

Magnetic Gradient Shape Optimization for Highly Accelerated Null Space Imaging

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Introduction: Previous research has demonstrated the utility of non-linear magnetic gradients such as the Z2 spherical harmonic for highly accelerated parallel imaging.¹ Furthermore, work using the non-linear orthogonal gradients similar to the C2 and S2 spherical harmonics suggests that non-linear fields may have lower peripheral nerve stimulation through virtue of a lower dB/dt .² In the present work, we present a systematic study of possible higher order gradients shapes that could be used for Null Space Imaging (NSI), a technique based on designing gradient encoding schemes complementary to parallel receiver coils spatial encoding.³ All combinations of sets of spherical harmonics through the fourth order and additional combinations such as those focused on orthogonal gradients (eg. C2 and S2 together with linear terms) were considered: a total of 21 combinations. This work demonstrates that a combined linear and second order gradient set (C2, S2, and Z2) is optimal for NSI imaging.

Method: NSI theory states that by analyzing the receiver coil sensitivity profiles with the singular value decomposition (SVD), spatial encoding gradient shapes can be designed which spatially localize signal in regions where parallel receive coils poorly localize signal. In the NSI formalism, $\mathbf{C}_i \cdot \mathbf{G}_m = 0$ and $\mathbf{G}_i \cdot \mathbf{G}_j = \delta_{ij} \mid i, j \in (1, M)$, where the imaging gradients are vectorized and dot product

orthogonal to the coil sensitivities and each other. Eight coil sensitivities were simulated from a microstrip array.⁴ When the SVD of \mathbf{C}_i is taken ($\text{svd}(\mathbf{C}) = \mathbf{U}\mathbf{\Sigma}\mathbf{V}^+$) the columns in \mathbf{V} after the initial L columns in \mathbf{V} , where L is the total number of coils, are constructed iteratively by the SVD and fulfill the first two conditions. The imaging gradient shape is the phase of the columns in \mathbf{V} . The Lanczos SVD of the gradient shapes provides the dominant components by eigenvalue.⁵ Combinations of the non-degenerate in-plane spherical harmonics through fourth order were used to approximate dominant components through a least squares fit (fig.1). For this study, the first four and eight components are selected corresponding to an acceleration of $R = 32, 16$ respectively for a 128×128 image. Whole body noise was injected at 5%. Reconstruction of the image from a spin echo sequence using one gradient shape per echo projection imaging was performed with the Kaczmarz iterative algorithm, an algebraic reconstruction technique.⁶

Results: From the possible combinations of spherical harmonics when taken by order (eg. second orders alone, second and third orders, etc.), and additional combinations such as orthogonal gradients (linear terms with C2 and S2, linear terms with C2, S2, C4, and S4, linear terms with Z2, etc.), the best combination were the first, third, and fourth order together (linear terms, Z2X, Z2Y, X3, Y3, Z4, Z2C2, Z2S2, C4, and S4) and the best combination restricting to second order and lower gradients were the first and second orders together (linear terms with Z2, C2, and S2). The recons shown in fig. 2 compare four of the gradient sets of interest. Here, the linear gradients exhibit the greatest sum of squared error (SSE), while the first and second order set has slightly more SSE than the linear with third and fourth order.

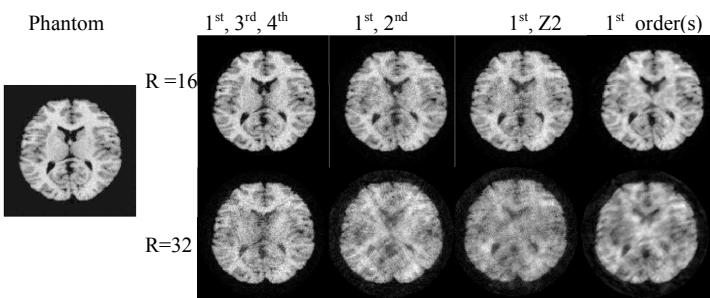


Figure 2. Pictured from left to right: Reference phantom; 1st, 3rd, and 4th order gradients; 1st and 2nd order gradients; linear terms with Z2 gradients; and linear terms (radial) NSI acquisitions at R = 16 and to push the limits of the method, R = 32. SENSE cannot be performed at acceleration factors greater than the number of receiver coils (R=16) and the radial comparison is shown instead.

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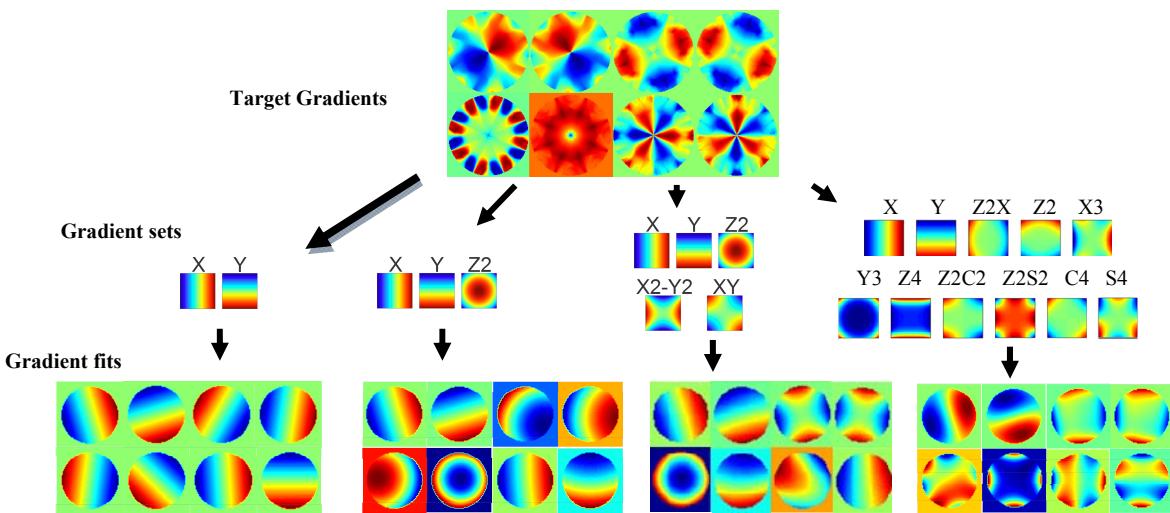


Figure 1. In NSI, a set of target imaging gradients are created tailored to receiver coil profiles. The target gradient shapes are approximated with sets of physical realizable spherical harmonics. Simulations are shown below for four strong performers.

Discussion: The present study empirically demonstrates the tradeoffs of using higher order nonlinear gradients during readout. Using only higher order gradient shapes leads poor encoding at the center of the image. A gradient set composed of the linear gradients along with higher order gradients captures image information and generates low SSE. A first and second order NSI gradient system exhibits low SSE at R=16 while retaining a manageable number of gradients channels.

References: ¹Stockmann et. al. Magn Reson Med. 2010; 64: p. 447-456. ²Hennig, et. al. ISMRM 2007, 453. ³Tam L.K., et al., Proc. Int'l. Soc. Magn. Reson. Med., 2010, p.2868. ⁴Lee, RF, et. al. Magn. Reson. Med 2004; 51:172. ⁵Golub, G. *Matrix Computations*, pg 456-457. ⁶Herman G.T. et. al. J. Theor. Biol. 42:1.