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O-Space with High Resolution Readouts Outperforms Radial Imaging

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Abstract

Purpose—While O-Space imaging is well known to accelerate image acquisition beyond traditional Cartesian sampling, its advantages compared to undersampled radial imaging, the linear trajectory most akin to O-Space imaging, have not been detailed. In addition, previous studies have focused on ultrafast imaging with very high acceleration factors and relatively low resolution. The purpose of this work is to directly compare O-Space and radial imaging in their potential to deliver highly undersampled images of high resolution and minimal artifacts, as needed for diagnostic applications. We report that the greatest advantages to O-Space imaging are observed with extended data acquisition readouts.

Theory and Methods—A sampling strategy that uses high resolution readouts is presented and applied to compare the potential of radial and O-Space sequences to generate high resolution images at high undersampling factors. Simulations and phantom studies were performed to investigate whether use of extended readout windows in O-Space imaging would increase k-space sampling and improve image quality, compared to radial imaging.

Results—Experimental O-Space images acquired with high resolution readouts show fewer artifacts and greater sharpness than radial imaging with equivalent scan parameters. Radial images taken with longer readouts show stronger undersampling artifacts, which can cause small or subtle image features to disappear. These features are preserved in a comparable O-Space image.

Conclusions—High resolution O-Space imaging yields highly undersampled images of high resolution and minimal artifacts. The additional nonlinear gradient field improves image quality beyond conventional radial imaging.

Keywords

O-Space imaging; nonlinear spatial encoding; high-resolution; parallel imaging

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I. INTRODUCTION

Nonlinear magnetic field methods [1-4] may provide a wide range of advantages, such as lower peripheral nerve stimulation, enhanced resolution at the edge of the FOV, and localized imaging both in-plane and through-plane. More recently, spatial encoding with multi-order nonlinear magnetic fields has been pursued to enhance parallel imaging [5]. O-Space imaging [6-7] was the first sequence explicitly designed to improve highly undersampled parallel imaging with nonlinear gradients, though many other methods have since been studied. These include Patloc Imaging [1], Null Space imaging [5], O-Space TSE imaging [8-10], Single Echo MRI [11], FRONSAC imaging [12-15], 4D-RIO [16], EPI-PatLoc [17], CS O-Space [18], Multi-Dimensional Encoding [19] and others [20-23].

O-Space imaging encodes spatial information with a single radially varying magnetic gradient field: $B_i = G_{ZZ}(z^2 - 1/2((x - x_i)^2 + (y - y_i)^2))$, which is created from a combination of linear gradients as well as the nonlinear “Z2” gradient whose coefficient is in units of Hz/cm² (Figure 1). Each projection is acquired under this radially varying field centered at different in-plane locations, (x_i, y_i) , which are also called center placements. The projections are acquired such that the center placements form a ring about the FOV center, typically with radius FOV/2. The circular isocontours of the frequency encoding field were chosen to maximize the complementarity between the gradient geometry and RF coil geometry. Previous reconstruction results [6-7] have shown this approach outperforms Cartesian SENSE [24-26], when the effective acceleration factor approaches, equals, or exceeds the number of radiofrequency (RF) coils. Compared to radial imaging, simulations predict that O-Space imaging should provide sharper resolution and more diffuse undersampling artifacts [6-7]. However, previous experiments have not rigorously detailed and analyzed the benefits of O-Space compared to radial imaging.

Increasing the readout resolution in radial imaging (i.e. acquiring further out in k-space) results in higher resolution encoding. But the larger azimuthal gaps in k-space also increase streaking artifacts, and in iterative least-squares optimized reconstructions, larger gaps in k-space also increase blur [26-27]. In O-Space imaging, increased readout sampling leads to more diffuse sampling at the edge of k-space [28] (see Figure 1b), and so it was hypothesized that increased O-Space readouts could better mitigate coherent artifacts in the undersampled image.

The purpose of this study is to demonstrate, by simulation and experiment, improvements to O-Space images reconstructed with extended readout windows. The advantage of this approach is improved image quality without incurring a time-penalty in terms of acquisition time. The results illustrate that extended-readout O-Space imaging can generate highly undersampled high-resolution images that are superior to more conventional radial acquisitions. High resolution O-Space images are sharper and show fewer coherent artifacts than comparable radial images. We show through analysis of the encoding matrices for radial and O-Space encoding that reconstruction performance is improved by the proposed strategy beyond radial imaging.

II. THEORY

O-Space imaging encodes spatial information through parabolically varying magnetic gradient fields, with circular isocontours. With linear gradient fields, increased readout windows are not expected to improve overall image quality or mitigate the effects of using fewer projections [6]. The increased readout window of a single projection only improves resolution in a single orientation. However, increased readout resolution in a single O-Space projection increases resolution in multiple directions at virtually no time cost, due to the curved nature of the isofrequency contours in the O-Space gradient field.

If we neglect relaxation effects, the magnetic resonance signal s_j from the j -th RF channel, $s_j(t) = \int M(\mathbf{X}) C_j(\mathbf{X}) e^{i\Phi(\mathbf{X},t)} d\mathbf{X}$, where $M(\mathbf{X})$ is the magnetization from a single slice at position $\mathbf{X}$, $C_j(\mathbf{X})$ is the sensitivity of coil j , and $\Phi(\mathbf{X},t)$ is the spatially dependent encoding phase for encoding at time t . The above signal equation may be rewritten in matrix notation: $\mathbf{S} = \mathbf{E}\mathbf{M}$, where $\mathbf{E}$ is the encoding matrix; $\mathbf{M}$ is the anticipated image; $\mathbf{S}$ is the measured signals. For traditional Cartesian or radial imaging, $\Phi(\mathbf{X},t)$ is equal to,

$$\Phi(\mathbf{X},t) = k_{x_i}(t)x + k_{y_i}(t)y, \quad (1)$$

where $\mathbf{X} = (x, y)$, $k_{x_i}(t) = \gamma \int_0^t G_{x_i}(\tau) d\tau$; $k_{y_i}(t) = \gamma \int_0^t G_{y_i}(\tau) d\tau$; and $G_{x_i}(t)$, and $G_{y_i}(t)$ express gradients waveforms along X, and Y directions that generate radial spokes. For O-Space imaging, the equation (1) becomes,

$$\Phi(\mathbf{X},t) = k_{x_i}(t)x + k_{y_i}(t)y - \frac{1}{2}k_{z2}(t)(x^2 + y^2), \quad (2)$$

Where $k_{z2}(t) = \gamma \int_0^t G_{z2}(\tau) d\tau$; $G_{z2}(t)$ are the waveforms of the corresponding gradient directions. Here, the linear gradient waveforms $G_{x_i}(t)$ and $G_{y_i}(t)$ are actually the same as those of radial imaging, and these set the (x_i, y_i) of the O-Space field via $x_i = G_{x_i}/G_{z2}$ and $y_i = G_{y_i}/G_{z2}$. $G_{z2}(t)$ is an additional constant gradient on the Z2 channel.

Because each O-space readout naturally encodes along isocentric circles, extended readouts are expected to eliminate the streaking artifacts. Assuming a fixed number of echoes, a longer readout window in radial imaging increase gaps at the edge of k-space, which in turn exacerbates artifacts. In O-Space imaging, longer readouts improve resolution along a range of orientations, due to the 2D nature of radially varying frequency encoding with each projection. Thus, more 2D encoding can be shifted to the rapidly acquired readout direction, allowing high-resolution images with fewer echoes.

In addition, Equations (1) and (2) suggest that the acquisition of (linear) k-space is different for radial and O-Space encoding. As seen as Figure 1(a), the sampling function for different time points in a radial sequence is a dot translating along radial trajectories through k-space. The sampling function for different time points in an O-Space acquisition is a stamp translating along radial trajectories through k-space³², i.e at each time-point signal from an extended region of k-space is acquired, which must be individually solved for using parallel

imaging. Furthermore, as the stamp goes further out in k-space, it samples a broader and more diffuse collection of data points, though this does not imply unambiguous determination of all the sampled k-space points. As seen as Figure 1(b), it shows that the corresponding linear and nonlinear gradient fields of radial and O-Space imaging with Figure 1(a). Here, radial imaging is equivalently that the strength of Z2 gradient field is 0 Hz/cm²; O-Space imaging uses the strength of Z2 gradient field is 51.2 Hz/cm².

The implications of this sampling for higher resolution readouts are highlighted in Figure 1(c), which shows a superposition of several sampling functions for a subset of time points. The gray shaded box represents the region of k-space acquired in the lower-resolution readout, while the larger box represents a higher-resolution readout. In radial imaging, the extended readout window results in larger gaps in k-space, which can lead to greater streaking artifacts. In O-Space imaging, extended readouts occur in tandem with broader samplings of k-space, which ameliorates the coherent undersampling artifacts that can result from large gaps in k-space. This is further illustrated by the normalized cumulative k-space encoding coverage of radial and O-Space imaging shown Figure 1(d).

To compare the encoding quantitatively, the rank of the encoding matrix $\mathbf{E}$ can be calculated based on the singular value decomposition. The entries of the encoding matrix $\mathbf{E}_j$ from the j -th RF channel for parallel imaging at any k-space position is defined as $\text{enc}_j(\mathbf{X}) = C_j(\mathbf{X})e^{i\Phi(\mathbf{X},j)}$, which consist of two factors: the gradient encoding factor $e^{i\Phi(\mathbf{X},j)}$ and the RF sensitivity encoding factor $C_j(\mathbf{X})$. For highly undersampled imaging ($R=16$), the rank of each encoding matrix $\mathbf{E}$ for O-Space imaging with 16, 32 and 64 points per echo are, respectively, 980, 1675 and 2886. But if we simulate radial imaging with 16, 32 and 64 points per echo, the rank of each encoding matrix $\mathbf{E}$ is 954, 1609 and 2461, respectively. More efficient encoding in MRI is possible, since MR images typically represent rank deficient matrices [29-30], and a higher rank encoding matrix $\mathbf{E}$ generally denotes a more efficient encoding [19, 31-32]. Therefore, the rank of the encoding matrices suggests that the proposed strategy, parallel imaging with O-Space acquisitions, is superior to parallel imaging with radial encoding, and the difference is increasingly pronounced at higher resolution readouts.

III. METHODS

To compare rank, each encoding matrix $\mathbf{E}$ was calculated for encoding with 8-channel experimental receiver coil profiles, a field of view (FOV) of 25cm, and a reconstruction resolution of 64×64. The trajectories acquired 4 echoes for a reconstruction resolution of 64×64. The same radial trajectories were used on the X and Y gradient channels, and for O-Space imaging, Z2 gradient was added to move the center placement to the edge of FOV.

Phantom data was 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/ α : 12ms/25ms/15°; BW: 320 and 160 Hz/pixel; FOV: 30cm² and 25cm²; the Z2 strength of O-space imaging: 19.2 mT/cm², voxel size: 0.4-0.6mm. One projection is collected with each TR. To double the duration of readout windows while maintaining gradient strengths, as in Figure 2, 320 Hz/pixel was used for the 512 point acquisitions and 160 Hz/pixel was used for 1024 point acquisitions.

This maintained dwell time and gradient strength, doubling the length of the readout window to achieve greater encoding. This approach was chosen to minimize effects from gradient imperfections, but the same encoding could have been achieved by increasing both gradient strength and sampling bandwidth.

In all experiments, the linear gradient strength was set by the typical Nyquist prescription, and an additional nonlinear field was added. The exact shape of the nonlinear gradient is experimentally mapped and characterized to 6th order for input in the reconstruction matrix. [7] All data were reconstructed retaining a 2× oversampling to accommodate the additional O-Space bandwidth, so the highest k_x corresponded to that prescribed for a 256 and 512 image respectively. For undersampling, echoes were omitted in the reconstruction, which was performed on a 512×512 matrix using the Kaczmarz reconstruction method [6-7] with $\lambda = 0.075$ and ten iterations. All calculations were performed in MATLAB (The MathWorks Inc, Natick, MA, USA).

To quantify the performance of radial and O-Space imaging, a sharpness metric was defined. Generally, sharpness determines the amount of detail an image can convey. Here, image sharpness was estimated using a simple gradient magnitude method proposed by Birdal [33]. Assuming $I(x_i, y_j)$ is normalized image intensity at the pixel location (x_i, y_j) , and N and M is the size of a region of interest, the sharpness metric is equal to,

$$Sharpness = \frac{1}{NM} \sum_{i=1}^N \sum_{j=1}^M \|\nabla I(x_i, y_j)\|_2, \quad (3)$$

where, $\nabla I(x_i, y_j)$ is the gradient of image intensity $I(x_i, y_j)$ at the pixel location (x_i, y_j) ; $\|\cdot\|_2$ is the ℓ_2 norm. In other words, this metric calculates the mean of all gradient ℓ_2 norms. Generally, a larger sharpness metric means the edges are sharper due to increased spatial resolution. In these studies, sharpness was measured over the entire phantom, masking out only the background region of each image. Though this single metric is an imperfect measure of true image sharpness, it is provided as a quantitative support to the conclusions that can be drawn from visual inspection of images and line profiles.

IV. RESULTS

Figure 3 (a) and (b) compare radial and O-Space images with 32 echoes and either 512 (320 Hz/pixel) or 1024 (160 Hz/pixel) readout points. Radial images contain artifactual grid lines extending beyond the actual borders of the plastic insert (left green arrows in each panel), but these are mitigated in the O-Space image, and nearly eliminated in O-Space imaging with an extended readout. Moreover, O-Space images show better contrast (right green arrows in each panel) between the dark plastic insert and the surrounding water. Panel (a) shows images taken with a 25cm FOV, which places the center placements at a radius of 19cm.

Using a weaker gradient strength in the linear gradient channels and the same Z2 strength brings the center placements in closer for relatively stronger Z2 encoding. These images,

shown in Figure 3(b), show still further reduced artifacts, and the enhanced sharpness compared to the radial image is more pronounced. Figure 3(c) illustrates the normalized image amplitudes of the green, cyan, blue and red dashed lines along X and Y axis of Figure 3(a) and (b). In particular, the profiles with 1024 pt readouts show higher peaks and deeper troughs with O-space (red) vs radial (green). Figure 3(d) reports the sharpness metrics of Panel (a) and (b). The sharpness results indicate that O-Space images become sharper with longer readout and are markedly sharper than their radial counterparts, though further studies will be required to establish statistical significance of this result and any dependence on slice orientation. All images show comparable SNR, ranging from 12.5-13.4 dB.

Figure 4 shows images acquired with a different phantom, again comparing radial and O-Space imaging each encoded at two different readout resolutions. It is notable that in the radial reconstructions, the zoomed-in regions show features (highlighted by the green arrow) which are obliterated by artifacts, and they are even further obscured in the higher resolution radial readout due to enhanced artifacts. In contrast, these image details are preserved in both O-Space images, and they are slightly sharper in the higher resolution readout O-Space image.

V. DISCUSSION

These results demonstrate that the unique frequency contours of O-Space imaging can improve the quality of highly accelerated images in the context of extended readout. O-Space acquires regions of k-space instead of single points at each time-point in its readout. While this does not amount to unambiguous knowledge of the sampled k-space points, this more diffuse coverage of k-space allows us to acquire high resolution information without incurring the sharp artifacts generated by large gaps in k-space. Therefore, it is potentially a better approach to accelerated high resolution MRI, including high resolution acquisitions like those demanded by clinical applications [26, 34].

Like radial imaging, O-space will show sensitivity to off-resonance and trajectory errors. Though the particular artifacts from a given off-resonance topology may be different for the two encodings, those artifacts can be reduced using similar techniques. [35]. Off-resonance artifacts can be reduced by shortening the readout window duration, though at the cost of reduced sampling efficiency, SNR, and increased error from trajectory deviations [36]. Conversely, trajectory errors can be reduced by reducing the readout gradient strength, as trajectory errors scale with the gradient amplitude; however longer readouts lead to blurring and signal cancellations from T2* and off-resonance. [37] In practice, better hardware makes it possible to use very short windows to minimize off-resonance effects, while not introducing significant trajectory errors.

Also like radial imaging, O-Space is a flexible image encoding method that can be used to acquire a broad range of clinically relevant contrasts. It is entirely compatible with magnetization preparation schemes, such as inversion recovery, fat suppression, and magnetization transfer. Since, like radial, it acquires the center of k-space with each projection, a center-out version of O-space could be used for ultrashort TE imaging. Multiecho acquisitions which require a discrete acquisition of the center of k-space are more

complicated for both radial and O-space, since the center of k-space is sampled with each projection. Yet for both methods, techniques have been introduced to overcome those challenges. In fact, the multiple samplings of the center of k-space can even make it possible to choose the contrast retrospectively in reconstruction. [8,10]

VI. CONCLUSIONS

In summary, O-Space imaging with high-resolution readouts improves highly accelerated images, providing better image quality with fewer artifacts than traditional radial imaging with a similar sampling strategy. Longer readouts can produce sharper features in O-Space imaging at essentially no time cost and without significantly increasing undersampling artifacts. The evidence from simulations, theoretical estimations of the rank of the encoding matrices, and the experimental results presented here all suggest that the 2nd order gradient at the heart of O-Space imaging is critical to achieving this enhanced image quality in highly accelerated image acquisitions. Furthermore, these results support the potential of O-Space for delivering high-resolution images with high acceleration factors.

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FIG. 1.

To illustrate the different k-space coverage of radial and O-Space encoding, panel (a) compares radial (top) and O-Space (bottom) encoding in the k-space domain at two time-points ($t_1 < t_2$); panel (b) shows that the corresponding linear and nonlinear gradient fields of radial (left) and O-Space (right). Panel (c) shows how these different sampling functions cover k-space for a number of readout points. Blue lines trace each nominal spoke, and yellow boxes represent the area of the sampling functions. Gray shaded boxes are provided to highlight the effect of moving to a higher-resolution readout, i.e. larger gaps appear at the edge of k-space when sampling with linear gradients only. Finally, panel (d) shows the normalized cumulative k-space coverage of radial and O-Space imaging for two different readout resolutions with a fixed number of projections. In radial, this is equivalent to the trajectory in k-space, but O-Space imaging diffusely samples more area, though each sample is a less definitive measure of the k-space point.

FIG. 2.

For a fixed number of echoes, readouts were performed with doubled acquisition windows, acquiring twice as many points under the same gradient strength. This is traditionally associated with a higher resolution image reconstruction. In accelerated Cartesian imaging, doubling the readout sampling does nothing to assist in the N/R ghosting problem in the y-direction. We also show in the following figures that this increased sampling has less benefit with radial acquisitions than with O-space imaging. In the high-resolution examples that follow, reconstruction is performed at a matrix size corresponding to the higher resolution encoding.

FIG. 3. Comparisons of radial and O-Space images (image sizes are 512×512) with 32 echoes ($R = 16$, $Gz2 = 19.2 \text{ Hz/cm}^2$). (a) Images in the first panel were obtained with $\text{FOV}=30\text{cm}^2$, and it is apparent that O-Space images do not exhibit artifacts outside the plastic grid insert (green arrow) and also show sharper contrast between the insert and surrounding solution. These differences become more pronounced for longer readouts. Images in panel (b) were obtained with a $\text{FOV}=25\text{cm}^2$, and with the corresponding center placements moved to a smaller radius, thereby providing more nonlinear encoding. Panel (c) illustrated the normalized amplitudes of the green, cyan, blue and red dashed lines along X and Y axis in (a) and (b). The improved sharpness is even more apparent in this case. Sharpness is quantified in panel (d).

FIG. 4.

Comparisons (image size of 512×512) of radial and O-Space images with 32 echoes ($R = 16$, $\text{FOV} = 25\text{cm}^2$, $Gz2 = 38.4\text{ Hz/cm}^2$). The features highlighted by the green arrows are obscured on the radial images but apparent on the O-Space images. Notably, moving to higher-readout in the radial images actually further obscures these features because of greater undersampling artifacts, but the O-Space images preserve these features.