Accelerated imaging of sub-volumes using region-of-interest focused O-Space: Experimental verification of rOi-Space

Kopanoglu E, Wang H, Peters DC, Galiana G, Constable RT
Diagnostic Radiology, Yale University, New Haven, CT, USA.

Synopsis

rOi-Space, which is a region-of-interest imaging technique, was demonstrated experimentally and compared to Radial imaging. The proposed method uses a nonlinear gradient field for improved accelerated imaging similar to O-Space but focuses the encoding effort to the region-of-interest rather than imaging the whole field-of-view. Simulations showed up to 70% reduction in reconstruction error compared to Radial, for acceleration factors around 4. Noise performance comparisons demonstrated degraded noise performance due to intra-voxel dephasing. Experiments showed improved resolution inside the ROI at the expense of noise performance. Hence, the method can be used for resolution enhancement in applications with adequate SNR.

Purpose

Nonlinear gradient fields (NLGFs) offer many advantages such as accelerated imaging[1-3], reduced SAR[4], improved excitation fidelity[5], curved-slice imaging[6], reduced peripheral nerve stimulation[7], motion navigation[8] peripheral resolution enhancement[9] and region-specific imaging[10]. O-Space imaging uses a second-order NLGF during readout for improved accelerated imaging, which results in a fairly uniform encoding over all field-of-view (FoV)[11]. Last year, we proposed an adaptation of O-Space imaging for region-of-interest (ROI) imaging[12]. Here, we compare the method to Radial and O-Space imaging techniques via simulations and experiments in terms of resolution, noise-performance and image quality.

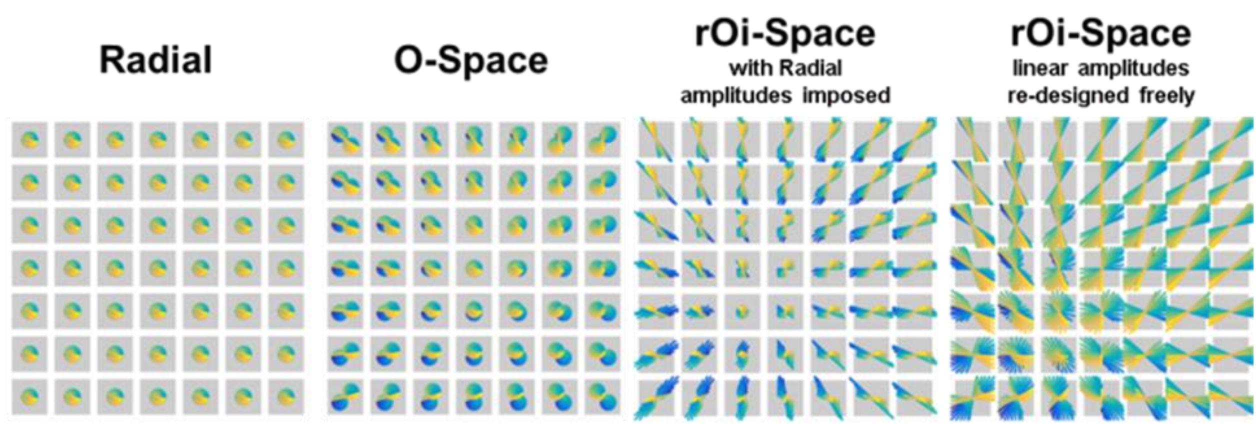

Figure 1: *Comparison of local k-space. Color coding indicates order of acquisition. Re-designing the LGF amplitudes (right-most) improves the local k-space coverage inside the ROI (Figure 2f) with respect to both Radial and O-Space as well as using the Radial amplitudes and designing the NLGF amplitude instead (middle-right).*

Methods

In O-Space imaging, a trapezoidal Z2-gradient waveform with constant amplitude is applied simultaneously with a Radial sequence to places the center of the NLGF (center-placements, CPs) at uniformly distributed points on a circle enclosing the FoV. In rOi-Space, the center is shifted to points on a boundary with a non-trivial shape, hence, the ratio between the two LGF amplitudes ($\frac{G_{max}x_0}{\max(x_0,y_0)}$ and $\frac{G_{max}y_0}{\max(x_0,y_0)}$) may vary significantly, hampering encoding along one direction (Figure 1). Therefore, we fixed the NLGF to 200mT/m/m so that the maximum field amplitude and field slew-rate generated inside a $(20\text{ cm})^3$ FoV are smaller than those generated by the 40 mT/m, 140 mT/m/msec gradient coils of the scanner available at the research center. Note that, the designed LGF amplitudes may exceed those in Radial, as will be discussed.

Simulations were performed in Matlab (Mathworks Inc., Natick, MA, USA). Images were reconstructed using Kaczmarz with 5 iterations, $\lambda = 0.75$, and random-ordering. In noisy simulations, the standard variation of the noise was adjusted to be 1.7% and 7% of the maximum intensity of the brain data. Center-placements were performed as outlined in [12].

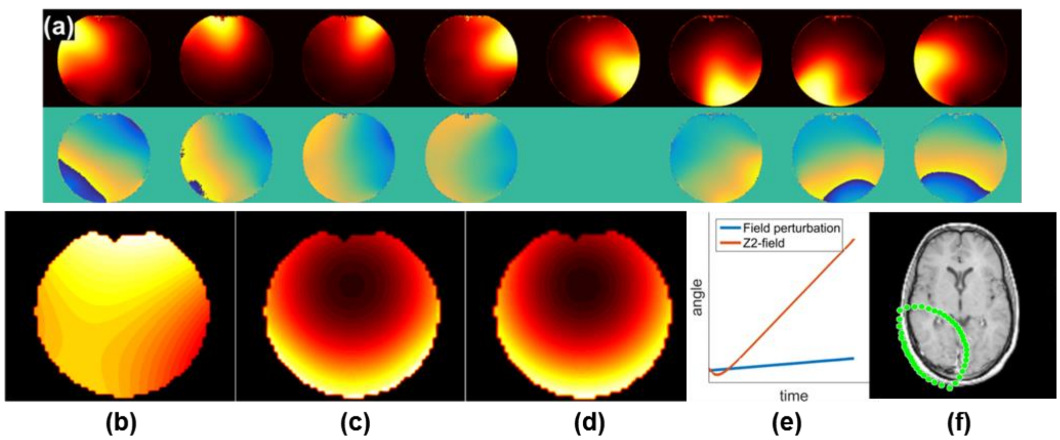

Figure 2: ***(a)*** *RF sensitivity maps (top: magnitude).* ***(b-e)*** *The field measured in the absence of the Z2-field (b) was subtracted from that measured in the presence (c) to characterize the Z2- field (d). Spatial and temporal mapping was performed on (b) and (d) to incorporate in reconstruction (e).* **(f)** Region-of-interest shown on brain-data.

Experiments were performed on a 3T scanner with an 8-channel head coil (Siemens Healthcare, Erlangen, Germany), using a nonlinear gradient insert (Resonance Research Inc., Billerica, MA, USA) and a cylindrical contrast phantom (J7239, JM Specialty Parts, San Diego, CA, length: 172 mm, diameter: 203 mm). Parameters were; FoV, $(256\text{mm})^2$, projections/CPs, 256; samples during full-echo readouts, 256; bandwidth, 80Hz/px; Kaczmarz reconstruction with 5 iterations and $\lambda = 0.02$. The NLGF amplitude was gradually increased such that center-placement radii ranged between 9.6 cm and 51.2 cm, with the center of the FoV being the center of the circular region-of-interest. The Z2-field was characterized using a slice-selective sequence with phase-encodes in both in-slice direction (Figure 2). B0-inhomogeneity was measured to be 0.7% as strong as the Z2-harmonic for CP radius of 12.8cm. In both simulations and experiments, experimentally obtained sensitivity maps[13] of the 8-channel coil were used (Figure 2). Because of the additional winding caused by the NLGF in rOi-Space, local encoding frequencies may exceed the Nyquist rate, and lead to intra-voxel dephasing. To account for this, the spatial encoding functions generated by the magnetic fields were averaged on a 7x7 higher density sampling grid.

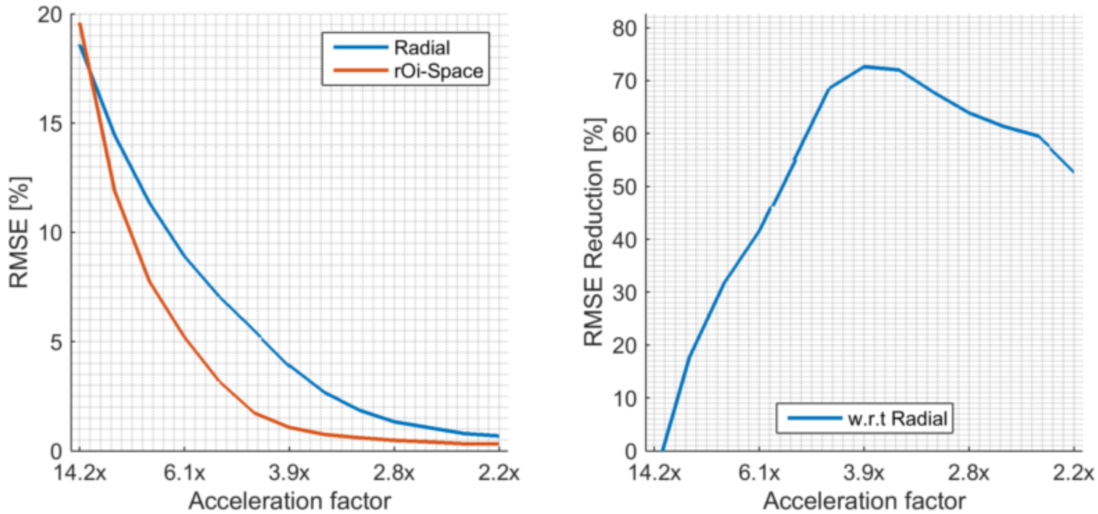

Figure 3: Left: *Root-mean-squared-error (RMSE) values were calculated inside the ROI (Figure 1f) for Radial and rOi-Space for acceleration factors between 2.2x and 14.2x.* ***Right:*** *The RMSE reduction in rOi-Space with respect to Radial.* FoV, (200mm)^2; resolution, 192x192; samples during full-echo readouts, 512; bandwidth, 200Hz/px, NLGF amplitude, 200 mT/m^2.

Results

Radial and rOi-Space were compared using simulations for various acceleration factors (Figure 3), demonstrating the efficiency of the proposed method in focusing the encoding effort into the ROI. For 3.9x acceleration, the root-mean-squared error calculated inside the ROI was reduced by more than 70%, compared to Radial.

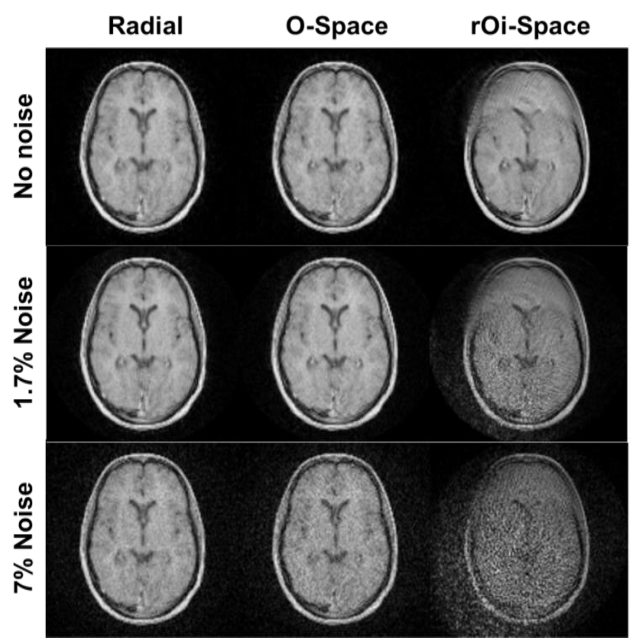

Figure 4: *Comparison of noise performance. Because of the additional winding in rOi-Space due to the additional fields, intra-voxel dephasing leads to SNR degradation.* FoV, (200mm)^2; resolution, 128x128; samples during full-echo readouts, 512; bandwidth, 200Hz/px, NLGF amplitude, 200 mT/m^2

When the linear gradient fields can be adjusted freely by the algorithm, the local k-space coverage is enhanced in the target region with a more homogeneous coverage in all directions (Figure 1). Intra-voxel dephasing leads to a degradation in signal-to-noise ratio as expected (Figure 4).

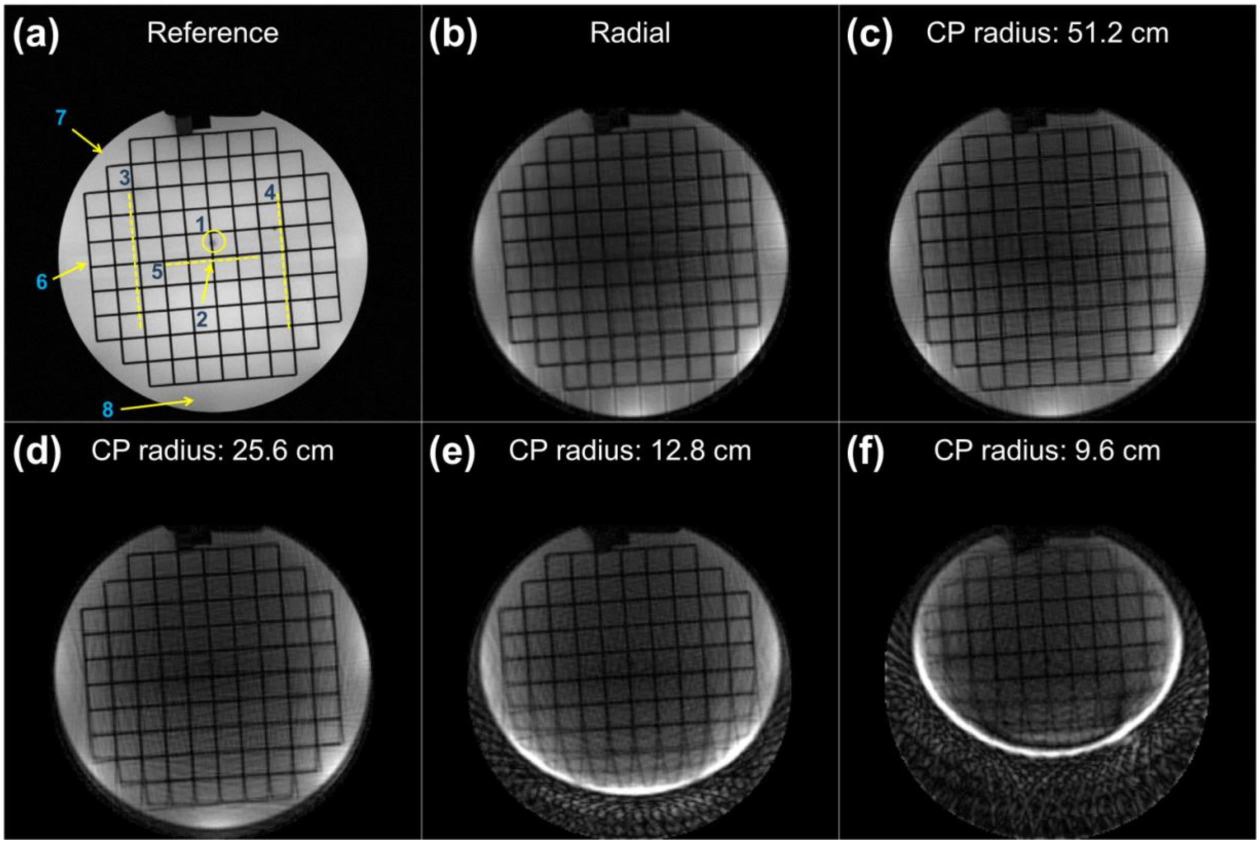

Figure 5: *In the experiments, rOi-Space center-placements were gradually brought closer to the center of the field-of-view by increasing the amplitude of the nonlinear gradient field. Indicated image details compare different methods: 1) detail, 2) intersection of gridlines, 3-5) straight lines, 6) intersection of gridlines, 7-8) homogeneous regions.*

Experimental results (Figure 5) show that at an acceleration factor of 4, Radial images show blurring of detail (1-2,5-6), incorrect reconstruction of straight lines (3-4) and artificial reconstruction of grid in homogeneous regions (7-8). As the nonlinear gradient field is introduced (Figure 5c) some details are improved (2-4,6) while some are worsened (5). Increasing the field strength improves all details (2-8) and finally at the maximum field strength, the inner detail (1) is recovered.

Discussion

The proposed method locally improves resolution by focusing the encoding effort to the ROI. The additional encoding leads to intra-voxel dephasing, which degrades noise performance. Hence, the method improves resolution at the expense of SNR (Figure 5).

In rOi-Space, the LGF amplitudes are re-designed, and may exceed those in Radial. Hence, an rOi-Space implementation may require a longer readout than a Radial counterpart using LGFs at the limits. However, this would degrade SNR performance of Radial due to prolonged readout. Here we used longer readouts for all compared methods so that SNR performances could be compared.

Conclusion

The proposed method creates a trade-off between resolution and SNR/readout duration, and hence, can be used to improve resolution in applications with adequate SNR or that can tolerate increased readout durations.

Acknowledgements

R01-EB012289, R01-EB016978

References

1. Stockmann JP, Ciris PA, Galiana G, Tam L, Constable RT. O-space imaging: Highly efficient parallel imaging using second-order nonlinear fields as encoding gradients with no phase encoding. Magn Reson Med 2010;64(2):447-456.
2. Tam LK, Stockmann JP, Galiana G, Constable RT. Null space imaging: nonlinear magnetic encoding fields designed complementary to receiver coil sensitivities for improved acceleration in parallel imaging. Magn Reson Med 2012;68(4):1166-1175.
3. Wang H, Tam L, Kopanoglu E, Peters DC, Constable RT, Galiana G. Experimental O-space turbo spin echo imaging. Magn Reson Med 2015:n/a-n/a.
4. Kopanoglu E, Yilmaz U, Gokhalk Y, Atalar E. Specific absorption rate reduction using nonlinear gradient fields. Magn Reson Med 2013;70(2):537-546.
5. Kopanoglu E, Constable RT. Radiofrequency pulse design using nonlinear gradient magnetic fields. Magn Reson Med 2015;74(3):826-839.
6. Weber H, Gallichan D, Schultz G, Cocosco CA, Littin S, Reichardt W, Welz A, Witschey W, Hennig J, Zaitsev M. Excitation and geometrically matched local encoding of curved slices. Magnetic Resonance in Medicine 2013;69(5):1317-1325.
7. Hennig J, Welz AM, Schultz G, Korvink J, Liu Z, Speck O, Zaitsev M. Parallel imaging in non-bijective, curvilinear magnetic field gradients: a concept study. MAGMA 2008;21(1-2):5-14.
8. Kopanoglu E, Galiana G, Constable RT. Motion Navigation using Non-Linear Gradient Fields. 2015; Toronto, Canada. p 3674.
9. Gallichan D, Cocosco CA, Dewdney A, Schultz G, Welz A, Hennig Jr, Zaitsev M. Simultaneously driven linear and nonlinear spatial encoding fields in MRI. Magn Reson Med 2011;65(3):702-714.
10. Layton KJ, Gallichan D, Testud F, Cocosco CA, Welz AM, Barmet C, Pruessmann KP, Hennig J, Zaitsev M. Single shot trajectory design for region-specific imaging using linear and nonlinear magnetic encoding fields. Magnetic Resonance in Medicine 2013;70(3):684-696.
11. Layton KJ, Morelande M, Farrell PM, Moran B, Johnston LA. Performance Analysis for Magnetic Resonance Imaging With Nonlinear Encoding Fields. Medical Imaging, IEEE Transactions on 2012;31(2):391-404.
12. Kopanoglu E, Wang H, Wan Y, Peters DC, Galiana G, Constable RT. rOi-Space: Accelerated Imaging of Sub-Volumes Using ROI Focused O-Space. 2015; Toronto, Canada. p 2465.
13. Walsh DO, Gmitro AF, Marcellin MW. Adaptive reconstruction of phased array MR imagery. Magnetic Resonance in Medicine 2000;43(5):682-690.