An optimal central gap size for the split gradient coil design

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Introduction: Combining magnetic resonance imaging with positron emission tomography (PET–MRI) in a single device can simultaneously provide complimentary information for oncology and other investigations[1]. Integrating PET sensors into an MRI scanner in a limited space can degrade the performance of both PET and MRI systems [1]. One approach to solve this problem is to split the MRI scanner into two halves, a central gap is therefore created for accommodating the PET system[2]. This approach, however, affects the gradient strength, wire spacing and shielding efficacy of the gradient coil that has to be split into two halves. In this work, the impact of the central gap over the gradient performance was studied for the split MRI scanner with a range of gap sizes. Coil performance metrics were studied; including the figure of merit (FoM), shielding efficacy and minimum wire spacing. The secondary magnetic field generated by the eddy currents in the region of interest (ROI) and the average power dissipated by the eddy currents in the cryostat warm bore, first and second cold shields were also investigated. This study will provide insight into the effect of incorporating a central gap on the MRI performance in PET-MRI hybrid systems. It also provides guidance for other imaging system development with a central gap, in terms of decisions about performance trade-offs for gradient sets in such systems.

Methodology: Two sets of split, actively-shielded, transverse gradient coils were designed with an inverse boundary element method (IBEM) [3, 4] with a range of central gap sizes. One set of coils was constrained to produce 99% shielding efficiency (called "eddy coils"), where the shielding efficiency was defined here as the ratio between the secondary magnetic field generated by the eddy currents and the primary gradient field generated by the gradient coils. In the second set of coils, the FoM was constrained to remain the same for each coil (called "performance coils"). This FoM was set to $\eta^2/L = 9.5\times10^{-6}\ T^2\cdot m^{-2}\cdot A^{-2}\cdot H^{-1}$, where η was the gradient coil efficiency (the field gradient produced by the coil carrying 1 Amp) and L was its inductance. The radii of the primary and secondary surfaces were 34.4 cm and 43.5 cm, respectively and their total length was 135.6 cm. The primary and secondary surfaces were connected at the ends of the coils furthest away from the ROI, as shown in Fig 1. The maximum gradient field error was constrained to 5% for all the cases with a gradient strength of 10 mT/m. The radius of the spherical ROI was 20 cm.

The eddy currents induced in the three split cryostat layers were calculated by the Fourier series network method [5]. The total lengths of the three cylindrical layers were 143 cm, 140 cm and 138 cm and the inner radii were 47 cm, 49.35 cm and 50.76 cm, respectively. Their thicknesses were 3 mm, 6 mm and 3 mm, respectively. The electrical conductivity of the stainless steel warm bore was 1.1×10^6 S/m and 3.8×10^7 S/m and 1.2×10^9 S/m for the 1st and 2nd aluminum cold shield, respectively. The gap between the two halves of the warm bore was the same as that of the split gradient coils.

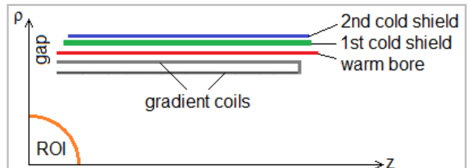

Fig 1. One quarter of the cross-section of the split whole-body MRI system.

Simulation and discussion: Fig 2 shows the behavior of the coil performance as a function of the central gap size. It was found that the FoM (a) of the "eddy coils" decreased when the central gap size increased. For the "performance coils", however, the shielding efficiency (b) decreased dramatically with increased gap size. The minimum wire spacing (c) decreased in all coils, which increased the coil inductances and would cause temperature hop-spots and fabricating difficulties.

The secondary magnetic fields generated by the eddy currents in the ROI are analyzed by their spherical harmonic components, as shown in Fig 3. The A_{11} harmonic, the secondary magnetic field gradient, increased when the central gap size increased. The non-linearity of the secondary magnetic field, characterized primarily by the A_{31} and A_{51} harmonics, increased when the central gap size was bigger than 12 cm. It was also found that the A_{31} and A_{51} harmonics had minimal amplitudes at 12 cm central gap size, which means the secondary magnetic field was most linear at this gap size.

Another eddy current effect is shown in Fig 4, where the power dissipated by the eddy currents induced in the three cryostat layers is plotted. It can be seen that he amount of power dissipation increased dramatically for gaps wider than 12 cm. This indicates that the split MRI cryostat system would have increased thermal load and possibly greater acoustic noise in a system with a central gap size larger than 12 cm. Another important finding is that the power dissipated in the second cold shield is 1 watt at the 24 cm gap case for both coil sets, shown in Fig 3(d). As 1 watt continuous power heating may boil off 1.4 liters liquid helium per hour [6], the stability of the helium vessel in split systems with large central gap size would be of concern.

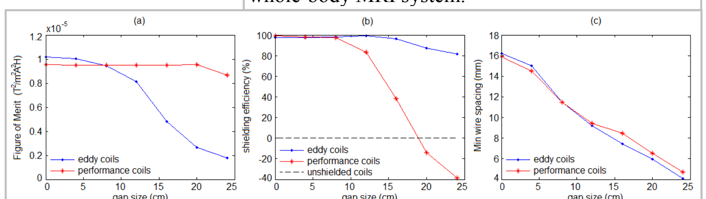

Fig 2. Gradient performance versus the central gap size. (a) FoM, (b) shielding efficiency, (c) minimum wire spacing.

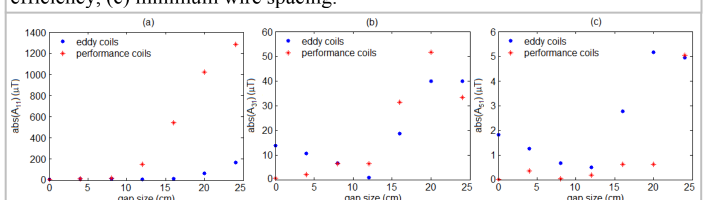

Fig 3. Amplitudes of the low order spherical harmonic components of the secondary magnetic field versus the central gap size. Harmonics (a) A_{11}, (b) A_{31}, (c) A_{51}

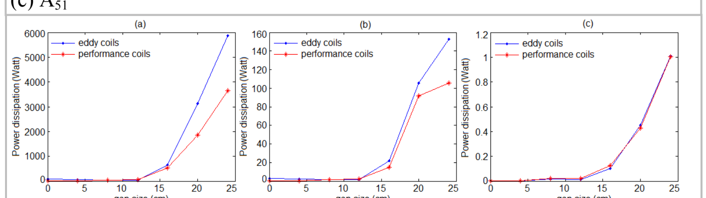

Fig 4. Total power dissipated in the cryostat layers versus the central gap size. Cryostat layers (a) warm bore, (b) first cold shield, (c) second cold shield

Conclusion: In this work, the gradient performance and the eddy current effects generated by split, actively-shielded, transverse gradient coils was studied and the impact of varying central gap size was analyzed for a split whole-body MRI system. The gradient performance was found to decrease when the gap size increased, as expected. The effects of the eddy currents were simulated to be more pronounced as a result of splitting the gradient assembly in two halves. *An optimal central gap size of 12 cm was found*. A split system with this optimal gap size may have small and linear secondary magnetic field in the ROI. This could improve the efficacy of eddy current compensation techniques and thus minimize the MRI image artifacts. In addition, the Ohmic power dissipated in the split cryostat layers was simulated to be at a similar level to the conventional un-split case. These findings may provide inform for the design of PET-MRI and other similar systems.

References: [1]. Shao, et al., *Physics in Medicine and Biology*, 1997. 42(10): p. 1965-1970. [2]. Lucas, et al., *Technology in cancer research treatment*, 2006. 5(4): p. 337-342. [3]. Pissanetzky, *Measurement Science and Technology*, 1992. 3(7): p. 667. [4]. Poole, et al., *MRM*, 2009. 62(5): p. 1106-1111. [5]. Lopez, Poole, and Crozier, *JMR*, 2010. 207(2): p. 251-261. [6]. Morich, 1993, *PhD thesis*, Case Western Reserve University.