Toward Gradient Systems with Really Identical Gradient Coils

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Purpose: Designs of gradient systems are proposed that eliminate differences between the three gradient coils with potential advantages for MR imaging.

Background: The differences between the longitudinal z-gradient and the transverse x- and y-gradients are reduced when three magic angle gradient coils [1] are arranged in a gradient system [2]. Such magic angle gradient coils generate gradient directions with an inclination to the transverse plane, preferably at the magic angle (35.26°). With this inclination, a single coil design may be used to construct all three coils, rotated by ±120°. When the coils are arranged on three layers with different radii, as proposed in [2], similar coil designs may be used; however, identical designs are not possible (see Fig. 1). Such designs are desirable to further reduce the differences of the coil properties such as switching speed or maximum gradient strength. MR acquisitions would potentially profit from such an approach, and, with identical designs, also the optimization and fabrication of gradient systems may be facilitated. In this abstract, gradient system designs are proposed that consist of such identical gradient coils.

Methods: The methods [3-5] were combined to compute and visualize optimized stream functions for different gradient coil designs using Matlab (The Mathworks, Natick, USA) and COMSOL Multiphysics (COMSOL Inc.). For Fig. 1, a surface with a constant radius of 35 cm was generated, and for Fig. 2, a radius was defined that increased from 34 cm at 0° to 37 cm at 360°. For the closed design of Fig. 1, the discretized surface mesh was connected at 0° and 360°. The designs were optimized for a gradient field with an inclination of 45° toward the z-axis. Not shown are closed designs for a longitudinal and a transverse coil which were optimized using the same method. A maximum of 5% deviation from gradient linearity was enforced within a ROI having a radius of 20 cm. The designs were optimized for low power dissipation and torque-balance constraints were added.

Results: The closed design shown in Fig. 1 for the magic-angle gradient coil has an efficiency of 89.98/88.97 μT m · A for a radius of 34/35/36 cm. This shows that the inner coil is almost 10% more efficient than the outer coil. The efficiency lies in between the efficiency of a pure longitudinal coil with 135 μT m · A for 35 cm and a pure transverse coil with 67 μT m · A. The open spiral-shaped design shown in Fig. 2 has an efficiency of 73 μT m · A and is therefore about 15% less efficient than a closed design. Fig. 3a shows a design of a gradient system having a 120°-symmetry where a coil design similar to the design shown in Fig. 1 might be used. Fig. 3b shows gradient system for open spiral-shaped coils as presented in Fig. 2, but with an extension of Θext > 360° along the circumference of the cylinder. When such gradient systems are constructed, the efficiency differences of the three gradient coils drop down from nearly 10% to 0%.

Discussion: This work shows that gradient systems with step- or spiral-shaped gradient coils may prove useful in eliminating differences of coil properties. While open designs may have advantages for the manufacturing process, torque-balance may become an issue. It is possible to ensure torque-balance for Θext = 360° (see Fig. 2); however, Fig. 4 illustrates that designs with Θext > 360° may be more useful in this regard. Closed designs (such as Fig. 3a), should be more benign with respect to torque-balance and have the advantage of being more efficient; however, the two ends of each coil need to be connected. As a consequence, wires need to cross each other. To reduce the wire density in areas of intersection, many possibilities, one might simply consider to avoid such intersections by connecting the wires at a z-location outside of the coil. This abstract has dealt with cylindrically-shaped gradients, but similar symmetric designs with identical gradient coils may also be used for (bi)planar gradient systems. Also, standard gradient systems may profit from identical transverse gradient coils. Fig. 3c shows a design of a standard gradient system, where the x- and y-gradient coils have exactly the same surface with the consequence, that these two coils will have identical properties.

Conclusions: Magic angle, (bi)planar as well as standard cylindrical gradient systems can be constructed such that the inherent geometrical symmetries of the gradient directions are reflected in their actual designs. This leads to an elimination of property differences of current gradient coils with potential advantages for MR imaging. The next step should be the construction of an actual prototype, a necessary step to support the ideas presented in this abstract.

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