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Influence of a Metallic Shield on RF-Induced Heating of a Lead with Straight and Helical Wires

Mikhail Kozlov
Max Plank Inst. for Human Cognitive and
Brain Sciences
Leipzig, Germany
kozlov@cbs.mpg.de

Wolfgang Kainz
U.S. FDA
Silver Spring, MD, USA
wolfgang.kainz@fda.hhs.gov

Luca Daniel
Massachusetts Institute of Technology
Cambridge, MA, USA
luca@mit.edu

Abstract—We present results including a lead electromagnetic model (LEM), power deposition, and RF-induced heating for a set of single electrode leads with straight and helical wires, as regular unshielded lead, and leads with a metallic shield. Our results were obtained numerically, employing 3D electromagnetic and thermal co-simulations at 128 MHz. We observe that the metallic shield raises the LEM calibration factor and thereby it increases the RF-induced heating of the lead with helical wires, a circumstance that previously had mostly been neglected.

Keywords— *electromagnetics, RF safety, heating, active implantable medical devices, transfer functions*

I. INTRODUCTION

Tissue damage near the lead tip of an active implantable medical device (AIMD), or near the edge of a passive implant can occur in a patient undergoing magnetic resonance imaging (MRI). This is due to tissue heating produced by radio frequency (RF) induced power deposition [1–4].

Domain decomposition is a common technique involving splitting a solution of a complex problem into a set of substantially simpler sub-tasks. For RF-induced heating, one possible domain decomposition approach consists of separating the assessment of the human RF exposure due to an MRI whole-body coil from the assessment of the AIMD RF-induced power deposition due to an incident RF field (as defined in Clause #8 Tier 3 of ISO/TS 10974:2018 [5]).

The total RF power (P) dissipated around the AIMD lead electrode can be derived integrating the volume loss density (VLD)

$$P = \int_{HSIV} (VLD_{\text{total}}(v) - VLD_{\text{backgnd}}(v)) \cdot dv \quad (1)$$

where: $VLD_{\text{total}}(v)$ considers the lead in place, while $VLD_{\text{backgnd}}(v)$ does not have the lead in place. HSIV is the hot spot integration volume. The volume loss density can be estimated using $\sigma |E(v)|^2$, where σ is electrical conductivity of the surrounding medium and E is the electrical field.

The net temperature increase (ΔT_p) as well as P , can also be estimated using the lead electromagnetic model (LEM) as defined in ISO/TS 10974:2018 [5]

$$\Delta T_p = A_{Tp} \cdot \left| \int_0^L S(l) \cdot E_{\text{tan}}(l) \cdot dl \right|^2, \quad (2)$$

$$P = A \cdot \left| \int_0^L S(l) \cdot E_{\text{tan}}(l) \cdot dl \right|^2 \quad (3)$$

where: A_{Tp} and A are the calibration factors of the LEM for P and ΔT_p , respectively, $S(l)$ is the transfer function (TF), $E_{\text{tan}}(l)$ is an incident tangential electric field along the AIMD lead trajectory, and L is the lead length.

Recently, [6] proposed using a metallic shield around the lead to reduce the RF-induced heating. In that approach, the metallic shield was in direct contact with the surrounding media, a situation that could generate bio-compatibility issues for real world leads, because usually an AIMD lead is coated by an insulator material in order to avoid bio-compatibility issues.

The main goals of our study were: (i) to evaluate the influence of the metallic shield on P , ΔT_p , and on the LEM for different lead properties; (ii) to evaluate the consequences of a shield that was with, or without contact to the surrounding medium in close proximity to the center electrode.

II. METHODS AND PROCEDURES

Our set of twelve generic leads was formed by leads with straight and helical titanium alloy wires, with and without a titanium alloy shield. The length of the leads was 320 mm. The tip electrode diameter was 0.25 mm with a length of 10 mm. The diameter of the unshielded lead insulation was 1.46 mm. The straight wire diameter was 0.73 mm. A helical structure was a 0.1 mm $\times$ 0.1 mm rectangular wire with a pitch of 0.35 mm and with an external diameter of 0.9 mm (Fig. 1a-b). The proximal lead end was capped with an insulator.

The shield and shield insulator outer diameters were 1.56 mm and 2.5 mm, respectively. An area to provide an electrical contact between shield and surrounding medium was located 3 mm away from the electrode and was 3 mm in length (Fig. 1c). The impedance between the inner wire and the external metallic shield was defined as infinite. When evaluating the shielded lead without medium contact to the shield, the contact area was covered by an insulator.

Values of relative permittivity (ϵ_r) of the insulators were 2.7 and 5.5, respectively. The electric conductivity of the titanium alloy was $\sigma = 595238$ S/m, specific heat $C_p = 526.3$ J/kg/K, isotropic thermal conductivity $k = 6.7$ W/m/K, and density $\rho = 4430$ kg/m³. The insulation material has $\sigma = 24$ μ S/m, $\epsilon_r = 2.7$, $C_p = 1000$ J/kg/K, $k = 0.2$ W/m/K, and $\rho = 1350$ kg/m³.

The leads were positioned parallel to the Z axis in the middle of a box (600 mm $\times$ 400 mm $\times$ 2400 mm) surrounded by a perfectly matched layer (PML). The box was filled by a

medium with electrical properties similar to blood at 128 MHz, namely $\epsilon_r = 78$ and $\sigma = 1.2$ S/m, and thermal properties: $C_p = 4181$ J/kg/K, $k = 0.6$ W/m/K, and $\rho = 1001$ kg/m³ (Fig. 1d).

Four antennas located along one yz side of the box generated the EM field at 128 MHz as in our previous study [7]. To acquire $E_{\tan}(l)$ along the lead trajectory 3D EM simulations were done without the lead in place. The heterogeneous $E_{\tan}(l)$ was equal to the $\hat{z}$ -component of the electric field at the location of the lead.

Fig. 1. a) Close-up view of unshielded straight lead geometry. b) Close-up view of unshielded straight lead geometry. c) Close-up view of the shielded lead geometry near the electrode. d) 3D electromagnetic simulation setup.

The transfer function $S(l)$ for each lead was obtained at 161 equidistant points, using the reciprocity approach outlined in [8]. In order to enable a comparison between different cases, $S(l)$ was normalized so that $\int_0^L ||S(l)|| \cdot dl = 1$. The dissipated power P was calculated for all $E_{\tan}(l)$ with the HSIV defined in Fig. 1a and in (1), using 3D EM simulations with the leads in place. ΔT_p was analyzed for the electrode tip face (Fig. 1c) as the net temperature increase after 60 seconds of continuous excitation. The time interval of 60 second was selected in order to avoid substantial influence of the medium thermal conductivity onto the thermal results.

The calibration factors of the LEM were derived from a linear regression analysis of P and ΔT_p versus the LEM predicted results

$$LEM = \left| \int_0^L S(l) \cdot E_{\tan}(l) \cdot dl \right|^2. \quad (4)$$

The 3D EM simulations were performed at 128 MHz using ANSYS HFSS (ANSYS, Canonsburg, PA, USA). VLD and

surface loss density from our 3D EM simulations were scaled with a scaling factor so that the maximum temperature rise in the thermal domain was less than 10°C for 15 minutes of continuous excitation. The thermal simulations were performed in ANSYS Non-Linear Thermal platform (ANSYS, Canonsburg, PA, USA). For our subsequent analysis the results of the thermal simulations were scaled to the $E_{\tan}(l)$ generated in the phantom without the lead in place. The tetrahedron mesh and the solver convergence setups were the same as in our previous study [7].

III. RESULTS AND DISCUSSION

The lead center wire geometry, (i.e., straight vs. helical) affected by a noticeable factor of two the $S(l)$ of the unshielded leads (Fig. 2a-b). Instead, the $S(l)$ of the shielded lead were very similar (difference up to 10 %) to the $S(l)$ of the unshielded leads with a straight wire (Fig. 2a,c-f) with corresponding insulator ϵ_r .

Fig. 2. Amplitudes and phases of $S(l)$ for different lead geometries and insulator ϵ_r : a) unshielded straight lead, b) unshielded helical lead, c) shielded straight lead with medium contact of the shield, d) shielded helical lead with medium contact of the shield, e) shielded straight lead without medium contact of the shield, f) shielded helical lead without medium contact of the shield.

Fig. 3. The regression analysis of P versus LEM for different lead geometries and insulator ϵ_r : a) unshielded straight lead, b) unshielded helical lead, c) shielded straight lead with medium contact of the shield, d) shielded helical lead with medium contact of the shield, e) shielded straight lead without medium contact of the shield, f) shielded helical lead without medium contact of the shield.

Despite the similar $S(l)$ of the unshielded and shielded straight lead, the calibration factor A significantly depends on the electrical contact of the shield with the medium. Without electrical contact, A and P of the shielded straight lead were similar (difference up to 20% for A , and 12% for P ,

respectively) to the unshielded straight lead. The contact with the surrounding medium reduced P of shielded straight lead by a factor of 2.7 and 1.7 (Fig. 3) for an insulator ϵ_r of 2.7 and 5.5, respectively.

Fig. 4. The regression analysis of ΔT_p versus LEM for different lead geometries and insulator ϵ_r : a) unshielded straight lead, b) unshielded helical lead, c) shielded straight lead with medium contact of the shield, d) shielded helical lead with medium contact of the shield, e) shielded straight lead without medium contact of the shield, f) shielded helical lead without medium contact of the shield.

Without and with medium contact of the shield ΔT_p were significantly higher for the shielded helical lead than for unshielded helical lead (specifically, higher by a factor of 8.2 and 14 for an insulator with $\epsilon_r=2.7$ and $\epsilon_r=5.5$, respectively). For the shielded helical leads the contact with the medium reduced both the scaling factor and ΔT_p by a factor of 3.1 and 1.4 (Fig. 4) for insulator ϵ_r of 2.7 and 5.5, respectively.

We observed a different dependence of P and ΔT_p on the insulator relative permittivity ϵ_r , wire geometry, and metallic shield. For the helical lead, the metallic shield resulted in approximately one order of magnitude increase in ΔT_p (Fig. 5): a highly undesired result. For the straight lead the largest effect of the metallic shield was observed on the calibration factor, while the transfer function $S(l)$ remained practically unaltered. One would assume that a shield around a lead reduces the heating for all cases. We believe that the inconsistent behavior of the shield, (i.e., heating increase or decrease depending on the lead design) is because the shield, interacting with the lead, absorbs more energy in the case of the helical lead design. This energy cannot be properly dissipated in the small 3 mm long contact region. Further investigations are planned to assess the effect of the shield when the shield to medium contact area is increased, up to the entire length of the lead.

Our results are limited to the chosen geometries, i.e., helical and straight lead, and cannot be applied to other lead geometries. However, we could show that the shield, which should reduce the amount of energy absorbed by the lead, increases the heating for the helical lead. Therefore, any new lead geometry needs to be carefully assessed to ensure the safety of the device under all possible scan conditions.

Fig. 5. ΔT_p versus index of incident field excitation for different lead geometries and insulator $\epsilon_r = 2.7$.

Fig. 6. ΔT_p versus index of incident field excitation for different lead geometries and insulator $\epsilon_r = 5.5$.

DISCLAIMER

The mention of commercial products, their sources, or their use in connection with material reported herein is not to be construed as either an actual or suggested endorsement of such products by the Department of Health and Human Services.

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