Bundesamt
für Strahlenschutz

Spotlight on EMF Research

Spotlight on “Action potential threshold variability for different electrostimulation models and its potential impact on occupational exposure limit values” by Soyka et al. in Bioelectromagnetics (2025)

Category [low frequency, dosimetry/exposure]

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Competence Centre for Electromagnetic Fields (KEMF)

1 Putting the paper into context by the BfS

Reference levels for exposure to electric and magnetic fields of low frequencies are derived from basic restrictions for body internal electric fields. The latter are obtained by determining thresholds for the excitation of neurons. Above a threshold, a neuron is “firing”, i.e., it is stimulated and sends signals to other parts of the nervous or neuromuscular system which can lead to effects such as pain perception or muscle contractions. The firing patterns of neurons can be estimated numerically. The most popular attempt was provided by the equations discovered by Hodgkin and Huxley, for which they received the Nobel Prize in Physiology or Medicine. A more accurate set of equations was provided by Frankenhäuser and Huxley (FH), based on measurements of frog neuron fibres, which was later used in a segmented model of a neuron. This is known as the spatially extended nonlinear node (SENN) model, which allows the calculation of neuron firing thresholds [2]. These calculations are the basis for contemporary occupational exposure limit values of the EU directive 2013/35/EU [3]. Although focusing on the occupational case, understanding the rationale behind exposure limit values is also relevant for the exposure of the general public.

2 Results and conclusions from the perspective of Soyka et al.

Soyka et al. [1] compare the threshold values for triggering an action potential (technical term for “firing”) obtained by several neuron excitation models at two different tissue temperatures. The results for the electric field values corresponding to the simulated transmembrane voltage are then compared to the current exposure limit values of the EU directive [3]. To this end, the authors use an implementation of the SENN model [4] and analyse different models of membrane channel dynamics. They derive threshold values for the electric field amplitude above which action potentials are generated in the corresponding simulations in a frequency range from 1 Hz to 10 MHz. For practical reasons, in this frequency range, the exposure limit values have a constant value or are a linear function of frequency. For comparison of these exposure limit values with the frequency-dependent thresholds obtained using the SENN model in the frequency range between 1 Hz and 100 kHz, an enveloping curve is constructed. The envelope analogously consists of a constant and a linear segment. To ensure conservativeness and to compensate for variability between different models, a reduction factor is applied to the enveloping curve.

To test the computations, the authors first successfully reproduce the SENN model results obtained by Reilly and Diamant [5] based on FH dynamics. Then, they repeat the analysis using four other models of channel dynamics which can be used in the SENN model: First, the Hodgkin-Huxley (HH) model, based on measurements of the giant squid axon, which is still a standard model in neuroscience. Second, the Chiu-Ritchie-Rogart-Stagg-Sweeney (CRRSS) model, which was obtained using voltage-clamp measurements of single myelinated rabbit nerve fibres. Third, the Schwarz-Eikhof (SE) model, based on single myelinated rat nerve fibres and fourth, the Schwarz-Reid-Bostock (SRB) model, based on current- and voltage-clamp measurements of human nerve fibres (obtained from nerve graft operations). At low frequencies (below 1 kHz), all derived envelopes, except for the ones of the HH model, reach higher electric field values than the FH model, i.e. the FH model is more conservative than the models of CRSS, SE and SRB for low frequencies. At high frequencies, the envelopes of the HH and CRRSS models lie slightly below the one of the FH model and are thus more conservative than the FH model in this frequency range.

In the next step, the authors compare the SENN model results for FH dynamics in the original implementation [5] with the performance of its implementation used in the software package Sim4Life [6], for two different temperatures of nerve tissue (22° C and 37° C). Both simulation environments agree well, with higher threshold values at 37° C (than 22° C) for frequencies below 300 Hz. Finally, the same analysis (at 22° C and 37° C) was performed for two other neuron models implemented in Sim4Life: MRG (McIntyre, Richardson, Grill)-Motor, a model for mammalian motor nerve fibres including detailed morphological structures like Ranvier nodes, paranodal and internodal sections, and MRG-Sensory, a similar model for mammalian sensory nerve fibres. The lowest threshold values are obtained at 22° C for MRG-Sensory, while the impact of temperature on the threshold values decreases with increasing frequency.

The authors observe that the enveloping curves strongly depend on the membrane channel model applied. The application of the FH model could potentially be too conservative, but compared to HH it may not be conservative enough. Furthermore, the authors remark that non-sinusoidal waveforms of electric field stimulation have never been considered in the literature in the context of exposure limit values. The most important aspect from a safety point of view are the up to ten times lower threshold values at low temperatures below 300 Hz obtained with the MRG models. However, in this frequency range, more research is needed to clarify the observations. The authors conclude by raising the question of whether current exposure limit values are conservative enough. In particular, at 50 Hz, the thresholds obtained from the MRG-Sensory model are below the current limit values. The authors emphasize that further experimental data are needed to verify the existing theoretical models and to choose between them.

3 Comments by the BfS

Soyka et al. use state-of-the-art implementations of neuron models. They employ a comparative approach and evaluate different neuron models and different underlying membrane channel dynamics. This ensures that many reasonable assumptions about neuron physiology are considered allowing for a more robust interpretation based on a consensus or disagreement between results. The results of the present study show differences depending on the choice of both the neuron model and the membrane channel dynamics. In particular, alternative exposure limit values derived from the MRG-Sensory model of Sim4Life are up to ten times below the values set by the current EU directive. The authors rightly point out that these simulation results need to be supported by further experimental investigation.

The present results are of interest for radiation protection. Assuming the validity of the MRG-Sensory model, computer simulations achieve threshold values that would be more conservative than the current exposure limits of the EU directive and even slightly more conservative than the corresponding values for the general population. The assessment of which neuron model and which membrane channel dynamics are most suitable for a specific type of nerve tissue, thereby providing realistic threshold values, remains an open research question. This can only be decided through further experimental and theoretical investigations.

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