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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.

1. 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: $B_i = G_{Z2}(z^2 - 1/2((x - x_i)^2 + (y - y_i)^2))$, which is created from a combination of linear gradients as well as the nonlinear "Z2" gradient whose coefficient is in units of Hz/cm^2 (Fig. 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

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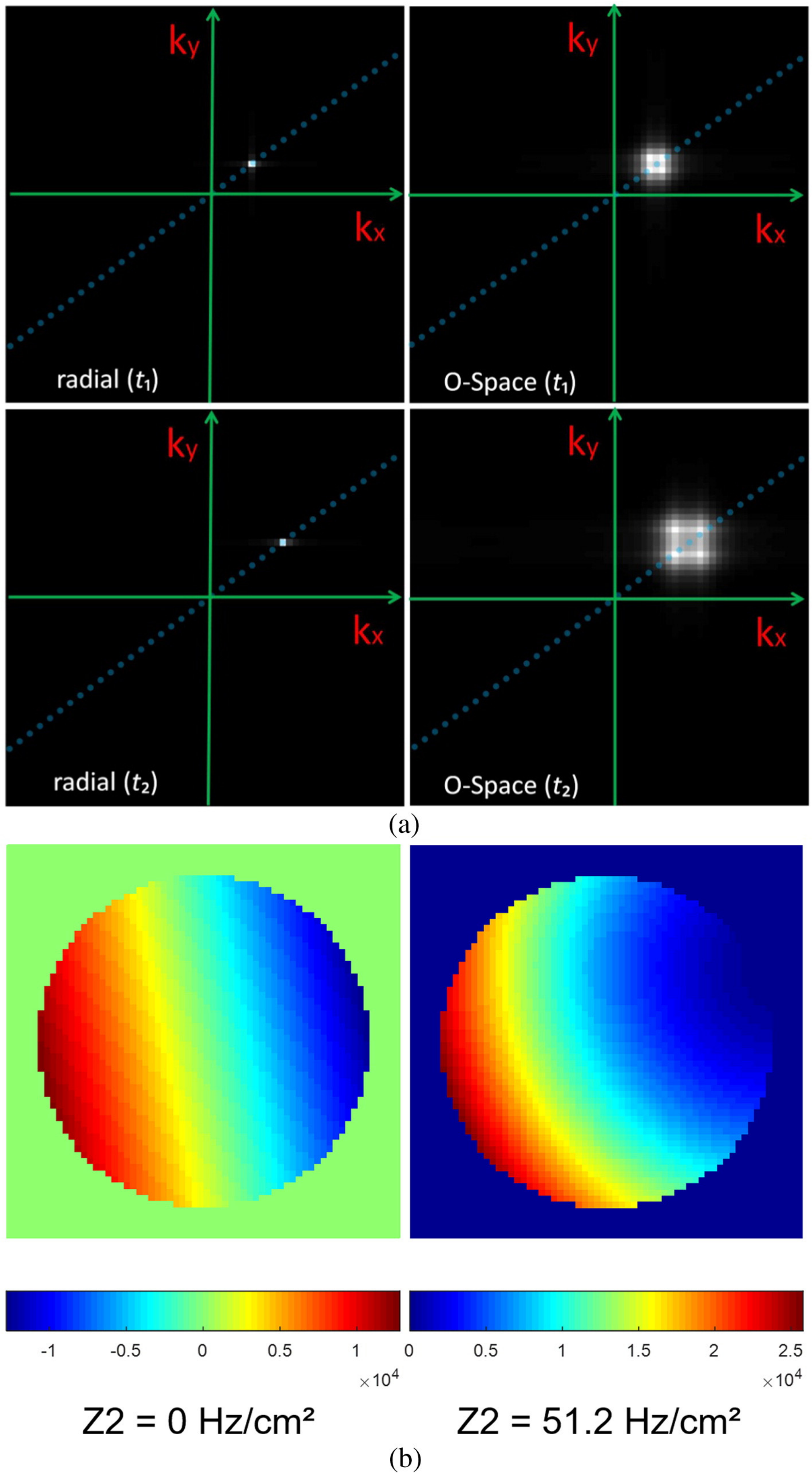

Fig. 1. To illustrate the different k-space coverage of radial and O-Space encoding, panel (a) compares radial (top) and O-Space (bottom) encoding in the k-space domain at two-time-points ($t_1 < t_2$); panel (b) shows that the corresponding linear and nonlinear gradient fields of radial (left) and O-Space (right) Panel (c) shows how these different sampling functions cover k-space for a number of readout points. 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. 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. 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.