Electromagnetic Analysis of Active Implantable Medical Devices During MRI Exposure Using a Schur-Complement Integral-Equation Method

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Computational methods are becoming increasingly more important for assessing the safety of patients with implanted medical devices under MRI exposure. The technical specification ISO/TS10974 defines four tiers to classify the methods used to evaluate the tissue heating hazard of active implantable medical devices (AIMDs) during MRI exposure. The higher tiers yield more accurate results with lower overestimation but require development and validation of implant models, their integration into anatomically accurate body models along different trajectories, and the evaluation of energy deposition for all relevant exposure conditions (E. Cabot et al., Bioelectromagnetics, Feb. 2013)—a difficult undertaking. This article presents a multi-region integral-equation method to efficiently obtain tier-4 results.

To demonstrate the proposed method, a generic AIMD is modeled inside the AustinMan and AustinWoman anatomical body models (J. W. Massey and A. E. Yılmaz, 38th Annu. Int. Conf. IEEE Eng. Med. Biol. Soc., Aug. 2016) placed inside an MRI birdcage coil. An equivalent surface is introduced to separate the AIMD (present in the internal equivalent problem) and the body (present in the external equivalent problem, which also includes the MRI coil model); thus, the AIMD and body/coil models can be developed separately and, importantly, their meshes are not required to be conformal. Surface and volume electric-field integral equations are formulated in each equivalent problem and these equations are fully coupled using the recipe in (J. W. Massey et al., USNC/URSI Rad. Sci. Meet., July 2015). To satisfy the tier-4 specifications, the proposed method must be able to (i) simulate realistic anatomical models, which can be comprised of over 100 million voxels, (ii) avoid poor conditioning that arises from surface integral equations enforced on PEC surfaces, and (iii) efficiently analyze AIMDs placed in multiple locations and multiple human-MRI coil models.

The first two requirements are addressed using an FFT-accelerated iterative solver (J. W. Massey and A. E. Yılmaz, URSI Nat. Rad. Sci. Meet., Jan. 2016) and either full-inverse surface-preconditioning (J. W. Massey et al., European Conf. Antennas Propag., Apr. 2016) or a Schur-complement approach (J. W. Massey et al., USNC/URSI Rad. Sci. Meet., June 2016). The third requirement is best met, however, by the Schur-complement technique applied to the internal-equivalent problem. In this approach, the solution to the internal-equivalent problem is computed once and then used as a transfer function from the equivalent surface back to the equivalent surface in the presence of the AIMD. Then, the external problem is solved using hybrid surface-volume adaptive integral method with full-inverse surface preconditioning.