In vivo O-Space imaging with a dedicated 12 cm Z^2 insert coil on a human 3T scanner using phase map calibration

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INTRODUCTION: Spatial encoding magnetic fields (SEMs) with nonlinear shapes have recently drawn attention for their potential to achieve faster gradient switching within safety limits, tailored resolution in regions of interest, and improved parallel imaging using encoding fields that complement the sensitivity profiles of RF receive arrays. Proposed methods can broadly be divided into those that employ phase encoding (PatLoc [1] and COGNAC [2]) and those that acquire nonlinear projections (O-Space [3], Null Space Imaging [4], and 4D-RIO [5]). Projection methods typically reconstruct images using iterative algorithms [3,5] to backproject the data by exploiting the full encoding matrix. For this reason, they are more sensitive than phase encoded methods to systematic errors introduced by imperfect knowledge of the encoding trajectory. In the present work, voxel-wise phase evolution is mapped at each acquired point in an O-Space trajectory using a variant of chemical shift imaging, capturing all spin dynamics caused by field strength, eddy currents, and timing, providing a recipe for projection imaging with nonlinear fields.

HARDWARE: An actively-shielded, liquid-cooled Z^2 SEM 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 coil is driven by a Techron Model 8606 amplifier (Elkhart, IN) able to up to 120 amps of current, corresponding to 14.5 KHz/cm^2. The amplifier is controlled by a Dynamic Shim Updating system originally designed to update shims on a slice-by-slice basis [6]. The DSU controller updates previously stored gradient strengths using TTL pulse triggers from the scanner console. An eight-channel transmit-receive was built using stripline elements and nested within the bore of the gradient insert, leaving a 10 cm diameter available for imaging. Coil profiles are acquired using the method in [7].

IMAGING EXPERIMENTS: Transverse (z=0) images of phantoms and human hands are acquired with approval of the Institutional Review Board of the Yale School of Medicine. The Z2 plays at the same amplitude during each readout. Linear SEMs play a radial k-space trajectory, translating the quadratic field to successive center placements lying along a ring with radius 4 cm. Radial and O-Space data are reconstructed using the Kaczmarz iterative algorithm [3] and compared to under-sampled Cartesian data reconstructed using SENSE [10]. **CALIBRATION**: Conventional methods such as field mapping provide inadequate information for high quality reconstruction. Instead, a variation of chemical shift imaging [8] (or point spread function mapping [9]) is used to provide phase maps at each point in the readout of the O-Space imaging sequence. This approach captures all spin dynamics caused by eddy currents, pulse timing, and concomitant fields. Phase maps from each receive coil are combined into a single map using a SENSE reconstruction with R=1, removing the B_1 weighting and improving SNR. The phase evolution through time in each voxel is used to estimate the frequency (slope), timing (intercept), and eddy currents (deviations from linearity). The resulting frequency maps are then least-squares fitted by polynomials up to sixth order and used to synthesize the applied Z^2 field for use in the iterative reconstruction. Eddy currents are further explored using a generalization of the approach in [11], wherein two readouts are acquired: one with the Z^2 field played as both slice select and readout gradient, and the other with the Z2 played only as slice select field. The derivative of the difference in phase between the two readouts is an estimate of the Z^2 field evolution in a hyperboloidal slice contour. Timing errors in the linear gradients are investigated by flipping the polarity of dephaser and readout lobes in a radial sequence [12].

Fig. 1 Quadratic Z2 SEM insert coil (top) and conforming home-built 8-channel transmit-receive RF coil.

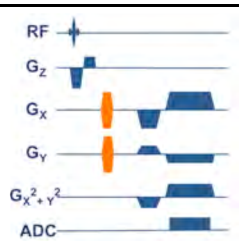

Fig. 2 In-plane phase encoding lobes (orange) are added to an O-Space imaging sequence to acquire phase maps.

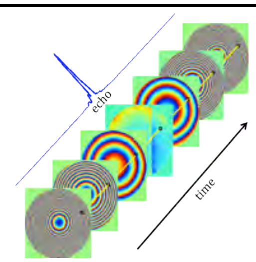

Fig. 3 Phase mapping provides phase images at each point in an O-Space readout, capturing all spin dynamics.

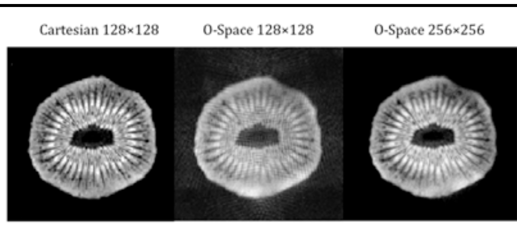

Fig. 4 The O-Space reconstruction grid must be chosen finely enough to avoid exceeding π-phase variation between neighboring voxels. The 128×128 O-Space image shows artifacts due to neighbor phase winding of nearly 2π. (FOV=6 cm)

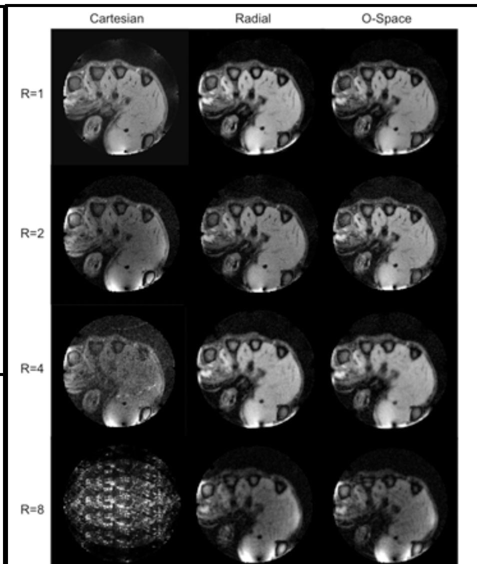

Fig. 5 *In vivo* human hand comparison of Cartesian, radial, and O-Space 256×256 images using equivalent amounts of under-sampled data. *R*=1 corresponds to 256 readouts. A B_1 inhomogeneity artifact is visible at the bottom of the hand. (FOV=10 cm)

RESULTS: Eddy currents were found to be negligible. We attribute this to the active shielding incorporated into the SEM coil design and the significant distance between the Z2 coil and the cryostat. Timing errors in the linear SEMs were found to be less than a quarter of one readout dwell time. Timing errors in the Z^2 pulse were small, but when large errors are deliberately introduced during reconstruction, they impart a quadratic phase to the object, leaving the magnitude unchanged. **DISCUSSION**: O-Space images degrade gracefully with under-sampling, exhibiting a gradual blur instead of the intense noise amplification of the Cartesian images. O-Space images are comparable in quality to under-sampled radial, but with finer resolution at the periphery, which has the most quadratic field variation. It is expected that future improvements in calibration, trajectory design, and reconstruction will preferentially benefit O-Space imaging, since radial imaging is already a mature methodology. **CONCLUSION**: We show the first experimental proof-of-concept O-Space images on *in vivo* and phantom samples, paving the way for more in-depth exploration of O-Space and other nonlinear projection imaging methods. Future work will explore imaging with a human head insert capable of generating multiple second-order SEMs. Quantitative analysis of O-Space noise and resolution properties will be performed using the methods in [13].

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