning, would be interesting. More researchers reported the MP exposure increase alpha band in EEG spectral power [28, 29]. For example, Croft et al. [30] have report

Table 2 The exposure results of the five points by 240 μT ELF-MF

Frequency/ recorded point	F3	F4	Cz	T3	T4
45	Alpha↓ (0.008)	Alpha↓ (0.045)	Alpha↓ (0.042)	**Alpha↓ (0.006)**	NS*
	Alpha↓ (0.005)	Theta↓ (0.039)			
	Delta↑ (0.034)				
17	NS*	NS*	NS*	NS*	NS*
10			**Delta↑ (0.042)**	Alpha1↑ (0.030)	Beta↓ (0.025)
	Delta↑ (0.023)		**Theta↑ (0.040)**	Theta↑ (0.017)	**Theta↑ (0.033)**
	Alpha↓ (0.005)	**Alpha↓ (0.007)**	**Alpha↓ (0.010)**	**Alpha↓ (0.021)**	**Alpha↓ (0.027)**
5	Beta↓ (0.040)	NS*	Beta↑ (0.023)	Theta↑ (0.001)	Theta↑ (0.015)
	Beta↑ (0.014)		**Alpha↑ (0.045)**		Alpha↑ (0.016)
3		Delta↑ (0.025)			Theta↑ (0.049)
		Beta↓ (0.008)	Beta↓ (0.009)		Delta↑ (0.003)
		Gamma↓ (0.022)			Beta↓ (0.044)
	Theta↑ (0.001)	**Theta↑ (0.017)**	**Theta↑ (0.005)**	**Theta↑ (0.048)**	
		Alpha↓ (0.022)	**Alpha↓ (0.023)**		

Significant changes of EEG bands in five measurement points are presented with their *P* values and also closed-eyes state showed with bold letter, ↑ increased power spectra, ↓ decreased power spectra

* Not significant in all defined EEG bands in context

Table 3 The exposure results of the five points by 360 μT ELF-MF

Frequency/ recorded point	F3	F4	Cz	T3	T4
45	**Alpha↓ (0.046)**	NS*	Theta↓ (0.010)	NS*	NS*
			Alpha↓ (0.023)		
17	NS*	Theta↑ (0.030)	NS*	**Theta↓ (0.033)**	NS*
		Beta↓ (0.047)			
10	NS*	Beta↓ (0.015)	NS*	NS*	NS*
5	NS*	**Beta↑ (0.042)**	NS*	NS*	Delta↑ (0.036)
3		NS*	Theta↑ (0.042)	Theta↑ (0.049)	
	Delta↑ (0.023)		**Delta↑ (0.045)**	Alpha↓ (0.037)	Alpha↑ (0.020)

Significant changes of EEG bands in five measurement points are presented with their *P* values and also closed-eyes state showed with bold letter,↑ increased power spectra, ↓ decreased power spectra

* Not significant in all defined EEG bands in context

significant increase in alpha band after the MP exposure. This effect was greater when the MP was on during the EEG recording session than before it [31]. While the effects in the brain signals, which we have observed during exposure to magnetic fields, were a decrease in alpha band.

The alpha rhythm is temporarily blocked by an influx of light (eye opening), other afferent stimuli (auditory, tactile, and other somatosensory stimuli), and mental activities. Some exposures to MF decreased alpha band of frontal and central areas in closed-eyes state, especially 45 Hz, 360 μT (Fig. 3) and 10 Hz [10], 240 μT (Fig. 3) were more effective. Like other senses, does the brain make sense the MFs directly due to such changes?

In applying the exposure to overall head, the central part is rarely influenced by the exposure, and if any effect occurs, this will increase the alpha band [12], which is opposite with the findings of the present study. The increase in delta, theta bands (slow wave) and reduction of beta and alpha bands can be explained by the exposure of the five points.

But based on the findings, we may design some protocols using a combination of various exposures to change the EEG band of specific points of the head; e.g., for example one of the anti-ADHD protocols used in neurofeedback training technique is reducing the theta band and increasing the beta band at position Cz (International

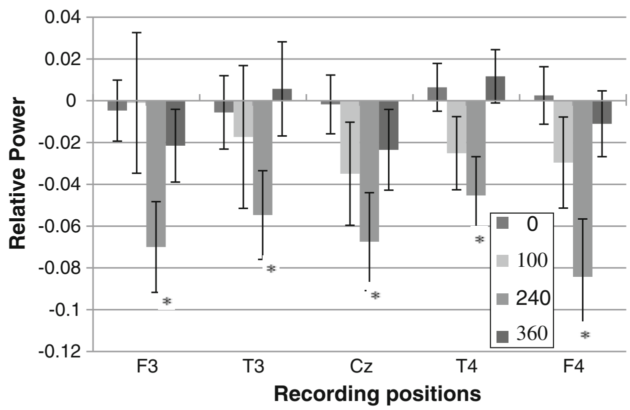


Fig. 3 The mean of subtraction of the relative power of alpha band in recorded brain signals, during Exposure ELF-MFs, in comparison prior to exposure in closed-eyes state (Mean ± SE) when all of F3, T3, Cz, T4 and F4 points have been exposed with 0 (sham), 100, 240 or 360 μT MF in 10 Hz frequency. Significant effect ($P < 0.05$) showed with (*asterisk*)

10–20 System; Jasper, 1958) [32]. Therefore, to achieve this situation we may expose 360 μT MF with a frequency of 45 Hz (Table 3), for reducing the theta band and expose 240 μT MF with a frequency of 5 Hz, for increasing the beta band (Table 2), or decreasing of beta band in alcoholics [33] by expose of 45 Hz, 100 μT ELF-MF. So we may conduct the brain and the brain signals using special ELF-MF exposure which has no certain harmful side effects. We suggest that similar to neurofeedback training (treating some disorders based on the changing of the EEG bands [34, 35]), the change of the EEG bands is done by exposure to some areas of the head with various intensities and frequencies, with regard to the results of the present paper for treating some symptoms in the next researches.

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