Designing biplanar gradient coils with minimum power dissipation for NMR microscopy

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Target audience: This work will be of interest primarily to system designers and hardware engineers, especially those working on gradient coils and NMR microscopy.

Purpose: A major goal of NMR microscopy is to achieve isotropic, single-digit μm resolution in the order of 1 min averaging time. To pursue this goal, fast, high-resolution MR imaging demands strong gradient fields. The gradient coils used to generate these fields must be placed as close to the sample as possible to maximise field strength. As a result, power dissipation becomes a primary issue in micro-gradient operation since large currents must be driven through small volumes of conducting material possessing high electrical resistance. Coil heating must be controlled carefully to avoid damage to the system and/or sample and cooling mechanisms face further compounding constraints at the micro-scale. In this work, we explored changes in coil topology as a means to reduce power dissipation by design. We employed a coil design method proposed recently[1] that allows specific features of the fabrication process to be included as part of the power calculation and coil optimization. We considered an insert biplanar system and analysed the design of *x*-, *y*- and *z*-gradient coils to be built from wires or tracks of variable width.

Methods: The geometry chosen for each coil was a pair of parallel square plates of length 20 mm and separated by 10 mm. The coordinate system was oriented such that the plates were symmetric about the plane $x = 0$ and centred on the x-axis. Between the plates a 6mm cubic region of interest (ROI) was considered, centred at the origin, within which the primary field was oriented in the *z*-direction. This orientation was chosen with the aim of reducing possible susceptibility effects of the coil materials on the primary field. Target gradient fields for each coil were set at 1 T/m with an average volumetric field error of 1% within the ROI (max error ≈ 5%). The coil optimization was performed in two stages. Firstly, a standard sum-of-sinusoids current density parameterization was performed and coefficients were solved using Tikhonov regularization involving a standard minimum power penalty function.[2] Secondly, this solution was used as an initial guess in an iterative optimization scheme involving a novel current density mapping that accounts for the build method to provide a more accurate estimation of power dissipation following the subsequent discretization into coil windings.[1] Multiple designs were generated and analysed for each coil type, including designs for coils to be built using tracks of variable width (min. gap between tracks = 0.1 mm; max. track width = 1 mm; track thickness = 0.3 mm) and wires of fixed width (0.3 mm). Coil windings were obtained by contouring the associated current density stream functions and the number of contours was varied from 2 to 20 for each design. Optimization was performed using the function *fmincon* from MATLAB's Optimisation Toolbox (interior point method) and the program FastHenry2 was used to simulate coil resistance.

Results: Fig. 1 displays the simulated dissipated power for all of the (a) *x*-gradient, (b) *y*-gradient and (c) *z*-gradient coils designed in this study. Fig. 1 includes the results for the coils designed in the first step (standard minimum power - blue diamonds) and the second step (genuine minimum power – red squares) of the optimization described above. These cases are further subdivided into those to be built using tracks of variable width (solid lines) and those to be built using wires (dashed lines). Fig. 2 displays the coil winding locations for the coils with the lowest power dissipation in each genuine minimum power case (black squares in Fig. 1).

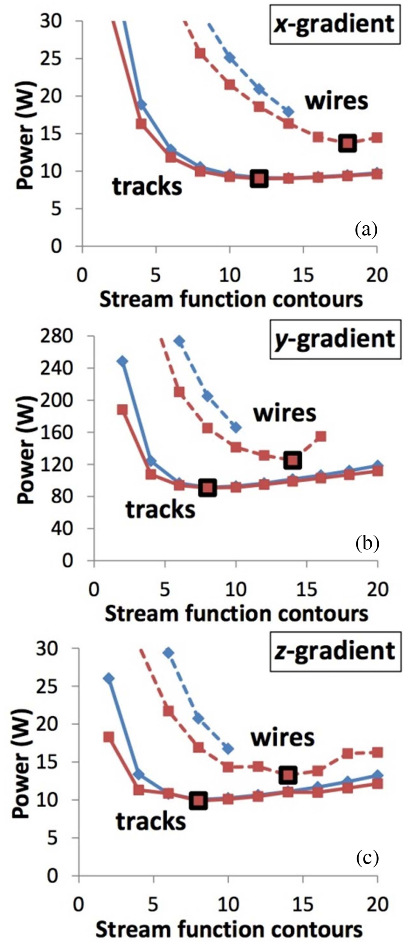

Fig.1: Dissipated power for all coils in survey (◆ – standard minP; ■ – genuine minP).

Discussion: From Fig. 1 we observe that for the coils to be built using tracks there is an optimum number of stream function contours (i.e. coil windings) for minimizing power dissipation, at which point there is little difference between the standard minimum power coils and the genuine minimum power coils. Power dissipation is found to increase sharply as the number of windings is reduced (e.g. for fabrication simplicity) and to increase moderately as the number of windings is increased (e.g. for coil efficiency). In these regions there is a small benefit to using the genuine minimum power method (~5→10%). From Fig. 1 we observe that for the coils to be built using wires there is a considerable benefit to using the genuine minimum power method (~20→25%). Furthermore, it is possible to design coils with a higher number of coil windings, thus improving the coil efficiency, whereas the standard method has an inherent maximum allowable number of wires in each case. Note that using tracks is always superior to using wires for the same number of windings but that using the genuine minimum power method approximately halves the penalty in dissipated power for the optimal designs. From Fig. 2 we observe that the coil winding patterns differ considerably between optimal track and wire cases. In future work, other coil geometries will be considered, including more closely spaced plates, along with alternative regions of interest and field orientations to explore their impact on power dissipation. Proto-types of optimal designs will be fabricated using a novel in-house micro-technology technique.

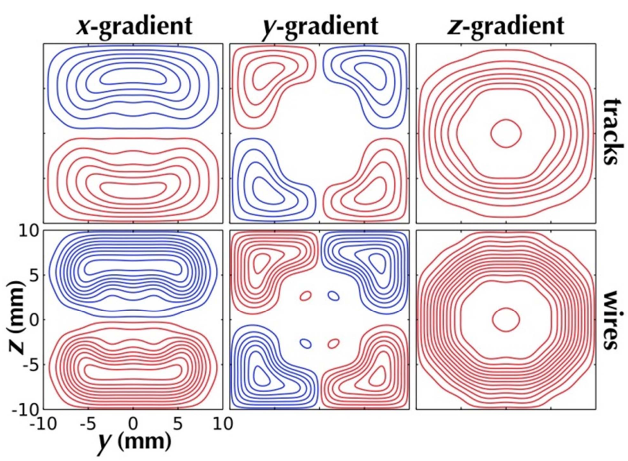

Fig.2: Coil winding patterns of optimal designs (*red*: current reversed).

Conclusion: A novel gradient coil design method has been applied to the design of biplanar micro-gradient coils such that they exhibit minimum power dissipation after discretization into coil windings. Significantly different optimal winding patterns were obtained for coils to be built using tracks of variable width compared to coils to be built using wires of fixed width and the number of coil windings was shown to be an important parameter in minimizing power dissipation.

References: [1] While PT, Korvink JG, Shah NJ, Poole MS. Theoretical design of gradient coils with minimum power dissipation: Accounting for the discretization of current density into coil windings. *J. Magn. Reson.* 2013; 235:85-94.
[2] Forbes LK, Crozier S. Novel target-field method for designing shielded biplanar shim and gradient coils. *IEEE Trans. Magn.* 2004; 40(4):1929-1938.