Flanged-edge transverse gradient coil design for a hybrid LINAC-MRI system

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Introduction: MRI scanners can be combined with a Linear accelerator (LINAC) to provide image-guided cancer treatment. This allows clinicians to obtain accurate information about tumor shape and position during the radiotherapy. In this work, a large central gap (50 cm) is designed for a hybrid LINAC-MRI system to provide dual access so that both the accelerator and the patient can be placed in either an axial or radial direction. There are a number of technical difficulties in designing split transverse gradient coils. Conventional gradient coil configurations are unable to meet the imaging requirements of the hybrid systems, therefore alternative solutions have to be explored. Here, a split, flanged-edge transverse gradient coil configuration is proposed and investigated as an alternative design for the large gap required split whole-body MRI system.

Methodology: The 3D structure of the flanged-edge transverse coil is shown in Fig. 1a. The coil surfaces close to the central region were folded along the radial surfaces of the split cryostat warm bore. This coil was compared with a classic split coil design [1], as shown in Fig. 1c. Figs. 1b and d present examples of each designed coil. Both of the coils were designed using the equivalent magnetization current method [2]. The radii of the primary and secondary inner surfaces were 33.3cm and 40cm, respectively. The outer radii of the primary and secondary flanges in Fig. 1a were 58.5cm and 66cm, respectively. The total lengths of the primary and secondary surfaces were 130cm and 140cm, respectively. The size of the central gap between the split coils was 46 cm. The gradient coils were driven by sinusoidal currents at 1 kHz to produce 30 mT/m gradient strength in the region of interest (ROI). The radius of the spherical ROI was 15 cm. The main static magnet system was 1.5 T. The comparison between the two coils was drawn in terms of coil efficiency, figure of merit (FoM), coil inductance and resistance as a function of shielding ratio. The coil efficiency, η, is defined as the field gradient produced by the coil carrying 1 Amp. The FoM is defined as η^2/L, where L is the coil inductance. The shielding ratio is defined as $\max(|B_z^{eddy}|)/\max(|B_z^{coil}|)*100\%$, where B_z^{eddy} is the field generated by the eddy currents induced in the aluminum cryostat cold shield and B_z^{coil} is the field generated by the gradient coils in the ROI. The power dissipation generated by the eddy currents on the copper RF shield and the stainless steel cryostat warm bore was then calculated. Two 16-slot RF shields were placed in either an axial (Fig. 2a) or radial direction (Fig. 2b). The radii of the RF shields were 30cm and 20cm, respectively. The split warm bore had a 42.5cm inner radius, 82cm outer flange radius, 6 mm thickness and 150 cm total axial length with a 59cm central gap. The split cold shield had a 43.5cm inner radius, 81cm outer flange radius, 3 mm thickness and 148 cm total axial length with a 61cm central gap. The eddy currents were calculated using a hybrid Boundary element method and Fourier series network method [3, 4].

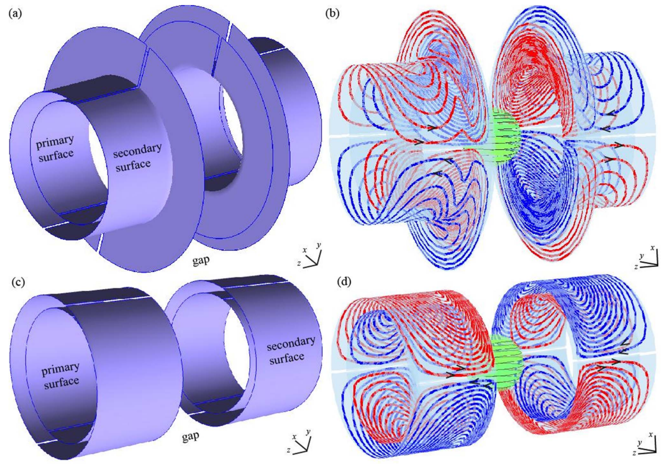

Fig. 1. 3D representations and examples of the transverse gradient coil designs. (a) flanged-edge coil structure, (b) flanged-edge coil example, (c) classic coil structure and (d) classic coil example. The green region is the ROI. The arrows show the current directions.

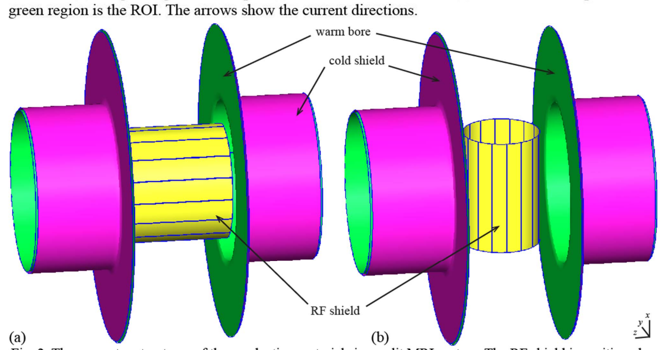

Fig. 2. The geometry structures of the conducting materials in a split MRI system. The RF shield is positioned along (a) axial or (b) radial direction.

Simulation and discussion: Fig. 3 shows the coil performance of each design as a function of the shielding ratio. It can be seen that the coil efficiency and FoM of the flanged-edge coil are much higher than those of the classic coil (see Figs. 3a and b), and the coil inductance and resistance of the flanged-edge coil are much smaller than those of the classic coil (see Figs. 3c and d). This is because in the classic coil design, high current densities appear at the central coil ends to generate the required gradient strength in the ROI. This results in most of the wires concentrated to the central ends, which in turn causes high coil inductance and resistance with low coil efficiency and FoM. The high coil resistance (Fig. 3d) in the classic coil design may produce high ohmic power heating on the coils, which had been addressed in [1] by using direct cooling systems to reduce the coil temperature. In the flanged-edge coil design, however, the current density was released from the central corner to the flanges. Higher coil performance is therefore obtained. The subsequent analysis of the eddy current-induced power dissipation was taken by inserting each designed coil into the simplified system, as shown in Fig. 2. Fig. 4 shows that compared to the classic design, less power dissipation was induced in the RF shield and the cryostat warm bore in the flanged-edge design. As the ohmic power is proportional to the acoustic noise [5], the flanged-edge design may also produce less eddy current-induced acoustic noise. Moreover, the power dissipation in the designs with radial RF shield was less than the designs with an axial RF shield. This is because less inductance coupling occurred between the radial RF shield and the axial-located gradient coils (Fig. 4a). The mutual inductance coupling between the radial RF shield and the axial-located cryostat warm bore was smaller compared to that in the designs when the RF shield was located in the same direction with the warm bore (Fig. 4b).

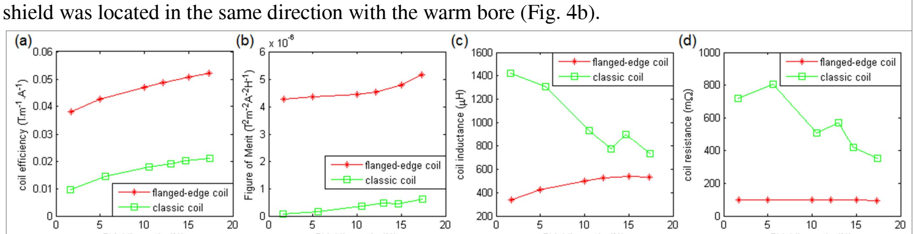

Fig. 3. The performance of the two coil configurations (see Figs.1a and c) as a function of the shielding ratio. (a) coil efficiency, (b) figure of merit, (c) coil inductance and (d) coil resistance

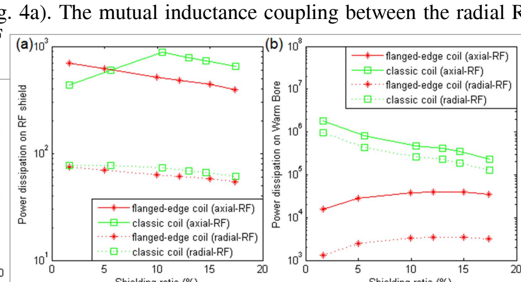

Fig. 4. Power dissipation as a function of the shielding ratio induced in the (a) RF shield and (b) cryostat warm bore.

Conclusion: This work presents a new approach to the design of split, actively-shielded, transverse gradient coils with a large central gap, which can be used for LINAC-MRI hybrid system development. A comparison was made between the flanged-edge, split coil and a classic split coil. Simulation results show that the former coil is of better coil quality. Furthermore, compared to the classic coil design, the flanged-edge coil design induced less eddy currents both on the RF shield and the cryostat warm bore and is therefore an alternate design worthy of further investigation.

References: [1] S. Shvartsman, et al. *ISMRM*, 2010: 3939. [2] H.S. Lopez, et al. *IEEE Trans Magn* 45: 767–775. [3] H.S. Lopez, et al. *JMagn Reson*, 207:251-261. [4] H.S. Lopez, et al. *ISMRM*, 2010: 2751. [5] Edelstein, W. A., et al. Magn Reson Med 2005; 53: 1013–1017.