Improve O-Space Imaging Using High-Resolution Oversampled Data Acquisitions

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TARGET AUDIENCE: The parallel imaging and nonlinear gradient encoding communities

PURPOSE: Many sequences have explored spatial encoding with nonlinear magnetic fields, such as, PatLoc imaging [1], O-Space imaging [2], Null Space imaging [3], 4D-RIO [4], etc. Among these methods, O-Space in particular was specifically designed to maximize the complementarity between gradient geometry and RF coil geometry, and it has been proved to outperform Cartesian SENSE when the effective acceleration factor approaches, equals, or exceeds the number of radiofrequency (RF) coils [5,6,7]. However, the advantages over radial imaging (which is the linear trajectory underlying O-Space) have been less clear. In this study, we show that increasing readout sampling, which carries essentially zero time cost, produces high-resolution O-Space images that are clearly superior, with sharper features and fewer artifacts. Increased resolution in the readout has little effect on radial image quality. The experimental results illustrate that the addition of nonlinear gradients can improve image quality and surpass conventional radial imaging in accelerated data acquisitions.

THEORY: With static linear gradients, increased readout sampling does not improve overall image quality or mitigate the effects of using fewer phase encode steps (Cartesian) or projections (Radial). The increased readout sampling of a single projection only improves resolution in one direction, and it can even exacerbate undersampling artifacts by increasing the largest gaps between k-space points as one moves further out in k-space. Increased readout in a single O-Space acquisition increases resolution in 2-directions due to the curved nature of the iso-frequency contours in the field the O-space gradient produces. Furthermore, as O-Space data collection is extended further in k-space, the local k-space becomes increasingly diffuse, so the gap between sampled k-space points does not increase. Neglecting relaxation effects, the magnetic resonance signal s_j from the *j*-th RF channel, $s_j = \int M(\boldsymbol{X}) C_j(\boldsymbol{X}) e^{i\Phi(\boldsymbol{X},t)} d\boldsymbol{X}$, where $M(\boldsymbol{X})$ is the magnetization at position $\boldsymbol{X}$, $C_j(\boldsymbol{X})$ is the sensitivity of coil j, and $\Phi(\boldsymbol{X},t)$ is the spatially dependent encoding phase at time *t*. For O-Space imaging, $\Phi(\boldsymbol{X},t)$ is equal to $\Phi(\boldsymbol{X},t) = k_x(t)x + k_y(t)y - k_{z^2}(t)½(x^2+y^2)$. Here, $k_x(t) = \gamma\int_0^t G_x(\tau)d\tau$, $k_y(t) = \gamma\int_0^t G_y(\tau)d\tau$, and $k_{z^2}(t) = \gamma\int_0^t G_{z^2}(\tau)d\tau$. $G_x(t)$, $G_y(t)$, and $G_{z^2}(t)$ are gradients waveforms on X, Y and Z^2 directions. According to the above equations, the entries of the encoding matrix $\mathbf{E}_j$ from the *j*-th RF channel for parallel imaging at the k-space positions is defined as $\mathbf{enc}_j(\boldsymbol{X}) = C_j(\boldsymbol{X}) e^{i\Phi(\boldsymbol{X},t)}$, which consist of two factors: the gradient encoding factor $e^{i\Phi(\boldsymbol{X},t)}$ and the RF sensitivity encoding factor $C_j(\boldsymbol{X})$. The condition number $\boldsymbol{\kappa}(\mathbf{E})$ of the encoding matrix $\mathbf{E}$, is calculated as $\boldsymbol{\kappa}(\mathbf{E}) = \|\mathbf{E}^{-1}\| \cdot \|\mathbf{E}\|$. Using 8 experimental coil profiles, a reconstruction resolution of 32×32, the same trajectories on the X and Y gradient channels, and a total of 4096 datapoints, the condition number $\boldsymbol{\kappa}(\mathbf{E})$ of O-Space imaging using high-resolution oversampled data acquisitions is 83.3, which is considerably better than the 205.5 for radial imaging. The condition number suggests that O-Space imaging using high-resolution oversampled readouts can provide better image reconstruction than radial imaging, with improvements directly related to the additional nonlinear field.

METHODS: Data from phantoms were experimentally acquired on a 3.0T MRI scanner (Siemens Healthcare, Erlangen, Germany) with an 8-channel head coil and a gradient insert that generated the nonlinear field. The sequence parameters were TE/TR/ θ: 12ms/25ms/15°; BW: 160Hz/pixel; FOV: $30cm^2$; the Z2 strength of O-space imaging: 20mT/m. The datasets were manually undersampled in MATLAB (The Mathworks, Natick, MA) and reconstructed to a 512x512 matrix size using the Kaczmarz method [2,5]. .

RESULTS: Figure 1 compares radial and O-Space images with 32 echoes and either 512 or 1024 readout points. The O-Space images show the true border of the plastic insert, while radial images contain artifactual grid lines extending beyond the actual borders of the plastic insert (left blue arrows in each panel). O-Space images also show better contrast (right blue arrows in each panel) between the dark plastic insert and the surrounding water. A sharpness metric reported below each image ($\|\nabla(\text{Image})\|_2$/(No. of pixels)), shows that O-Space images become sharper with longer readout and are markedly sharper than their radial counterparts. Similar trends and features are seen in Figure 2, which compares images taken with 16 echoes and the same number of readout points.

DISCUSSION: These results demonstrate that the curvilinear frequency contours of O-Space imaging improve the quality of highly accelerated images. Static linear gradients only provide encoding in a single direction, and encoding in other directions must be done via additional TRs, which significantly lengthens scan time. By using curved gradients, more 2D encoding can be shifted to the rapidly acquired readout direction, allowing high-resolution images with fewer echoes.

CONCLUSION: O-Space with extended readout windows creates better accelerated images than radial, with fewer artifacts and sharper features. Both theoretical calculations on the encoding matrices and the experimental results presented here suggest that the 2nd order gradient at the heart of O-Space imaging is critical to the enhanced image quality of highly undersampled images.

REFERENCES: **1**. Hennig et al. MAGMA. 21(1-2): 5-14, 2008; **2**. Stockmann et al. MRM. 64(2): 447-456, 2010; **3**. Tam et al. MRM. 69(4): 1166-1175, 2012; **4**. Gallichan et al. MAGMA. 25(6): 419-431, 2012; **5**. Galiana et al. CMR Part A 40A(5): 253-267, 2012; **6**. Stockmann et al. MRM. 69(2): 444-455, 2013; **7**. Wang et al. ISMRM. 4244, 2014.

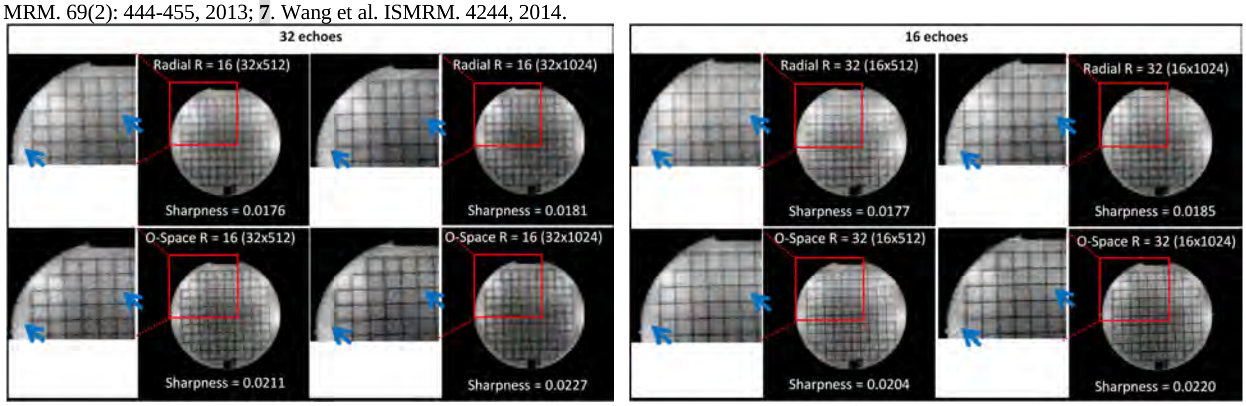

Figure 1 compares radial and O-Space images with 32 echoes. O-Space images do not exhibit artifacts outside the plastic insert (blue arrow) and also show sharper contrast between the insert and surrounding water. Sharpness metrics, reported at the lower left corner of each panel, show that O-Space images are sharper than radial, and become increasingly sharp with longer readouts. **Figure 2** compares radial and O-Space images with 16 echoes and shows the same trends.