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Modeling the SIGMA-Eye Applicator for Hyperthermia via Multiple Infinitesimal Dipoles

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Over the past several decades, cancer is still one of the leading causes of human deaths. Hyperthermia treatment, which is mostly performed in clinic as an assistant therapy method combined with chemotherapy or radiation therapy, has been also playing a more and more important role in tumor therapy. Driven by the developments of computing power and computational techniques, personalized hyperthermia treatment planning (HTP) is becoming possible and essential for clinical practice, aimed at achieving maximum treatment effects for tumor targets and minimal side effects for the surrounding tissues simultaneously. As an essential step of Electromagnetic Hyperthermia Treatment Planning, electromagnetic simulation with the phased-array applicator, SIGMA-Eye hyperthermia applicator, was explored.
The approach of the basic-building-block-based modified Infinitesimal Dipole Model (IDM) as a virtual source model was developed and used for modeling the hyperthermia SIGMA-Eye applicator (BSD Medical Corporation) in this work. The basic idea of the IDM is to replace the antenna with a series of infinitesimal dipoles which generates the same electric field as the antenna does. On the basis of the conventional IDM, a modified IDM is proposed, in which number and locations of dipoles are predefined. The reduced set of dipole parameters leads to a simpler objective function of the modified IDM in comparison to the conventional IDM concerning parameter fitting. In addition, the concept of a ‘basic building block’ is introduced: the antenna under test (active antenna) and its neighboring antenna elements (passive antennas) are considered as a basic building block. The dipole model of the antenna under test will be fit by approximating the electric field of the block in order to correctly treat the mutual coupling between antenna elements. Therefore, electric fields generated by a phased-array applicator (with significant mutual coupling between elements) can be modeled.
In this work, each antenna of the SIGMA-Eye applicator was modelled using the basic-building-block-based modified IDM. Taking the electric field data of the basic building block computed from the software COMSOL Multiphysics as reference, the global optimization algorithm OQNLP (OptQuest Nonlinear Programming) was used for parameter fitting of the dipole models. And then the SIGMA-Eye applicator was simulated by the superposition of each simulated antenna.
Electromagnetic simulations with different phase combinations of the antenna elements of the applicator were performed. The resulted electromagnetic energy deposition patterns were compared to the measurement data presented in the reference paper, where the electric field measurement within the phantom placed inside the SIGMA-Eye applicator was performed. The relative differences of energy deposition patterns ranged from 1.40% to 17.90% with an average at 5.07%. The agreement of energy deposition patterns between simulation data and measurement data justified the applicability of our virtual source model to hyperthermia forward planning and further to the commissioning of new systems. In addition, the frequency dependence and water-bolus permittivity and conductivity dependence of the block-based modified IDM was explored, and it was found that this approach is applicable for a narrow-band frequency, and is adaptable to the uncertainty of the water-bolus permittivity and conductivity. When operating at a frequency further away from the reference frequency, or the surrounding environment of the antennas changes a lot, the applicator needs to be simulated using a new equivalent model.