Numerical Evaluation of Miniaturized Coils for Focal Magnetic Stimulation

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Peripheral magnetic stimulation (PMS) is emerging as an alternative to standard electrical stimulation of the peripheral nervous system, due to its ability to affect sensory and motor transmission, without the discomforting pain sensation typical of electrical stimulation. Despite the great potential of PMS, the use of large stimulators, typical of transcranial magnetic stimulation, such as the figure-of-eight or the circular coils, prevent its application on smaller, superficial nerves, thus reducing PMS range of application. To scale the dimension of large magnetic stimulators is not straightforward and can have several drawbacks, such as the need of large currents that would produce an excessive amount of heat, by Joule effect, and large magnetic forces that are not tolerated by conventional wires. To this regard, we proposed an alternative strategy to conventional copper wires that is the use of adhesiveness copper-clad coated polyimide film technology, that allows to obtain coils with reduced diameter and a high number of turns (>100) [1]. For instance, with an overall length of the flex substrate of approximately 3 m, it is possible to obtain a miniaturized coil (i.e., mcoil) with a 15 mm diameter and 123 turns. To maximize the performances of a coil miniaturized in such a way, a multilayer structure could be recommended. Hence, in this study we numerically evaluated the optimal geometry to achieve peripheral nerve stimulation, and we performed an intersubject variability study to predict changes in the coil stimulation ability when applied to subjects with different anatomies. Numerical simulations were performed using the electromagnetic (EM) simulation software Sim4Life (v. 5, Zurich MedTech, AG). The copper trace deposited over the flexible substrate can be modeled as planar loop wound up 123 turns. The effect of adding more layers was studied by investigating a two-layered and four-layered single circular mcoil. Furthermore, to improve the coil focality, a figure-of-eight configuration was tested by coupling two circular four-layered mcoils, fed in counter-phase. The mcoils were placed over the radial nerve of the neurofunctionalized female model Yoon-Sun (Virtual Population, ViP. 4.0 [2]). The orientation of the induced electric (E-)field with respect to the nerve was studied (i.e., E_{tan}). The mcoil with the maximum E_{tan} was considered optimal and able to attain stimulation of the target nerve. The optimal mcoil model was then employed to conduct the dosimetry and neuronal-dynamics study over the Yoon-Sun model and Jeduk model [2]. The two models differ in terms of wrist diameter (6 cm vs 8 cm) and location of the radial nerve (3 mm vs 8 mm). Electromagnetic properties of the tissues were assigned from the LF IT'IS Database. The EM simulations were computed using the Low Frequency (LF) Magneto-Quasi static solver, feeding the coils with 70 A and 1.9 kHz. Results showed that the presence of two extra copper layers increased E_{tan} peak by 50%. Whereas the figure-of-eight mcoil was able to induce a peak E_{tan} more than triplicated in intensity (i.e., 38 V/m), with the same feeding conditions as the two circular mcoils. Hence, the figure-of-eight mcoil was considered potentially optimal to achieve stimulation of the radial nerve and was tested in NEURON to estimate the current required to attain stimulation of the radial nerve (i.e., the nerve stimulation threshold) on two different neurofunctionalized models (i.e., Yoon-Sun and Jeduk). The anatomical differences between the two models translated in different stimulation thresholds. For the Yoon-Sun model the stimulation threshold was 58 A, conversely, 73 A was estimated for Jeduk. Consequently, the figure-of-eight mcoil fed at 70 A could elicit action potentials in the radial nerve of the Yoon-Sun model, but not in the Jeduk model. Nevertheless, it would require only an increase of 5% in the feeding current to stimulate a nerve located 5 mm deeper inside the arm. Hence, this miniaturization process is effective for a focal stimulation of peripheral superficial nerves, without affecting the surrounding excitable tissues.

References

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