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EEG frequency analysis of 60 Hz magnetic field exposure within the MRI

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SUMMARY

The effects of human exposure to power-line frequencies (50-60 Hz) are a major concern, particularly occupational exposure to workers, which can feature high electromagnetic field strengths coupled with long-duration exposures. Many studies focus on the extent to which workers or the general public are exposed to powerlines in terms of magnetic field (MF) strength and duration and much research centres on its potentially carcinogenic effects. However, the current literature lacks comprehensive measures of the neurobehavioral, physiological and cognitive impact of frequencies within this range. Furthermore, although the long-term effects such as carcinogenesis have been investigated, the more subtle outcomes of MF exposure have not been examined in detail. For example, there may be a risk that small changes in brain activity such as balance, proprioception, reaction speed, judgement and fine motor control may be amplified when working at elevated high voltage lines. There is therefore a need for more objective analyses, especially for utility workers, of environmentally relevant parameters when investigating powerline frequency effects.

Previously, our group has conducted work to explore the effects of 60 Hz, 1800 μT MF exposure on human neurophysiology. Subtle effects on postural tremor (increase in the 7-12 Hz range) and standing balance (significant decrease in oscillations amplitude) were found. Recently, we have also conducted studies to examine the effects of a 1 hour, 60 Hz, 3000 μT MF, and have found that brain functional activation was significantly modulated in both a tapping task and a mental rotation task as measured by functional magnetic resonance imaging (fMRI). To further explore these results, a new phase of this project is currently initiated in which electroencephalography (EEG) is complementing MRI in order to compensate for the limited temporal resolution of MRI (on the order of seconds).

Consequently, we are currently investigating the effects of a 60 Hz MF using our 3T MRI unit as an active exposure system (by using custom MRI sequences programmed by Dr Jean Théberge, Medical Physicist at Lawson) at a highest level of amplitude (up to 8 mT) in human subjects, while recording EEG. The EEG was recorded using a 64-channel MRI compatible cap. Continuous (90 s) and intermittent (150 cycles of 2 s of exposure, then 1 s without exposure) 60 Hz MF exposure were tested. Frequency analysis was performed on the recorded EEG to evaluate the possibility to analyze EEG data acquired in humans during exposure.

We will be the first to our knowledge to demonstrate that EEG during 60 Hz exposure within the MRI environment can be examined without distortion by the MR environment. Therefore, future powerline research

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can be directed towards more objective measures of neurophysiological and cognitive effects using simultaneous technologies such as fMRI, EEG and electromyography (EMG). Moreover, observing effects during acute exposure may help validate or determine regulatory limits for MF field strength.

KEYWORDS

Power-line magnetic fields, electroencephalography, magnetic resonance imaging, event-related potentials, frequency analysis.

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INTRODUCTION

There is extensive experimental evidence that extremely low-frequency (ELF, < 300 Hz) magnetic fields (MF) interacts with human neurophysiology [1]. Levels of MF amplitude regarding workers and general public exposure and safety has been recently re-evaluated by the International Commission on Non-Ionizing Radiation [2]. The guidelines of ICNIRP are mainly based, to establish the safe limits of ELF MF exposure, on the MF amplitude at which magnetophosphenes occur. Magnetophosphenes consist in the perception of flickering lights caused by ELF MF exposure, and can occur at approximately 5 mT at 20 Hz [2]. However, to date, no reliable threshold at which systematic response of the human central nervous system occur is known, motivating further human research to provide new evidence aiming at establishing guidelines such as those provided by ICNIRP.

Modulation of brain functional activation after a one-hour exposure to a 3 mT, 60 Hz MF has been reported by our group during a finger tapping task and a mental rotation task [3, 4] using functional magnetic resonance imaging (fMRI). Also, previous studies on human resting electroencephalogram (EEG) has shown that ELF MF exposure can modulate the EEG alpha (8-12 Hz) rhythm [5, 6]. One limitation is that, these studies, EEG recordings have been performed between or after exposure periods, and not during. Importantly, recording of human EEG during the exposure itself is one way to obtain deeper understanding of ELF MF effects on human neurophysiology. Therefore, it appears crucial to improve knowledge of the interaction mechanisms and effects of ELF MFs on human neurophysiology, including effects observed during the exposure, in order to establish a solid ELF MF amplitude at which systematic effects are observed.

In the recent years, combined EEG-MRI has proven a promising hybrid neuroimaging technique to investigate the spatio-temporal dynamics of brain physiological and pathophysiological states [7]. Indeed, EEG has a poor spatial resolution (approx. 1 square centimetre) but an excellent time resolution (on the order of a fraction of millisecond); while MRI has a good spatial resolution (on the order of the millimeter) but a poor temporal resolution (on the order of a second). Therefore, using EEG and MRI simultaneously offers the possibility to evaluate which brain networks are involved with a given condition, and what the dynamics of these networks are (evolution of electrical activity as measured by EEG, and/or of functional activation as measured by functional MRI as a function of time). Consequently, EEG-fMRI appears as an appropriate objective technique to study the effects of power-line MFs on brain activity.

In this paper, we present some preliminary results of EEG data acquired in the MRI environment during 60 Hz MF exposure (provided by the Z gradient of the scanner) at up to 7 mT in a human subject. In these results, we identify some difficulties related to the recording in the MRI environment, and present solutions to overcome them. We discuss the significance of these results for future developments in bioelectromagnetics research, that pave the way for a detailed, quantitative study of power-line MFs on human brain activity not only before and/or after exposure, but also during the exposure.

MATERIALS AND METHODS

First, “EEG” data were acquired on a phantom (i.e., a model of a human head, consisting of a watermelon in our experiment, which is standard in EEG research) in order to investigate how to deal with various artefacts occurring in the MRI environment. Indeed, artefacts resulting from the MRI environment and its strong static and time-varying MF had to be characterized in details and filtering techniques were developed allowing the recording of clean time series. Therefore, prior to the testing of this subject, we used a watermelon set up with an MRI-compatible 64-channel EEG cap (Neuroscan, Charlotte, USA). Then, a female subject from our research group volunteered for this pilot work, and did not have an history of cardiovascular, neurological or psychiatric disorders, neither of chronic disease. The subject was setup with an MRI-compatible 64-channel EEG cap (Neuroscan, Charlotte, NC, USA). The protocol was approved by the Health Sciences Research Ethics Board of the University of Western Ontario (REB 13460). In both cases (human subject and phantom), we ensured that most EEG electrodes impedances were below 10 kΩ.

We used a 3T MRI scanner (Verio, Siemens, Germany) as an exposure system, similarly to previous studies from our group [3, 4], and a 12 channel head coil. The gradient coil of the MRI is designed to produce zero field at the isocentre of the bore, therefore the patient table was moved so that the entire brain would be exposed to the 60 Hz MF field. The subject was blind to the exposure condition. The head of the subject (the watermelon in the case of the phantom) was then placed in a 3T MRI scanner (Verio, Siemens, Germany), in an MRI head coil including foam. In the case of the watermelon, two different foams were tested to identify which one would be the most suitable to dampen the small mechanical vibrations of the table (that occur when the gradient field is turned “on or “off”) to use in human subject data. Once in the MRI, the subject completed a session of 15 minutes during which we acquired first a sequence of resting EEG (duration 4 minutes and 30 seconds) decomposed in 3 sub-sequences of 1 minute and 30 seconds each: sham, exposure at a 60 Hz MF (amplitude of approx. 7 mT, with a gradient field of 38 mT/m, with a table position at 20 cm from the isocentre), sham. After this resting EEG session, we acquired an "ERP-like" sequence (ERP standing for Event-Related Potential, defined as a systematic oscillatory response recorded in human EEG after, say, presentation of a visual stimulus, and characteristic of information processing by the brain. This sequence was designed to identify a potential systematic EEG response (similar to an ERP) following the onset or offset of intermittent exposure to a 60 Hz MF. This session consisted of a repetition of the following cycle: 1) 2s of 60 Hz exposure (generated by the Z-coil of the MRI scanner), 2) 1s without exposure. This cycle was repeated 150 times. These two sequences were tested both on the subject and on our phantom. During each sequence, the subject was asked to stay relaxed, as still as possible, and also to close his eyes.

The EEG data obtained during these two sequences (resting EEG with a period of continuous 60 Hz exposure, and intermittent 60 Hz exposure) was analyzed using custom-made analysis scripts (Matlab, The Mathworks, USA). To remove the 60 Hz artefact, the EEG data was bandpass-filtered (2-30 Hz) using the FFT-iFFT method. The post-exposure average EEG response was obtaining by extracting all the post-exposure sweeps (between 60 Hz exposure epochs) and averaging them. The frequency band of interest in EEG data was the alpha (8-12 Hz) band, since previous studies have found a modulation of alpha activity in human resting EEG after exposure to pulsed MF [5, 8] and 50 Hz exposure [6].

RESULTS

Phantom data: effect on the type of foaming on the quality of EEG acquisition in the MRI

As mentioned above, we have first acquired data on a phantom to evaluate possibilities with artefacts in EEG data recorded in prior pilot data. Indeed, when the MRI scanner is used as an exposure system, mechanical vibrations occur at patient table level when the gradient field is switched “on” or “off”. For this phantom data, we tested the impact of two different foams (dampening more or less the mechanical vibrations) to support the phantom in the head coil on the amplitude of the post-exposure artefact presented in Fig. 1. The comparative time course of EEG illustrating the amplitude of two typical post-MF exposure artefacts using these two different foams, during an intermittent 60 Hz MF exposure, is presented in Fig. 1.

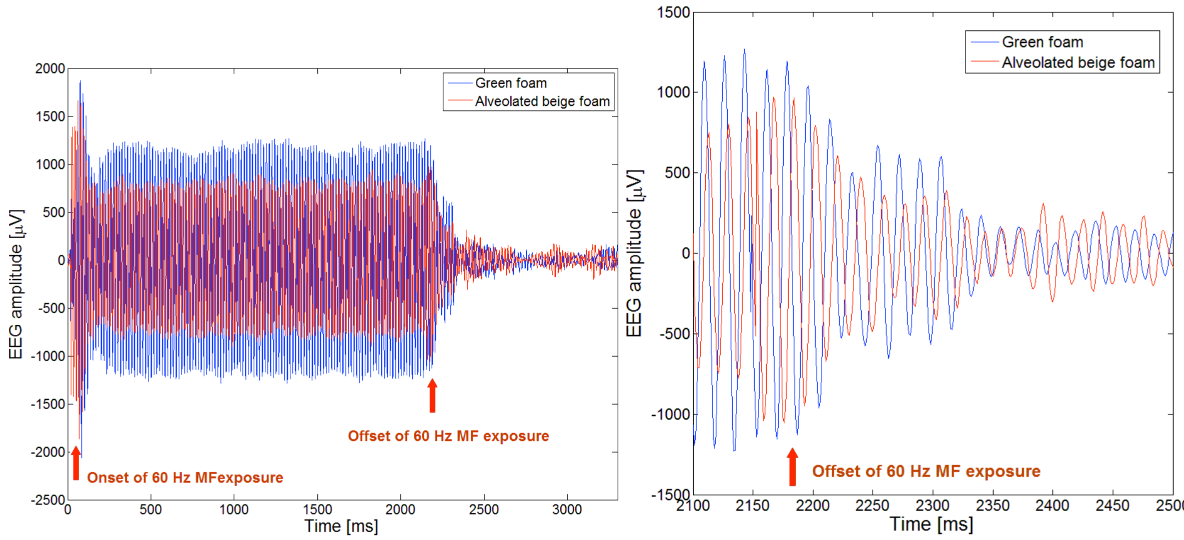

Figure 1. Left: time course of the EEG data during an intermittent 60 Hz MF exposure. Right: zoom on the portion after the offset of the 60 MF exposure. Blue: EEG data acquired with the green foam typically used when scanning human subjects. Red: data acquired with a lighter alveolate foam material (seems more effective in dampening the vibrations).

From the results presented in Fig. 1, it appears that the second foam used allows to decrease the amplitude of the pre- and post-MF exposure artefacts induced by mechanical vibrations of the MRI scanner table while the high intensity 60 Hz signal is generated. More quantitatively, the maximal amplitude of the mechanical vibration artefact (transients excepted) drops approximately from 1100 µV to 800 µV with the beige foam (approx. 30% decrease), and the standard deviation of the signal drops from 701 µV to 501 µV (approx. 30% decrease). Therefore, the type of foam used for subject comfort in the MRI head coil should be carefully chosen depending on the MRI sequences to be used, since it can significantly improve the quality of the EEG signal. Consequently, in the human data presented below, the alveolate beige foam was used.

Phantom data: effect on the MRI helium pump noise

During our first pilot data acquisition, we have noticed during resting EEG acquisition in the MRI without any imaging sequence that a very regular artefact was present, and that its occurrence was directly synchronized with the sound from the helium pump of the MRI (conducting the liquid helium needed to cool down the coils of the scanner in order to keep them supraconductive). Therefore, we have decided to turn off the MRI helium pump for a short period of time to evaluate the effect on the EEG signal. As soon as the helium pump was turned off, the quality of the EEG signal dramatically improved. We present the transition between helium pump "on/off" in Fig. 2 (left) in the time domain (10 seconds before/10 second after the pump was turned off), and also present in Fig. 2 (right) the power spectrum of the EEG signal for the "on" and "off" periods.

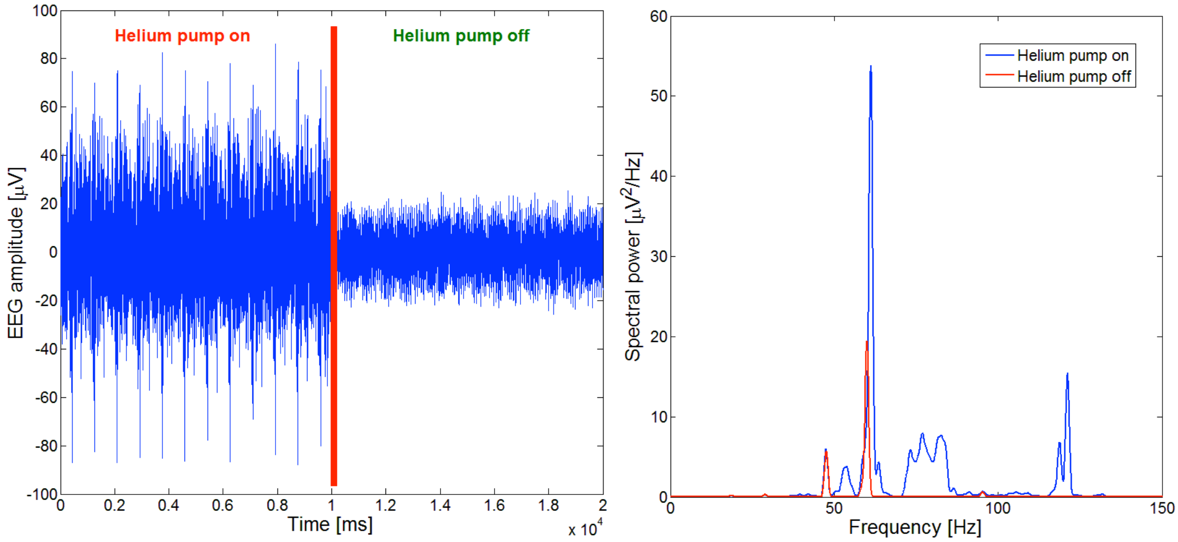

Figure 2. Left: P2 EEG channel (parietal electrode) before and after shutting down the MRI helium pump, for a total duration of 20 seconds (10 seconds for each condition -helium pump "on" or "off"-). Right: Power spectrum of the P2 EEG channel 10 seconds before (left) and after (right) that the MRI helium pump was switched off.

The standard deviation of noise in the EEG signal recorded at the level of the P2 electrode dropped from 21.95 μV to 9.06 μV when the MRI helium pump was turned off, representing a 59% decrease (illustrated in Fig. 2, left). Importantly, the noise power spectrum of the EEG presents two strong peaks at 60 Hz and 120 Hz with the helium pump "on". When the MRI helium pump is switched off, the 60 Hz peak is strongly decreased, and the 120 Hz peak is completely suppressed (see Fig. 2, right). Furthermore, other frequency bands of noise are suppressed, such as 50-55 Hz and 70-85 Hz. Therefore, MRI helium pump noise can induce bias in several frequency bands, including not only power-line frequency (60 Hz) and its harmonic. Consequently, for the acquisition of human EEG data presented below, the MRI helium pump was turned “off” to improve data quality.

Resting EEG in a healthy human

As an illustration of the possibility to remove the artefact generated by the 60 Hz MF exposure, we present in Fig. 3 the raw EEG data and the EEG data filtered using the procedure described in the Materials and Methods section.

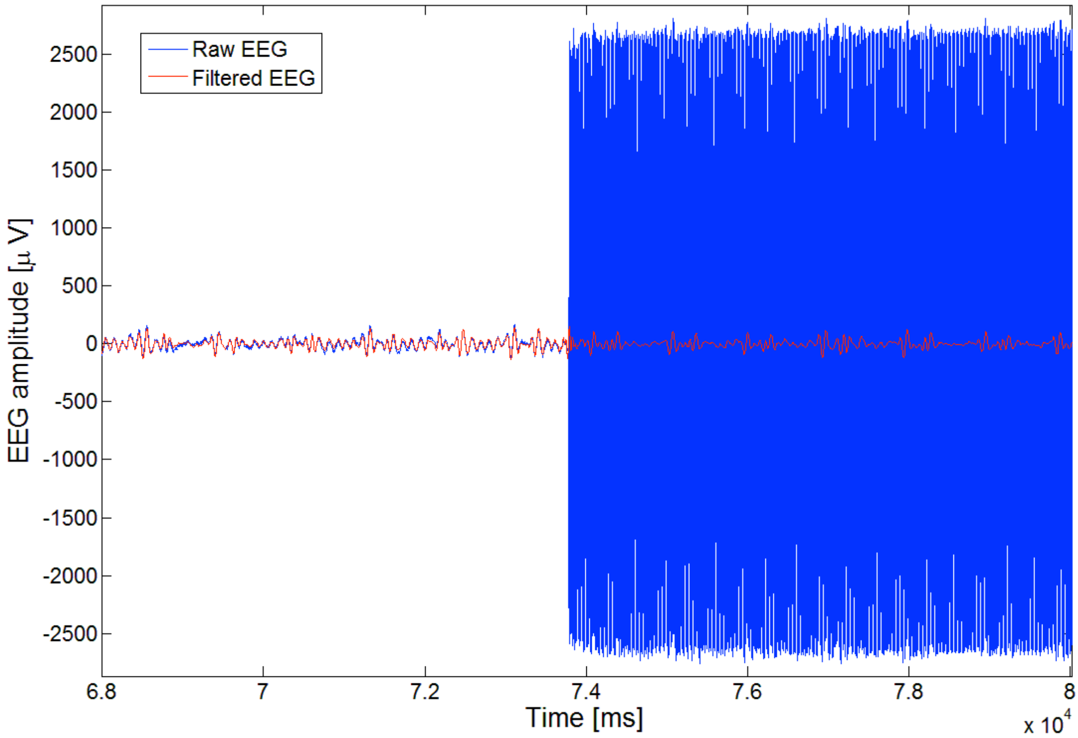

Figure 3. Comparison between the raw EEG acquired in the MRI environment (blue line) and the filtered EEG (red line).

Therefore, one can conclude from the results presented in Fig. 4 that the 60 Hz MF exposure generates a strong artefact in the EEG signal (about 20 times the amplitude of the EEG signal itself). Nevertheless, the bandpass-filtering process results in a clean EEG that can be used for frequency analysis, as we present below. We compared the power spectrum obtained for the EEG portion before exposure (Fig. 4, blue curve), during exposure (Fig. 4, green curve) and after exposure (Fig. 4, red curve), and also computed the spectral power of the alpha band (8-12 Hz) of the EEG.

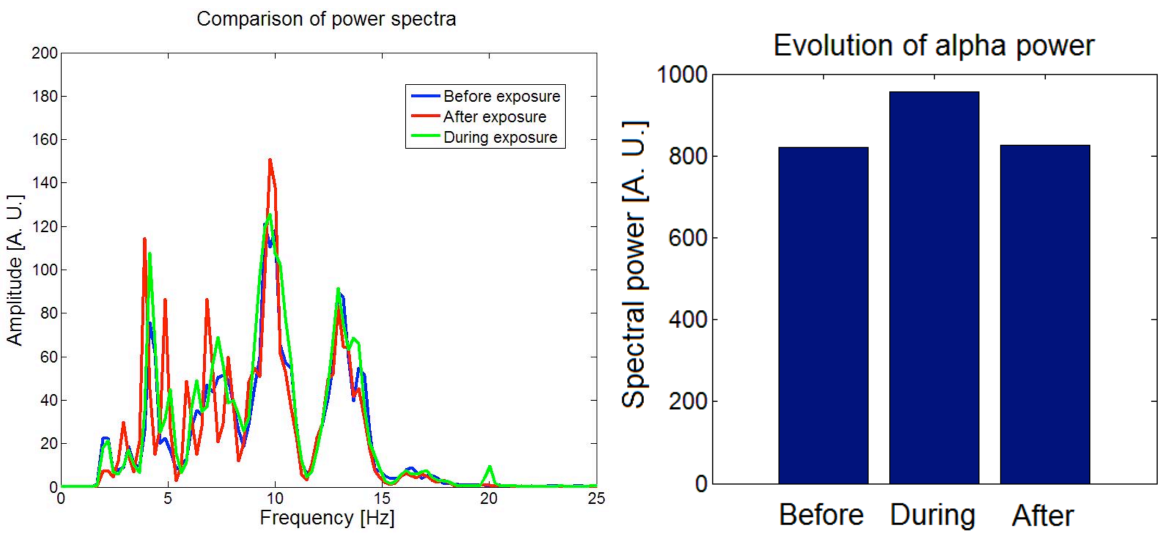

Figure 4. Left: Comparison of the power spectrum for the electrode O2 in the different conditions of exposure (before, during and after exposure). Each condition lasted 1 minute

and 30 seconds. Right: evolution of the spectral power of the alpha band before, during and after exposure 60 Hz exposure.

Interestingly, the power spectra indicate changes in alpha activity. In all occipital and posterior-occipital electrodes (but PO8 and POZ), there was a transient increase of alpha activity during exposure, with a return to baseline after exposure (Fig. 4, right for an illustration with the electrode O2). Parietal electrodes exhibited regions where alpha power was increased (P4, P6, P8, P7), whereas the others decreased over the course of the experiment. Instead, in all central, central-posterior, frontal-central, frontal (except F1 where a transient increase occurred during exposure); alpha power was constant or decreased during the course of the experiment. Interestingly, there was a transient decrease of alpha power in all anterior-frontal electrodes and frontal-parietal electrodes during the 60 Hz exposure period, with a return to a value lower than pre-baseline values after exposure (suggesting a possible lasting effect of the exposure).

Even-related potentials (ERPs) in a healthy human

As explained above, we used a custom MRI sequence consisting in intermittent 60 Hz (amplitude of 7 mT) MF exposure presented above ("ERP-like" sequence). By averaging the 150 sweeps between 60 Hz exposure time periods, we obtained the EEG response presented in Fig. 5 below.

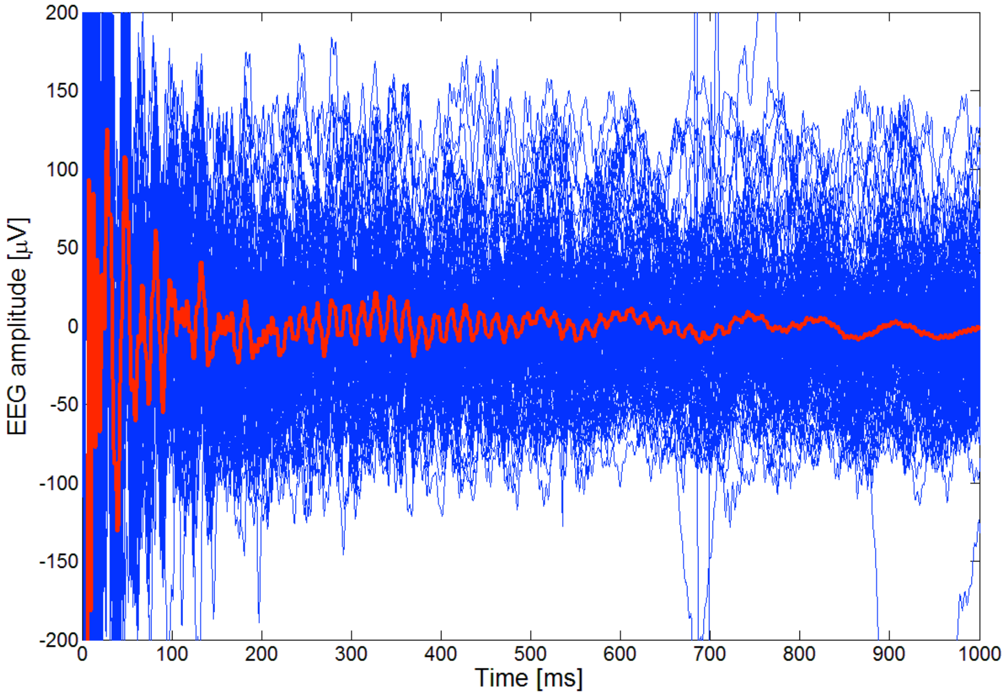

Figure 5. Average EEG response after cessation of intermittent 60 Hz exposure (red) and individual sweeps (blue).

The averaged response has a small amplitude, on the order of 5 to 10 µV (after the transient dampening of mechanical oscillations). Even if it is not possible to draw conclusions at this stage, small oscillations occur in the [600 ms, 1000ms] segment, and could possibly constitute part of a systematic response, which is speculative at this stage. It is likely that, in order to obtain an average EEG response of higher quality, we will have to increase the length of intermittent 60 Hz MF exposure to obtain a high number of sweeps. Indeed, the smaller ERP amplitude is, the higher the number of sweeps has to be.

DISCUSSION

In this paper, we have shown that it is possible to significantly improve the quality of EEG acquired in the MRI, which is critical when subtle effects of MF exposure are investigated in humans. First, we emphasize that the impact of mechanical vibrations caused by 60 Hz exposure (in this specific case) on the quality of the EEG signal should not be underestimated. We have shown that the padding on which the subject lies his head has to be carefully chosen for his capacity to minimize mechanical (including acoustic pressure) vibration, which decreases the amplitude of mechanical vibration artefact that can occur at the onset and offset of MF exposure induced by the Z gradient coil. Second, if possible, the helium pump (or 'head pump') should be turned "off" before recordings and imperatively turned "on" back again after. Let us emphasize that the choice of shutting down the helium pump is critical, if one is interested in more subtle variations of the EEG, such as ERPs (that have an amplitude on the order of 10 μV), then it seems that shutting down the MRI helium pump is critical to obtain data of good quality and meaningful results. Also, if repeated EEG-MRI sessions have to take place at different days, it is possible that the artefact induced by the MRI helium pump is not consistent, therefore it is also recommended to switch it off in this case, if possible.

We have also presented, to the best of our knowledge, the first EEG human data during exposure to 60 Hz MF. These pilot results acquired in only one subject suggest a possible transient increase of alpha activity in occipital and posterior-occipital regions associated with the 60 Hz exposure. Interestingly, previous works have shown modulation of alpha activity in these regions following pulsed MF exposure or 50 Hz exposure [2, 6, 8]. However, our results have to be taken with great caution, since to obtain meaningful results, we will have to perform similar analyses on a phantom, but also to acquire data in a larger sample of subjects, which will be done soon in our group. Nevertheless and more importantly, our results illustrate the possibility to perform EEG analysis during 60 Hz MF exposure in a human subject, using an MRI scanner as an exposure system. Another limit of this work is that, if an entrainment phenomenon exists (i.e., a systematic response occurs in the brain at 60 Hz), then the filtering procedure used here for analysis will not make it possible to detect it. Other data analysis approaches would therefore have to be considered.

CONCLUSION

In this paper, we have presented a new technique combining the use of EEG and MRI to study the effects of power-line MF on human brain electrical activity. Importantly, the present results represent the first experimental demonstration that it is possible to acquire and analyze EEG during exposure to 60 Hz MF in humans. Our results suggest a possible transient increase of EEG alpha power in occipital and parietal-occipital regions, as well as a transient decrease of EEG alpha power in frontal-parietal and anterior-frontal regions; but further work is needed to draw conclusions. We have also presented possibilities to deal with artefacts occurring in the MRI environment, which will be useful for researchers using combined EEG-MRI as a tool to probe the effects of 60 Hz MF on brain function. Experiments are being conducted in our group to go further and acquire at the same time EEG and functional MRI during exposure to intermittent 60 Hz MF. This should provide us with a detailed understanding of which brain regions are modulated by 60 Hz MF exposure, but also of the dynamics of this modulation. Such quantitative estimate of MF exposure impact on brain function will provide knew experimental results of significant interest when re-evaluating international guidelines for workers and public to MF exposure.

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