Implementation of High-Performance Non-linear O-space Gradient Coil for Accelerated Neuroimaging

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Target Audience: The gradient hardware, parallel imaging, and non-linear gradient encoding communities. **Introduction**: O-space imaging has demonstrated that non-linear magnetic gradients such as the Z^2 spherical harmonic enable highly accelerated parallel imaging with improved peripheral resolution.[1] Furthermore, PatLoc imaging with orthogonal non-linear gradients suggests that non-linear fields may have lower peripheral nerve stimulation through virtue of a lower dB/dt, and a gradient with the C^2 and S^2 spherical harmonics coil was tested.[2,3] The present work focuses on the design and implementation of a non-linear gradient insert capable of head imaging with high gradient strength and sequence flexibility via integration with the standard gradient amplifiers allowing analogous operation to the traditional linear gradients.

Method: The initial designs for non-linear gradient fields faced an obstacle where the strength and homogeneity of the fields differed from the target field as the measured position moved from isocenter. The non-linear gradient produces concomitant fields of a higher order with the same polarity. The imaging coil can only draw and dissipate a limited amount of power before prohibitive cost and safety limits are reached. This led to an examination of the trade-off between resistive power and homogeneity.

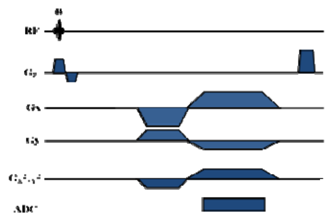

Fig. 1. The O-space approach is a gradient echo projection imaging sequence with three readout channels,

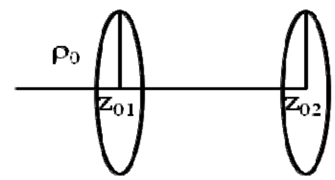

Fig. 2. A sample diagram of two Z^2 wire winding locations is shown. The locations of the windings were optimized based on resistive power and field inhomogeneity. Large gauge wire (AWG #10) was used instead of copper sheets to deliver power (625 W).

Field Purity Levels within Coil

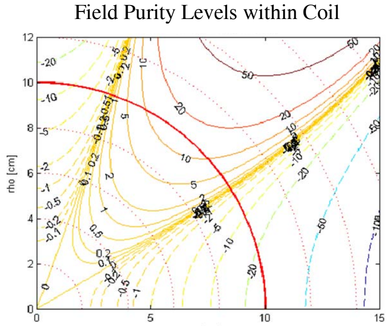

Fig. 3. Inhomogeneity levels within the 20 cm bore of the gradient insert were suppressed to approximately 10% of the nominal field.

Resistive Power vs. % Inhomogeneity

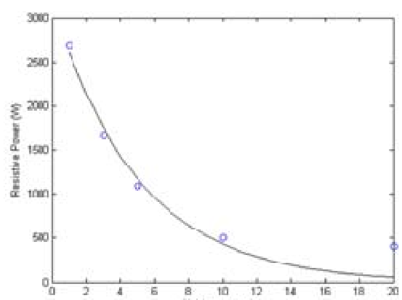

Fig. 4. Inhomogeneity suppression for the Z^2 fields comes at the cost of increasing power and windings and with diminishing returns.

Contrast phantom and *in vivo* images at:

R1 R2 R4 R8

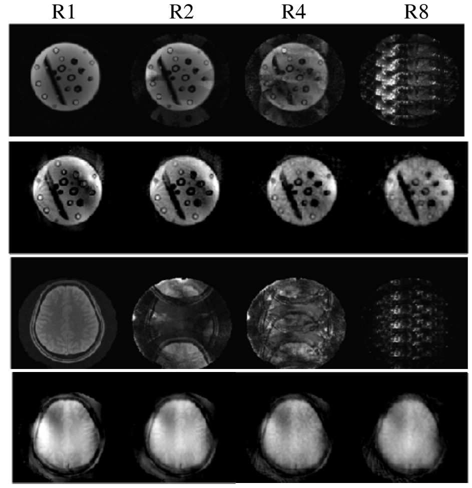

Fig. 6. Contrast phantom and first *in vivo* head images (pair-wise SENSE/O-space, top and bottom respectively) at varying acceleration factors. Images were taken at matrix size = 128x128 (contrast phantom), 256x256 (head). TR=100 ms. TE = 5.5 ms. Hz/px = 390. Num. coils = 8. FOV = 250 mm. Slice thickness = 3 cm. Inhomogeneities in the head images affected Cartesian SENSE more adversely than O-space.

Reference (top) and Simulated Multi-slice Brain Image at 10% Inhomogeneity (bottom)

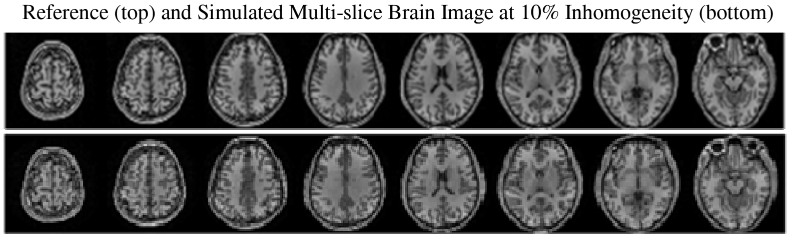

Fig. 5. A 128x128x8 numerical phantom reconstructed at R_z=2, R_y=4 gave accurate reconstructions (MSE =0.0248) with 10% inhomogeneity contingent on incorporation of field deviations into the reconstruction.

For the optimization function, the base strategy was a proprietary version of Powell's method (Resonance Research, Inc. Billerica, MA, USA), an unconstrained conjugate direction minimization.[4] For the Z^2 winding (fig. 2), independent variables were the location of the coil windings, e.g. (ρ_0, z_{01}), (ρ_0, z_{02}), etc. Once a winding pattern was created, simulations evaluated imaging quality at selected inhomogeneity levels. The coil was integrated with a 3T Trio (Siemens AG, Erlangen, Germany) via a master-slave set of gradient amplifiers and controllers.[5,6]

Results: The acceptable power gave a 10% inhomogeneity from nominal strength (fig. 3) as it was found that the homogeneity could be increased, but at the expense of a resistive power curve with diminishing returns (fig. 4). Simulations confirmed imaging quality was feasible given precise knowledge of the field deviations from nominal specifications (fig. 5). Imaging with a contrast phantom and a human head (fig. 6) showed successful integration of the new system with existing hardware and software.

Discussion: The present study reports preliminary success in the implementation of a non-linear gradient head insert with requisite field purity. Further investigations seek to utilize the advantages of non-linear encoding for fast neuroimaging, for example using parallel echo planar imaging.

References: [1]Stockmann et. al. Magn Reson Med. 2010. 64: p. 447-456. [2]Hennig, et. al. ISMRM 2007, 453. [3]Zaitsev, M. et. al. ISMRM 2012, 2579. [4]Powell, M. Comp. J. 7: 155-162. [5]Fontius, U. et. al. ISMRM 2006: 127. [6]Kim, S-E, et. al. ISMRM 2009, 1372.

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