Evaluation of effects of permanent magnet circuits on gradient field linearity

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INTRODUCTION:
The design of gradient coils for permanent magnets is based on calculation of magnetic field in free space. In reality, however, magnet field gradients produced by the gradient coils are enhanced by magnetic materials because of mirror image currents flowing in the pole pieces [1,2]. Furthermore, the mirror currents may also affect gradient field linearity and degrade image quality. Despite the importance, this effect has not been quantitatively evaluated. In this study, we experimentally evaluate the effects of magnetic circuits on gradient field linearity. We show that the gradient field generated by a gradient coil set differs when it is inserted in different magnetic circuits, and that the gradient field linearity decreases under the influence of pole pieces.

MATERIALS AND METHODS:
Figure 1 shows the insertable gradient coil assembly used in this study. The transverse gradient coils (Gx and Gy) were designed using the target field approach [3] and the axial (Gz) gradient coil was designed using a genetic algorithm. The design parameters for the gradient coils were as follows: diameter of the current flowing plane = 160 mm, coil gap = 74 mm, number of turns = 36. The coil elements were wound on FRP (fiber reinforced plastic) square plates (20 cm × 20 cm, 0.5 mm thick) and fixed using epoxy resin. The Gx, Gy, and Gz coil elements were stacked from the inside to the outside as shown in Fig.1. Two phantoms were used to evaluate the magnetic field gradients. The first phantom was a water phantom which comprised an acrylic sphere (diameter = 29.7 mm) and a cylindrical plastic container (diameter = 36 mm, height = 44 mm) filled with $CuSO_4$ water solution. The second phantom was a cylindrical 3D lattice oil phantom (diameter = 64 mm, height = 100 mm) as shown in Fig.2.

The gradient coil efficiencies were measured using the water phantom and 2D spin echo sequences for four permanent magnets (A1, A2, A3, and B). The field strengths and nominal gap widths of the magnets were listed in Table 1. The gradient field distributions were measured using the 3D lattice phantom and 3D spin echo sequences with positive and negative readout gradients for two permanent magnets (A1 and B). All the measurements were performed using a gradient power supply (±10 A) to minimize measurement error. The gradient field distribution was analyzed and fitted to fourth polynominal function using a customized program. The nonlineariy of the gradient field generated by the Gz coil, α_z, was calculated as

$$\alpha_z = (\partial B_g/\partial z)/(\partial B_g/\partial z)_0 - 1,$$

where B_g is the gradient magnetic field and $(\partial B_g/\partial z)_0$ is its differential value at the coil center.

RESULTS AND DISCUSSION:
Table 1 shows the measured efficiency of gradient coils for different magnets. For magnets A1, A2, and A3, the efficiencies were close to those obtained from calculations within the experimental errors, indicating that gradient field enhancement is negligibly small in these cases. This is reasonable because these magnets have large gap distances and their pole pieces located well away from the gradient coil. For magnet B, in contrast, the relative efficiencies of Gx, Gy, and Gz coils were significantly large (1.3~1.4). This is because the magnet gap for magnet B (90 mm) was close to the coil gap (74 mm) and the mirror current effect was not negligible. Figure 2 shows the gradient field nonlinearity α_z measured in the cubic area ($(69\ mm)^3$) for magnets A1 and B, which demonstrates a similar tendency as the efficiency. For magnet A1, which is free from the mirror current effect, the gradient field had a large linear region where α_z is close to zero. On the other hand, the gradient field linearity decreased for magnet B. The volume fraction of the region with the linearity within 10 % was 73.9 % for A1 and 64.9 % for B, corresponding to a 9.0 % decrease due to the mirror currents. Our findings reveal that the gradient field linearity largely decreases when the gradient coil locates near the pole piece, and hence the design of gradient coils requires consideration of the mirror current effect.

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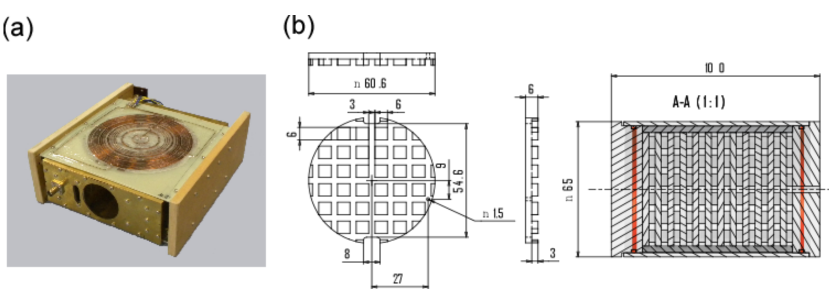

Fig. 1 (a) Gradient coil. (b) Design of lattice phantom.

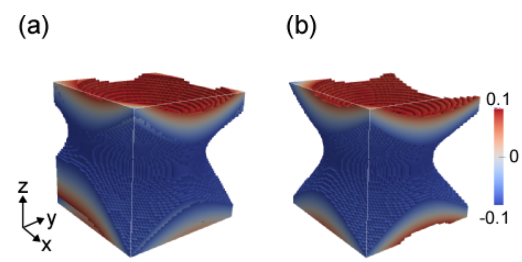

Fig. 2 Gz Gradient field nonlinearity in the cubic area ($(69\ mm)^3$) for (a) A1 and (b) B.

Magnet	A1 [0.208 T/250 mm]	A2 [0.204 T/160 mm]	A3 [0.208 T/160 mm]	B [1.03 T/90 mm]
Gx	0.954 (0.976)	0.979 (1.00)	0.976 (0.998)	1.28 (1.31)
Gy	0.927 (0.978)	0.949 (1.00)	0.942 (0.993)	1.26 (1.33)
Gz	0.890 (0.992)	0.939 (1.05)	0.922 (1.03)	1.22 (1.36)

Table 1. Gradient coil efficiency (G/cm/A) for different magnets. Values in the parentheses show the efficiency relative to that from calculations.