O-space Imaging: Tailoring Encoding Gradients to Coil Profiles for Highly Accelerated Imaging

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Introduction: O-space imaging is a novel MR imaging method, intended to achieve very short imaging times compared to conventional imaging, by using optimal imaging gradients with respect to coil sensitivities, thus improving the orthogonality of each acquisition. High acceleration factors are achievable in parallel imaging with proper coil designs using conventional Fourier based acquisitions with frequency and phase encoding by increasing the number of independent coil elements in the direction of acceleration, provided that coil and electronics losses and coupling are kept low [1] [2]. Rather than only optimizing the coil array for conventional phase and frequency encoding, o-space imaging selects an optimal gradient to complement the spatial localization provided by a coil array in the dimension where coil localization is poorest, to collect highly independent information thus minimize the data requirement for a certain resolution.

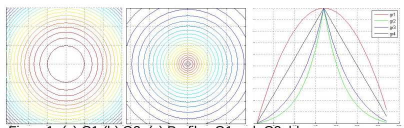

Figure1: (a) G1 (b) G2 (c) Profiles G1:red, G2: blue

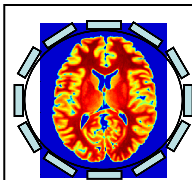

Figure2: Test image and distribution with 8 coils

We hypothesized that a radially varying gradient field may provide a good complement to a coil array that is circumferentially distributed, the gradient providing better localization in an orthogonal direction with respect to the coil localization. Spatial encoding with non-unidirectional, non-bijective fields has previously been used in conjunction with conventional phase encoding in the orthogonal direction, to overcome peripheral nerve stimulation limits, however, suffers from holes in the centers of images due to flat regions of gradients [3][4]. Another novelty in o-space imaging is disposing of conventional phase encoding in favor of alternative encoding schemes to provide spatial resolution everywhere in the FOV, where the entire encoding gradient is moved within the FOV to prevent any such regions of slowly varying gradient causing holes, resulting in projection directions that are orthogonal to coil sensitivity profiles as well as each other. The ultimate coil and gradient combination is a topic we are currently investigating.

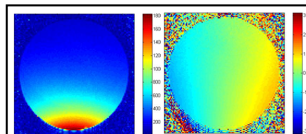

Figure3: Coil sensitivity (a) magnitude (b) phase

In this work we evaluated o-space imaging using an existing spherical harmonic gradient and a simulated gradient, with coils distributed along the circumference of the region of interest under various noise levels, and number of coil elements, and have identified superior encoding schemes (center placements). The results indicate the feasibility of high acceleration factors, where 256x256 resolution reconstruction was possible with as few as 4 echoes and 32 coils.

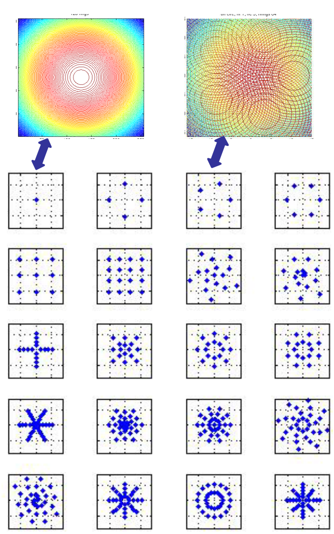

Figure4: Sample encodings/center placements

Methods: Feasibility of reconstruction was simulated under a variety of noise levels (0-10% additive Gaussian on phantom, 0-√10 on each coil), with varying number of coils (8 to 32), for various encoding schemes with a different number of center placements (1 to 32). Two gradients were evaluated under each condition: G1: the Z2 shim gradient, $z2 - ((x - x_0)^2 + (y - y_0)^2)$ (Figure 1a) currently available on our scanner; or G2: a simulated gradient (Figure 1b) which based on numerical evaluations of the Biot-Savart law. A capacitatively-shortened microstrip resonator [6] was built for signal reception with improved depth penetration over a similar sized loop. Coil sensitivity maps were acquired on a 4T MRI (Bruker Biospin, Ettlingen Germany) equipped with the capability of dynamically updating 3 first and 5 second order spherical harmonic shim gradients and one receive channel. Multiple coils were simulated by rotation of the single coil, and inductive coupling was not modeled. Data was acquired with a modified spin-echo pulse sequence without phase encoding and with a combination of X, Y and Z2 gradients for frequency encoding to achieve desired center placements, and a projection of the sample was obtained along different curvilinear paths for each center placement. The signal for each echo from each coil was $s(t) = \iint \rho(x,y)\, C(x,y) \exp(-j2\pi G t) = A\rho$

where C is coil sensitivity, and G is the gradient moved to x_0, y_0 locations for the various encoding schemes shown in Figure 4. The matrix equation was solved using the lsqr algorithm [5] as implemented in Matlab (Mathworks, Natick MA). T2 decay was not modeled.

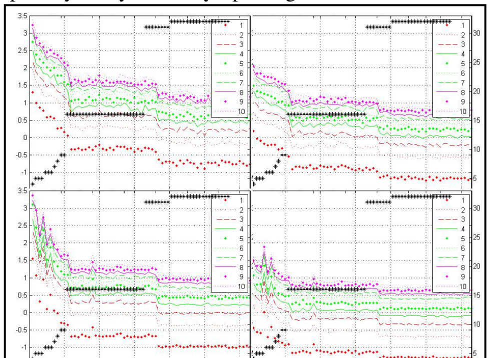

Figure5: o-space reconstruction errors (top: GR1, bottom: GR2, left: 8 coils, right: 32 coils, left axis: log10 errors, right axis: number of centers *)

Results: Sum of squared errors are shown (Figure 5) on a log scale for 8 and 32 coil arrangements, up to 10% noise, 1 to 32 centers (echoes). Reconstruction error decreases as expected with increasing number of echoes, and coils, and increases with noise. Gradient shape G2 with a sharp drop off in the center always outperforms the Z2 gradient shape (which has a sharp drop off at edges) by almost 2 orders of magnitude. While very large fluctuations were not observed within the tested encoding schemes with equal scan time, those with center placements along concentric rings perform consistently well under various conditions. Simulations show feasibility of a 128x128 reconstruction from a single channel and 17 echoes, and of a 256x256 reconstruction from 32 channels with only 4 echoes (Figures 6 and 7).

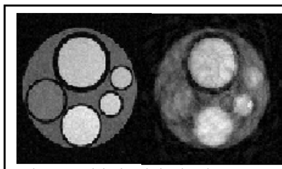

Figure6: Original and simulated recon 128X128, 1 coil, 17 echoes

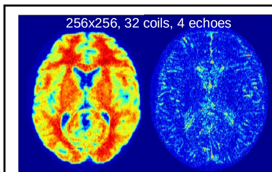

Figure7: Simulation reconstruction and error

Conclusion: We have shown the feasibility of o-space imaging, and introduced robust encoding schemes that can be used with existing coil geometries and shim gradient fields. Accurate knowledge of the field is critical to reconstruction, and preliminary acquisitions suggest some susceptibility to field deviations (Figure 8). Nevertheless, matching encoding gradients to coil sensitivity profiles holds great potential to optimize data acquisition and achieve higher acceleration rates through customization.

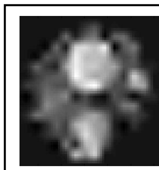

Figure8: Preliminary o-space recon of real data

References: [1] Adriany. MRM 2008; 59(3):590-7. [2] Hardy. JMRI 2008; 28(5):1219-25. [3] Hennig. Proc ISMRM 15, 2007. [4] Hennig. Magma 2008; 21:5-14. [5] Paige. ACM TMS 1982;8(1):43-71. [6] Lee. MRM 2004; 51:172-183.