

Low or Medium Frequency Magnetic Fields Simplified by Modeling of Implanted Medical Devices

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Abstract

When exposed to time-varying magnetic fields, such as those generated during certain diagnostic and therapeutic biomedical treatments, implanted medical devices with metallic filamentary closed loops (such as fixation grids, stents) produce electric currents. For low or medium frequency fields, a simplified method for efficiently computing these currents, estimating the altered electromagnetic field distribution in biological tissues, and evaluating the resulting biological effects is proposed. Decoupling the handling of the filamentary wire from the anatomical body is the foundation of the proposed method. In order to accomplish this, a circuital solution is used to investigate the metallic filamentary implant and is inserted into an electromagnetic field solution that involves biological tissues. The implant's calculated Joule losses are then utilized as a forcing term for the bioheat Pennes' equation-defined thermal problem. A reference solution to a model problem is used to validate the methodology. In realistic exposure scenarios, the proposed simplified methodology is found to be sufficiently accurate and simple to apply to closed loop wires in the low to intermediate frequency range. Analyzing a wide range of exposure scenarios for various types of small implants, including orthopedic grids and coronary and biliary stents, is made possible by this modeling tool.

Keywords: In silico modeling; Metallic implants; Magnetic hyperthermia; Magnetic resonance imaging

Introduction

In silico models are a powerful tool that are largely used to analyze the interaction between humans and electromagnetic fields (EMFs), with the primary goal of determining whether technologies are safe and how well they work. The population-based study of interactions with implanted medical devices has received significant attention in recent years. Metallic substances that are present in the body have the ability to either alter the induced electric field, which can result in peripheral nerve stimulation or increase power deposition, which can cause temperature increases in native tissues [1-3]. Biomedical technologies that use EMFs for diagnostic or therapeutic purposes, such as Magnetic Resonance Imaging (MRI), Magnetic Hyperthermia (MH), and Transcranial Magnetic Stimulation (TMS), account for a significant portion of the possible exposure scenarios.

The risk of implant-bearing patients being exposed during MRI scanning has been the subject of extensive research. Specific consideration has been paid to dynamic implantable clinical gadgets (AIMD) (e.g., heart defibrillators and Profound Cerebrum Triggers, DBS, yet additionally uninvolved inserts (e.g., obsession lattices, stents) were concentrated on lately. Biomedical technologies in development also utilized in silico models to identify potential exclusion criteria for implant-carrying patients [4]. In the presence of implants, it is possible to investigate the interaction between EMFs and anatomical models using potent computational methods that are frequently backed up by commercial software. Regardless, investigations stay a test because of explicit mathematical or useful qualities of the electromagnetic issue, similar to the instance of embedded gadgets including metallic fibers.

A pulse generator in AIMD is connected to the local electrodes by metallic wires. However, structures made of thin wires can also be found in passive implants, such as the metallic stents used to enlarge vessels or ducts or the metallic grids used in Orthopedics to fix bone fractures. The use of voxelized anatomical models, whose elements typically have a size of 1 mm, is difficult due to the extremely small diameter of the wires (down to 0.1 mm or less). Indeed, a voxel size suitable for replicating the wire geometry would significantly increase

the electromagnetic simulations' computational burden [5-7]. In this scenario, non-structured meshes might be used, as in studies of the local Specific Absorption Rate (SAR) deposition caused by DBS electrodes or cardiac leads caused by MRI radiofrequency fields. However, the quality of the mesh remains a problem and the pre-processing phase necessary to discretize the anatomical models may be critical when implants have a complicated shape.

The Huygens approach is frequently used in the literature to decompose the problem into two subsequent simulations in order to preserve a voxel-based discretization. The first one uses a rough mesh to simulate the entire anatomical model without the metallic wires and serves as the boundary conditions for the subsequent simulation, which discretizes only a portion of the original domain around the wire. For instance, in helical structures in DBS were handled with a mesh size of 0.05 mm or less. In order to reduce the likelihood of making mistakes when evaluating the electric field at the electrode tip, the reciprocity theorem and the Huygens principle were also applied in. Introduce a surrogate model for the device as an alternative to meshing the filamentary structure with the anatomical model [8]. A transfer function, which links the incident electric field's tangential component to the scattered electric field at its tip, is commonly used to describe elongated wires in RF. It was also suggested to extend to short wires. Combining the implant's experimental characterization with simulations is possible with this implant-specific method.

Along the structure's axis, a 10 mT spatially uniform magnetic flux density was applied at a frequency of 10 kHz to 10 MHz. It is

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important to note that the characteristics of this model problem enable us to increase the frequency above the normal limit of the proposed method's applicability. The induced current density will always be perpendicular to any longitudinal plane containing the cylinder axis precisely because the problem has axial symmetry. As a result, the geometric confinement of the metal within which the loop wires induce currents is required by the assumptions of the elementary approach [9]. Without referring to any particular application, it was possible to test the elementary model under conditions ranging from a weak to a relevant reaction field by expanding the comparison to 10 MHz. By comparing the 2D FEM model and CST results for the total power dissipated in the native tissues, the currents induced in the wires, and the magnetic flux density amplitude in the center of the domain, the proposed electromagnetic solution was found to be correct.

The quantitative evaluation of the phenomena induced both within the metallic wires and in the surrounding tissues demonstrates that the proposed elementary approach (shown as 3D-1 in the tables) is in good agreement with the 2D and CST solvers. Due to numerical errors in computing the reaction field close to the wires, the effects of the reaction field cause the error to increase with frequency. The number of segment N_s used to discretize the wire also has a small impact on the error. In comparison to the 2D solution, the current amplitude error was never greater than 3%. An estimate of the power lost in wires and an estimate of the power lost in tissues are both within 5% and 10% of each other due to this result. The latter error, on the other hand, is caused by the use of a voxel-based structured mesh to discretize the computational domain rather than the proposed method [10]. Because the error is kept in the same order of magnitude as the computed Joule losses in the wires, the testing on thermal solutions suggests that the approximation used to distribute the dissipated power within the voxels is adequate due to an error of less than 5% in the temperature increase in tissues. In addition, it indicates that, in comparison to the Joule losses in the wires, the power directly deposited in the tissues, where the error is greater due to the voxel structure, is negligible. The temperature trends estimated by Voxel-3D and FEM2D-p3D are also consistent, as shown further supporting the previous analysis.

Conclusion

The presence of looped metallic wire implants in anatomical human models necessitated the development of a simplified method

specifically for this purpose. Comparing the results on a test model with a commercial 3D software and a 2D axisymmetric FEM solver (used as a reference) revealed good accuracy in spite of the procedure's approximations (average errors in current amplitudes induced in the wires around 2.5% up to 1 MHz, which results in errors less than 5% in terms of power released in the metallic components and 10% in power density in tissues). In addition, comparable or even superior computational time is found for the commercial software under consideration in relation to the test problem.

Declaration of Competing Interest

The authors declare that they have no conflict of interest.

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