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Reduction of artifact of metallic implant in magnetic resonance imaging by combining paramagnetic and diamagnetic materials

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The method of coating the metallic implant made of paramagnetic materials with diamagnetic materials has been proposed to reduce the magnetic disturbance of metallic implants which causes artifact in magnetic resonance imaging. The optimal thicknesses of the diamagnetic coatings have been obtained for a straight cylindrical hip joint and an aneurysm clip by using the magnetic field analysis of the finite element method (FEM). Whereas in the manufacturing, with respect to the mechanical force of the diamagnetic material, etc., the new structure of dual-material model with diamagnetic material inside and paramagnetic material outside is considered better. In this paper, first the effectiveness of the structure of the dual-material model with actual diamagnetic material inside and paramagnetic material outside is investigated by using the FEM. Then optimal thicknesses of paramagnetic coating of two models are obtained. Finally the effectiveness of the dual-material model is verified by the experiment. © *2010 American Institute of Physics*.
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I. INTRODUCTION

To reduce the artifact in magnetic resonance imaging (MRI) generated by metallic implants made of paramagnetic materials such as titanium (Ti), Co–Cr–Mo alloy, etc., the method of coating the metallic implant with diamagnetic material has been proposed.[1] The associations of various susceptibilities χ_{par} and χ_{dia} of the paramagnetic and diamagnetic materials when the respective opposite magnetizations of them can cancel each other were obtained for a straight cylindrical hip joint and an aneurysm clip by using the magnetic field analysis of the finite element method (FEM).[2] However, the actual diamagnetic materials which are not only suitable for the coating but also effective on artifact reduction when combined with actual paramagnetic materials were difficult to find. For example, the diamagnetic materials silica (SiO_2, susceptibility $\chi=-16.3\times10^{-6}$) and alumina (Al_2O_3, $\chi=-18.1\times10^{-6}$) are suitable for coating with respect to the mechanical strength, biocompatibility, and coating performance, while their susceptibilities are too small compared with those of paramagnetic materials often used for metallic implant (such as Ti, $\chi=1.8\times10^{-4}$ and Co–Cr–Mo alloy, $\chi=5.2\times10^{-4}$) and the magnetic disturbance cannot be much reduced. Also, the diamagnetic materials bismuth (Bi, $\chi=-1.6\times10^{-4}$) and graphite ($\chi=-6.0\times10^{-4}$) with larger susceptibilities are effective for artifact reduction when combined with Ti and Co–Cr–Mo alloy, respectively, whereas their mechanical strength is not good. Therefore, the new structure of dual-material model with diamagnetic material inside and paramagnetic material outside is considered better for the actual production.

In this paper, first the effectiveness of the structure of the dual-material models of the straight cylindrical hip joint with diamagnetic material Bi inside and paramagnetic material Ti outside under flux density in one direction is investigated. Then the optimal thicknesses of the paramagnetic materials in the dual-material models of the straight cylindrical hip joint and aneurysm clip with material combinations (Ti–Bi and Co–Cr–Mo alloy-graphite) under flux densities in two different directions are obtained. Finally, the effectiveness of the dual-material model structure is proved by experiment.

II. MODELS DESCRIPTION

The analyzed dual-material models for the straight cylindrical hip joint and the aneurysm clip are shown in Fig. 1. Only 1/8 of the whole region is analyzed due to symmetry. For simplicity, the straight cylindrical hip joint and the circular ring of the aneurysm clip are modeled as a straight cube model and a horn-shaped cube model. t is the thickness of the paramagnetic material outside. Two combinations of paramagnetic and diamagnetic materials are chosen. One is that inner part is diamagnetic material Bi ($\chi=-1.6\times10^{-4}$) and outside is paramagnetic material Ti ($\chi=1.8\times10^{-4}$). The other is that graphite ($\chi=-6.0\times10^{-4}$) inside and Co–Cr–Mo alloy ($\chi=5.2\times10^{-4}$) outside. The body tissues around them are assumed to be water ($\chi=-9.1\times10^{-6}$) in the analysis. The uniform flux density of 1.5 T is applied in x and z directions.

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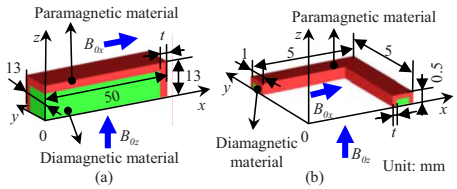

FIG. 1. (Color online) Dual-material models for optimization, (a) straight cylindrical hip joint model and (b) aneurysm clip model.

III. METHOD OF ANALYSIS

The magnetic disturbances are calculated by using the three dimensional linear magnetostatic analysis of FEM with the first order brick edge elements. The fundamental equation is as follows:

$$\mathrm{rot}(\nu\,\mathrm{rot}\,\boldsymbol{A}) = 0, \tag{1}$$

where $\boldsymbol{A}$ is the magnetic vector potential and ν is the reluctivity. The applied uniform magnetic field is generated by imposing the boundary condition to the analyzed models. The magnetic disturbance B_d is defined as $B_d = B_{pi} - B_{0i}$ (B_{0i} is the applied flux density and B_{pi} is the component of the calculated flux density parallel to the applied flux density). The optimal thickness t_{opt} of the paramagnetic material in the dual-material model is determined by making the maximum distance from the metallic implant to the 3 ppm ($=4.5 \times 10^{-6}$ T) contour line of magnetic disturbance smallest.

IV. EFFECTIVENESS OF NEW DUAL-MATERIAL MODEL

The effectiveness of the new structure of the dual-material model is investigated using the straight cylindrical hip joint model with Bi inside and Ti outside under flux density B_{0x} as shown in Fig. 1(a). The distributions of the magnetic disturbance B_d in the central plane of the analyzed model with different thicknesses t under B_{0x} are shown in Fig. 2. The plus and minus 3 ppm contours of magnetic disturbance are indicated by the white solid arc lines. In Fig. 2(a) for the ordinary model with $t = 13$ mm, large magnetic disturbance concentrates around the edge of the model in a large area. In Figs. 2(b)–2(d) when t is decreased gradually, the leakage flux from the paramagnetic coating around the edge continues decreasing, whereas the leakage flux from the diamagnetic material inside around the edge is increasing.

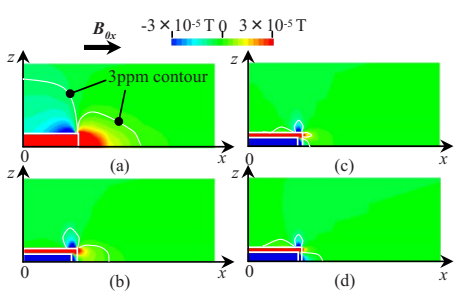

FIG. 2. (Color online) Calculated magnetic disturbance B_d of the straight hip joint model at $y=0$ subjected to flux density B_{0x}: (a) ordinary model (Ti) $t=13$ mm, (b) dual-material model (Ti–Bi) $t=4$ mm, (c) dual-material model (Ti–Bi) $t=3$ mm, and (d) dual-material model (Ti–Bi) $t=2.5$ mm, respectively.

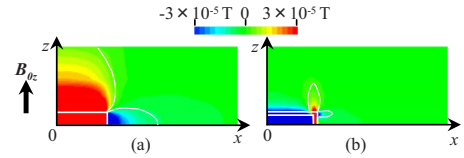

FIG. 3. (Color online) Calculated magnetic disturbance B_d of the straight hip joint model at $y=0$ subjected to flux density B_{0z}: (a) ordinary model (Ti) and (b) optimal dual-material model (Ti–Bi), respectively.

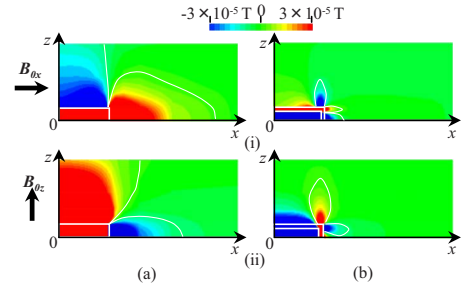

FIG. 4. (Color online) Calculated magnetic disturbance B_d of the straight hip joint model at $y=0$ subjected to flux densities (i) B_{0x} and (ii) B_{0z} for (a) ordinary model (Co–Cr–Mo) and (b) optimal dual-material model (Co–Cr–Mo alloy-graphite), respectively.

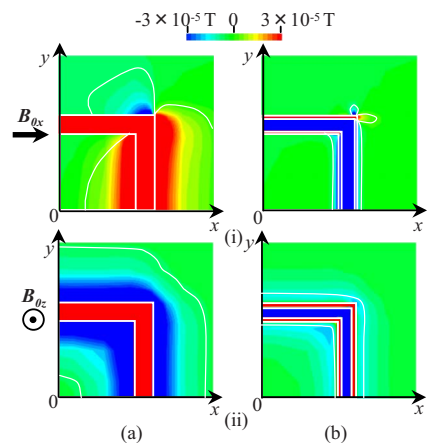

FIG. 5. (Color online) Calculated magnetic disturbance B_d of the aneurysm clip model at $y=0$ subjected to flux densities (i) B_{0x} and (ii) B_{0z} for (a) ordinary model (Ti) and (b) optimal dual-material model (Ti–Bi), respectively.

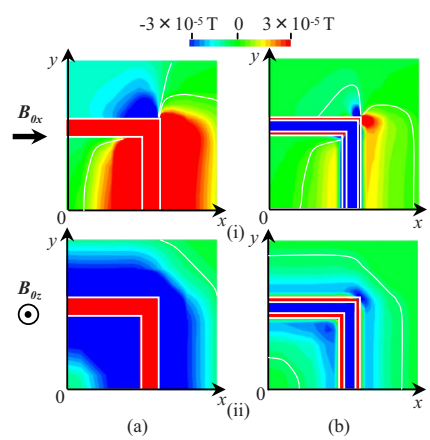

FIG. 6. (Color online) Calculated magnetic disturbance B_d of the aneurysm clip model at $y=0$ subjected to flux densities (i) B_{0x} and (ii) B_{0z} for (a) ordinary model (Co–Cr–Mo alloy) and (b) optimal dual-material model (Co–Cr–Mo alloy-graphite), respectively.

TABLE I. Optimal thickness of paramagnetic material outside.

Models	Material combinations	Applied flux B_{0x}		Applied flux B_{0z}	
		t_{opt}	Ratio[a]	t_{opt}	Ratio[a]
The straight cylindrical hip joint model	Ti–Bi	3	0.2	3.5	0.3
	Co–Cr–Mo alloy-graphite	3.5	0.3	4	0.3
The aneurysm clip model	Ti–Bi	0.15	0.3	0.2	0.4
	Co–Cr–Mo alloy-graphite	0.2	0.4	0.2	0.4

[a]Ratio of optimal thickness to total thickness.

However, $t=3$ mm is the optimal thickness for the paramagnetic material, as the maximum distance (8.7 mm) from the edge to the 3 ppm contour in Fig. 2(c) is the smallest compared with those (32.5 and 17.5 mm) in Figs. 2(b) and 2(d), respectively. It is obvious that the area with large magnetic disturbance in the water region of the optimal dual-material model is much smaller than that of the ordinary model.

V. EFFECTIVENESS OF THE NEW DUAL-MATERIAL STRUCTURE ON VARIOUS MODELS UNDER DIFFERENT CONDITONS

In this section, to investigate the effectiveness of the new dual-material structure on various models under different conditions, the optimal thicknesses of the straight cylindrical hip joint and the aneurysm clip models shown in Fig. 1 with different material combinations (Ti–Bi and Co–Cr–Mo alloy-graphite) under flux B_{0x} and B_{0z} are obtained. The distributions of the magnetic disturbance B_d in the central plane obtained are shown in Figs. 3–6. For the two optimal dual-material models, the areas with large magnetic disturbance in the water region under each condition are much smaller than those of the ordinary models composed of paramagnetic material only. Therefore, the dual-material structure of paramagnetic material outside and diamagnetic material inside is effective on reducing the magnetic disturbance for various models under different situations.

The optimal thicknesses of paramagnetic materials for all eight cases are shown in Table I. It is found that the optimal thicknesses of the paramagnetic materials for each model are not changed so much under different flux densities. Also if the susceptibility ratio of two combined materials is kept the same, the ratio of the optimal thickness to the total thickness of the model also remains the same. Therefore, the dual-material structure is quite applicable for various models under various conditions.

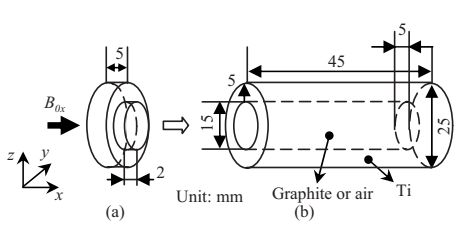

FIG. 7. Measured cylindrical model subjected to flux density B_{0x}: (a) the cap part and (b) the body part.

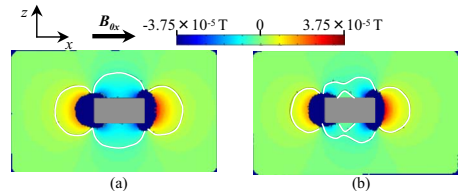

FIG. 8. (Color online) Measured magnetic disturbance B_d of the straight cylindrical hip joint subjected to flux density B_{0x}: (a) hollow model with air inside (Ti) and (b) dual-material model (Ti outside and carbon inside), respectively.

VI. VERIFICATION BY EXPERIMENT

Two models composed of two parts, a cap part and a body part as shown in Fig. 7 with the same outermost size, are measured: one is a hollow straight cylinder made of Ti only and the other is a dual-material cylinder with Ti outside and carbon ($\chi=-2.0\times10^{-4}$) inside. For the dual-material cylinder, the Ti-carbon is chosen because a mold for making the body part thinner is not available at present. So the carbon with large susceptibility is chosen to combine with the Ti and in this case the body part can be thicker and the model can be made. The experiment method is the same with that expressed in Ref. 2. The distributions of the magnetic disturbance B_d in the central plane obtained from measurement are shown in Fig. 8, where the white solid arc lines also indicate the plus and minus 3 ppm ($=4.5\times10^{-6}$ T) contours. Also, the magnetic disturbance around the metallic implant shown as dark blue means the absolute magnetic disturbance is over 25 ppm ($=3.75\times10^{-5}$ T). The figures are not symmetric because the models are not symmetric. We can find that the area with large magnetic disturbance over 3 ppm of the dual-material model is smaller than that of the hollow model. So the dual-material structure model is proved to be effective on reducing the black-hole artifact of metallic implant under MRI because the opposite leakage flux of the diamagnetic and paramagnetic materials are cancelled with each other.

VII. CONCLUSION

In this paper, the structure of the dual-material models of the straight cylindrical hip joint and the aneurysm clip with diamagnetic materials (Bi and graphite) inside and paramagnetic materials (Ti and Co-Cr-Mo alloy) outside are confirmed to be effective on reducing the magnetic disturbance by using the FEM. Also in the measurement, the area of magnetic disturbance generated by the dual-material model composed of carbon inside and Ti outside is also smaller than that of the hollow model made of Ti. So the structure of dual-material model with actual diamagnetic material inside and paramagnetic material outside is effective on reducing the black-hole artifact of metallic implant under MRI.

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