Toward Gradient Systems with Really Identical Gradient Coils

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Target Audience: Gradient coil specialists.

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 $\pm 120°$. 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 35cm was generated, and for Fig. 2, a radius was defined that increased from 34cm at 0° to 37cm 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 20cm. 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 $89/86/82\ \mu\mathrm{T/m \cdot A}$ for a radius of 34/35/36cm. 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 $135\,\mu\mathrm{T/m \cdot A}$ for 35cm and a pure transverse coil with $67\ \mu\mathrm{T/m \cdot A}$. The open spiral-shaped design shown in Fig. 2 has an efficiency of $73\ \mu\mathrm{T/m \cdot A}$ 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 $\Theta_{tot} > 360°$ 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 $\Theta_{tot} = 360°$ (see Fig. 2); however, Fig. 4 illustrates that designs with $\Theta_{tot} > 360°$ 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. It is therefore necessary to reduce the wire density in areas of intersection. Among 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 the 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.

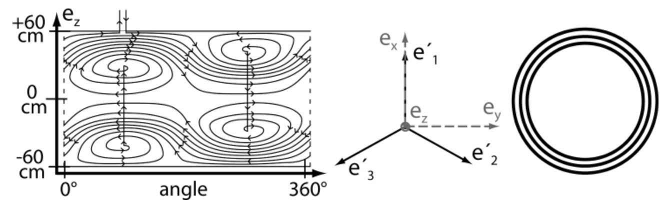

Figure 1: Variant of a magic angle gradient system. (a) Closed gradient design for a coil that generates a gradient with equal components in the transverse plane and along the z-axis. The design shares properties of a standard transverse coil (4 vortices) and a longitudinal coil (windings around the cylindrical geometry). (b) Rotated by $\pm 120°$ around the z-axis, such a design may be used for all three coils. The reference coordinate system in gray indicates the x-y-z-directions and the coordinate system in black shows the three gradient directions. One can see the 120°-symmetry. Not visible is that each gradient also has a component along the z-axis, which points into the plane. (c) As suggested in [2], the three coils may be constructed on three cylindrical shells. As each shell has a different radius, the coil designs are similar; however, they are not identical and therefore also the coil properties differ.

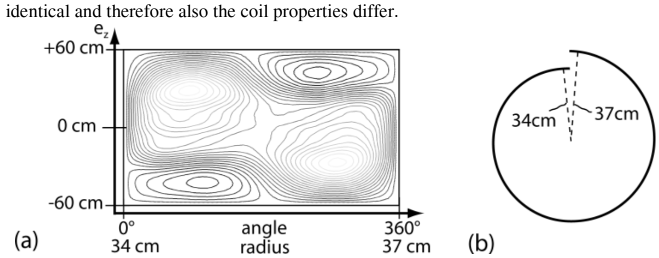

Figure 2: Open spiral-shaped design. (a) The open design generates a gradient field that is very similar to the field that is generated by the closed design shown in Fig. 1. (b) The design was calculated for a spiral-shaped coil surface and is torque-balanced.

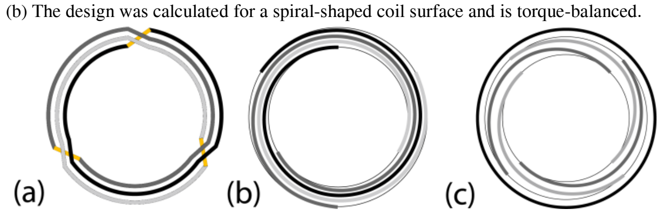

Figure 3: Gradient systems with identical coils. (a,b) Two possibilities for a magic-angle gradient system. (c) A possibility for a standard x-y-z-gradient system. (a) The coils, repeated each 120°, change the radius twice, each 120°, in a step-wise fashion. A closed coil design as shown in Fig. 2 may be used, but care must be taken at the locations of intersections (orange). (b) No intersections exist when open designs such as those shown in Fig. 2 are used. Here, a gradient system is shown where each coil has an extension of $\Theta_{tot} > 360°$ along the azimuthal direction. (c) Also the x- and y-gradients can be constructed to be identical using a spiral design. Each coil may be broken into two parts because a transverse coil does not need windings around the former.

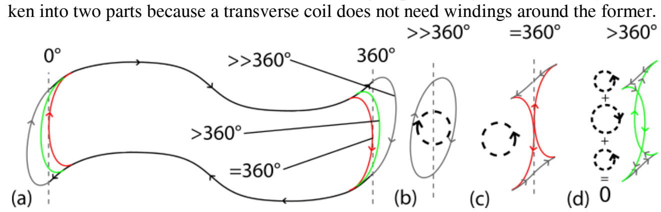

Figure 4: Is it useful to construct a coil with an extent of >360° along the azimuthal direction? (see Fig. 3b). (a) Shown in black are two current paths of the torque-balanced design of Fig. 1. For open designs (as Fig. 2) these wires need to be connected. Three different situations are shown. In gray a design with >>360°, in green a design with >360° and in red a design with exactly one rotation. (b) The additional wires are equivalent to a small loop of current on the surface of the coil, thereby generating a positive torque for an extent >>360°. (c) For an extent of 360°, the net torque is negative. (d) For a gradient coil that has an extent along the azimuthal direction that is slightly larger than one rotation, the coil is torque-balanced. It may therefore be useful to use open designs >360° (such as Fig. 3b).

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References: [1] JMR 115A:55-59, 1995; [2] EP1122552B1; [3,4] Concepts MR 26B:67-80, 2005; 31B:162-75, 2007; [5] Comp Phys 191:305-21, 2003.