Couple Electromagnetic and Neuronal Dynamics Simulation of Gradient Coil Switching Induced Nerve Stimulation

Ioannis Vogiatzis Oikonomidis[1,2], Esra Neufeld[1], Johanna Wolf[1], Deepika Sharma[1,3], Yngve Hamnerius[2], and Niels Kuster[1,3]

[1]*IT'IS Foundation, Zurich, Switzerland,* [2]*Signals and Systems, Chalmers University of Technology, Gothenburg, Sweden,* [3]*Information Technology and Electrical Engineering, Swiss Federal Institute of Technology, Zurich, Switzerland*

Introduction: Nerve stimulation by low frequency electric fields, induced by the rapidly changing magnetic fields of switching gradient coils, is a safety concern in MR. It is typically addressed through limits on the switching rate ([T/m/s]), the E-field magnitude, or occasionally by investigation of the activating function (2^{nd} derivative of potential, related to membrane hyper-/depolarization of axons and neurons). Thresholds have often been derived using simplified models of the human anatomy and the generic SENN model[1] of neuron dynamics. However, it is known that the field variation along the neuron trajectory has an impact, that the neuronal dynamics are affected by the local temperature, and that the detailedness (distinguished tissues, resolution) of the modeled anatomy influences the predictions. While the SENN model can be parameterized to mimic various types of neuron (e.g., motor-neurons), it is by design a strongly simplified model, hence the relevance of more complex and realistic neuron models should be investigated. Therefore, a general platform coupling EM simulations involving complex anatomical models with neuronal dynamics simulations has been realized. For comparison purposes and standard related questions, the SENN model has been realized on this platform and extended to allow accounting for the impact of local temperature variations on neuron dynamics. The stimulation of a sciatic nerve by a switching gradient coil has been studied.

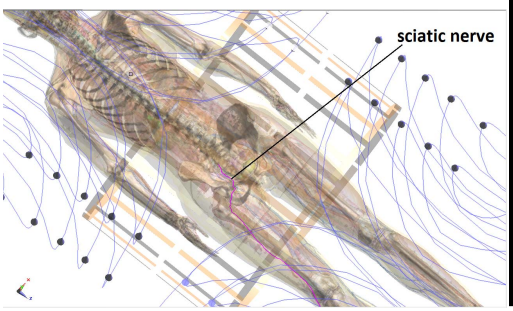

Fig. 1: Anatomical model, within generic 3T I/Q birdcage and z-gradient coil (shield not depicted)

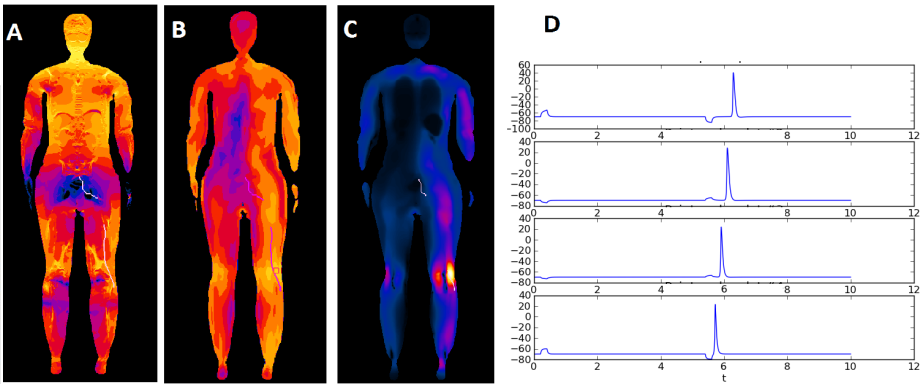

Fig. 2: a) Gradient coil E-field b) RF coil SAR c) RF induced heating d) Neuron response (transmembrane voltage over time at four locations along sciatic nerve) using SENN(T)

Methods: Our existing EM and thermal simulation platform has been extended by integrating the NEURON software[2] and coupling them via the external potential mechanism. It offers an EM FDTD solver as well as multiple electro- and magneto-quasi-static solvers for low frequency simulations (incl. a novel FEM solver that considers the varying tensorial anisotropy of nerve tissue dielectric properties, which can be determined for instance by DTI measurements). Stimulus pulse shape and neuron trajectory can be flexibly defined and existing detailed neuron models from the ModelDB[3] can be imported. The platform has been extensively validated, e.g., by implementing a SENN model and reproducing results from Reilly[4]. To allow accounting for the effect of local temperature, the known temperature dependence of the Frankenhauser-Huxley model underlying the SENN model has been integrated and temperature distributions calculated using the thermal solver can be considered.

Results: The simulation platform has been applied to the investigation of gradient coil switching induced neuron activity in a sciatic nerve (Fig. 1). The sciatic nerve has been traced in the Ella model of the Virtual Population[4], and fields induced by the gradient switching have been calculated using a magnet-quasi-static FVM solver for a z-gradient coil model (resolution: 1.3 mm). The field strength has been scaled to correspond to a switching rate of 100 T/m/s. In addition, the power deposition (SAR) from a 3T RF-birdcage coil has been simulated (2 W/kg whole body SAR) and used to determine the induced tissue heating (using the linear Pennes Bioheat equation and neglecting the impact of thermoregulation). The potential distribution along the nerve was estimated by integrating the tangential E-field along the trajectory and coupled to dynamic neuron models. Three neuron models were compared: i) the SENN model, ii) the temperature dependent SENN(T) model, and iii) a motor neuron model extracted from the ModelDB. Titration was performed to identify the stimulation threshold.

The calculated peak gradient coil E-field, $B_1^+{}_{,max}$ and dB/dt were comparable to previously reported values[6,7] (slightly higher, probably as a result of the high model detailedness and resolution[7]). Titration indicates that the stimulation threshold is only slightly above realistically occurring gradient switching rates. End-stimulation seems to be the most relevant mechanism. However, the stimulation threshold is significantly lower than the one found using the SENN model in a homogeneous field, indicating that the potential distribution along the nerve has an influence. When the impact of local temperature is considered (SENN(T)), only a small effect on the stimulation threshold is observed. However, the spiking dynamics and the propagation speed are strongly modified (greater than factor 2).

Conclusions: A coupled EM-NEURON simulation platform has been developed, which allows considering the combined effect of field distributions in inhomogeneous realistic anatomical models and complex neuronal dynamics. In addition, a SENN(T) variant of the SENN model has been implemented that accounts for the impact of local temperature. The platform has been used to model gradient coil switching induced spiking in the sciatic nerve of a realistic anatomical model, while considering the influence of heating by the RF birdcage coil. It has been found that the detailed field distribution has an impact on the stimulation thresholds and that the temperature, while only weakly affecting the threshold, strongly influences the dynamics. The developed EM-NEURON simulation platform provides a valuable tool for safety assessment and stimulation mechanism investigation. It can also be employed to study safety in the presence of implants, which due to the large resulting field gradients are expected to interact with neurons in ways that cannot be captured by field thresholds only. Such a platform will be particularly powerful when combined with functionalized anatomical models that integrate nerve trajectories and potentially even dynamical neuron models.

References: [1] Reilly. Med. & Biol. Eng. & Comput. 1989;27:101ff, [2] Carnevale, et al, M.L. The NEURON Book. Cambridge, UK: Cambridge University Press, 2006. [3], Hines et al. J Comput Neurosci. 2004 Jul-Aug;17(1):7ff, [4] Reilly et al. 2011, Electrostimulation, Theory, Applications and Computational model, Artech House, [5] Gosselin et al. 2013; http://www.itis.ethz.ch/itis-for-health/virtual-population, [6] Turk et al, Trans. On Biom. Eng. 2012; 59:2845ff, [7] So et al, Trans. Biom. Eng 2004:51 1907ff