LETTER TO THE EDITOR

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The Underestimated Role of Gradient Coils in MRI Safety

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MRI scanning of patients carrying implants is becoming a reality in many hospitals, because of the wide increase of population with implants, particularly in the orthopedic ones (1). The responsibility for this practice falls on the subscribing physicians or radiologists, who rely on guidance establishing safety and compatibility of implants in the MR environment (eg, (2)), which basically address issues related to magnetically induced mechanical actions and radiofrequency (RF) induced heating of tissues. Even if large-scale MR safety studies on orthopedic implants have been published that show no evidence of specific risks for patients' health (eg, (3)), additional analyses of the interaction between MR fields and metallic implants can contribute to support the scan decision on a firm scientific rationale.

In a recent paper (4), we showed that the tissues surrounding a metallic hip prosthesis exposed to a gradient field (GF) may undergo a nonnegligible heating (up to some degree), as a result of the electromagnetic energy deposited in the implant. Since then, we have realized that in the MR community these results are generally received with some skepticism, probably because of the fact that most of the scientific papers dealing with thermal problems in MRI focus on RF fields (5–16). Similarly, the attention of relevant standardization and regulatory bodies is focused solely on RF-induced heating (2,17). This tendency is absolutely well-grounded when studying native tissues, where GFs are not able to develop significant thermal effects. However, in the presence of metallic foreign bodies the situation is different.

Many papers show that a significant heating can be associated with the exposure of such bodies to RF fields, especially with wire-like structures, which may act as antennas (18–30). In this case, RF typically deposits a relatively low power inside the metallic parts, but their presence may cause the enhancement of the specific absorption rate directly developed in the tissues anyway. What we would like to highlight here is that, in presence of bulky metallic prostheses, GFs can produce a nonnegligible heating too, because of the thermal power generated inside the metal (Joule effect), which involves the tissues indirectly, by diffusion ("indirect effect" (31)). The GF thermal effect, which becomes sizable only for prostheses far from the coils' isocenter, has been considered up until now by a few articles (4,32–34). To sustain these findings, we exploit an analytical solution (35) that is not affected by possible artifacts of numerical results. The solution provides the current density J (in complex notation) induced within a nonmagnetic metallic sphere, with radius R, conductivity σ and permeability μ_0, immersed in a nonconductive background. When the sphere is radiated by a homogeneous, time-harmonic, magnetic flux density B (peak value) at frequency f, the current density in an internal point is

$$J = \frac{B}{\mu_0}\frac{3k^2R}{2\sin(kR)}\left[\frac{\sin(kr)}{(kr)^2} - \frac{\cos(kr)}{kr}\right]\sin\theta \quad [1]$$

with

$$k = \sqrt{-j2\pi f \mu_0 \sigma} = \frac{\sqrt{-2j}}{\delta} \quad [2]$$

where r is the distance from the sphere center, θ is the colatitude measured from the sphere diameter parallel to the magnetic field, δ is the penetration depth, and $j^2 = -1$. The current density is azimuthal everywhere.

This solution is used to simulate the effect of GFs, considering that they are approximately homogeneous in correspondence to the quite small volume taken up by the sphere (which is placed away from the coils' isocenter). The total Joule losses (P) are obtained by integration of the power density $|J|^2/(2\sigma)$ over the sphere and therefore scale as B^2; in contrast, for a given B amplitude, it can be proved that P increases monotonically with frequency.

The same solution turns out to be useful also for simulating a homogeneous rotating RF field (like that of birdcage antennas around the system isocenter), decomposable into two time-harmonic fields, with a 90° shift both in phase and geometrical disposition. The total current density is obtained by superposing the two corresponding contributions given by (1) (taking into account their direction and phase). For the rotating field, P is double than that given by a single oscillating field (with the same frequency and amplitude).

Table 1 indicates the power developed in spheres of different radii, considering two conductivity values close to those of typical alloys adopted for prostheses (eg, 0.58 MS/m for Ti-6Al-4V). The results refer to a GF of 6 mT (eg, the dominant longitudinal component produced by a 30 mT/m gradient, at 0.2 m from the coils' isocenter) at 100 Hz or 1 kHz (the most significant harmonic components of many real sequences fall within this range) and a RF rotating field of 10 μT at 64 or 128 MHz.

As can be seen, in some cases GFs give rise to power values higher than, or at least comparable to, those resulting

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Table 1
Total Joule Losses P (in watt) Developed within the Sphere

	Gradient field (6 mT)				RF field (10 μT)			
	$f = 100$ Hz		$f = 1$ kHz		$f = 64$ MHz		$f = 128$ MHz	
R (mm)	$\sigma = 10^6$ S/m ($\delta = 50.3$ mm)	$\sigma = 10^5$ S/m ($\delta = 159$ mm)	$\sigma = 10^6$ S/m ($\delta = 15.9$ mm)	$\sigma = 10^5$ S/m ($\delta = 50.3$ mm)	$\sigma = 10^6$ S/m ($\delta = 62.9$ μm)	$\sigma = 10^5$ S/m ($\delta = 199$ μm)	$\sigma = 10^6$ S/m ($\delta = 44.5$ μm)	$\sigma = 10^5$ S/m ($\delta = 141$ μm)
40	$3.00 \cdot 10^{-1}$	$3.05 \cdot 10^{-2}$	12.8	3.00	$3.03 \cdot 10^{-2}$	$9.50 \cdot 10^{-2}$	$4.30 \cdot 10^{-2}$	$1.35 \cdot 10^{-1}$
20	$9.52 \cdot 10^{-3}$	$9.53 \cdot 10^{-4}$	$8.70 \cdot 10^{-1}$	$9.52 \cdot 10^{-2}$	$7.55 \cdot 10^{-3}$	$2.40 \cdot 10^{-2}$	$1.07 \cdot 10^{-2}$	$3.36 \cdot 10^{-2}$
10	$2.98 \cdot 10^{-4}$	$2.98 \cdot 10^{-5}$	$2.96 \cdot 10^{-2}$	$2.98 \cdot 10^{-3}$	$1.90 \cdot 10^{-3}$	$5.90 \cdot 10^{-3}$	$2.67 \cdot 10^{-3}$	$8.35 \cdot 10^{-3}$
5	$9.30 \cdot 10^{-6}$	$9.30 \cdot 10^{-7}$	$9.30 \cdot 10^{-4}$	$9.30 \cdot 10^{-5}$	$4.70 \cdot 10^{-4}$	$1.40 \cdot 10^{-3}$	$6.63 \cdot 10^{-4}$	$2.06 \cdot 10^{-3}$

from RF (in particular for bulky prostheses). This happens because B is much lower for RF fields than for GFs. Note that, at RF, P is higher when the implant is less conductive, and vice versa for GFs. The case $R = 20$ mm is representative for the femoral head of a hip prosthesis, whose P at 1 kHz is similar to that found in previous realistic simulations (4,36), in which nonnegligible heating was predicted (4). Because the duty cycle of GFs is typically higher than that of RF fields, their contribution would appear even more significant in terms of energy.

In conclusion, these findings may contribute to the theoretical understanding of induced heating in metallic implants, demonstrating that GFs can provide a measurable effect, particularly when the implant is at some distance from the coil's isocenter, also in light of the tendency of designing higher and higher gradient-strength systems.

REFERENCES

1. Agency for Healthcare Research and Quality. HCUPnet, Healthcare Cost and Utilization Project. 1.usa.gov/1lVlwCW. Accessed July 29, 2013.
2. U.S. Food and Drug Administration. Establishing safety and compatibility of passive implants in the magnetic resonance (MR) environment. http://www.fda.gov/downloads/medicaldevices/deviceregulationandguidance/guidancedocuments/ucm107708.pdf. Accessed December 11, 2014.
3. Koff MF, Parina S, Hollis GP. Clinical implementation of MRI of joint arthroplasty. Am J Roentgenol 2014;203(1):154–161.
4. Zilberti L, Bottauscio O, Chiampi M, et al. Numerical prediction of temperature elevation induced around metallic hip prostheses by traditional, split, and uniplanar gradient coils. Magn Reson Med 2015;74:272–279.
5. Murbach M, Neufeld E, Samaras T, Córcoles J, Robb FJ, Kainz W, Kuster N. Pregnant women models analyzed for RF exposure and temperature increase in 3T RF shimmed birdcages. Magn Reson Med 2016. doi:10.1002/mrm.26268.
6. Dharmadhikari S, James JR, Nyenhuis J, Bansal N. Evaluation of radiofrequency safety by high temperature resolution MR thermometry using a paramagnetic lanthanide complex. Magn Reson Med 2016; 75:2121–2129.
7. Kraff O, Ladd ME. MR safety update 2015: where do the risks come from? Curr Radiol Rep 2016;4:34.
8. Griffin GH, Anderson KJT, Celik H, Wright GA. Safely assessing radiofrequency heating potential of conductive devices using image-based current measurements. Magn Reson Med 2015;73:427–441.
9. Graedel NN, Polimeni JR, Guerin B, Gagoski B, Wald LL. An anatomically realistic temperature phantom for radiofrequency heating measurements. Magn Reson Med 2015;73:442–450.
10. Hartwig V. Engineering for safety assurance in MRI: analytical, numerical and experimental dosimetry. Magn Reson Imaging 2015; 33:681–689.
11. Powell J, Papadaki A, Hand J, Hart A, McRobbie D. Numerical simulation of SAR induced around Co-Cr-Mo hip prostheses in situ exposed to RF fields associated with 1.5 and 3 T MRI body coils. Magn Reson Med 2012;68:960–968.
12. Collins CM, Wang Z. Calculation of radiofrequency electromagnetic fields and their effects in MRI of human subjects. Magn Reson Med 2011;65:1470–1482.
13. Kumar R, Lerski RA, Gandy S, Clift BA, Abboud RJ. Safety of orthopedic implants in magnetic resonance imaging: an experimental verification. Orthop Res 2006;24:1799–1802.
14. Nyenhuis JA, Park SM, Kamondetdacha R, Amjad A, Shellock FG, Rezai AR. MRI and implanted medical devices: basic interactions with an emphasis on heating. IEEE Trans Device Mater Reliab 2005; 5:467–480.
15. Ho HS. Safety of metallic implants in magnetic resonance imaging. J Magn Reson Imaging 2001;14:472–477.
16. Guidelines to prevent excessive heating and burns associated with magnetic resonance procedures. http://www.mrisafety.com/SafetyInfov.asp?SafetyInfoID=166. Accessed August 1, 2016.
17. ASTM. Standard test method for measurement of radio frequency induced heating on or near passive implants during magnetic resonance imaging. ASTM F2182 – 11a, 2011.
18. Eryaman Y, Turk EA, Oto C, Algin O, Atalar E. Reduction of the radiofrequency heating of metallic devices using a dual-drive birdcage coil. Magn Reson Med 2013;69:845–852.
19. Gorny KR, Presti MF, Goerss SJ, et al. Measurements of RF heating during 3.0-TMRI of a pig implanted with deep brain stimulator. Magn Reson Imaging 2013;31:783–788.
20. Iacono MI, Makris N, Mainardi L, Angelone LM, Bonmassar G. MRI-based Multiscale model for electromagnetic analysis in the human head with implanted DBS. Comput Math Method Med 2013;694171.
21. Liu Y, Chen J, Shellock FG, Kainz W. Computational and experimental studies of an orthopedic implant: MRI-related heating at 1.5-T/64-MHz and 3-T/128-MHz. J Magn Reson Imaging 2013;37:491–497.
22. Liu Y, Shen J, Kainz W, Qian S, Wu W, Chen J. Numerical investigations of MRI RF field induced heating for external fixation devices. Biomed Eng Online 2013;12:12.
23. Elwassif MM, Datta A, Rahman A, Bikson M. Temperature control at DBS electrodes using a heat sink: experimentally validated FEM model of DBS lead architecture. J Neural Eng 2012;9:046009.
24. Gill A, Shellock FG. Assessment of MRI issues at 3-Tesla for metallic surgical implants: findings applied to 61 additional skin closure staples and vessel ligation clips. J Cardiov Magn Reson 2012;14:3.
25. Mohsin SA, Nyenhuis J, Masood R. Interaction of medical implants with the MRI electromagnetic fields. Progress Electromagn Res C 2010;13:195–202.
26. Neufeld E, Kuhn S, Szekely G, Kuster N. Measurement, simulation and uncertainty assessment of implant heating during MRI. Phys Med Biol 2009;54:4151–4169.
27. Mattei E, Triventi M, Calcagnini G, Censi F, Kainz W, Mendoza G, Bassen HI, Bartolini P. Complexity of MRI induced heating on metallic leads: experimental measurements of 374 configurations. Biomed Eng Online 2008;7:11.
28. Pisa S, Calcagnini G, Cavagnaro M, Piuzzi E, Mattei E, Bernardi P. A study of the interaction between implanted pacemakers and the radio-frequency field produced by magnetic resonance imaging apparatus. IEEE Trans Electromagn C 2008;50:35–41.
29. Gray RW, Bibens WT, Shellock FG. Simple design changes to wires to substantially reduce MRI-induced heating at 1.5 T: implications for implanted leads. Magn Reson Imaging 2005;23:887–891.
30. Baker KB, Tkach JA, Nyenhuis JA, Phillips M, Shellock FG, Gonzalez-Martinez J, Rezai AR. Evaluation of specific absorption rate as a dosimeter of MRI-related implant heating. J Magn Reson Imaging 2004;20:315–320.

31. International Commission on Non-Ionizing Radiation Protection. Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300 GHz). Health Phys 1998;74:494–522.
32. Zilberti L, Bottauscio O, Chiampi M, Hand J, Sanchez Lopez H, Crozier S. Collateral thermal effect of MRI-LINAC gradient coils on metallic hip prostheses. IEEE Trans Magn 2014;50:5101704.
33. El Bannan K, Handler W, Chronik B, Salisbury SP. Heating of metallic rods induced by time-varying gradient fields in MRI. J Magn Reson Imaging 2013;38:411–416.
34. Graf H, Steidle G, Schick F. Heating of metallic implants and instruments induced by gradient switching in a 1.5 T whole body unit. J Magn Reson 2007;26:1328–1333.
35. Bidinosti CP, Chapple EM, Hayden ME. The sphere in a uniform RF field—revisited. Concept Magn Reson B. 2007;31B:191–202.
36. Zilberti L, Bottauscio O, Chiampi M, Hand J, Sanchez-Lopez H, Brühl R, Crozier S. Power deposition into a metallic hip prosthesis exposed to switched gradient fields. In Proceedings of the ISMRM 24th Annual Meeting and Exhibition, Singapore, 2016. Abstract 2225.