Frequency preference in a Hodgkin-Huxley neuron interacting with extremely low-frequency magnetic fields: implications for biological effects

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INTRODUCTION

Despite evidence that non-thermal extremely low-frequency (ELF, < 300 Hz) magnetic fields (MFs) interact with human neurophysiology [1,2], interaction mechanisms remain elusive. It has been highlighted that ELF MFs frequency might play a critical role in determining the response of nervous tissue [1]. To clarify this issue, we developed an Hodgkin-Huxley (HH) neuron model interacting with sinusoidal ELF MFs at frequencies between 1 and 500 Hz. Results indicate that predominately two ELF MFs frequency bands modulate membrane potential time course. We propose that this frequency preference could explain partly results on human electroencephalogram modulation by ELF MFs exposure.

MATERIALS AND METHODS

We used the HH model, the gold standard for realistic simulation of neuronal activity [3]. This model describes the time course of voltage-gated ionic currents in response to external currents (e.g., synaptic), and consists in four coupled, non-linear differential equations:

$$\begin{cases} C_m\dot{V} = -g_L(V-E_L) - g_{Na}m^3h(V-E_{Na}) - g_K n^4(V-E_K) + \sum I_{syn} + \xi(t) \\ \dot{m} = \alpha_m(V)(1-m) - \beta_m(V)m \\ \dot{n} = \alpha_n(V)(1-n) - \beta_n(V)n \\ \dot{h} = \alpha_h(V)(1-h) - \beta_h(V)h \end{cases}$$

where C_m is membrane capacitance; $\alpha_x(V), \beta_x(V)$ are voltage-dependent functions for variable x; g_i is ionic channel i conductance; E_i is equilibrium potential of channel i; m,n,h are activation/inactivation variables; $\sum I_{syn}$ is the total synaptic current and $\xi(t)$ is synaptic noise. Parameter values were: C_m=1 µF/cm^2; g_L=0.3 mS/cm^2, g_K=36 mS/cm^2, g_{Na}=120 mS/cm^2, E_K=-12 mV, E_{Na}=115 mV, E_L=10.6 mV, Gaussian noise had zero-mean and standard deviation 2 mV. Time-varying MF induces an electric field $E(t)$ in brain tissue, resulting in membrane depolarization obeying to $\delta\dot{V} + \tau^{-1}\delta V = \tau^{-1}\lambda E$,where λ is the polarization length [4], introduced in the HH model such that $V \to V + \delta V$ [5], with $\delta V \approx 60$ µV (at 60 Hz, assuming τ=20 ms, λ=0.5 mm, MF amplitude is approx. 50 mT). HH equations were solved in Matlab® using a 4th-order Runge-Kutta method. MF frequency was varied from 1 to 500 Hz (1 Hz steps), and for each frequency we computed the difference φ_f between membrane potential trace without exposure ("sham"), $\gamma=[V_0,...,V_N]$, where V_i is the potential at time t_i) and "exposed" condition at frequency f, γ_f, such that $\varphi_f = \int_0 (\gamma_f - \gamma)dt$. Thus φ_f quantifies membrane potential perturbation induced by ELF MF exposure at frequency f. For each frequency tested, one second was simulated (longer simulation duration were tested and did not affect the results). 50 runs were performed.

RESULTS

We present in Figure 1 the perturbation in membrane potential in response to ELF MF exposure between 1 and 500 Hz, averaged over the 50 runs of one second of spiking activity.

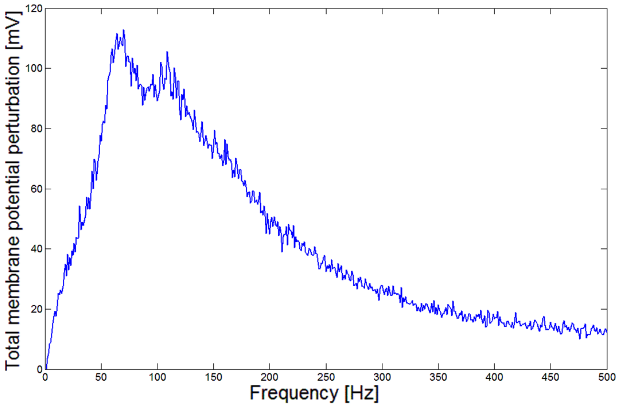

Figure 1: Membrane potential perturbation of a Hodgkin-Huxley neuron during exposure to an ELF MF from 1 to 500 Hz.

Our results show that membrane potential perturbation induced by ELF MF exposure is maximized in two frequency bands (60-70 Hz and 100-120 Hz). Interestingly, a recent modeling work using the Hodgkin-Huxley model to study stochastic resonance and detectability of ELF MFs by neurons [5] found that the signal-to-noise ratio was maximal in their model in similar frequency bands. Therefore, this frequency preference appears consistent and deserves further experimental and theoretical investigation.

CONCLUSIONS

Importantly, perturbation of membrane potential is maximal in a frequency range that includes the North American power-line frequency (60 Hz), at an amplitude higher than experiments conducted so far (50 mT). Even if our results are derived using a single neuron model, frequency specificity is of interest. Indeed, our recent experimental results have shown modulated brain functional activation by 60 Hz MF during finger tapping [6] or mental rotation tasks [7]. Further work is needed to check if these results hold at the neural network level.

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