Evaluation of 60 Hz MF effects thresholds on the EEG using biophysical modeling

J. Modolo[1,2,3], A.W. Thomas[1,2,3], A. Legros[1,2,3,4]

1 : Human Threshold Research Group - Lawson Health Research Institute

2 : Department of Medical Biophysics, Western University

3: Department of Medical Imaging, Western University

4: School of Kinesiology, Western University

London, ON, Canada

Introduction

Understanding and characterizing the effects of extremely low-frequency (ELF, < 300 Hz) magnetic fields (MF) on human neurophysiology is the object of intense research. Several biological effects have been reported in humans due to ELF MF exposure, such as a modulation of the pain threshold, physiological tremor [1,2,3], functional brain activity measured using fMRI [4], or of learning in a cognitive test involving short-term memory [5]. Also, lasting effects of 60 Hz MF exposure have been suggested: for example, a 60-minute exposure to a 1.8 or 3 mT 60 Hz MF induces a modulation of the fMRI blood oxygen level-dependent (BOLD) signal in humans, as measured during two different tasks (motor, finger tapping; and cognitive, mental rotation [6,7]). However, the MF flux density threshold resulting in reproducible detectable effects in humans is currently unknown at power-line frequencies.

In order to clarify the interaction mechanisms involved in the effects reported experimentally, and to evaluate a threshold in MF flux density for which systematic effects could be induced in humans, we have developped a biophysical model of cortical activity based on neuroanatomical and neurophysiological knowledge of human cortical organization. The model simulates the alpha rhythm (8-12 Hz) of the human electroencephalogram (EEG), and includes the interaction between the electric field induced by a 60 Hz MF and the membrane potential of specific neuronal populations. The objective was to estimate the threshold in MF flux density at 60 Hz resulting in a systematic modulation in the simulated EEG. Several target neuronal populations were tested in order to investigate how the MF flux density threshold depends on the type of modeled-neurons modulated by the induced electric field. We discuss how the threshold in MF flux density leading to reproducible detectable effects in the EEG depends on the involvement of GABAergic interneurons modulated, but also on their type.

Material and Methods

We developed a type of biophysical model termed as "neural mass model" (for examples, see [8,9,10]). In brief, neural mass models describe the cortex with the cortical column as a fundamental unit. The cortical column is the basic pattern of neuronal organization in the cortex, and includes four main types of neurons: pyramidal neurons (glutamatergic, excitatory); inhibitory interneurons (slow and fast GABAergic); and excitatory interneurons. The main connectivity pathways between these neuronal populations are described in Figure 1.

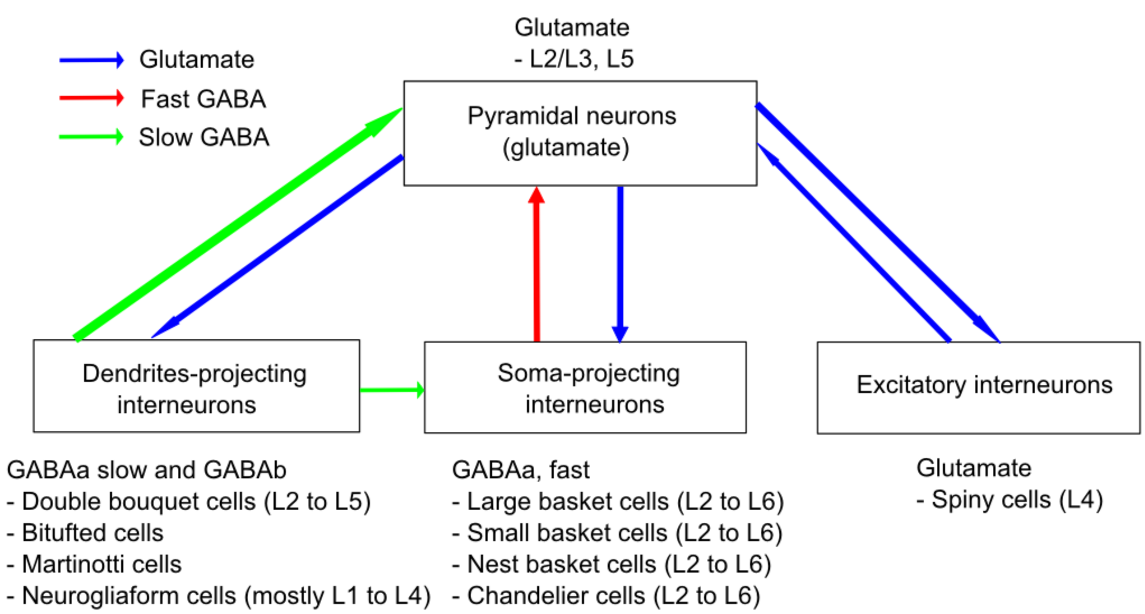

Figure 1. Functional model of the cortical column used in our biophysical model. (Modified from [9]).

If we consider a synapse of type *i* (e.g., glutamatergic or GABAergic), the post-synaptic response *Vi(t)* at the level of a post-synaptic neuronal population is described by the following equation [9]:

$$\frac{d^2}{dt^2}V_i(t)+2.a.\frac{d}{dt}V_i(t)+a^2.V_i(t)=A.a.\upsilon_i(t) \qquad (1)$$

where *A* is the post-synaptic response amplitude for synapse *i* expressed in mV; *a* is the response time constant expressed in ms; and υ_i(t) in the incoming firing rate (expressed in Hz) at the type of synapses *i*. By writing a similar equation for each block of post-synaptic potentials for each synaptic projection presented in Figure 1, we can obtain the full model (not shown here, since it consists in a set of 34 coupled differential equations).

The interaction with the 60 Hz MF was modeled using an additive membrane depolarization due to the effect of the induced electric field on the neuron membrane, that can be expressed as [11,12]:

$$dV=\frac{\lambda\cdot E}{\sqrt{1+\omega^2\tau^2}} \qquad (2)$$

where λ is the polarization length, *E* the induced electric field amplitude, $\omega=2\pi f$ where f is the frequency, and τ is the polarization time constant. This membrane depolarization dV(t) was added to the membrane potential of pyramidal neurons in the model, such that $V_{pyr}(t) \rightarrow V_{pyr}(t)+dV(t)$. In order to study the possible effect of the induced electric field on populations of GABAergic neurons (slow, fast, or both), we followed the same approach by adding the membrane potential dV(t) to the membrane potential of the considered neuronal populations.

The simulated exposure protocol was the following: 30 minutes without exposure (sham condition), 1 hour exposure (exposed condition), and 30 minutes without exposure (sham condition). Four different maximal values of dV were tested: 125, 250, 500, and 1000 µV (corresponding MF flux density is discussed in the Results section). For each of these values, we computed the EEG alpha spectral power before, during and after exposure. Ten simulations were run for each maximal value of dV.

Results

The EEG alpha power before, during and after exposure for dV values from 125 to 1000 µV is presented in Figure 1.

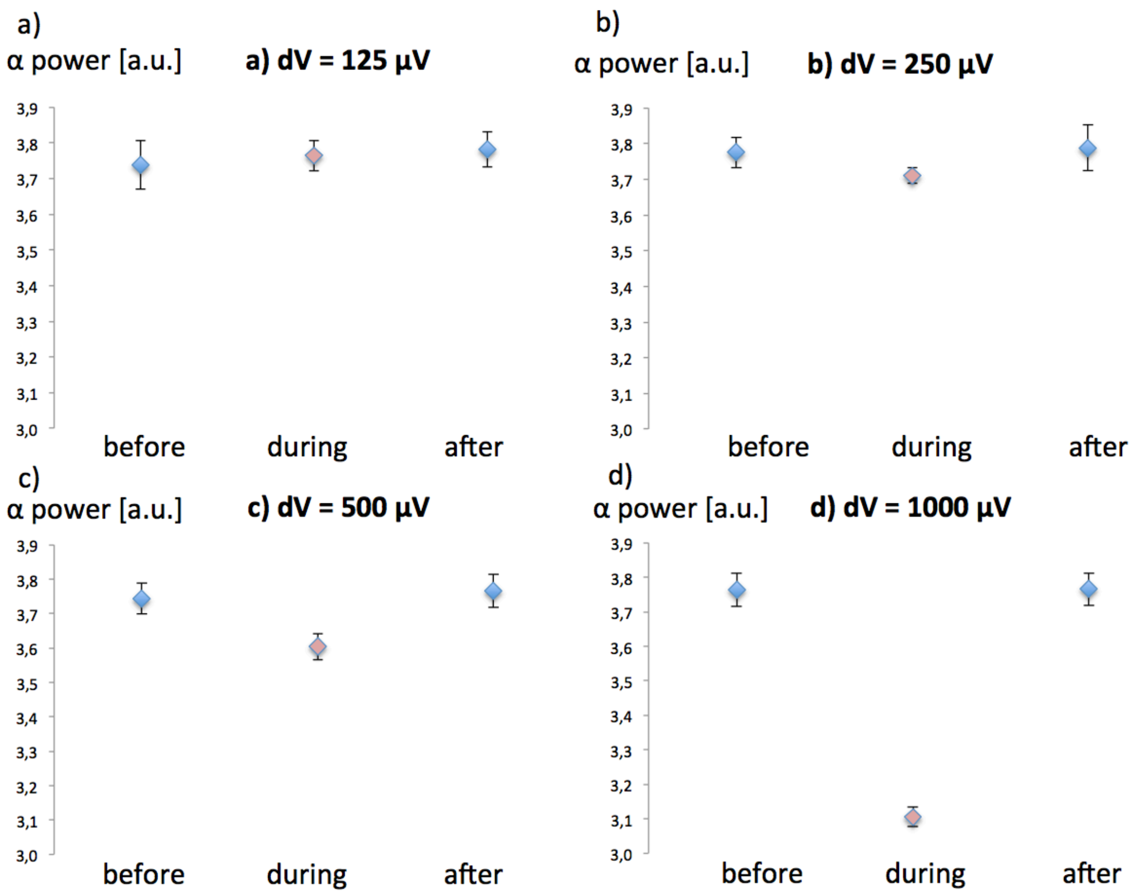

Figure 1. EEG alpha spectral power as a function of the MF-induced membrane polarization dV maximum value. a) dV=125 µV; b), dV=250 µV; c) dV=500 µV; d) dV=1000 µV.

The results presented in Figure 1 illustrate a decrease in EEG alpha power as the value of dV (proportional to the MF flux density) increases. In order to estimate the threshold value for which a significant effect is achieved on the EEG alpha power, we used an ANOVA for repeated measures, with a standard p-value of 0.05 (Greenhouse-Geisser) as the significance threshold. The software SPSS 20 (IBM, USA) was used to conduct this analysis. The decrease in EEG alpha power becomes statistically significant for dV=500 µV ($p<0.001$), indicating that the MF flux density threshold resulting in a significant effect on the EEG induces a membrane depolarization between 250 and 500 µV. By expressing the induced field as $E=\pi RfB$, where R=0.15m is the head radius, f= 60 Hz is the MF frequency, and by using an intermediate value of dV of 375 µV in Equation (2), it is possible to evaluate the corresponding MF flux density depending on the polarization time constant. For a polarization time constant of 1 ms, the threshold would correspond to an MF flux density of 15 mT at 60 Hz; and for a constant of 5 ms the threshold value would increase at 25 mT at 60 Hz.

Using the same exposure protocol, a possible effect of the induced electric field on GABAergic interneurons was tested (not shown here, the results will be presented at the conference). The results show that the effect of the exposure on fast GABAergic interneurons does not modulate significantly the MF flux density threshold resulting in a significant decrease of the EEG at 60 Hz. Conversely, the decrease in EEG alpha power due to the exposure drops from 17% to 5% if slow GABAergic neurons are modulated by the induced electric field, thereby increasing the MF threshold in flux density resulting in systematic effects on the EEG at 60 Hz.

Discussion and conclusion

Results from the model indicate that a 60 Hz MF resulting in a membrane depolarization between 250 and 500 microvolts should induce a systematic decrease in EEG alpha power, if cortical pyramidal neurons are modulated by the induced electric field. Considering a cell polarization time constant on the order of 5 ms, this would correspond to a threshold value of 25 mT at 60 Hz. If fast GABAergic interneurons are also modulated by the induced electric field, the threshold value is not significantly affected; which is not the case if slow GABAergic interneurons are modulated (smaller effect of the exposure).

These results will have the impact on the interpretation of experimental EEG data that will be obtained soon in our group in the near future, in healthy subjects exposed to 60 Hz MF up to 50 mT. If the threshold value in EEG modulation by the 60 Hz MF exposure is higher than predicted, it will suggest that slow GABAergic neurons are also modulated by the induced electric field (in addition to pyramidal neurons). Therefore, the model will provide support to identify for the neurophysiological substrate of interaction between the 60 Hz MF exposure and the human cortex. The model will also be extended to take into account different mechanisms of synaptic plasticity in order to investigate possible cumulative, long-term effects of ELF MF exposure.

[1] Legros, A., and Beuter, A. (2005). Bioelectromagnetics, 26(8):657-669.

[2] Legros, A., Gaillot, P., and Beuter, A. (2006). Med. Eng. Phys. 28(8):827-836.

[3] Legros, A., Miller, J., Modolo, J., Corbacio, M., Robertson, J., Goulet, D., Lambrozo, J., Plante, M., Prato, F. S., and Thomas, A. W. (2011). Electra, 14-18.

[4] Corbacio, M., Brown, S., Dubois, S., Goulet, D., Prato, F. S., Thomas, A. W., and Legros, A. (2011). Human cognitive performance in a 3 mT power-line magnetic field. Bioelectromagnetics, 23(8):620-633.

[5] Legros, A., Miller, J. E., Modolo, J., Corbacio, M., Robertson, J. R., Goulet, D., Lambrozo, J., Plante, M., Souques, M., Prato, F. S., and Thomas, A. W. (2010) 32nd Annual Conference of the Bioelectromagnetics Society, Seoul, South Korea.

[6] Miller, J. E., Modolo, J., Robertson, J. R., Corbacio, M., Dubois, S., Goulet, D., Lambrozo, J., Plante, M., Souques, M., Prato, F. S., Thomas, A. W., and Legros, A. (2010). 32nd Annual Conference of the Bioelectromagnetics Society, Seoul, South Korea.

[7] ICNIRP – International Commission on Non-Ionizing Radiation Protection (2010). Health Phys. 99(6):818-836.

[8] Jansen, B. H., and Rit, V. G. (1995). Biol. Cybern., 73:357-366.

[9] Wendling, F., Bartolomei, F., Bellanger, J. J., and Chauvel, P. (2002). Eur. J. Neurosci. 15(9):1499-1508.

[10] Sotero, R. C., and Trujillo-Barreto, N. J. (2008). Neuroimage, 39(1):290-309.

[11] Gianni, M., Liberti, M., Appollonio, F., and D'Inzeo, G. (2006). Modeling electromagnetic fields detectability in a HH-like neuronal system: stochastic resonance and window behavior. Biol. Cybern. 94(2):118-127.

[12] Molaee-Ardekani, B., Benquet, P., Bartolomei, F., and Wendling, F. (2010). Neuroimage, 52(3):1109-1122.