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Study of the frequency parameters of EEG influenced by zone-dependent local ELF-MF exposure on the human head

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It has been reported that human subjects exposed to electromagnetic fields exhibit changes in human EEG signals at the frequency of stimulation. The aim of the present study was to expose different parts of the brain to extremely low-frequency magnetic fields locally and investigate EEG power spectrum alters at the frequency of stimulation. EEG relative power spectrum were evaluated at 3, 5, 10, 17, and 45 Hz frequencies at T4, T3, F3, Cz, and F4 points, respectively, when these points were exposed to magnetic fields with similar frequencies and 100 μT intensity. The paired t-test result**s** showed that power value of EEG did not alter significantly at the frequency of stimulation ($P < 0.05$). Further, significant changes in different EEG bands caused by locally exposing to ELF-MF in different points of brain were observed. The changes in the EEG bands were not limited necessarily to the exposure point.

Keywords ELF magnetic fields, Local exposure, EEG, Resonance Effect, Frontal

INTRODUCTION

Electromagnetic fields (EMFs) of various frequencies and strengths are generally produced by electrical and electronic appliances and power lines. Recently, there has been increasing scientific evidence that extremely low-frequency magnetic fields (ELF-MFs) can strongly influence the biological systems. For example, the long-term ELF-MFs (50 Hz, 1 mT) may reduce the bone quality by affecting mineralization and collagen integrity (Gurgul et al., 2008). ELF-MFs can affect epiphysial growth, bone build-up, and fracture repair (Sert et al., 2002). Much evidence has accrued over the last decade that specific combinations of static and time-varying fields can affect some biological processes (Belova et al., 2007; Blackman et al., 2001; Novikov et al., 2008). For instance, combination of weak static and ELF-MF affects on tumor growth (Novikov et al., 2009).

Some studies suggest that exposure to ELF-MFs influences the peripheral and central nervous functions that are related to sensory evoked potentials

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(Graham and Cook, 1999; Lyskov et al., 1993). Human's attention, perception performance, and recognition accuracy reduce in the MF (Podd et al., 1998).

Various studies have investigated the effects of pulsed and sinusoidal MFs on the brain activity by analyzing the spectral power at the main frequency bands of EEG (Bell et al., 1992b, 1994a,b; Cook et al., 2009; Ghione et al., 2005; Heusser et al., 1997; Lyskov et al., 1993; Marino et al., 1996), although only a few researchers proposed a resonance effect (RE), in which EEG power alters at the frequency of stimulation (Bell et al., 1992a, 1994b).

In investigating the effect of ELF-MF on EEG, researchers usually take the advantage of a uniform field produced by Helmholtz coils, which encompass the head. As a result, all neurons and EEG sources in the brain are equally exposed to MF and no regular effects are observed while changing amplitude, frequency, and duration. In this article, the existence of such a RE in the local exposure of different parts of head is investigated. Besides, the changes in different EEG bands caused by locally exposing to ELF-MFs in different points of the brain are studied. This study and similar additional research will provide different protocols for local exposing and recording of its influence on EEG, which may offer a tool in psychology to treat several symptoms.

METHODS

Subjects

The subjects consisting of 19 males with the mean age of 25.6 ± 1.6 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 positive history for epilepsy, chronic pain, or psychological disorders leading to take long-term medication. They did not drink coffee or tea at least three hours 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). The left brain hemisphere electrodes, F3 and T3, were all referenced to A1 (left ear), while F4, T4, and Cz electrodes were referenced to right ear A2, and the ground was on the forehead. Controlled change and control of EEG especially in temporal, central, and forehead regions (particularly F3 and F4) causes an improvement in some disease symptoms, which is employed in neurofeedback training; hence, the mentioned points were selected based upon their importance in treatment of some symptoms (Budzynski, 2009; Gunkelman and Johnstone, 2005; Othmer, 2005). Data acquisition sampling rate was 992 Hz and a band-pass filtration was performed from 2–50 Hz with a 50 Hz notch filter. The obtained data were stored and analyzed off-line.

ELF- MF Exposure

MF**s** were produced using a coil (2 cm in diameter, 0.5 cm in height) consisting of 250 turns of copper wire. The 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 (Fig. 1B).

Burst current of the coil was produced by a home-made signal generator with the fallowing specification: frange, 0.5–100 Hz; voltage range of sinus wave, 0–4 V; current range, 0-1A; and duty cycle, 10–100%.

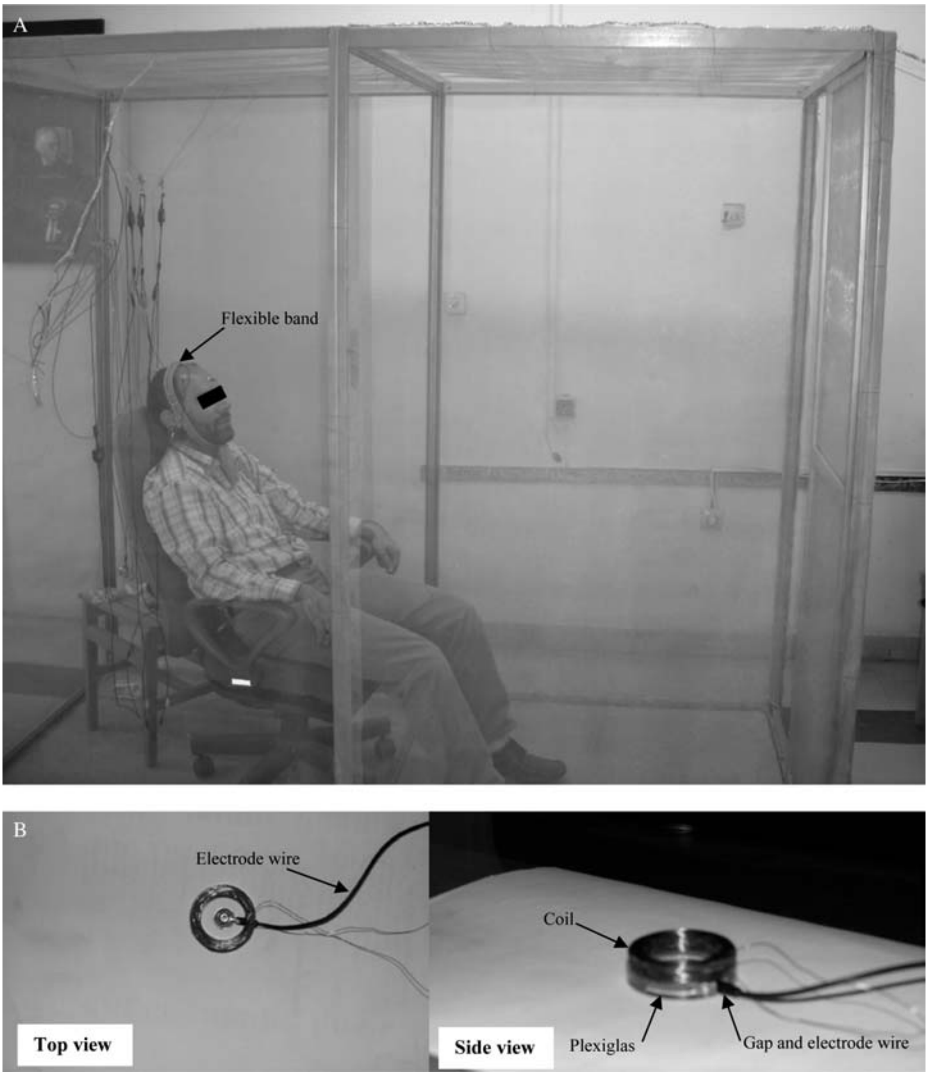

FIGURE 1 A: The recordings took place inside a Faraday cage and the coil was placed on the Cz point by a flexible band. B: MFs were produced using a coil (2 cm in diameter and 0.5 cm is height). The coil was fixed to a C-shape ring of Plexiglas with 3 mm in thickness. The gap on the ring was for crossing of the electrode wire of EEG apparatus.

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 as $100_{\pm}10\,\mu T$. There were no visual or auditory signs to the participants indicating the presence or absence of MF. The room was partially sound-proof, but occasional sounds due to a nearby construction work in progress could be heard in it.

Procedure

Each subject underwent two 120-min sessions with two-day to one-week interval (Exposure and sham groups). All experiments were performed from 3.00 p.m. – 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 ($2 \times 1.\ 2 \times 1.8$ m) constructed of

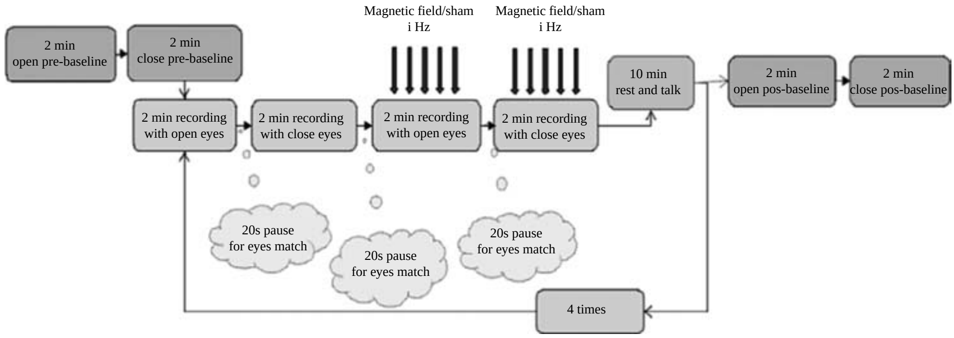

FIGURE 2 Each 120 min session consisted of 5 stages plus 2 base-line recordings prior and subsequent to them. The 2 min recordings were separated with a 20 s pause between them.

mesh wire (2 × 2 mm) and aluminum frames. Each experiment consisted of the following stages:

After placing the electrode at each of the 5 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 coil was randomly placed on one of the five points by a flexible band (Fig. 1A). Next, two subsequent pairs of open- and closed-eyes records were taken, each with 2 min duration with 20-s intervals. Two more records were then immediately done concomitant with the exposure of ELF-MF. This facilitates 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 that 7 min after 15 min of ELF exposure (Cook et al., 2004). Thus, the next round of record and exposure was implemented after 10 min in a similar manner in another point with the respective frequency to guarantee the absence of persistent effect caused by the first record. Finally, after applying the exposure to the five points, a record was again done in the absence of coil, 10 min after the exposure on the fifth point, similar to the first record (Fig. 2). It is worth noting that the above procedure was also implemented for the sham group sessions, but the signal generator did not produce any electrical signals. So, there was not any MF.

Magnetic Field Design

In each exposure block (2 min), duration of the burst exposure was 5 s (2 s ON and 3 s OFF; Fig. 3). Regarding the coil's position on the head, the frequency of sinusoidal MF was set as shown in Table 1.

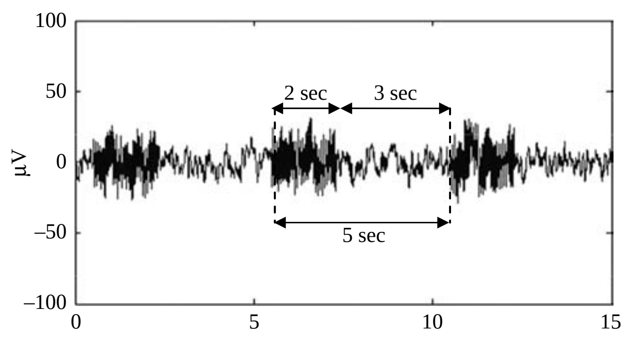

FIGURE 3 A typical EEG recording from the Cz point exposed to 17 Hz ELF-MFs. Vertical axis is signal amplitude in (μV) and horizontal axis is time (sec).

TABLE 1 Frequency of ELF-MF at each point.

Point	Frequency (Hz)
T4	3
T3	5
F3	10
Cz	17
F4	45

The frequency of sinusoidal MF was presented, regarding the coil's position in each of the five measurement points.

Choice of the frequencies 3, 5, 10, 17, and 45 Hz was due to observing the effect MFs in these frequencies, especially the resonance effects in frequencies 5 and 10 Hz (Bell et al., 1992a, 1994b; Cvetkovic and Cosic, 2009; Heusser et al., 1997; Lyskov et al., 1993). Furthermore, frequencies were selected such that each of them were put into one of defined frequency bands in order to measure the synchronize effect of the exposure MF on its respective band

Data Analysis

In each record, the 2 s segments during the MF exposure were noisy completely then 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. Also, for 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. Twenty noiseless segments were selected for each state of open-eyes and closed-eyes as well as prior to and during the 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 and obtaining a power spectrum with low fluctuation, 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). Furthermore, the Alpha 1 (8–10 Hz) and Alpha 2 (10.5–12.5 Hz) bands were also evaluated because of their importance in psychology. Also, to investigate RE in MF exposure locally, the relative power was evaluated at 45, 17, 10, 5, and 3 Hz frequencies at T4, T3, F3, Cz, and F4 points, respectively.

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 $P < 0.05$.

TABLE 2 The exposure results of Cz point by 17 Hz ELF-MF in closed-eyes state.

EEG Recording Points ELF-MF	T4	T3	Cz Exposure	F3	F4
B = 0	Alpha 2 (p = 0.133) Beta (0.220)	Theta (0.255) Beta (0.080)	Delta (0.269)	N.S.*	N.S.*
B = 100 μT	Alpha 2 ↑ 0.024 ± 0.009 Beta ↓ 0.043± 0.015	Theta ↑ 0.029± 0.010 Beta ↓ 0.054 ±0.018	Delta ↑ 0.030± 0.012	N.S.*	N.S.*

↑ Increased power spectra; ↓ Decreased power spectra; *Not significant in all defined EEG bands in the context.

Significant changes of EEG bands in five measurement points are presented as Mean ± SE. Also P-values of the same bands are given in the sham group.

TABLE 3 The exposure results of Cz point by 17 Hz ELF-MF in open-eyes state.

EEG Recording Points ELF-MF	T4	T3	Cz Exposure	F3	F4
B = 0	N.S.*	N.S.*	N.S.*	Alpha (0.649)	Alpha (0.181) Alpha 2 (0.251)
B = 100 μT	N.S.*	N.S.*	N.S.*	Alpha ↓ 0.033± 0.014	Alpha ↓ 0.046± .015 Alpha 2 ↓ 0.018± 0.007

↑ Increased power spectra; ↓ Decreased power spectra; *Not significant in all defined EEG bands in the context.
Significant changes of EEG bands in five measurement points are presented as Mean ± SE. Also P-values of the same bands are given in the sham group.

In order to study 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 $P < 0.05$.

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

Investigation of relative power at 45 Hz EEG during the 100 μT MF exposure with 45 Hz frequency in the F4 point revealed no significant changes as compared to the state prior to the field exposure, using paired t-test. The test also showed no significant difference for the relative power of 17, 10, 5, and 3 Hz frequencies for the recorded signals at the points Cz, F3, T3, and T4, when these regions were exposed to the MFs with 100 μT intensity and 17, 10, 5, and 3 Hz frequencies, respectively. These results were observed for both states of open-eyes and closed-eyes. In spite of observing no RE, several EEG bands were changed in each MF exposures (Tables 2–6). In each table point under exposure as well as the participant's state, i.e., with open-eyes or closed-eyes, are shown separately. Also, Tables 2–6 show the results obtained from the paired t-test comparison of relative the power spectra prior to and during the exposure, along with the bands with significant changes ($P < 0.05$). Mean and S.E. (mean ± SE) of the difference between the relative power of each band prior to and during the exposure using SPSS software are presented as well for significant change.

Upward and downward arrows indicate increase and decrease in a particular band, respectively. In the cases without exposure (sham group), B = 0, P values are provided for the states prior to and during the exposure.

TABLE 4 The exposure results of F3 point by 10 Hz ELF-MF in closed-eyes state.

EEG Recording Points ELF-MF	T3	T4	Cz	F3 Exposure	F4
B = 0	Beta (0.095)	N.S.*	N.S.*	N.S.*	Alpha 2 (0.480)
B = 100 μT	Beta ↓ 0.038± 0.015	N.S.*	N.S.*	N.S.*	Alpha 2 ↑ 0.023± 0.010

↑ Increased power spectra; ↓ Decreased power spectra; *Not significant in all defined EEG bands in the context.
Significant changes of EEG bands in five measurement points are presented as Mean ± SE. Also P-values of the same bands are given in the sham group.

TABLE 5 The exposure results of F3 point by 10 Hz ELF-MF in open-eyes state.

EEG Recording Points ELF-MF	T3	T4	Cz	F3 Exposure	F4
B = 0	Delta (0.473) Gamma (0.744)	N.S.*	N.S.*	Delta (0.184) Gamma (0.189)	N.S.*
B = 100 μT	Delta ↑ 0.045± .020 Gamma ↓ 0.075± 0.030	N.S.*	N.S.*	Delta ↑ 0.027 ± 0.011 Gamma ↓ 0.016 ± 0.006	N.S.*

↑ Increased power spectra; ↓ Decreased power spectra; *Not significant in all defined EEG bands in the context.
Significant changes of EEG bands in five measurement points are presented as Mean ± SE. Also P-values of the same bands are given in the sham group.

Also, when T3 and F4 points were exposed to local MF exposure of 5 and 45 Hz frequencies, respectively, no significant effect was observed in the analysis of relative power spectra of the EEG bands as compared with their states prior to the exposure either with open-eyes or closed-eyes, only a significant increase in Alpha 1 in F3 point (0.029 ± 0.012) after the exposure of F4 point in open-eyes state was observed. Absence of effect observed in this case is not in accordance with the findings from the exposure to the whole head (Bell et al., 1992a; Lyskov et al., 1993). Additionally, exerting 100 μT MF with 3 Hz frequency on T4 point in close-eyes state led to no significant effect.

Comparison of the EEG prior to the exposure and the EEG recorded 10 min after the last exposure showed no specific change in the different bands regarding the records at the mentioned 5 points, which is in agreement with Cook's opinion on the removal of changes caused by influence of the fields 7 min after exposure (Cook et al., 2004). Hence, the assumption of removal of the field effect after 10 min is still valid.

Since MF does not change uniformly on the major axis and the axis perpendicular to it, each type of Gauss-meter may show a different value according to its sensitivity area. Therefore, the researchers who intend to make use of the findings of the present study are better to consider the current available in the coil during the exposure, $i_{rms} = 118$ mA as well as the coil characteristics.

DISCUSSION

No RE was observed in the manner reported by (Bell et al., 1994b), who stated that MF with 10 Hz frequency increases the amplitude of 10 Hz frequency in the EEG power spectrum. The contradiction is possibly to difference in the exposure intensity

TABLE 6 The exposure results of T4 point by 3 Hz ELF-MF in open-eyes state.

EEG Recording Points ELF-MF	T3	T4 Exposure	Cz	F3	F4
B = 0	N.S.*	N.S.*	Alpha 2 (0.405) Beta (0.873)	N.S.*	Alpha (0.113) Alpha 1 (0.122)
B = 100 μT	N.S.*	N.S.*	Alpha 2 ↑ 0.018 ±0.008 Beta ↓ 0.018 ±0.006	N.S.*	Alpha ↑ 0.035± 0.012 Alpha 1 ↑ 0.024± 0.010

↑ Increased power spectra; ↓ Decreased power spectra; *Not significant in all defined EEG bands in the context.
Significant changes of EEG bands in five measurement points are presented as Mean ± SE. Also P-values of the same bands are given in the sham group.

at thalamus region, since one of origins of Alpha waves locates there such that if the connection between thalamus and cortex is broken, Alpha waves will be removed despite the presence of Delta and Theta waves (Guyton and Hall, 2000). Also, as the intensity of applied exposure field in this experiment decreases inversely with the square of distance, the central part of the brain experiences much lower field intensities. Therefore, regarding the fact that the intensity of MF produced by coil at 1.5 cm from the skin surface is 100 μT, it is rejected that no influence yields as RE with the cortex origin in exposure of MF with the intensity of 100 μT and the frequency of 10 Hz in the F3 point. The average distance of cortex layer from the external surface of skin is approximately 1.2 cm (Rush and Driscoll, 1969). Even the observation of RE for Delta and Theta waves in the T3 and T4 points, which are supposed to be of cortex origin, was not possible. Besides, no increase in the intensity of waves with 17 and 45 Hz frequencies in the Cz and F4 points was observed by the exposure of MF with the frequencies of 17 and 45 Hz, respectively. A better and more in-depth discussion can be made by carrying out similar experiments with intensities higher than 100 μT.

An issue of much significance is observing effects in the frontal region of the brain. Observing simultaneous effects in the two points of F3 and F4 when Cz point is under exposure in the state of open-eyes (Table 3) and no simultaneous effects in the same points in the state of closed-eyes (Table 2) my occur be due to the connections between the mentioned two points and their common EEG origins (especially Alpha origins). Such connections are known in psychology and treatment of psychological disorders through changing EEG (QEEG) pattern (Budzynski, 2009; Hale et al., 2009; Othmer, 2005) as neurofeedback (Hammond, 2006). The local exposure in the present work confirmed this issue.

Moreover, although no frequency bands belonging to the waves produced by frontal region were observed in the studies where the overall head has been exposed (Cook et al., 2004), we observed considerable effects in applying the local exposure to this region. It can be attributed to the gradient of MF at the surface of the neurons and cells that are in connection with each other.

Contrary to the findings of Cvetkovic et al. (2006), the local exposure does not cause the amplification of bands in which the frequency of the applied MF are placed. In addition, the changes made in EEG are not limited to radiation point and may also be observed in other points; this may be attributed to complex connections of different brain neurons or the attenuated MF around the coil. In the present work, we observed effects in the central part only when the T4 point was exposed (Table 6). 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 (Sergio et al., 2005), which is in accordance with the findings of the present study. The change in Alpha band and reduction of Beta band can be explained by the exposure of T4 point at 100 μT.

Applying the exposure to T4 region in the state of open eyes results in a remarkable raise in the Alpha band in the Cz and F4 regions (Tables 5 and 6). These regions pertain to pain relief in neurofeedback treatments and are based upon EEG changes (Othmer, 2005; Sime, 2004). Also, increase in the Alpha band observed in MF exposure with 3 Hz frequency in the T4 point can induce a kind of peace or pain relief (Sime, 2004). This finding needs more in-depth clinical investigation.

Another attractive phenomenon that requires further studies is absence of effects in Cz point when it is exposed to MF exposure with 17 Hz frequency, while increase in Alpha band is observed in the F3 and F4 points in open-eyes state. Some studies that tried to confirm the significance of Potassium cyclotron resonance effect via combinational exposure composed of AC MF with 15.5–17.5 Hz frequencies and static DC seem to be important (Kato, 2006; Novikov et al., 2008, 2009). According to the findings of the mentioned studies, combining of an extremely weak ELF-MF, even less than 1 μT, with the static MF of about 40 μT can cause amplification of cyclotronic motion of several ions. On the other hand, considering the earth's static MF and also attenuation of the produced ELF field, the probability of the occurrence of this phenomenon at longer distances from the exposure location is high. This may justify the observed effects in the frontal region due to the exposure on Cz point, whereas Cz point itself exhibits no change in its recorded EEG in spite of having been exposed to a stronger MF.

Finally, considering the occurrence of these significant effects, it is suggested to perform similar experiments with intensities higher and lower than 100 μT. Extending the studies and providing different protocols for local exposure and recording its influence on EEG can offer a tool in psychology for EEG alterations in favorite directions so as to treat several symptoms.

Declaration of interest
The authors report no conflicts of interest. The authors alone are responsible for the content of and writing of the article.

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