Design and Manufacture of a Planar Gradient Set for Rapid Body MRI with Intense Gradients

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Introduction: Because the power required to produce a gradient scales roughly as the fifth power of the coil radius, local gradient coils can offer enormous advantages in strength, speed and efficiency for leading edge MRI applications. We report on the design and fabrication of a flat gradient module (1), that solves the limiting problems of heat generation and unbalanced force, and fits in the bed space of an existing 1.5T scanner, as shown in Fig 1. The design incorporates innovative cooling methods, materials and manufacturing processes, maximizing gradient strength while keeping operating temperature and mechanical loads within safe limits.

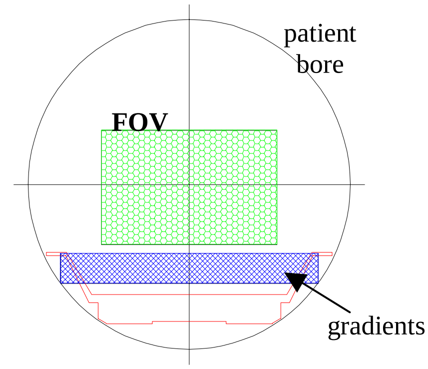

Figure 1. Configuration of Local Gradients.

Methods: Flat gradient coil sets are brought closest to the imaging volume of a 55 cm bore GE 1.5T Signa MRI system by mounting them flush with the table support (Fig 1). Two flat boards printed with windings per gradient direction are used to increase ampere-turns. The manufacturing process was pushed to the limit of small conductor (3 mm) and cut (1.2 mm) widths to maximize the number of turns in a given area. Detailed heat transfer analyses were performed, and axial cooling methods, high temperature epoxy, adhesives and substrates were used to handle the large heat loads and keep surface temperature below 40C.

Because field generating boards are on only one side of the imaging volume, there is an inherent degradation in gradient strength moving away from the boards. Therefore, better linearity was obtained over the volume by optimizing the gradient field on a fixed horizontal plane, rather than on the whole imaging volume. Current patterns were modeled as linear combinations of harmonics (2,3) in two dimensions on a planar surface, expanded to fourth order. Coefficients of harmonics were optimized for a given linearity by using MATLAB software, while heat generation was used as the limiting parameter. Inherently, there is no net force or moment on the X and Y boards in a uniform field. The design of Z coil was optimized for zero net moment (1), resulting in the additional loops at the bottom and top of the final Z coil (Fig 2). To ensure that the coils will remain safe during failure, we computed the maximum loads that might be generated in worst case failure scenarios, and designed a mounting system capable of accommodating them.

Results and Discussion: The gradient boards were printed from the computed stream-line functions on 3.125mm thick, 42 x 60 cm sheets of copper printed circuit boards, embedded, in X-Y-Z order from the patient cavity, in high-temperature epoxy resin, separated by 5-mm high water-cooling pipes. They are pictured in Fig 2. The gradients can reach more than 250 mT/m in X and Y, and more than 500 mT/m in Z with existing 320A current supplies. As noted above, the gradient strength decreases away from the boards, but maintains a minimum strength of 100 mT/m in X, and 150 mT/m in Y and Z gradients at 10 cm away from the gradient surface. The resulting imaging volume at this strength is 16 cm x 10 cm x 16 cm. After mapping the nonlinearities in the gradient field, simulated images could be corrected with standard algorithms for spatial remapping and intensity correction. Each gradient board generates several kW of heat and is designed to operate at up to 120 C with a current of up to 600 A. At 600 A, the strength would double to 500 mT/m in X and Y, 1000 mT/m in Z.

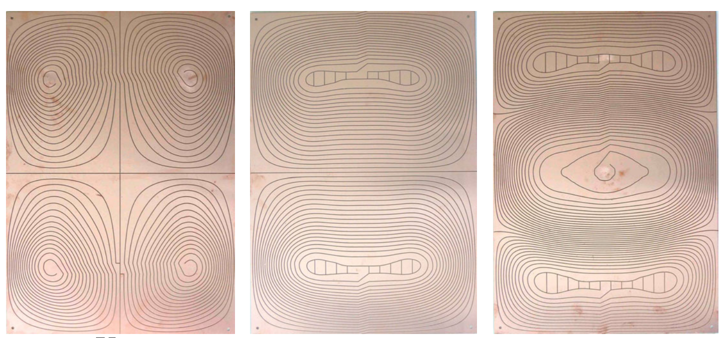

Figure 2. Gradient Boards

We conclude that local planar gradients can be designed to fit and operate safely within the bore of a conventional 1.5T MRI system, and produce very large gradient strengths of potentially up to 1T/m over limited but useful imaging volumes. Their smaller size provides the additional benefit of inherently lower impedance and hence higher slew rates compared to conventional volume gradient coils. Because the gradients are applied over a much smaller volume than conventional systems, and because the ∂B/∂T threshold for nerve stimulation increases when the period that ∂B/∂T occurs is reduced, we expect these coils to operate safely at levels that would be unacceptable for volume coils due to nerve stimulation (4). However, we plan safety studies to test this. We believe these new coil designs could play an important role in high speed cardiac MRI, and in diffusion MRI for brain fiber tracking.

References:

1- C. von Morze, et al, 11th ISMRM, p. 2420.
2- J.F. Schenck, et al, US patent 4,646,024.
3- Green, et al, 10th ISMRM, p.819.
4 - J. Schaefer et al, 6th ISMRM, p. 474.

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