3D Null Space Imaging: Nonlinear magnetic encoding gradients designed complementary to 3D coil sensitivity profiles for rapid volume imaging

Leo K Tam[1], Jason P Stockmann[1], Gigi Galiana[2], Dana C Peters[2], and R. Todd Constable[2]
[1]*Biomedical Engineering, Yale University, New Haven, CT, United States,* [2]*Diagnostic Radiology, Yale University, New Haven, CT, United States*

Introduction: Previous research has demonstrated the utility of nonlinear magnetic gradients such as the Z2 spherical harmonic for highly accelerated parallel imaging in 2D[1]. Furthermore, work using the nonlinear orthogonal gradients similar to an in-plane slice of the C2 and S2 spherical harmonics suggests that nonlinear fields may have lower peripheral nerve stimulation through virtue of a lower dB/dt[2]. Previous studies using nonlinear gradients have been performed at the isocenter with receiver coils that have near uniform Z sensitivity. This work utilizes two innovations: the Null Space Imaging (NSI) method, which designs a set of gradients complementary to parallel receiver coils for volume imaging[3], and a twisted receiver coil design to provide efficient encoding in Z. The results demonstrate that a second order NSI gradient set enables a parallel acquisition to be tailored to 3D receiver coil sensitivities for accelerated volume imaging.

Method: In the NSI approach, receiver coil sensitivity profiles are analyzed with the singular value decomposition (SVD) to yield spatial encoding gradients that localize signal where receiver coils poorly localize signal, thereby increasing encoding efficiency. In the NSI formalism, $\mathbf{C}_l \cdot \mathbf{G}_m = 0$ and $\mathbf{G}_i \cdot \mathbf{G}_j = \delta_{ij} \mid i, j \in (1, M)$, where $\mathbf{G}_i$ are imaging gradients that are vectorized 3D volumes and dot product orthogonal to the coil sensitivities and to each gradient shape. The Lanczos SVD of the gradient shapes provides the dominant components by eigenvalue[4]. Combinations of second order spherical harmonics gradients (common names: X, Y, Z, C2, S2, ZX, ZY, and Z2) were used to approximate dominant components through a least squares fit (Fig.1). The set of gradients composed of different mixtures of spherical harmonics were used as volume projection imaging gradients. The receiver coil sensitivity profiles were simulated for a microstrip receiver coil design with a novel twisted stripline design to generate a rotation in the receiver coil sensitivity profiles as one moves along Z (Fig.2). For this study, the first 32 components are selected corresponding to an equivalent acceleration factor of Rz =4, Ry =8 for a 32x32x32 isotropic volume (not pictured) or 64x64x8 volume. Whole body noise was injected at 5% level. Reconstruction of the volume from a spin echo sequence using one gradient shape per echo was performed with the Kaczmarz iterative algebraic reconstruction technique[5].

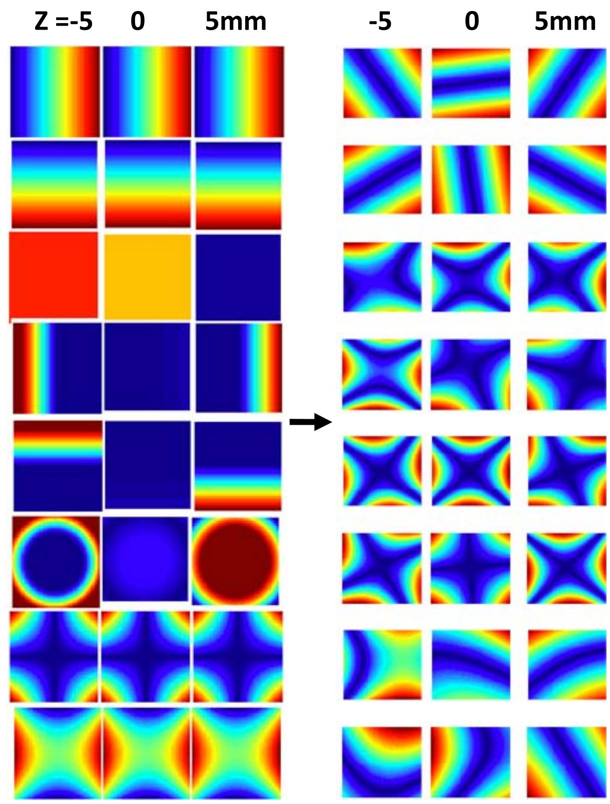

Figure 1. (Left) The first and second order spherical harmonics at increasing z distance, by common name: X, Y, Z, XZ, YZ, Z2, XY, and C2. (Right) The first 8 imaging gradients at different z slices as found by the NSI method.

Results: Reconstructed 3D volumes compare NSI and Cartesian 2D SENSE on an 8 slice volume reconstruction. The Cartesian SENSE reconstruction amplifies noise as the acceleration factor exceeds the number of coils. The simulations demonstrate that NSI reduces the mean-sum-squared-error (MSE) compared to Cartesian SENSE (NSI = 0.0248 versus SENSE = 0.0807 at Rz = 4, Ry = 4) for the 8 slice acquisition. The Cartesian SENSE cannot exceed R = 4 in any given dimension as noise amplification becomes problematic.

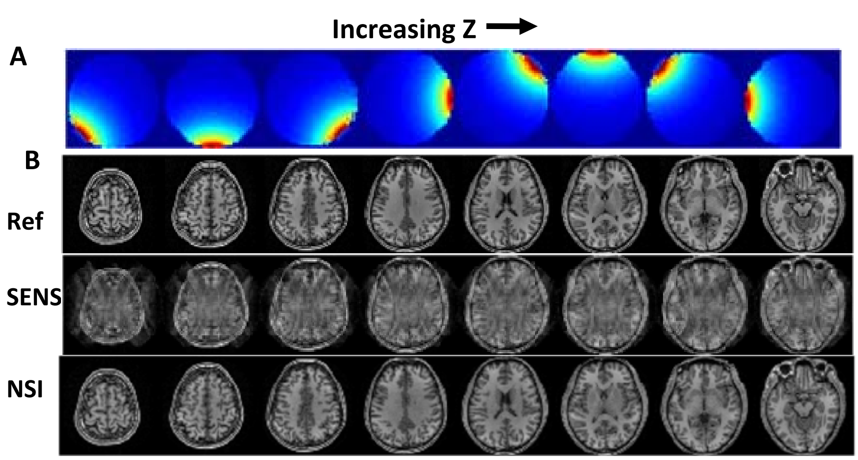

Figure 2. (A) As the z slice direction is traversed, the receiver coil sensitivity for a single channel rotates relative to the center. (B) An 8 slice brain reference phantom reconstructed to 64x64x8 at an equivalent Rz = 4, Ry = 8 (MSE = 0.0248) using NSI gradients as shown in Fig. 1 (right). Below is an Rz = 4, Ry = 4, Cartesian SENSE reconstruction (MSE = 0.087).

Discussion: The present study demonstrates the utility of nonlinear gradients to complement receiver coil sensitivities in 3D parallel imaging. Using nonlinear gradients leads to projection imaging gradients adapted to the 3D variation in the receiver coil sensitivities. While there remains a tradeoff between number of slices and resolution, the NSI method shows an effective way to reach accelerations greater than those achievable with Cartesian SENSE.

References: [1]Stockmann et. al. Magn Reson Med. 2010. 64: p. 447-456. [2]Hennig, et. al. ISMRM 2007, 453 [3]Tam L.K.., et al., ISMRM., 2010, p.2868. [4]Golub, G. *Matrix Computations*, pg 456-457. [5]Herman G.T. et. al. J. Theor. Biol. 42:1. [6]Lee, RF, et. al. Magn. Reson. Med 2004; 51:172.

Acknowledgements: This work supported by NIH BRP R01 EB012289-01 and a National Science Foundation Graduate Research Fellowship.