

Long-Term Evolution Electromagnetic Fields Exposure Modulates the Resting State EEG on Alpha and Beta Bands

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Abstract

Long-term evolution (LTE) wireless telecommunication systems are widely used globally, which has raised a concern that exposure to electromagnetic fields (EMF) emitted from LTE devices can change human neural function. To date, few studies have been conducted on the effect of exposure to LTE EMF. Here, we evaluated the changes in electroencephalogram (EEG) due to LTE EMF exposure. An LTE EMF exposure system with a stable power emission, which was equivalent to the maximum emission from an LTE mobile phone, was used to radiate the subjects. Numerical simulations were conducted to ensure that the specific absorption rate in the subject's head was below the safety limits. Exposure to LTE EMF reduced the spectral power and the interhemispheric coherence in the alpha and beta bands of the frontal and temporal brain regions. No significant change was observed in the spectral power and the inter-hemispheric coherence in different timeslots during and after the exposure. These findings also corroborated those of our previous study using functional magnetic resonant imaging.

Keywords

EEG, electromagnetic field exposure, long-term evolution, resting state, functional magnetic resonance imaging, specific absorption rate

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Introduction

Ubiquitous radiofrequency (RF) electromagnetic fields (EMFs) have unprecedentedly facilitated communication between people, but they have also introduced potential risks to human health.¹ The modulation of the brain activity by exposure to RF EMF has been studied extensively, in which electroencephalography (EEG) has played an important role.²⁻⁴

EEG has advantages in terms of its compatibility with the EMF exposure system, making it a suitable tool for measuring spontaneous and immediate changes in neural processes caused by EMF exposure.⁵ However, the results of resting state EEG experiments have been contradictory. For example, some studies have reported enhancement of the alpha (8-12 Hz) and beta (13-30 Hz) band power values after exposure to pulse-modulated 450- and 900-MHz signals,^{6,7} pulse-modulated magnetic fields,⁸ and active mobile phone signals.^{9,10} In contrast, some studies have shown decreased alpha band activity after 20 minutes of extremely low-frequency EMF exposure,^{11,12} or 5 minutes of magnetic field exposure,¹³ or global system for mobile communications (GSM) EMF exposure.¹⁴ Many studies also found no changes in the EEG after either modulated or unmodulated EMF exposure.¹⁵⁻¹⁷ These inconsistencies could be attributed not only to the differences in the signal type, the modulation, the exposure frequency, the exposure intensity, individual anatomy, the ages of the subjects, and the exposure

duration^{16,18-20} but also to the lack of rigorous experimental designs.

Most of the previously published studies have focused on GSM,³ WiFi,²¹ and Universal Mobile Telecommunications System (UMTS),¹⁰ signals. An emerging technology, “long-term evolution” (LTE) wireless service, has been deployed since 2009 and the number of global LTE subscribers is expected to reach 1.37 billion by the end of 2015.²² Other than our previous functional magnetic resonance imaging (fMRI) study,²³ there are very few reports on the effect of exposure to LTE EMF on brain function.

We previously found that 30 minutes of exposure to LTE EMF modulated the spontaneous low-frequency fluctuations.²³ We were interested in confirming our previous results using another

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neurophysiological method and also sought to assess the evolution of the effect over time during such exposure. In this article, we have investigated for the first time the changes in the resting state EEG caused by exposure to LTE signals. The exposure dose was below the current safety limit. In order to assess brain activities on different levels, we evaluated spectral power and interhemispheric coherence, which allowed investigation of EEG changes in specific brain regions, as well as their correlations, at different time points. We show that exposure to LTE EMF decreased the alpha and beta band power spectrum and interhemisphere coherence.

Materials and Methods

Subjects

The experimental procedure was comprehensively explained to all participants in the study, and all of them provided written consents prior to the experiment, according to the established guidelines of the review boards of China Academy of Telecommunication Research.

Twenty-five male volunteers participated in the study. All subjects were right-handed and none had any medical or psychiatric disorders. The age of the subjects was 30.2 ± 2.7 years. The subjects were instructed to abstain from alcohol, nicotine, and the beverages containing caffeine and to maintain their regular life habits, during the day prior to the experiment. They were moderate mobile phone users (voice communication for less than 30 minutes per day), and none used a mobile phone for more than 10 minutes during the day prior to the experiments.

Exposure System

The time-division LTE signal (2.61 GHz) was produced using a signal generator (CMW500, R&S, Munich, Germany), using a standard formulation for LTE signals.²⁴ The applied radio frame (10-ms total length) consisted of 2 half-frames of equal length. Each half-frame comprised 5 subframes, each 1 ms in length. We selected the maximum emission configuration (6 uplink subframes in the radio frame). The radiation duration (including the uplink subframes and the upPTS [uplink pilot time slot] special subframes) accounted for 63.3% of the total length of the frame. The signal was augmented by an RF power amplifier (AR40S1G4, AR, Bothell, WA, USA). A plastic spacer of 1 cm was used to maintain the distance between the right ear and a standard dipole. We applied 2 power meters (E4416A, Keysight, Santa Clara, CA, USA) to ensure a constant incident power to the emission dipole.²⁵ The power delivered to the dipole was 24 dBm (peak value), equivalent to a theoretical maximum emission by an LTE terminal. Figure 1 displays the schema of the exposure system and the exposure setup. The experiments were conducted in an anechoic room.

Design and Procedure

All 25 subjects participated in the double-blind and counter-balanced experiment. The right ear was exposed because the

mobile phone subscribers were assumed to be right-hand dominant.²⁶ The experiment included 2 sessions, which were separated by 1 week. Each session lasted 50 minutes and comprised 5 time slots. We indicated each time slot (10 minutes) in a session as sub1 to sub5. The radiation dipole was power off for the first (preexposure, sub1) and the last 10 minutes (postexposure, sub5) timeslots. Subjects were exposed to real EMF exposure in the 3 time slots (sub2 to sub4) between the first and the last 10 minutes in only 1 of the 2 sessions. The order of the 2 sessions was randomly selected per subject. The subjects were not informed of the sequence of each session; however, they were aware of the possibility of being exposed. On the other hand, the staff who analyzed the data did not know the sources of the EEG traces.

During the experiment, the subjects were instructed to take on a comfortable sitting posture on the chair and close their eyes. Instruments were controlled from another room, so that subjects could not observe the operators. The alertness of the subjects could be observed by a video monitor installed in the anechoic chamber. The background E-field strength in the chamber was less than 1 V/m (0-4 GHz, measured with an HI-6105 Electric Field Probe, ETS-Lindgren, Cedar Park, TX, USA).

EEG Recording and Analysis

The EEG was acquired from 19 passive electrodes according to the international 10-20 system. The reference electrode was placed on the left ear lobe and the ground electrodes were placed on the right shoulder of each participant. The signals were obtained with an amplifier (UEA-FZ, Syntop, Beijing, China) at a sampling rate of 512 Hz. Then, signals were filtered with a 0.5- to 40-Hz bandpass filter. During signal acquisition, the impedance on each electrode was maintained below 5 kohm.

We used the EEGLAB toolbox²⁷ to remove artifacts. First, independent component analysis (ICA) was applied to decompose the EEG signals. Then, the ADJUST plugin within the EEGLAB toolbox was used to capture and to remove the stereotyped artifacts, such as those caused by blinks, eye movement, heartbeat, and generic discontinuities.²⁸ This entire procedure has been elaborated elsewhere.²⁹

The processed signals were used for spectral analysis. The data were segmented into 2-second intervals. Segments containing data greater than $\pm 100 \mu\text{V}$ were automatically eliminated (78.4% of the data were retained, on average). Then, the processed epoched time series were passed through a Fourier transform (Hanning window), with a window size of 2 seconds (without overlap). Consequently, the EEG bands were extracted (delta band, 1-3 Hz; theta band, 4-7 Hz; alpha band, 8-12 Hz; and beta band, 13-30 Hz).

The EEG signals from the electrodes in the same individual were dependent, and thus we grouped the EEG channels into 10 brain regions (left frontal region: Fp1, F7, F3, Fz; right

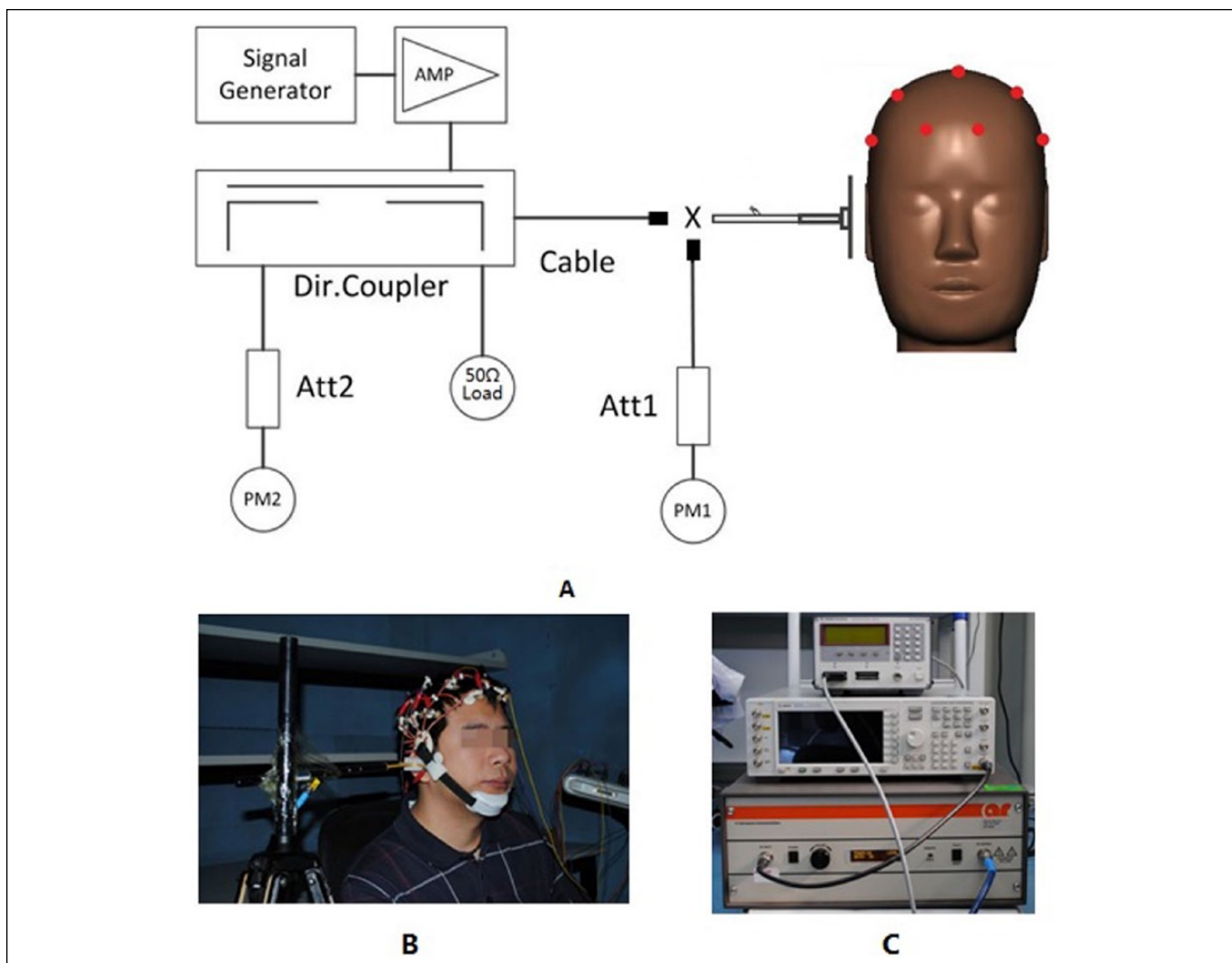


Figure 1. The experimental setup. (A) The schematic of the exposure system. Amp, amplifier; Dir. Coupler, directional coupler; Att, attenuator; PM, power meter. (B) The subject under exposure. (C) The component of the exposure system.

frontal region: Fp2, F8, F4, Fz; left central region: C3, Cz; right central region: C4, Cz; left temporal region: T3, T5; right temporal region: T4, T6; left parietal region: P3, Pz; right parietal region: P4, Pz; left occipital region: O1; right occipital region: O2). Consequently, the EEG power and the spectral power-based interhemispheric coherence (left-right frontal region, left-right central region, left-right temporal region; left-right parietal region; left-right occipital region) were analyzed. Interhemispheric coherence was calculated according to Equation (1):

$$C_{xy}(f) = \frac{P_{xy}(f)^2}{P_{xx}(f) \cdot P_{yy}(f)} \quad (1)$$

where P denotes the spectral estimate of 2 EEG signals, x and y , for a given frequency f . The numerator contains the cross-spectrum for x and y (P_{xy}), while the denominator contains the respective auto-spectra for x (P_{xx}) and y (P_{yy}).

To note, the electrodes on the brain sagittal midline (Fz, Cz, and Pz) were allocated to both sides (left and right regions) during the interhemispheric coherence analysis. In that case, the EEG power on each lateral was balanced. The same protocol has been used in the published report.³⁰

To assess the interference of the RF signals on the EEG, the EEG electrodes were mounted on a watermelon. The EEG signals during the periods of RF ON and OFF were recorded and analyzed.

Numerical Dosimetry

The distribution of the specific absorption rate (SAR) during the exposure experiment was simulated using SEMCAD X v.14.8 (SPEAG AG, Zurich, Switzerland). The head of a Chinese adult male model^{31,32} was used and the resolution was $1 \times 1 \times 1 \text{ mm}^3$. In the simulations, we computed the peak SAR, averaged over 10 g (pSAR10g) and 1 g (pSAR1g) human head

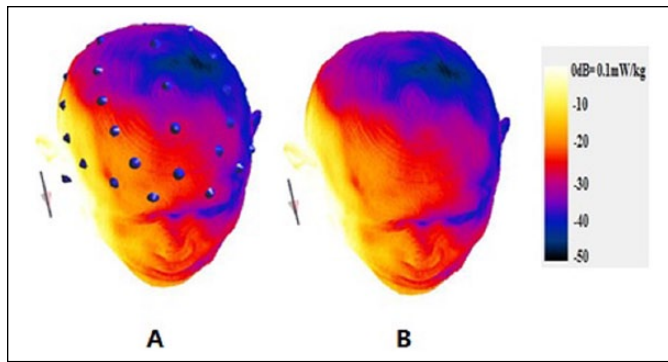


Figure 2. The SAR distribution with and without the EEG electrodes. (A) is the head model with the electrodes and (B) is without the electrodes.

tissue, as well as the temperature change, with and without the electrodes.

Statistical Analysis

EEG power/interhemisphere coherence estimates per frequency band and per brain region/brain region pairing were subjected to 5×2 (Time Slot $\times$ Experimental Session) repeated-measures analyses of variance (ANOVAs). The Time Slot variable consisted of 5 levels: sub1, sub2, sub3, sub4, and sub5. The Experimental Session variable included 2 levels: exposure and sham. Greenhouse-Geisser adjustment was applied to correct the degrees of freedom if the assumption of sphericity failed (by Mauchley's test). We used multiple comparisons to detect the difference between experimental sessions (exposure vs sham) if a 2-way interaction was evident. Paired t tests were used to examine differences between different time slots for each of the 2 experimental sessions. Bonferroni correction of the α value ($0.050/4 = 0.013$) was applied to minimize the likelihood of a type I error. SPSS 21.0 (IBM, Endicott, NY, USA) was used for statistical analysis in the study.

Results

Numerical Evaluation for the Exposure Dose

The simulations yielded 1.34 W/kg (pSAR10g) and 1.96 W/kg (pSAR1g), with the electrodes, and 1.27 W/kg (pSAR10g) and 1.78 W/kg (pSAR1g), without the electrodes (Figure 2) when the dipole emitted radiation. Therefore, the presence of the EEG electrodes increased pSAR10g and pSAR1g by about 5.5% and 10.1%, respectively. Accordingly, the maximum resultant temperature increase was no more than 0.1°C , which was unlikely to affect the EEG. The results were consistent with those of a previous report.³³

Interference of EMF With the EEG

EEG signals from the watermelon during RF ON and RF OFF periods did not show any difference (after applying the

bandpass filter and the ICA). As such, the possibility of EMF interference with the EEG signals was ruled out.

Effect of EMF

Spectral Power. Two-way repeated-measures ANOVA revealed significant Time Slot $\times$ Experimental Session interaction in the left frontal region (alpha band: $F = 3.00$, $P = .02$; beta band: $F = 3.74$, $P = .01$) and the right temporal region (beta band: $F = 3.06$, $P = .02$). The means and standard deviations (SDs) of the spectral power for the brain regions showing significant differences are listed in Table 1. The between-group results (Table 2) demonstrated a significant change for sub2 to sub5 in alpha (left frontal region: $P < .05$) and beta (left frontal region: $P < .02$; right temporal region: $P < .04$) band power. The within-subjects tests (Table 3) showed a reduction in alpha (left frontal: $P < .01$) and beta band (right frontal: $P < .00$; right temporal region: $P < .00$) power for the during- and postexposure time slots (as compared with the preexposure time slot) during the real exposure session. No significant change ($P > .27$) was observed between sub2 to sub5 by the paired t tests in the real exposure session. Similarly, for the sham session, no significant difference in power spectrum was found.

Interhemispheric Coherence. Two-way repeated-measures ANOVA showed a significant interaction for Time Slot $\times$ Experimental Session for the left-right frontal region pairing (beta band: $F = 9.60$, $P = .0004$) and left-right temporal region pairing (alpha band: $F = 4.35$, $P = .003$). The between-subjects results (Table 2) demonstrated a decrease in the alpha (left-right frontal region pairing: $P < .03$) and beta (left-right temporal region pairing: $P < .04$) bands during sub2 to sub5. The within-subjects tests (Table 3) showed a reduction in the alpha (left-right frontal: $P < .00$) and beta band (left-right temporal: $P < .00$) coherence for the during- and postexposure time slots (as compared with the preexposure time slot) during the real exposure session. No significant change ($P > .96$) was observed between sub2 to sub5 by the paired t tests during the real exposure session. We did not find any significant differences in the sham session.

Discussion

SAR and EMF-Induced Temperature Rise

The exposure system used in this study could radiate subjects with a stable power incident to the antenna, which was comparable to the maximum conducted power of a mobile phone. We computed the SARs using the head of a Chinese adult male model, because precisely reconstructing an anatomical head for each subject was extremely time- and energy-consuming. The head model was from a 35-year-old male, which was close to the age of the participants in the study (30.2 ± 2.7 years). As such, the anatomical variability was minimized. The temperature rise caused by exposure was insufficient to induce changes in the EEG.

Table 1. Comparison for the Power Spectrum and the Interhemispheric Coherence.

		sub1	sub2	sub3	sub4	sub5
PWR: L FR (α)	Exposure	64.12 $\pm$ 6.37	43.92 $\pm$ 8.51	49.22 $\pm$ 7.24	50.98 $\pm$ 6.23	51.22 $\pm$ 7.81
	Sham	69.54 $\pm$ 4.90	63.91 $\pm$ 7.72	64.20 $\pm$ 9.7	60.54 $\pm$ 5.52	62.82 $\pm$ 6.04
PWR: L FR (β)	Exposure	56.37 $\pm$ 7.57	42.15 $\pm$ 6.60	40.16 $\pm$ 8.61	38.38 $\pm$ 7.53	40.23 $\pm$ 6.12
	Sham	57.39 $\pm$ 9.90	54.64 $\pm$ 7.18	56.98 $\pm$ 8.12	56.79 $\pm$ 8.64	59.88 $\pm$ 9.22
PWR: R TR (β)	Exposure	78.10 $\pm$ 11.62	56.47 $\pm$ 10.69	54.99 $\pm$ 10.15	56.91 $\pm$ 9.67	54.09 $\pm$ 10.72
	Sham	74.77 $\pm$ 12.99	73.05 $\pm$ 11.55	74.93 $\pm$ 17.35	77.03 $\pm$ 10.11	76.13 $\pm$ 11.18
IHC: L-R FR (β)	Exposure	0.77 $\pm$ 0.08	0.58 $\pm$ 0.07	0.58 $\pm$ 0.07	0.51 $\pm$ 0.07	0.53 $\pm$ 0.07
	Sham	0.71 $\pm$ 0.08	0.77 $\pm$ 0.08	0.79 $\pm$ 0.09	0.75 $\pm$ 0.08	0.78 $\pm$ 0.08
IHC: L-R TR (α)	Exposure	0.87 $\pm$ 0.05	0.74 $\pm$ 0.03	0.73 $\pm$ 0.04	0.76 $\pm$ 0.03	0.73 $\pm$ 0.03
	Sham	0.88 $\pm$ 0.09	0.87 $\pm$ 0.06	0.84 $\pm$ 0.07	0.85 $\pm$ 0.08	0.86 $\pm$ 0.06

Abbreviations: PWR, power spectrum, unit in μV^2 ; IHC, interhemisphere coherence; FR, frontal region; TR, temporal region; L, left; R, right; α , alpha band; β , beta band.

Table 2. Between-Subjects Comparison.^a

	sub1		sub2		sub3		sub4		sub5	
	t	P	t	P	t	P	t	P	t	P
PWR:L FR (α)	-0.48	.63	-1.91	.05	-2.20	.04	-4.44	.00	-3.03	.00
PWR: L FR (β)	-1.04	.31	2.47	.02	-2.50	.02	-3.55	.00	-2.65	.01
PWR: R TR (β)	-0.27	.79	3.92	.00	-2.49	.02	-5.15	.00	-2.06	.04
IHC: L-R FR (β)	1.61	.12	-4.04	.00	-7.81	.00	-2.91	.01	2.30	.03
IHC: L-R TR (α)	-1.39	.18	2.47	.02	-3.66	.00	-2.12	.04	2.78	.01

Abbreviations: PWR, power spectrum, unit in μV^2 ; IHC, interhemisphere coherence; FR, frontal region; TR, temporal region; L, left; R, right; α , alpha band; β , beta band.

^aExposure versus sham.

Table 3. Within-Subjects Comparison Results for the Exposure Session.^a

	sub2 vs sub1		sub3 vs sub1		sub4 vs sub1		sub5 vs sub1	
	t	P	t	P	t	P	t	P
PWR: L FR (α)	2.88	.01	2.46	.02	5.42	.00	-2.74	.01
PWR: L FR (β)	5.68	.00	7.02	.00	8.51	.00	5.65	.00
PWR: R TR (β)	3.90	.00	4.31	.00	3.00	.00	4.84	.00
IHC: L-R FR (β)	4.37	.00	3.74	.00	4.78	.00	-4.79	.00
IHC: L-R TR (α)	3.27	.00	3.26	.00	2.92	.00	-2.86	.01

Abbreviations: PWR, power spectrum, unit in μV^2 ; IHC, interhemisphere coherence; FR, frontal region; TR, temporal region; L, left; R, right; α , alpha band; β , beta band.

^aBonferroni correction, adjusted threshold is 0.013.

EEG Results

Comparison With fMRI Results. The correlation between previous EEG and fMRI experiments has been contentious: some of the studies on blood oxygen level-dependent (BOLD) contrast imaging and EEG showed negative alpha and beta correlations, and positive delta correlations,^{34,35} while others showed a positive BOLD-beta correlation,³⁶ particularly in the default mode network (DMN) regions.³⁷ In both our studies, we found a positive correlation (decrease in EEG alpha and beta power spectrum vs decrease in BOLD) in the DMN regions (temporal and frontal sites). From this point of view, the results from the fMRI and the EEG studies were consistent.

Comparison With Previous EEG Studies on Other Exposure Frequencies. Previous studies on GSM and UMTS signal exposure frequently reported changes in interhemispheric coherence^{18,20} and the spectral power¹² in the alpha band in the frontal and temporal regions, which were also confirmed by our results on LTE EMF exposure. Moreover, modulation of the power spectrum in the beta band, including both an increase and a decrease, was reported.^{10,38} Several reasons may account for the inconsistency. First, the signal frequency and its modulation influenced the affected EEG band: for example, exposure to 2G signals affect the alpha rhythms, whilst exposure to 3G signals do not.^{10,19} In contrast, the modulated 450-MHz

signals of various intensities can change beta activity much more markedly than alpha band power.³⁹ Second, gender and the individual sensitivity^{38,40} may influence the effect on different bands. Hence, we attempted to reduce the variability by enrolling the subjects with the same gender and age.

In particular, power spectral analysis has shown significant differences in the left frontal brain regions, that is, the remote side, on exposure. This may be associated with modulation of neural activity in the remote/contralateral brain regions. The remote effects of EMF have been observed in many previous studies.^{2,9,41,42} Our results reconfirmed that the effects were also seen with LTE EMF exposure.

The power spectrum and the interhemispheric coherence did not differ significantly over sub2 to sub5. Thus, the observed effect did not change with the exposure time and the effect was therefore not developing.

The reduction in alpha band activity has been associated with a decrease in individual information-processing ability, alertness, and cognitive performance.^{16,43-48} The decrease in beta band activity could be interpreted as decreased alertness, arousal, and excitement⁴⁹ or a low level of fatigue.⁵⁰ Notably, EEG power fluctuation was not in one-one correspondence with the change in behavioral/cognitive performance which should be evaluated by specifically designed experiments as the report by Haarala et al.⁵¹ No conclusion could be obtained by our study that the present EMF exposure affected the subjects' cognitive abilities.

In our experiments, a surveillance video was implemented to capture the features of drowsiness (accelerated eye blinking, yawning, etc). Moreover, the subjects' state of vigilance was controlled by visual inspection of EEG traces and subject's drowsiness (eg, slowing of EEG, appearance of sleep spindles and K complexes). No indicator of decreased vigilance was identified in any of the participants. In contrast, the results of the sham exposure sessions (using the same setup as for the real exposure sessions) did not show reduced alpha or beta band activities, indicating that the duration of the experiment did not induce fatigue, and that the observed effect was attributable to LTE EMF exposure.

Admittedly, the dose-effect relationship was important in evaluating the changes in EEG.³⁹ However, we could not repetitively radiate the subjects using different power levels (ie, low, medium, and high dosimetric levels) due to ethical concerns and aversion of the subjects. In the experiments, the radiation power that we selected was equivalent to the maximum emission of the products. Therefore, the exposure strength was typical (the worst case) and representative.

We conducted the experiments with "eyes-closed" condition, which had at least 2 advantages. First, it could preclude the confounding EEG changes by visual stimuli. Second, the alpha band wave, whose changes were reported in many EMF-EEG studies, was pronounced in the close eye condition. As such, the changes in EEG were unlikely to be smeared by the noise. Consequently, many published studies adopted the "eyes-closed" configuration.^{38,40} As a study reporting the effect, it was preferred to focus on a less complicated condition (same

gender, similar age, and eyes closed eyes setup) at the first stage.

Baseline correction could be applied in the EEG power spectral analysis. It assumed that the EEG changes were addable (deducible) from the preexposure spectral power, or the changes were proportionally decreased or increased with respect to the magnitude of prestimulus power. By the correction, the comparison was made between the exposure and control groups so that the hypothesis as the EMF exposure induced EEG change would be evaluated. In contrast, the aims of the present article were whether the EMF exposure induced EEG changes and whether the changes developed with time elapse (including pre-, during-, and postexposure). If the preexposure data were used for baseline correction, the difference between the preexposure and the consequent time slots could not be examined. Therefore, EEG analysis without baseline correction was appropriate in this EMF-EEG study. The protocol has also been reported by the published EEG-EMF studies.¹⁴

Conclusion

This work studied EEG changes caused by LTE EMF exposure. An exposure system with a fixed power incident to a radiation dipole was used; this simulation demonstrated that the SAR was within the safety limits. LTE EMF exposure modulated the EEG in the alpha and beta bands at the frontal region of the near and remote sides, and at the temporal region on the near side. No developing effect was found in the periods during and after the exposure. Our results agreed to some extent with those of our previous fMRI study on LTE exposure. Our finding indicated that the LTE EMF exposure with the intensity beneath the safety limits could modulate the brain activities.

Future studies should focus on the correlation of EEG changes with spatial SAR distribution. By taking individual anatomical structure into consideration, a precise dose-effect relationship can be established. EEG changes with a finer temporal resolution during the exposure session should also be evaluated.

Authors' Note

Authors Lei Yang and Qinghua Chen contributed equally to this article.

Author Contributions

LY contributed to design; contributed to acquisition and analysis; drafted manuscript; gave final approval; agrees to be accountable for all aspects of work ensuring integrity and accuracy.

QC contributed to conception; contributed to acquisition and analysis; drafted manuscript; gave final approval; agrees to be accountable for all aspects of work ensuring integrity and accuracy.

BL contributed to conception; contributed to interpretation; critically revised manuscript; gave final approval; agrees to be accountable for all aspects of work ensuring integrity and accuracy.

TW contributed to conception and design; contributed to acquisition, analysis, and interpretation; critically revised manuscript; gave final approval; agrees to be accountable for all aspects of work ensuring integrity and accuracy.

Declaration of Conflicting Interests

The author(s) declared no conflicts of interest with respect to the research, authorship, and/or publication of this article.

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