NEUROPHYSIOLOGICAL AND BEHAVIORAL EFFECTS OF HUMAN ACUTE EXPOSURE TO A 60 HZ MAGNETIC FIELD UP TO 1800 µT: PRELIMINARY RESULTS

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HUMAN ACUTE EXPOSURE TO A 60 HZ, 1800µT MAGNETIC FIELD

Abstract

For the past two decades, researchers have actively been studying the effects of time-varying magnetic fields (MF) on humans, principally examining the potential for the field to have acute effects on human physiology, neurophysiology and behaviour. The more consistent results reported in recent literature seem to show an increase in occipital alpha rhythm of resting electroencephalographic activity (EEG) with exposure (Cook et al., 2004; Ghione et al. 2005). Interestingly, other studies have demonstrated that human motor behavior can be modulated by exposure to an Extremely Low Frequency (ELF) MF, showing a reduction in anteroposterior standing balance oscillations (Thomas et al., 2001) and a decrease in physiological tremor intensity (Legros et al, 2006). However, to establish a connection between these observations would require a project that, in one procedure, investigates physiological, neurophysiological and behavioural parameters. Therefore, subject testing has begun, in a project approved by the University of Western Ontario (Health Sciences Research Ethics Board # 11956E), to investigate the effects of a 60 Hz, 1800 µT MF on heart rate (frequency and variability), peripheral blood perfusion, brain electrical activity (EEG), postural oscillations, voluntary motor functions, and physiological tremor. Preliminary results will be presented and should provide reliable information concerning human exposure to power-line frequency MF.

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Introduction

Domestic electrical appliances, distribution and transport power-lines, and residential wiring are some of the numerous sources of magnetic field (MF) in our everyday environment. Over the past several years, studies have been conducted with the aim of characterizing the effects of Extremely Low Frequency (ELF, below 300Hz) MF on human health and performance. Despite the amount of work that has been done in this area, there remains no consensus as to the effects of ELF MF on humans.

From brain electrical activity to motor behaviour, a number of aspects of human physiology and behaviour have been examined in scientific literature in response to acute exposure to ELF MF. Among the potential effects, many studies detected neuropsychological changes induced by the exposure (Keetley *et al.* 2001; Preece *et al.* 1998). That these studies are still relatively rare, and often have conflicting findings prevents the confident characterization of the field's effects. Further, exposure protocol and neuropsychological evaluating tools differ between studies, and reported effects are tenuous or even absent. Nevertheless, the examination of these studies shows that any notable cognitive effects generally appear to affect high level cognitive processes such as attention mechanisms, learning and memory; and executive functions such as working memory, flexibility, categorization, deduction and problem solving (see Kazantzis *et al.* 1998; Podd *et al.* 2002; Preece *et al.* 1998; Stollery 1986). Moreover, authors have found that the changes influence the quality and the precision of high level cognitive mechanisms rather than the velocity of execution.

If such neuropsychological functions are effectively modulated by the exposure to ELF MF, effects should be detectable at a neurophysiological level. Several studies have shown effects of MF exposure on human electroencephalogram (EEG) or evoked potentials (Bell *et al.* 1992; Bell *et al.* 1994a; Bell *et al.* 1994b; Cook *et al.* 2005; Cook *et al.* 2004; Ghione *et al.* 2005; Heusser *et al.* 1997; Lyskov *et al.* 1993a; Lyskov *et al.* 1993b; Marino *et al.* 2004). Still, no consensus exists on the direction of these effects, though the most conspicuous results seem to suggest a higher resting EEG in the alpha rhythm after exposure (8-13 Hz, see for example Cook *et al.* 2004; Ghione *et al.* 2005).

Other studies analyzing the interaction between heart rate (HR) behavior and MF have shown that electrophysiological rhythms can also be modified at the peripheral level and that the exposure to 60 Hz MF could induce a slowing of the HR that may or may not be associated with changes in HR variability (Cook *et al.* 1992; Graham *et al.* 2000a; Maresh *et al.* 1988; Sastre *et al.* 1998; Sastre *et al.* 2000). Again, other works did not detect any exposure effect on HR (Graham *et al.* 2000b; Graham *et al.* 2000c; Kurokawa *et al.* 2003). For a better understanding of the mechanisms underlying observed changes in HR, electrophysiological data should be completed by the monitoring of hemodynamic parameters such as blood flow.

Another way to investigate the effects of MF on the human body in its entirety is to evaluate human motricity. A few studies have demonstrated an effect on human motor control resulting from exposure to time-varying MF. Thomas *et al.* 2001a, for example, explored human postural oscillations and reported significant decrease in anteroposterior balance using a pulsed MF at 200 µT. Legros *et al.* explored human physiological tremor (Legros and Beuter 2005; Legros and Beuter 2006; Legros *et al.* 2006). They did not report any significant effect of a 50 Hz, 1000 µT MF on physiological tremor occurring during a goal directed task. However, the analysis of tremor occurring during a postural task of the index finger suggested a relaxing effect induced by the exposure, decreasing tremor size. Interestingly, Cook et al. who, in 2004, showed an effect of a pulsed 200 µT MF on EEG alpha activity, also underlined the link between resting posterior alpha activity and the state of relaxed wakefulness (Niedermeyer 1999).

Reported results are subtle and often not replicated. These discrepancies defining the effect of an ELF MF on humans can be attributed to the heterogeneity in intensity, shape and frequency of the MF used, as well as the differences in exposure duration. Furthermore, results differ with continuous versus intermittent exposure, and depending on whether the testing of the subjects is performed during or after the exposure.

Objective

The main objective of this study is to evaluate subtle effects of a 60 Hz MF exposure up to 1800 µT on human physiology, neurophysiology and motor functions in a single procedure. This intensity has been chosen because the International Commission on Non-Ionizing Radiation Protection (ICNIRP) guidelines establishes that current density induced by MF occupational exposure "should be limited to fields that induce current densities less than 10mA/m2" (ICNIRP 1998), and this corresponds to computed MF value which can reach 1800 µT (Stuchly and Dawson 2002, http://www.emfs.info/sci_Numerical.asp). This global approach will then establish a better understanding of the effects of high intensity MF on these functions. Conclusions will be drawn from the examination of human blood perfusion, HR (frequency and variability), brain electrical activity (EEG), posturo-kinetic activity as postural sway, voluntary motor functions as rapidly alternating movements and involuntary movements through the measurement of postural tremor.

Based on results in the literature, we hypothesize that MF exposure will (1) not affect ECG or blood flow, (2) increase EEG power in alpha band activity, especially in the posterior regions of the brain, (3) decrease the quantity and the variability of anteroposterior displacements of postural sway, (4) increase the rapid voluntary movements' maximum frequency, and (5) decrease postural tremor amplitude. Effects should appear after several minutes of exposure. The results could be useful in the development of public policy regarding the safety of MF exposure.

Methods

This is a currently ongoing study. To date, 8 subjects have completed at least 1 of the 2 sessions of testing. All participants give their informed consent before participating (University of Western Ontario Health Sciences Research Ethics Board # 11956E). At term, 70 healthy adults between 18 and 55 years of age will have completed the full protocol consisting of 2 counterbalanced exposure sessions given on 2 separate days (with at least 2 days in between): 1 active exposure condition (real) and 1 control exposure condition (sham) as detailed in Figure 1a. None of the participants have ever experienced an epileptic seizure; have motor limitation; suffer from chronic illness (e.g., diabetes, severe psychiatric, cardiovascular or neurological diseases); or have a cardiac or cerebral pacemaker. They have no history of head, eye or thorax injury involving metal fragments; they do not wear metal braces on their teeth. Finally, women cannot be pregnant, nor have an intrauterine device. A double blind computer driven procedure controlling for variables is used such that neither the participant nor the experimenter know when the real or sham condition occurs. Each session lasts 1 hour and 45 minutes and is composed of four 15 minute blocks of testing with 15 minutes rest in between. 1 hour of MF exposure is given from minute 15 to minute 75 of the real exposure session. There is no MF exposure in the sham session.

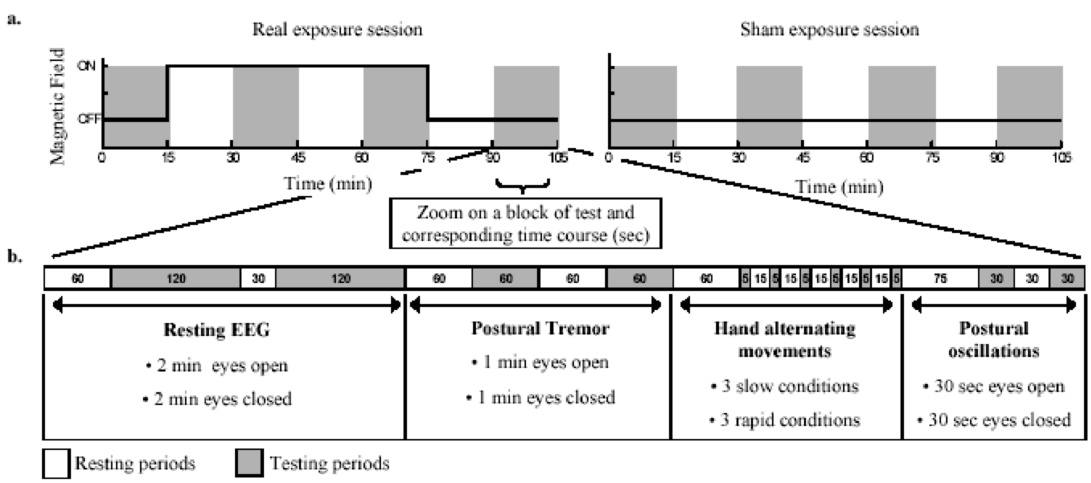

Figure 1: a. Time course of the 2 exposure sessions (real and sham). The horizontal black line represents the MF status (OFF when down, ON when up). Note that during the sham exposure session, the MF is never ON. Vertical grey bands represent the four 15-minute blocks of testing. **b.** Zoom on the time course of a block of testing (the same for each block). White cells represent resting periods and grey cells represent testing periods (duration is displayed in seconds inside the cells). The table below indicates the tests to which these periods correspond.

Each subject is equipped with the recording devices and his handedness is determined with the Oldfield questionnaire (Oldfield 1971). For the experiment, he is seated in an armchair in the exposure facility. The exposure system generating the MF has been designed for this experiment. It is composed of 2 octagonal coils, 1.6 meters in diameter, running parallel to each other 1.2 meters apart. Each coil contains 80 turns of AWG-10 wire mounted with a nonconductive cooling/heating tubing system. The system is configured to generate a homogenous 60 Hz field, up to 1800 µT, centred at the level of the head.

Prior to testing, the subject receives written directions, and is shown an audio-video demonstration of each task through a LCD screen and speakers, both positioned 1 meter in front of him. The room temperature is maintained at 23 °C. From the beginning of the testing session, both the subject and experimenter wear ear plugs to make it impossible to detect the subtle noise produced by the coils when the field is generated. The time course of the testing, as well as the MF generation and data acquisition, are entirely automated and computer driven (Labview 8.0 and Data acquisition card NI PCI-6289, National Instrument Inc., USA); except for recording of EEG, ECG and blood flow data. Automatic audio directions are given to the subject throughout the duration of the experiment. He obtains visual information about the timing of the experiment through the screen in front of him.

Each of the 4 blocks of testing in each session follows the same time course (Figure 1b). The subject first relaxes for 1 min. Then his resting eyes-open-EEG is recorded for 2 min. After 30 sec of inactivity, his resting eyes-close-EEG is recorded for another 2 min. Baseline local blood perfusion (recorded at the tip of the non dominant index finger, PF 5010 Laser Doppler Perfusion Monitoring unit and probe 407-1, Perimed, Sweden) and ECG are recorded simultaneously. EEG and ECG are recorded at 512 Hz with a 32 channels ambulatory unit (Siesta unit, Compumedics Inc., USA). During the real exposure session, the MF is switched OFF during the second minute of both EEG recordings (eyes open and eyes closed) to keep 1 minute free of MF artefact in the data.

The subject is then asked to open his eyes, and after a resting period of 1 minute, his eyes-open postural tremor is recorded at the extremity of his dominant index finger for 1 minute. A Class II laser diode pointing toward the ground (Micro laser sensor LM10, series ARN11, Matsushita Electronic Work, Ltd., Osaka, Japan) and located 8 cm above the piece of white cardboard fixed on nail of the index finger enables 1000 Hz vertical displacement recording. A target horizontal line gives feedback about the index finger's vertical position, and is also displayed on the LCD screen. In this test, the subject must point the index finger (in extension at the level of the metacarpophalangeal joint) to keep the target line centred in the middle of the screen for 1 minute at the "zero position". After another 1 minute rest, he performs the same test with his eyes closed and therefore, with no visual feedback.

After another 1 min period, the subject is asked to extend his arms in front of him, parallel to the floor, and then to bend them to a 90 degree angle at the elbow, with hands open, palms facing each other. From this starting position, he has to execute alternating hand movements that involve rotating the hands at the wrist axis: (1) with the right hand at a natural rhythm; (2) with the left hand, natural rhythm; (3) with both hands, natural rhythm; (4) with the right hand at a higher frequency; (5) with the left hand, higher frequency; and (6) both hands, higher frequency. For the higher frequency condition, the subject is asked to rotate his hands "as fast and as far as possible". Recordings last 5 sec each, with a 15 sec rest between any two. Recordings are done with the liberty system (Polhemus inc., USA), with 2 transducers fixed like watches on the dorsal side of the wrists, allowing recording of movement kinematics with 6 degrees of freedom at 200 Hz in the used configuration (3D and 3 angles of rotation, accuracy of 0.03 RMS for X, Y, Z position and 0.15° RMS for orientation). The Liberty system is an electromagnetic tracking system and therefore, during MF exposure session, the field has to be turned OFF during each 5 sec recording periods so as not to affect data.

Finally, the subject has 75 sec to step onto a force plate (standardized socks, feet parallel, 1 cm apart) and to relax before his postural sway is recorded during 30 sec eyes open, and 30 sec eyes closed, with a 30 sec period in between. The 3-D force plate used in previous works (Thomas *et al.* 2001a; Thomas *et al.* 2001b, OR6-7-1000, AMTI, Watertown MA) is mounted on the floor in the centre of the MF exposure system, and measures the force and momentum applied by the subject's feet at a sampling rate of 1000 Hz. These measurements can be converted to centre of pressure (COP) values, i.e. the perpendicular projection of the centre of gravity through the force plate. Postural sway is then the change the COP over time.

As detailed in the Figure 1b, this block of testing is given 4 times over a session. During a real exposure session, this would mean that the testing begins: 15 minutes before the beginning of the exposure period, 15 minutes after the beginning of the MF exposure, 45 minutes after the beginning of the MF exposure, and 15 minutes after the end of the MF exposure. Skin temperature is monitored throughout the experiment. After each block, the subject has to answer the Field Status Questionnaire (FSQ, Cook *et al.* 1992) to assess his ability to detect the presence of the field.

Data processing and Analysis

As an ongoing study, data are still being collected and analysed. Therefore, given the advancement of the study and in a concern of clarity of the purpose, it has been chosen to focus here on a limited set of data, including EEG in the occipital region of the brain (O1, O2), postural tremor data, and postural sway data.

First, the ambulatory EEG data are recorded on a flash memory card, and then an averaged reference montage is used to import data in Matlab for processing (The MathWorks Inc., Natick, USA). Fast Fourier Transform (FFT) and inverse Fast Fourier Transform (iFFT) are used to extract time series in the theta (4-7 Hz), alpha (8-13 Hz), and beta (14-35 Hz) frequency bands. The average amplitude in each band is then computed for each electrode (O1, O2 here, see example in Figure 2).

Secondly, the laser system records vertical displacement with a resolution of 13 µm (i.e. 2σ, where σ is the standard deviation of a recording on a stationary target) which is effectively reduced to 5 µm after filtering out high frequencies (above 25 Hz, FFT, iFFT). Data are transferred to Matlab for A/D conversion to mm given a calibration constant (-3.97). Position and velocity data (obtained by differentiation of the raw displacement data) are used for indexes computation in time and frequency domains (Beuter and Edwards 1999; Edwards and

Beuter 2000) allowing the characterization and the examination of temporal, frequential and morphological components of the signals (see also Legros and Beuter 2005; Legros and Beuter 2006). Here, amplitude, drift, median frequency and frequency concentration are computed (see Appendix 1 for index definitions and Figure 3 for an example).

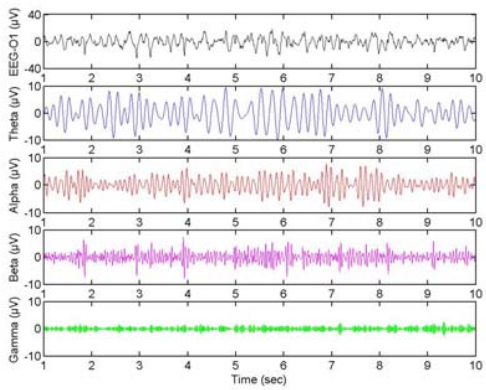

Figure 2: From the top to the bottom: 10 sec of O1 EEG trace and corresponding theta, alpha, beta and gamma components respectively extracted using FFT and iFFT. Averaged amplitude for this sample are: Theta = 3.909 µV, alpha = 2.485 µV, beta = 1.757 µV; gamma = 0.641 µV.

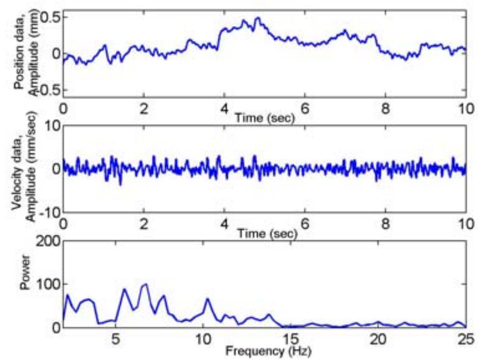

Figure 3: Position data (top), velocity data (middle) and corresponding power spectrum (bottom) for 10 sec of recording during MF exposure with eyes open (block 3). The computed values on this sample are: Amplitude = 0.032 mm; drift = 0.106 mm, median frequency = 7.04 Hz; and frequency concentration = 6.31 Hz.

Third, postural sway data are exported under Matlab and converted from volts to COP trajectories (in meters) using a calibration matrix. Through the inclusion of two dimensional trajectories (X vs. Y), the following validated characteristics have been computed (Despres *et al.* 2000; Thomas *et al.* 2001a): Mean sway, sway, velocity and sway area (see Appendix 1 for index definition and Figure 4 for an example).

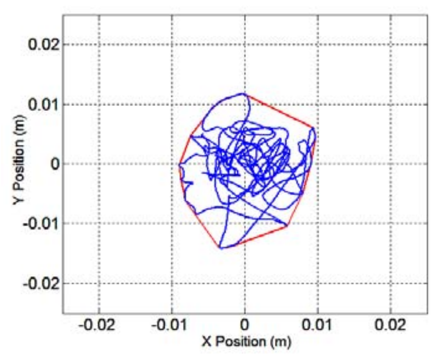

Figure 4: 30 sec of postural sway recording during MF exposure (block 3) with the eyes are closed. The smallest polygon including the entire trajectory is also displayed. The computed characteristics on this sample are: Mean sway = 0.53 cm; sway velocity = 1.62 cm/sec, sway area = 3.41 cm^2.

Preliminary results

For 3 of the 8 subjects who have completed at least 1 of the 2 sessions of testing, the first session was a real exposure condition. Therefore 3 subjects who have completed the sham session first have been chosen to afford a control group (i.e. the sham condition), which allowed providing a preliminary assessment of the exposure effects on their behaviour. According to the small sample size available at this step, a simplified statistical procedure has been chosen, focusing on the data acquired in the block 1 (before exposure) and the block 3 (during exposure, and after a 45 min period of continuous exposure, see Figure 1). A within-subject ANOVA including a between-subject factor (sham vs. real) have been conducted on each of the above mentioned indexes: ANOVA 2 (eyes open vs. eyes closed) x 2 (block1 vs. block3) x 2 (sham vs. real). The level of significance has been set at $p < .05$ and no adjustment for multiple comparisons has been applied.

No Block main significant effect has been found either for EEG, postural tremor or postural sway recordings. However, with eyes closed, subjects had significantly higher EEG alpha activity in the occipital region (O1: $F = 24.85$, $p < .01$, $Eta^2 = .86$; O2: $F = 20.54$, $p < .05$, $Eta^2 = .83$), larger and faster postural oscillations (mean sway: $F = 17.38$, $p < .05$, $Eta^2 = .81$; sway velocity: $F = 51.47$, $p < .005$, $Eta^2 = .92$; sway area: $F = 35.14$, $p < .005$, $Eta^2 = .89$), and higher index finger drift ($F = 12.19$, $p < .05$, $Eta^2 = .75$) with eyes closed than with eyes open. No interaction effect was found.

Discussion-Conclusion

Preliminary results confirm that this experimental protocol is adapted to detect subtle changes in the neurophysiological characteristics investigated, despite the small number of subjects tested at this point. Indeed, as expected we observed significant differences between open and closed eyes conditions in EEG, tremor and postural sway. However due to the small number of subjects tested we did not detect a significant effect due to the presence of MF. This is why we performed a sample size analysis.

The sample size calculation for 2 independent samples with common variance was done on the sway velocity characteristic because this is the lowest p value for the interaction block x sham/real ($F = .509$, $p = .51$, $Eta^2 = .113$). In the present configuration, the decrease of .072 cm/sec observed for the real exposure group would be significant with two groups of 34 subjects (p fixed at .05, power = .80). We have planned to test a sample of n = 70 subjects which should be sufficient to detect the MF effects on the characteristics examined. We have to keep in mind that, at this stage of the study, 2 groups of subjects were evaluated. However in the final study all participants will have been tested under both MF conditions with a counterbalanced protocol. This should contribute to make the protocol more sensitive to subtle effects (reducing the impact of the between-subjects variability).

The results presented in this paper are only partial results on selected tests recorded. They will be completed by heart rate frequency and variability, blood flow perfusion, alternating movement performance. Finally data acquisition will be completed in 2007.

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Appendix 1

Postural tremor characteristics:

Amplitude: Root Mean Square (RMS) of position time series centered on their mean (highpass and lowpass filtered, between 2 and 25 Hz).

Drift: RMS of the low frequency component of the time series (below .01 Hz), quantifying slow movements of the finger.

Median frequency: Determines the value at which 50% of the power spectrum is below this frequency, and 50% is above. It is computed on the power spectrum between 2 and 25 Hz.

Frequency concentration: Quantifies the degree of organization of tremor by computing the width of the interval containing 68% of the power of the spectrum between 2 and 25 Hz.

Postural sway characteristics:

Mean Sway: Average distance between the geometric center of all recorded forces and each point visited by the Center of Pressure (COP) during a test.

Sway Velocity: Average velocity of the COP displacements.

Sway Area: Area of the smallest polygon including the entire trajectory of the COP.