Efficient "O-Space" Parallel Imaging with Higher-order Encoding Gradients and No Phase Encoding

J. P. Stockmann[1], P. A. Ciris[1], and R. T. Constable[2]

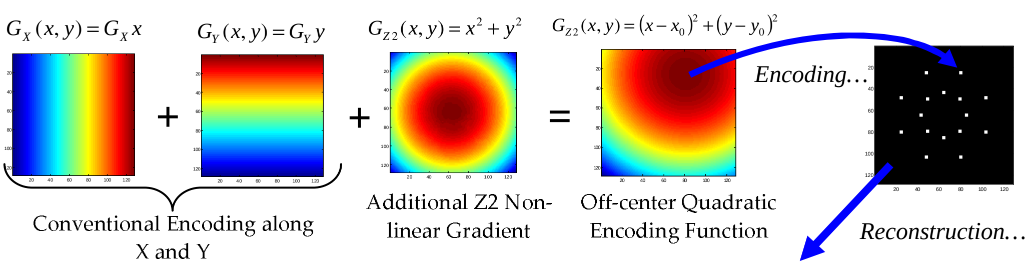
[1]Biomedical Engineering, Yale University, New Haven, CT, United States, [2]Diagnostic Radiology & Neurosurgery, Yale School of Medicine, and Biomedical Engineering, Yale University, New Haven, CT, United States

INTRODUCTION: Parallel imaging methods take advantage of the combined spatial information of gradient encoding fields and surface coil profiles to reconstruct images from undersampled k-space datasets [1]. Recent improvements in parallel imaging performance have been driven by the use of ever-greater numbers of independent surface coils to limit the degree of aliasing at high acceleration factors [2]. This work takes a different approach to enhancing accelerated imaging by tailoring the shape of the gradient encoding fields so as to best exploit the information in the coil profiles. For circumferentially distributed coils around a FOV, a radially-symmetric gradient complements the coil array better than a linearly-varying gradient. Higher-order gradient shapes may also allow for faster gradient switching times due to the reduced $\Delta B0$ excursion over the FOV [3]. In principle, optimal gradient shapes can be constructed from spherical harmonics or any other set of basis functions satisfying Laplace's equation. For purposes of this abstract, we demonstrate the concept using a combination of first order gradients and the Z2 spherical harmonic. The Fourier transform of an echo obtained in the presence of a radially symmetric gradient yields a projection of the object onto a set of rings centered on the applied readout gradient. Instead of conventional phase encoding, multiple echoes are acquired with different center placements (CP's) of the higher-order gradient, hence different projections of the object onto another set of rings.

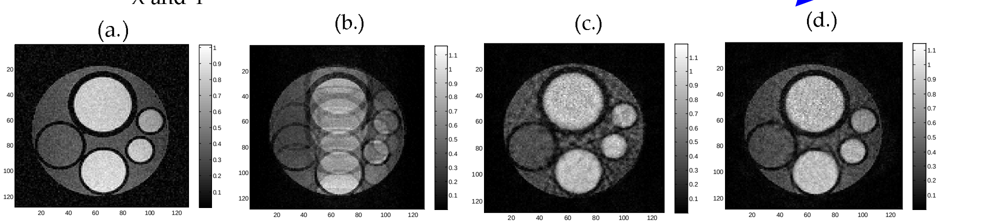
METHODS: The radially-symmetric quadratic shape of the Z2 gradient can be translated around the FOV using linear gradients and a B0 offset to complete the square. We simulate the spin echo experiment show below, in which different combinations of the X and Y gradients create projections of the object onto frequency isocontour rings concentric about a particular CP in the FOV. The isocontours of each pair of CP's are not orthogonal everywhere in the FOV. However, the condition of gradient orthogonality is compromised in order to make the gradients better tailored to the coil profiles, improving the overall hybrid encoding function. Projections are simulated for the t^{th} echo time point, n^{th} surface coil, and m^{th} CP:

$$s_{m,n}(t) = \iint \rho(x,y) C_n(x,y) e^{-j2\pi G\left((x-x_m)^2+(y-y_m)^2\right)t} dxdy = A_{m,n,t}\rho$$

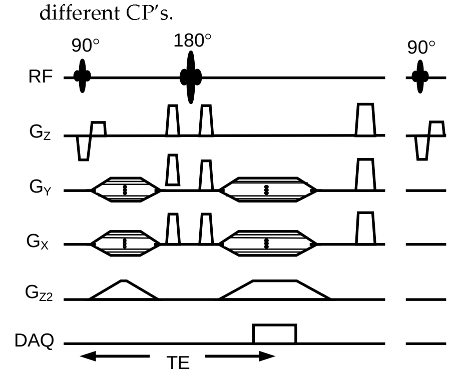
The integral equation is solved directly for the object $\rho(x,y)$ using the Kaczmarz iterative algorithm – also known as ART, or Algebraic Reconstruction Technique – a method often used in CT and cryo-EM. Kaczmarz is advantageous in that it can handle any encoding function, represented here by the projection matrix $A_{m,n,t}$. Because our integral kernel does not have the form of a Fourier Transform, it does not map the object into k-space in the traditional sense, preventing the use of density compensation and regridding methods used in non-Cartesian MRI.



LEFT: The Z2 shim field is shifted off-center using a combination of linear encoding gradients. **NEAR LEFT:** CP's are chosen within the FOV so as to make the isocontours of each pair of functions as orthogonal as possible. **BELOW**: A spin echo sequence that performs o-space projection imaging. Different X and Y gradient strengths correspond to different CP's.



ABOVE: Using the Kaczmarz algorithm, 128x128 images are reconstructed from a reference image (a.) using three different 8-fold undersampled simulated datasets with 8 surface coils: Cartesian k-space data with 16 phase encode lines (a.), radial k-space data with 16 spokes (c.), and o-space with 16 CP's (d.).



In order to avoid radial aliasing in o-space, the sampling BW and Z2 gradient strength, G_{Z2}, must be chosen so that the outermost frequency ring does not fall within the object for a particular CP: $r_{\max} = \sqrt{BW / G_{Z2}}$

DISCUSSION: The o-space reconstruction displays better resolution and fewer artifacts than the corresponding radial k-space reconstruction. Since the radial k-space data is essentially what the o-space would become if the Z2 were removed, valuable spatial information is indeed provided by the inclusion of the Z2 gradient. Experimental data is presently being sought on a system equipped with a dynamic shimming unit which allows the shim coils to be dynamically pulsed during an acquisition [5]. Overall this work represents a novel approach to enhancing the efficiency of parallel imaging by designing the spatial encoding gradients to provide maximally complementary information relative to the coil encoding.

REFERENCES: [1] Pruessmann KP *et al.* MRM 1999;42:952–62. [2] Wiggins CG *et al*. Proc. ISMSM 2008, p. 1075. [3] Hennig J. *et al.* MAGMA 2008;21:5-14. [4] Herman GT and Lent A. Comput. Biol. Med. 1976;6:273-294. [5] De Graaf RA et al. MRM. 2003;49:409-416.