Design and Fabrication of a Three-Axis Hybrid-Quadrupole Gradient Coil for MR of the Breast

K. L. VanderWerf[1], J. T. de Bever[2], K. Butts Pauly[3], B. A. Chronik[1,2]

[1]Medical Biophysics, University of Western Ontario, London, Ontario, Canada, [2]Physics, University of Western Ontario, London, Ontario, Canada, [3]Radiological Sciences Laboratory, Stanford University, Stanford, California, United States

INTRODUCTION: In order to obtain the high gradient slew rates and strengths necessary for real-time SSFP and diffusion-weighted imaging of breast lesions, we have proposed the design of a three-axis hybrid quadrupole gradient coil. This coil has a transverse orientation and is composed of two hybrid quadrupole coils for the Gx and Gz axes and a fingerprint coil for the Gy coil. In this abstract, we report the proposed design for all the axes of the coil.

METHOD: The basic architecture for a hybrid quadrupole is shown in figure 1. The cylinders are aligned in the y-direction, transverse to the main field direction (z). The windings are spaced azimuthally according to a cos2θ current density distribution. The windings on the inner cylinder provide the imaging gradient field, while the outer cylinder serves as a return path for the inner windings. We define alpha to be the ratio of outer to inner cylinder diameter, and beta to be the ratio of the coil height to the inner cylinder diameter. This basic architecture allows the imaging region to be placed adjacent to the top of the coil; furthermore, this design yields a naturally torque-balanced coil. Both the Gx and Gz axes can be produced using this design. The wire pattern shown in figure 1 corresponds to a Gz coil; the Gx axis is achieved by rotating the coil 45 degrees about the y direction.

Coils of varying alpha and beta were designed and the resulting coils were evaluated according to three criteria: size of imaging region, distance from physical edge of coil to the extent of the imaging region, and figure of merit (M) defined as follows: $M = \eta a^{2.5}/L^{0.5}$. The results of this hybrid quadrupole gradient design study were reported in [1].

The Gy coil is a standard fingerprint coil used in traditional scanners but rotated into the transverse plane. We utilized the relation that $\nabla x B = 0$ to rotate the fingerprint coil by $\pi/2$ about the x-axis. Since the curl of the magnetic field is zero, $dBy/dz = dBz/dy$. Hence, the Gy coil in the longitudinal plane can be tipped into the transverse plane and still provide the same function. A symmetrical wire pattern for the Gy axis was developed using a stream function. An example of the Gy wire pattern is shown in figure 2.

This method of determining "optimal" coil parameters has been further extended to the two-axis case (Gx and Gz). Additional physical constraints were taken into consideration such as the available space in the intended General Electric double-donut MR system, the concentricity of the axes, and the cooling system incorporated within the coil layers. The open region in the GE scanner between the two main magnets is approximately 58 cm. The proposed system is equipped with forced chilled-water cooling. In order to fulfill our original criteria, the extent of the imaging region of each coil is required to extend up to or beyond the physical top edge (represented by a Delta value ≤ 0). This implies outer coil possesses an imaging region with a Delta of at most 0 and the inner coil a negative Delta value of at least the difference in the axis heights. An inductance of 800 μH was required in order to ensure compatibility with our amplifiers. The number of wires for all three coils was determined based on this requirement.

A new method of construction was developed in order to simplify the construction process. This process involved dividing each axis up into quadrants. A test winding was performed for each axis to determine the relative location of the axes with respect to the concentricity. First, a quadrant for the inner axis was wound. The plates for the outer quadrant were then attached to this wound structure and the outer axis quadrant was wound. This is best visualized in the left image of figure 3. Following the winding process, tubing was inserted between the windings of the inner and outer radii for cooling purposes. The system as a whole was then assembled and potted in epoxy.

RESULTS/DISCUSSION: The inner coil was chosen to be the Gz axis. For an inner diameter of 26 cm the geometry assigned had (alpha, beta) values of (1.4, 0.95); this corresponds to an outer diameter and height of 36.4 cm and 12.30 cm, respectively. The geometry for the outer coil, Gx, with an inner diameter of 24 cm had (alpha, beta) values of (1.6, 0.72); this corresponds to an outer diameter and height of 38.4 cm and 15.9 cm, respectively. Each of the hybrid quadrupole coils is composed of 264 windings. A summary of the parameters for each axis including: inductance, resistance, DSV, Delta, Merit, Gmax, SRmax, and efficiency is summarized in table 1. Due to spacing restrictions, we were unable to achieve the 800 μH desired inductance for the Gz coil. The improvement factors for the Gx coil compared to currently available gradient systems on open MR systems were greater then 22 in strength and 71 in slew rate. The improvement factors for the Gz coil were 13 in strength and 67 in slew rate.

One obvious concern with this method of construction is the potential variance in quadrant level and position prior to and during the potting procedure. Through computer simulation, it was found that variations of up to 5 cm did not affect the imaging parameters of the coil. Guide holes and dowels/screws were used to align the upper quadrant with its lower counterpart prior to the second winding and to align neighbouring quadrants during the final construction. The Gy axis is located within the inner diameter of the Gx coil. It has an inner diameter of 10.16 cm and is composed of 114 windings.

We are currently in the process of completing a three-axis prototype (as seen in figure 4) and will be using it to conduct experiments to determine the electric field production of the coil (which, leads to peripheral nerve stimulation). Simulations have been performed to predict the electric field that will be produced by the proposed coil.

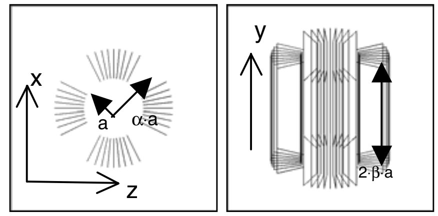

Figure 1: (left) wire positions according to cos2θ current density distribution and outer radius scaling parameter, (right) concentricity of coil and height scaling parameter.

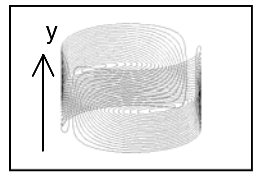

Figure 2: An example of the wire pattern for a 50 winding (25 per side) fingerprint coil for the Gy axis.

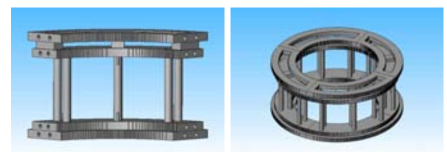

Figure 3: (left) concentricity of hybrid-quadrupole axes shown for one quadrant, (right) concentricity of hybrid-quadrupole axes shown for proposed design.

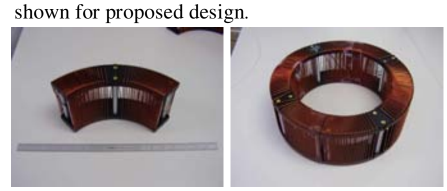

Figure 4: (left) a single Gz quadran(t right) the Gz coil wound using the proposed method of breaking the coil up into quadrants and then reassembling.

Table 1: Summary of the parameters for each of the axes.

	Gx	Gz
Inductance	963 μH	585 μH
Resistance	0.7431 Ω	0.4797 Ω
DSV	12.32 cm	16.82 cm
Delta	-1.16 cm	-3.41 cm
Merit	0.183	0.165
Gmax	227 mT/m	131 mT/m
SRmax	710 T/m/s	673 T/m/s
Efficiency	1.1398 mT/m/A	0.1648 mT/m/A

ACKNOWLEDGEMENTS: NIH NIBIB 5R21 EB003170-01

REFERENCES: [1] K.L. VanderWerf, et al. Hybrid Quadrupole Gradient Coil Design for MRI of the Breast. Proc. ISMRM: 852 (2005).