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LETTER TO THE EDITOR

Magnetic Resonance in Medicine

RF-induced heating of metallic implants simulated as PEC: Is there something missing?

The possible heating of metallic devices implanted in the patient's body is a source of concern in MRI, discussed in many papers and standards.[1-15] Two fields may produce heating in the presence of metallic implants: gradient fields (which may deposit significant Joule losses within bulky metallic objects[16-20]) and radiofrequency (RF) fields. In the latter case, thermal effects are commonly evaluated in terms of specific absorption rate (SAR) around the implant and, sometimes, of the consequent heating.[21-28]

In most papers investigating the problem via simulations, metallic implants at RF are modeled as perfect electric conductors (PEC), forcing the electric and magnetic fields to be purely perpendicular and tangential, respectively, to the external surface of the implant, whose volume is removed from the computational domain.

As a drawback, the PEC approximation prevents from looking inside the object; thus, the simulation of the heating process misses the contribution coming from the power deposited by the field in the metallic volume. Moreover, when metallic implants are not described as PEC, but discretized into elements whose size is larger than the penetration depth (as done, for instance, in Refs. 24,27-28), the computation of the Joule losses deposited inside them cannot be considered as accurate, because the adopted mesh is unsuited to reconstruct the internal field pattern.

Many appliances exploit medium frequency magnetic fields to heat/anneal/melt metallic objects by direct dissipation of energy inside them.[29-30] In addition, for a given amplitude of the incident field, analytical solutions show a monotonic increase of the power deposited inside conductors as the frequency increases.[18] Hence, a curiosity about the amount of heating directly produced inside metallic implants by the MRI RF fields seems to be justified. To settle the question, we propose to combine the Surface Impedance Boundary Conditions (SIBC) and the Poynting vector. For good conductors at RF, the SIBC allow avoiding the extremely tiny discretization required to obtain a proper description of the field distribution within metallic objects, where the penetration depth (on the order of some tens of micrometers, at typical Larmor frequencies of MRI) would lead to very heavy computational burdens. At the same time, the SIBC provide the correct distribution of the electromagnetic field over the surface of the object.[31-36] Therefore, this distribution can be used to compute the complex Poynting vector, whose real part allows quantifying the amount of power locally deposited in a thin layer corresponding to the field penetration. The procedure, realized by us through the software COMSOL Multiphysics, has been validated by comparison with the analytical calculation of the power deposited inside a metallic sphere exposed to a homogeneous RF magnetic field,[18] obtaining an excellent agreement (discrepancy < 0.2%). Figure 1A shows such a power and compares it to Finite Element (FE) solutions, for different resolutions. As reported, FE solutions converge to the reference value, but are not accurate until the resolution approaches the penetration depth. Moreover, the convergence may be non-monotonic.

Once validated, the proposed procedure has been applied to a realistic CoCrMo hip prosthesis (conductivity: 1.26 MS/m) embedded in a cylindrical phantom (with the properties defined in Ref. 12) exposed to the field of a birdcage working in circular polarization at 128 MHz (Figure 1B). The results have been scaled to get a partial-body SAR equal to the limit recommended in Ref. 11 for normal operating mode. Finally, thermal simulations have been performed using as driving terms, separately, the SAR around the implant and the power deposited inside it (see Figure 1C). After 6 minutes of exposure, the maximum heating (occurring at the tip of the stem, where, without the implant, SAR would have produced a heating around 0.25 K) was about 1 K. Less than 1% of this temperature elevation was due to the power deposited inside the prosthesis. The relative contribution to the heating due to the internal power reached a maximum of about 15% near the center of the stem, where the absolute temperature was much lower (<0.1 K), anyway. The test was repeated for a long femoral nail (length: 240 mm, diameter: 9 mm) in longitudinal position. After 6 minutes, the maximum heating (at the tip of the nail) was about 0.9 K and the contribution due to the internal power was lower than 1%. This confirms that the

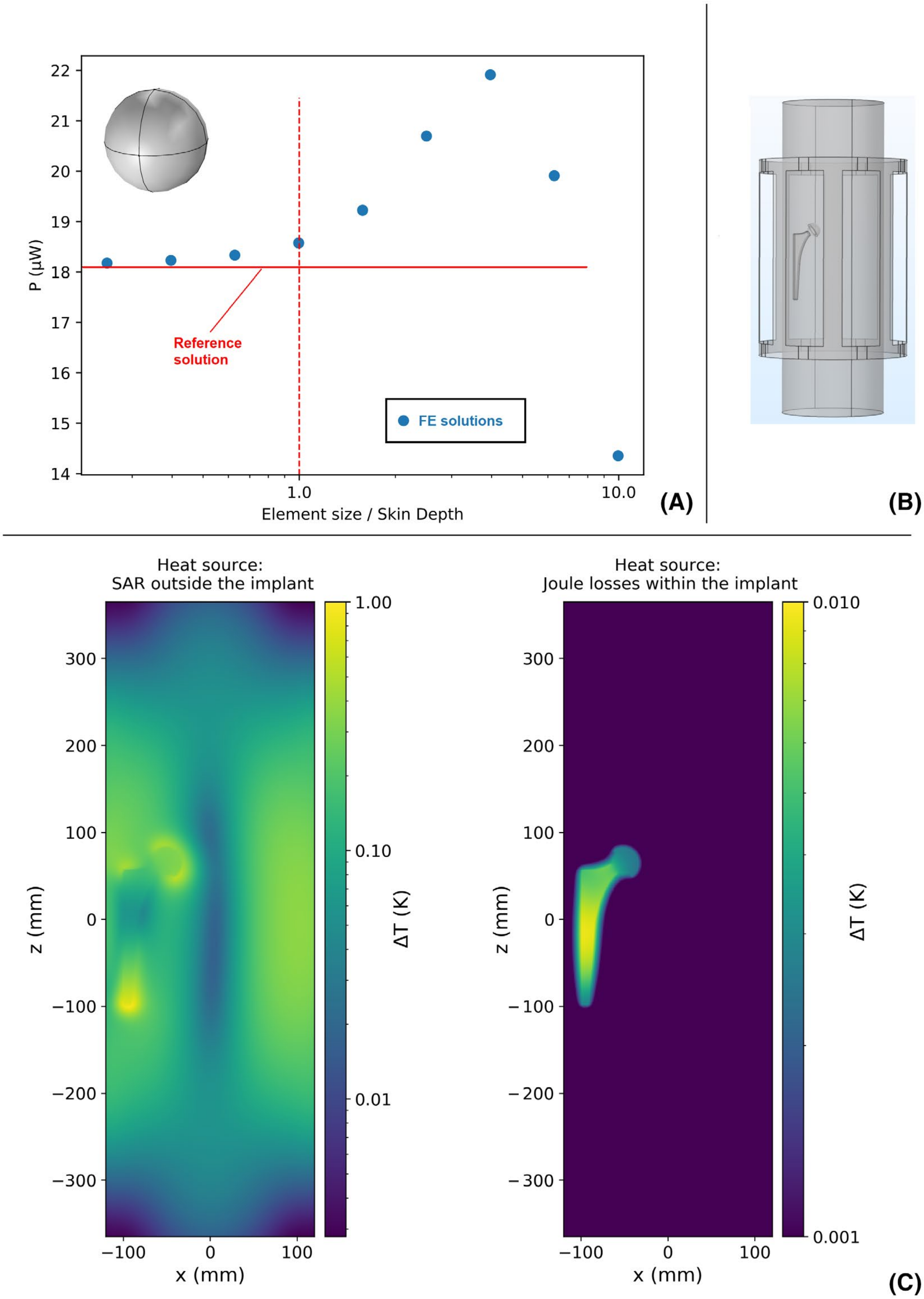

FIGURE 1 RF-induced heating of CoCrMo objects at 128 MHz, where the penetration depth is ~40 μm: A, Joule losses induced in a sphere (radius: 1 cm; applied magnetic flux density: 1.2 μT), computed with the proposed approach based on the SIBC and Poynting vector (red horizontal line) and with a Finite Element solver for different values of the element size (blue dots); B, scheme of the analyzed hip implant embedded in a gel phantom, radiated by a birdcage antenna; C, maps comparing the temperature increases of the hip implant continuously radiated for 6 min, using as heat source the SAR around the implant itself or the Joule losses deposited within it.

heating due to Joule losses within the implant at RF is negligible. Hence, on a practical side, PEC models are acceptable, as are previous results based on discretizations larger than the penetration depth.

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