First O-Space images using a high-power, actively-shielded, 12-cm Z2 gradient insert on a human 3T scanner

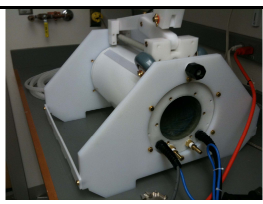
J. P. Stockmann[1], G. Galiana[2], L. Tam[1], T. Nixon[3], and R. T. Constable[1,2]

[1]Biomedical Engineering, Yale University, New Haven, CT, United States, [2]Diagnostic Radiology, Yale University, New Haven, CT, United States, [3]Diagnostic Radiology, Yale University, New Have, CT, United States

INTRODUCTION: MR imaging using nonlinear gradients has recently attracted attention for its potential to achieve faster gradient switching without violating safety limits [1], for its spatially-varying resolution that can be tailored to a region of interest, and for improved parallel imaging using gradient shapes that are complementary to RF coil profiles [2]. Proposed nonlinear imaging schemes include a phase encoding trajectory using a pair of multi-polar gradients (PatLoc) [1], a projection method in which a quadratic gradient is played while linear gradients traverse a radial trajectory (O-Space) [2], and an approach in which pairs of linear and second-order gradients each traverse alternating radial-like trajectories (4D-RIO) [3]. It has also been argued that linear combinations of higher-order spherical harmonics can be chosen so as to efficiently encode information residing in the null space of a given multi-channel RF coil array [4]. In this work, we present the first O-Space images obtained using a custom 12-cm diameter gradient insert capable of generating a powerful field varying as $Z^2 – ½ (X^2+Y^2)$, the spherical harmonic denoted "Z2". This proof-of-concept paves the way for future work with O-Space imaging, which has been shown in simulations to outperform conventional parallel imaging at a variety of acceleration factors [2].

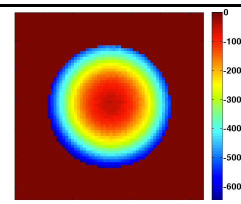
HARDWARE: An actively-shielded, liquid-cooled Z2 gradient insert with a 12-cm bore was designed by Resonance Research, Inc. (Billerica, MA) to conform mechanically with a 3T Siemens Trio patient table (Erlangen, Germany). The gradient coil is driven by a Techron Model 8606 amplifier (Elkhart, IN) capable of supplying up to 120 amps of current, corresponding to 14.5 KHz/cm^2. The amplifier is controlled by a Dynamic Shim Updating system that was originally designed to update shims on a slice-by-slice basis [5]. The DSU controller updates previously stored gradient strengths using TTL pulse triggers called during a FLASH pulse sequence. A birdcage RF coil was adapted to fit within the gradient insert.

CALIBRATION: Field mapping was performed by applying Z2 pulses ranging in duration from 0 to 900 µsec in between RF excitation and readout in a FLASH sequence. The frequency at each voxel was calculated as the slope of the phase across the 10 images. A least squares fit was performed to quantify all concomitant spherical harmonics up to third order. Field mapping was repeated at 1% intervals over the range [-3%, +3%] and the response was found to be highly linear. At higher gradient strengths, field mapping could not be performed due to intra-voxel dephasing. Instead, amplifier current was monitored via oscilloscope over the entire operating range to verify linearity. Eddy currents induced by the Z2 gradient coil were assessed in two ways. First, the Z2 field was switched off at a range of time intervals just prior to RF excitation in a FLASH sequence and the resulting phase images were compared to reference images acquired without Z2 pulsing. In the second approach, due to Duyn [6], two readouts were acquired: one with the Z2 played as both slice select and readout gradient, and the other with the Z2 played only as slice select gradient. The former readout is divided by the latter, leaving only the phase evolution imparted by the Z2 gradient. The derivative of the unwrapped phase provides an estimate of the gradient field evolution over time. In both experiments, eddy currents were found to be negligible, a result attributable to the active shielding incorporated into the gradient coil design and the significant distance between the Z2 coil and the cryostat.

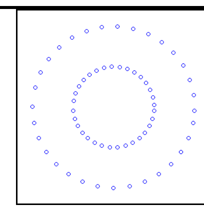


Actively-shielded 12-cm Z2 gradient insert able to generate field strengths up to 14.5 KHz/cm^2 at 3T when paired with a Techron Model 8606 amplifier.

Gradient insert mounted on the 3T Siemens Trio patient table with receiver coil hardware in place.



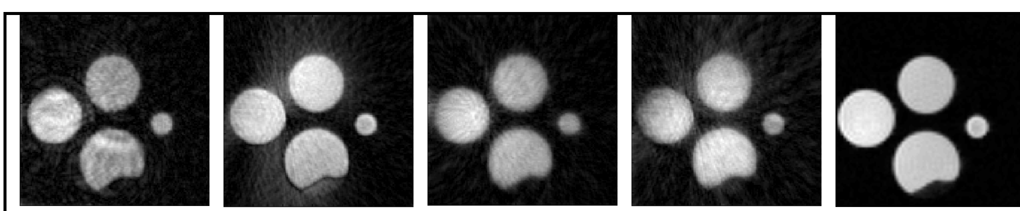
Axial-slice field map in Hz with Z2 coil set to 290 Hz/cm^2 (2% of max), showing a slight offset between the Z2 and magnet isocenters.



Center Placement (CP) scheme showing the location of the quadratic field used to encode during each readout.

IMAGING EXPERIMENTS: In O-Space imaging, the quadratic gradient plays a dephasing pulse and then a constant amplitude rephasing pulse, forming a projection of the object along concentric rings. The linear gradients play out two interleaved undersampled radial trajectories, each with different k-space coverage. This combination of gradients has the effect of translating the quadratic field to a different position in the FOV during each readout. Data were acquired using a water bottle phantom with undersampling factors of R=2 and R=4 as compared with a conventional fully-sampled Cartesian dataset. The encoding matrix was specified using all measured concomitant fields up to third-order. Since the encoding matrix is too large to fit in computer memory, image reconstruction was performed on a line-by-line basis using the algebraic reconstruction technique, also known as the Kaczmarz algorithm [7].

DISCUSSION: O-Space images at both R=2 and R=4 show fewer streaking artifacts than images from equally undersampled radial trajectories, owing to the more incoherent nature of overlapping quadratic frequency isocontours. However, careful calibration was required to obtain usable images, highlighting the sensitivity of nonlinear projection imaging to errors in the assumed field strength, as shown previously in [2] and [3]. To explore parallel imaging with the Z2 gradient, a compact 8-channel RF transceive array is now being built. Efforts are also underway to improve the accuracy of field mapping, which was found to be sensitive to the through-plane phase evolution imparted by the Z^2 field variation during acquisition of axial-slice images.



O-Space 64-CP | Radial 64-CP | O-Space 32-CP | Radial 32-CP | Fully-sampled GRE Reference image

128×128 axial-slice O-Space and radial trajectory images using single-channel birdcage coil data. Undersampling artifacts appear more pronounced in the radial images, suggesting that projection imaging with nonlinear gradients may produce less coherent artifacts than comparable trajectories using only linear gradients.

ACKNOWLEDGEMENTS: The authors wish to thank Piotr Starewicz and William Punchard at Resonance Research, Scott McIntyre and Peter Brown at Yale, and Anna Welz at Freiburg University. Grant support comes from NIH BRP R01 EB12289-01.

REFERENCES: [1] Hennig J *et al*. MAGMA 2008;21:5-14. [2] Stockmann JP *et al*. MRM 2010;64(2):447-456. [3] Gallichan D, ISMRM 2010 #547. [4] Tam L, ISMRM 2010 #2868. [5] Blamire AM *et al*. MRM 1996;36(1):159-65. [6] Duyn JH *et al*. J Mag Res, 1998;132:150-153. [7] Herman GT *et al*. Comput Biol Med 1976;6:273-294.