Curved gradient coil designs for anatomically specific imaging applications

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Introduction

A powerful, all-purpose method has been developed over the past several years that allows for gradient design of virtually arbitrary geometry [1,2]. We have implemented this boundary element (BE) method following the particular approach of Poole and Bowtell [1]. In the current study, this method has been used to design and analyze the performance of curved gradient coil geometries as a function of the degree of curvature over all three axes, with designs varying continuously from planar to full cylindrical. We hypothesize that a form of curved gradient coil could serve as anatomically-specific gradient channels to be used in conjunction with larger, whole-body coils to comprise a 4- to 6-channel hybrid system [3]. The function of the anatomically-specific channels could include the ability to provide very high performance diffusion weighted imaging in a specified volume of tissue such as the breast, prostate, or posterior regions of the brain. Furthermore, pseudo-planar geometry gradient designs have been shown experimentally to offer significantly improved peripheral nerve stimulation properties in high-performance applications as compared to traditional, cylindrical geometry, whole-body gradient designs [4].

Methods

The BE method minimizes a functional over a discrete finite element mesh. In this study, our functional was chosen to minimize field inhomogeneity, power dissipation, and torque. A series of 11 coils were designed per axis, ranging in geometry from completely flat up to a full cylinder by equal increments of curvature. For the geometries ranging from flat to a half cylinder, the coils were scaled in size so as to have a maximum width of 52 cm in the x-direction. For the geometries extending beyond a half cylinder to full cylinder, the radius of curvature was held constant at 26 cm, again resulting in a total coil width of 52 cm. In all cases, the length of the coils in the z-direction was constrained to 60 cm. All coils were optimized to match a set of target points within a sphere 12 cm in diameter located 10 cm above each coil surface. Note that this region of interest results in vertically asymmetric gradient coil designs as the curvature approaches the closed cylinder case, as the region of interest lies below the geometric centre of the coil. A minimum region of 30% gradient uniformity was required over a region of interest 10 cm in diameter in order for a design to be considered adequate. The BE method resulted in continuous current densities defined over the geometries described above which were converted into discretized wire patterns using stream-function methods we have developed using Matlab®.

Results

Wire paths for five examples of the x-, y-, and z-gradient coils are shown in Figure 1. Fig. 1a-c shows the planar geometry (0°), Fig. 1d-f shows the coils with an angle of curvature of 108°, Fig. 1g-i shows the half cylinder geometry (180°), Fig. 1j-l displays the coils with an angle of curvature of 288°, and lastly, Fig. 1m-o shows the full cylindrical geometry (360°). The wire density for each coil was scaled so as to produce 800 μH of inductance. The efficiency was calculated for all three axes and plotted versus increasing angle of curvature in Figure 2. When coil designs approached the "half-cylindrical" geometry, coil performance began to level-off, producing efficiencies of 0.76 $\mathrm{mTm^{-1}A^{-1}}$, 0.71 $\mathrm{mTm^{-1}A^{-1}}$, and 0.76 $\mathrm{mTm^{-1}A^{-1}}$ for the x-, y-, and z-gradients respectively. Increasing curvature beyond this point did not significantly increase or decrease efficiency.

Discussion

The problem of peripheral nerve stimulation in whole-body gradient coils has generally motivated the investigation of anatomically-customized gradients and more complicated "4+" channel gradient systems. In order to rationally develop such systems, the performance trade-offs between the most open gradient coil designs (arguably the planar coil geometry) and the traditional complete cylindrical coils should be understood as a continuous transition from one architecture to the other. We are finding that from a performance perspective and for relatively focused regions of interest, the half-cylinder geometry represents an interesting trade-off between performance and access. In order to take full advantage of the versatility of the BE method, this design study is being extended to geometries that more closely conform to anatomical regions of interest including the breast, head, and extremities.

References

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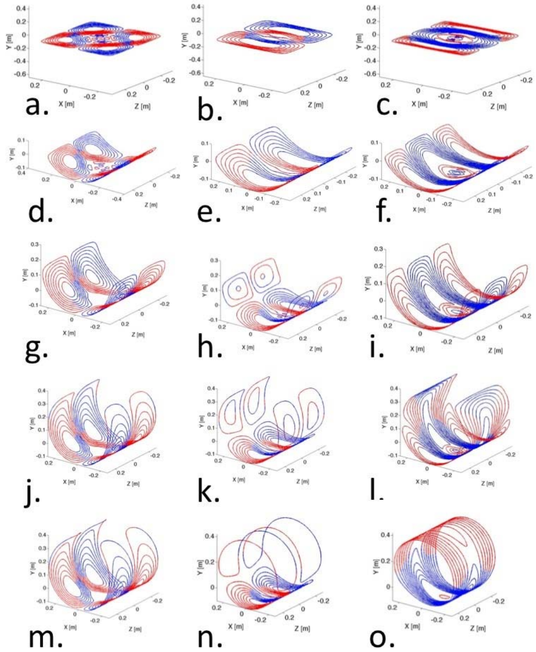

Figure 1. x-(a, d, g, j, m), y-(b, e, h, k, n), and z-(c, f, I, l, o) gradient coil patterns for five different angles of curvature: (a-c) planar (0°), (d-f) 108° curvature, (g-i) half-cylindrical (180°), (j-l) 288° curvature, and (m-o) full-cylindrical (360°).

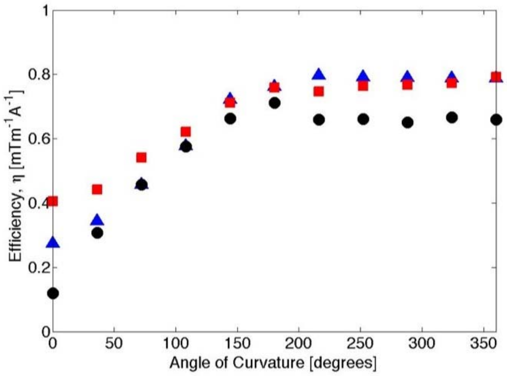

Figure 2. Gradient efficiency scaled for 800 μH inductance versus angle of curvature for the x-axis (blue triangle), y-axis (black circle), and z-axis (red square).