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Analysis of the effect of high-frequency electromagnetic radiation on electroencephalography wave frequencies

Analiza uticaja visokofrekventnog elektromagnetnog zračenja na frekvenciju talasa na elektroencefalografiji

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Abstract

Background/Aim. Interest in the effects of electromagnetic fields on the human organism has grown significantly with the advent of digital mobile communication systems, which employ pulsed high-frequency electromagnetic fields. In standby mode, a mobile phone does not emit significant signal power, while during active communication, the intensity of the electromagnetic field may reach values of up to 250 mW. The aim of this study was to examine whether exposure to high-frequency electromagnetic fields affects the frequency of electroencephalography (EEG) waves. **Methods.** The study included 60 participants (30 males and 30 females). Each participant underwent two consecutive EEG recordings, each lasting approximately 20 min. The first EEG recording was performed at rest, without exposure to an electromagnetic field generator. This was followed by a second EEG recording while using a mobile phone for 10 minutes on one ear, then a break of about 2 minutes was made and the recording was repeated on the opposite ear, also for 10 minutes. A standard mobile phone was used as the source of the high-frequency electromagnetic field. **Results.** The analysis of EEG wave frequencies revealed no statistically significant differences in either sex before and after mobile phone exposure in the alpha, beta, or delta frequency bands. A change in the theta frequency band in female participants following mobile phone exposure was localized to the right hemisphere. **Conclusion.** Methodological limitations are the most likely reason for the absence of recorded changes in the majority of participants. The observed effects may be sufficiently subtle or infrequent to evade detection by standard EEG recordings. Therefore, the lack of observed changes cannot be interpreted as evidence that high-frequency electromagnetic fields have no effect on EEG activity.

Keywords:
cell phone; electroencephalography; electromagnetic fields; health; risk assessment.

Apstrakt

Uvod/Cilj. Interesovanje za uticaje elektromagnetnih polja na ljudski organizam značajno je poraslo sa pojavom digitalnih mobilnih komunikacionih sistema, koji koriste pulsirajuća visokofrekventna elektromagnetna polja. U stanju mirovanja mobilni telefon ne emituje značajnu snagu signala, dok tokom aktivne komunikacije intenzitet elektromagnetnog polja može dostići vrednosti do 250 mW. Cilj rada bio je da se ispita da li izlaganje visokofrekventnim elektromagnetnim poljima utiče na frekvenciju talasa na elektroencefalografiji (EEG). **Metode.** Istraživanje je obuhvatilo ukupno 60 ispitanika (30 osoba muškog pola i 30 osoba ženskog pola). Svakom ispitaniku su urađena dva uzastopna EEG snimanja u trajanju od oko 20 min. Prvo EEG snimanje obavljeno je u stanju mirovanja bez upotrebe generatora elektromagnetnog polja. Nakon toga je usledilo drugo EEG snimanje tokom korišćenja mobilnog telefona u trajanju od 10 min na jednom uvu, potom je načinjena pauza od oko 2 min i snimanje je ponovljeno na suprotnom uvu, takođe u trajanju od 10 min. Kao izvor visokofrekventnog elektromagnetnog polja korišćen je standardni mobilni telefon. **Rezultati.** Analiza frekvencija talasa na EEG nije pokazala statistički značajne razlike kod oba pola pre i posle izlaganja mobilnom telefonu u alfa, beta i delta frekventnim opsezima. Promena u teta frekventnom opsegu kod ženskih ispitanica nakon izlaganja mobilnom telefonu bila je lokalizovana u desnoj hemisferi. **Zaključak.** Metodološka ograničenja su najverovatniji razlog za odsustvo zabeleženih promena kod većine ispitanika. Uočeni efekti mogu biti toliko suptilni ili sporadični da standardna EEG snimanja ne uspevaju da ih detektuju. Iz tog razloga, izostanak uočenih promena ne može se tumačiti kao dokaz da visokofrekventna elektromagnetna polja ne utiču na EEG aktivnost.

Ključne reči:
mobilni telefon; elektroencefalografija; elektromagnentna polja; zdravlje; rizik, procena.

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Introduction

Interest in studying the effects of electromagnetic fields (EMFs) on the human organism has increased significantly with the introduction of digital mobile radiotelephone systems. These communication systems use high-frequency pulsed EMFs in the lower microwave range. Since the power density of Global System for Mobile Communications signals is generally insufficient to induce thermal effects, research attention has been directed toward possible non-thermal mechanisms of action. Over several decades of investigations into the interaction of low-intensity microwave radiation with biological systems, only a limited number of effects have been identified as reproducible and physiologically relevant, in addition to those whose mechanisms of action are most likely of thermal origin [1–3].

Mobile phones use wireless communication technologies in which signal transmission typically occurs within the 900–1,800 MHz frequency range, with the signal modulated at a pulse frequency of 217 Hz. Under standby conditions, when the user is neither making nor receiving a call, the emitted power is negligible. However, during active communication, the output power of the pulsed EMF may reach a maximum value of 250 mW. There is concern that such pulsed EMFs may penetrate neuronal structures and directly affect cell membrane function, a notion supported by the results of numerous studies indicating alterations in certain physiological processes [4, 5].

In studies focused on assessing the effects of mobile phone use in humans, electroencephalography (EEG) is most commonly employed because of its high sensitivity to immediate changes in neuronal function. Although previous EEG studies have not provided consistent evidence for specific effects, the observed inconsistencies are likely due to methodological limitations. Therefore, there is a clear need for the development of appropriate experimental models that would allow a reliable demonstration of the potential impact of exposure to active mobile phones on neuronal cell function [6].

The insufficiently clarified reasons for the contradictory findings in studies examining the influence of mobile phones on electroencephalographic activity may be attributed to methodological variations in the application of EEG techniques, as well as to differences in the duration of exposure to mobile phones [7]. Detection of subtle changes in brain electrical activity induced by high-frequency electromagnetic waves requires the use of non-conventional analytical approaches that go beyond the scope of classical visual EEG analysis. In this context, the introduction of digital EEG has enabled the effective application of quantitative EEG methods, primarily the analysis of amplitude and frequency, as well as the mapping of the obtained results [8].

The aim of this study was to determine whether exposure to high-frequency electromagnetic radiation emitted by a mobile phone affects the bioelectrical activity of the brain as recorded by EEG, or rather to assess whether exposure leads to increased variability in EEG wave frequencies.

Methods

The study included 60 participants (30 males and 30 females), aged between 20 and 30 years. The monitored parameters were changes in EEG frequency before and after exposure to an active mobile phone, analyzed separately for each side of exposure.

All participants were free of any neurological or psychiatric disorders and had not used any medications or psychoactive substances for at least one month prior to the beginning of EEG recordings. Alcohol and caffeine intake were prohibited for a period of four days prior to EEG recording and up to the time of examination. Each participant served as their own control. The EEG recordings obtained prior to exposure to electromagnetic radiation were compared with those obtained after exposure.

Upon arrival at the laboratory, demographic data were collected, after which participants were connected to the EEG system and positioned in the recording booth. All experimental procedures were conducted in a sound-attenuated electrophysiological laboratory. In all cases, testing was performed in the morning, between 9:00 a.m. and 12:00 p.m.

The EEG recordings were performed with participants in the supine position, in a relaxed yet alert wakeful state, with eyes closed. Monopolar EEG derivations were obtained using silver/silver chloride (Ag/AgCl) surface electrodes positioned according to the international 10–20 system on a 32-channel EEG device, and the signals were analyzed using a bipolar longitudinal montage. Electrode impedance was maintained below 5 kΩ, and the scalp was thoroughly cleansed with alcohol prior to electrode placement. Artifacts related to eye or body movements were automatically excluded by rejecting epochs in which the amplitude of any channel exceeded predefined voltage thresholds. A 50 Hz notch filter was applied to reduce power line interference.

Each participant underwent two consecutive EEG recordings, each lasting approximately 20 min, separated by a break of about 5 min. The first EEG recording was obtained at rest, without exposure to an EMF generator. After a pause of approximately 3 min, the EEG recording was repeated during mobile phone use for 10 min with the phone placed at one ear, followed by a break of approximately 2 min, after which the recording was repeated with the phone placed at the opposite ear, also for a duration of 10 min.

High-frequency EMF exposure was generated using a standard mobile phone operating as a receiver and source of electromagnetic radiation (approximately 900 MHz EMF, 217 Hz pulse repetition rate, 0.577 μs pulse width; estimated average power output 3–4 mW; actual emissions during the experiment were not directly measured). The phone was positioned approximately 2 cm radially from the participant's head, midway between the occipital midline (Oz) and parietal midline (Pz) electrodes.

The study was approved by the Ethics Committee of the Faculty of Medicine, University of Priština/Kosovska Mitrovica, Serbia (No. 489/1, from September 20, 2011).

Statistical analysis

For statistical analysis, the MedCalc software was used. Descriptive statistical measures included the arithmetic mean with a 95% confidence interval, standard deviation (SD), and minimum and maximum values. Statistical procedures for group comparisons comprised exploratory descriptive methods (Student's *t*-test) and confirmatory methods (analysis of variance and *t*-test).

Results

Mean values and variability of EEG frequencies in male participants at the right ear before and after mobile phone exposure are presented in Table 1. The mean ± SD of alpha-wave frequency before exposure was 11.1 ± 1.2 Hz and 11.4 ± 1.5 Hz after exposure, with no statistically significant difference ($t = 1.524$; $p = 0.138$). The mean ± SD of beta-wave frequency before exposure was 20.8 ± 4.4 Hz and 22.3 ± 6.1 Hz after exposure; there was also no statistically significant difference ($t = 1.445$; $p = 0.159$). The mean ± SD of theta-wave frequency before exposure was 5.7 ± 1.0 Hz and 5.6 ± 1.1 Hz after exposure, with no statistically significant difference ($t = 0.223$; $p = 0.825$). The mean ± SD of delta-wave frequency before exposure was 2.6 ± 0.8 Hz and 2.5 ± 0.8 Hz after exposure; there was no statistically significant difference ($t = 0.397$; $p = 0.695$).

Mean values and variability of EEG frequencies in male participants at the left ear before and after exposure are presented in Table 2. The mean ± SD of alpha-wave frequency before exposure was 10.7 ± 1.2 Hz and 10.8 ± 1.3 Hz after exposure, without a statistically significant difference ($t = 0.260$; $p = 0.797$). The mean ± SD of beta-wave frequency before exposure was 19.3 ± 3.8 Hz and 19.9 ± 3.5 Hz after exposure, with no statistically significant difference ($t = 0.161$; $p = 0.873$). The mean ± SD of theta-wave frequency before exposure was 5.7 ± 1.2 Hz and 5.9 ± 1.2 Hz after exposure, again without statistical significance ($t = 0.644$; $p = 0.524$). The mean ± SD of delta-wave frequency before exposure was 2.7 ± 0.7 Hz and remained 2.7 ± 0.7 Hz after exposure, with no statistically significant difference ($t = 0.339$; $p = 0.737$).

Table 1

Mean values and variability of frequency in male participants at the right ear before and after exposure to a mobile phone

Waves	Mean ± SD	Median	Min–Max	*p*
Alpha				
before	11.1 ± 1.2	11.0	(8.7–13.8)	0.138
after	11.4 ± 1.5	11.1	(8.7–14.0)	
Beta				
before	20.8 ± 4.4	20.2	(15.6–31.3)	0.159
after	22.3 ± 6.1	20.8	(14.6–33.6)	
Theta				
before	5.7 ± 1.0	5.7	(4.1–7.6)	0.825
after	5.6 ± 1.1	5.5	(4.1–7.8)	
Delta				
before	2.6 ± 0.8	2.2	(1.0–3.9)	0.695
after	2.6 ± 0.8	2.6	(1.1–3.9)	

SD – standard deviation; Min – minimum; Max – maximum.

Table 2

Mean values and variability of frequency in male participants at the left ear before and after exposure to a mobile phone

Waves	Mean ± SD	Median	Min–Max	*p*
Alpha				
before	10.7 ± 1.2	10.4	(8.8–13.1)	0.797
after	10.8 ± 1.3	10.6	(8.8–13.8)	
Beta				
before	19.3 ± 3.8	19.8	(15.5–30.1)	0.873
after	19.9 ± 3.5	19.0	(15.7–29.9)	
Theta				
before	5.7 ± 1.2	5.8	(4.1–7.9)	0.524
after	5.9 ± 1.2	5.8	(4.1–7.9)	
Delta				
before	2.7 ± 0.7	2.3	(1.1–3.9)	0.737
after	2.7 ± 0.7	2.7	(1.8–3.9)	

SD – standard deviation; Min – minimum; Max – maximum.

Frequency variability in female participants when the right ear was exposed is shown in Table 3. The mean ± SD of alpha-wave frequency before exposure was 10.9 ± 1.3 Hz and 11.3 ± 1.5 Hz after exposure, with no statistically significant difference (t = 1.240; p = 0.225). The mean ± SD of beta-wave frequency before exposure was 20.8 ± 4.4 Hz and 20.6 ± 4.8 Hz after exposure; again, there was no statistical significance (t = 0.245; p = 0.808). The mean ± SD of theta-wave frequency before exposure was 6.0 ± 1.0 Hz and increased to 6.3 ± 0.9 Hz after exposure, representing a statistically significant difference (t = 2.347; p = 0.026). The mean ± SD of delta-wave frequency before exposure was 3.1 ± 0.6 Hz and remained 3.1 ± 0.7 Hz after exposure, with no statistically significant difference (t = 0.087; p = 0.931).

Frequency variability in female participants at the left ear before and after exposure is presented in Table 4. The mean ± SD of alpha-wave frequency before exposure was 11.3 ± 1.2 Hz and 11.4 ± 1.6 Hz after exposure, with no statistically significant difference (t = 0.230; p = 0.820). The mean ± SD of beta-wave frequency before exposure was 19.9 ± 3.8 Hz and remained 19.9 ± 3.5 Hz after exposure, without statistical significance (t = 0.188; p = 0.852). The mean ± SD of theta-wave frequency before exposure was 6.4 ± 1.1 Hz and decreased to 5.7 ± 1.2 Hz after exposure, indicating a statistically significant difference (t = 2.637; p = 0.013). The mean ± SD of delta-wave frequency before exposure was 2.6 ± 0.7 Hz and remained 2.6 ± 0.7 Hz after exposure, with no statistically significant difference (t = 0.152; p = 0.880).

Discussion

In this study, the observed changes primarily involved alterations in the spectrum of baseline electroencephalographic activity, predominantly within the alpha and theta rhythms. An increase in alpha spectral power was noted, accompanied by changes in slower activity, which were mainly manifested within the theta spectrum.

Table 3

Mean values and variability of frequency in female participants at the right ear before and after exposure to a mobile phone

Waves	Mean ± SD	Median	Min–Max	*p*
Alpha				
before	10.9 ± 1.3	11.0	(8.8–13.1)	0.225
after	11.3 ± 1.5	11.2	(8.7–13.6)	
Beta				
before	20.8 ± 4.4	19.5	(14.9–31.9)	0.808
after	20.6 ± 4.8	19.8	(14.9–31.8)	
Theta				
before	6.0 ± 1.0	6.0	(4.0–7.8)	**0.026**
after	6.3 ± 0.9	6.3	(5.0–7.8)	
Delta				
before	3.1 ± 0.6	3.1	(2.0–3.9)	0.931
after	3.1 ± 0.7	3.2	(1.1–3.9)	

SD – standard deviation; Min – minimum; Max – maximum.
The bold value is statistically significant (p < 0.05).

Table 4

Mean values and variability of frequency in female participants at the left ear before and after exposure to a mobile phone

Waves	Mean ± SD	Median	Min–Max	*p*
Alpha				
before	11.3 ± 1.2	11.4	(8.9–13.5)	0.820
after	11.4 ± 1.6	11.0	(8.9–13.9)	
Beta				
before	19.9 ± 3.8	19.8	(15.5–30.1)	0.852
after	19.9 ± 3.5	19.0	(15.7–29.9)	
Theta				
before	6.4 ± 1.1	6.7	(4.1–7.9)	**0.013**
after	5.7 ± 1.2	5.7	(4.1–7.8)	
Delta				
before	2.6 ± 0.7	2.4	(1.1–3.9)	0.880
after	2.6 ± 0.7	2.8	(1.1–3.9)	

SD – standard deviation; Min – minimum; Max – maximum.
The bold value is statistically significant (p < 0.05).

The *in vivo* study conducted in humans indicates that electroencephalographic activity in the awake state, following exposure to radiofrequency fields emitted by mobile phones, demonstrates a delayed increase in spectral power density, particularly in the alpha frequency band [9]. In the cited study, the potential effects of EMFs on human brain activity were evaluated through changes in EEG signals. Healthy volunteers were exposed to EMFs emitted by a mobile phone, and the exposure resulted in a statistically significant increase in EEG power in the alpha and beta frequency bands. In our study, exposure to the mobile phone was limited to 10 min, and EEG changes were monitored during exposure, whereas in the aforementioned study, it was observed that mobile phone activity led to an increase in EEG power in certain frequency bands with a temporal delay of approximately 15 min after cessation of exposure.

Similar findings were reported by Takashima et al. [10], who described a reduction in high-frequency EEG bands accompanied by a simultaneous increase in low-frequency components. In contrast, some studies failed to identify consistent changes in EEG spectral power following exposure to continuous microwave fields [11].

Croft et al. [7, 12] reported that exposure to an active mobile phone induces changes in resting-state electroencephalographic activity, manifested as a reduction in activity within the 1–4 Hz frequency range and an increase in activity within the 8–12 Hz range. Although these authors observed EEG changes in the awake state, they did not detect an increase in delta activity, which was the only finding registered in our frequency analysis. This discrepancy may be explained by methodological differences between studies. Croft et al. [7, 12] discussed the possible origins of inconsistencies in results regarding the effects of mobile phones on the human brain. They concluded that prolonged sitting on a chair may have induced drowsiness in participants, thereby altering baseline activity. This suggests that differences in results among studies may arise from methodological variations, such as the duration of exposure to an active mobile phone, and that the effects of EMF exposure from mobile phones on EEG activity are time-dependent. These authors also concluded that active mobile phones affect neuronal function in humans in relation to the duration of exposure.

In the study by Preece et al. [13], a limited number of studies examining the effects of magnetic radiation on cognitive and perceptual processing in humans were analyzed. In this context, time-independent changes in the delta band may be interpreted as a relatively direct response to mobile phone exposure, whereas a time-dependent increase in alpha activity may reflect a more indirect effect of exposure. Specifically, studies with shorter exposure durations do not often detect changes associated with mobile phone effects.

In our study, in addition to changes in the frequency spectrum, similarly to the studies by Kramarenko and Tan [14] and Zhang et al. [15], an increase in the amplitude of alpha activity and a decrease in the amplitude of beta activity were observed. The frequency spectrum shifted toward increased alpha power and slow-wave activity; however, these changes did not reach statistical significance.

A study analyzing results published between 1995 and 2023 investigating EMF effects on EEG has most consistently reported changes in the alpha band, while findings in other frequency ranges remain heterogeneous [16]. When effects were observed, they primarily involved increases in alpha and beta activity. Short-term exposure has also been associated with alterations in alpha power, generally without evidence of adverse health consequences. Overall inconsistencies highlight the need for methodological standardization and a clearer definition of EEG outcome parameters [17–20].

In the present study, we focused specifically on EEG wave frequency, a comparatively underexplored parameter. Unlike spectral power, frequency may more sensitively reflect subtle changes in neuronal synchronization and oscillatory network dynamics induced by high-frequency, pulse-modulated EMFs [7, 12]. Such effects could manifest as minor frequency shifts without substantial alterations in signal power, potentially indicating discrete modifications in cortical excitability.

There is a lack of clear evidence regarding EEG changes during or following mobile phone exposure in conjunction with functional magnetic resonance imaging findings in the same participants, and these associations are typically interpreted indirectly rather than through formal real-time EEG-functional magnetic resonance imaging correlation analyses [21].

Study limitations

In the present study, the specific absorption rate was not directly measured, and no individual dosimetric assessment of exposure was conducted during the experimental protocol. The experimental configuration was designed to replicate typical patterns of everyday mobile phone use. In this context, the dynamic variability of the device's output power constitutes a methodological limitation, as it may influence the precise estimation of individual energy absorption during the experiment. Therefore, the study should be interpreted as an approximation of real-life mobile phone use rather than a strictly controlled dosimetric exposure model.

Conclusion

Analysis of electroencephalography frequency activity in male and female participants before and after exposure to the electromagnetic field emitted by a mobile phone did not reveal statistically significant differences in the variability of alpha, beta, or delta wave frequencies. The only parameter demonstrating statistical significance was a change in theta frequency following mobile phone exposure in female participants, observed in the dominant hemisphere. Although a statistically significant change in theta-band frequency was observed in female participants, localized to the right hemisphere, this finding was not accompanied by consistent effects in other frequency bands, nor was it detected in both sexes or bilaterally. Therefore, this isolated theta-band result most likely represents a potential chance finding. Given that the specific absorption rate was not measured in the present study, and that the experimental configuration was designed to reproduce typical patterns of everyday mobile phone use, the investigation should be interpreted as an approximation of real-life exposure rather than a strictly controlled dosimetric model.

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