Multipole anisotropy measured by STI in the p-space is not an artifact of zero filling

Chunlei Liu[1,2]

[1]*Brain Imaging and Analysis Center, Duke University, Durham, NC, United States,* [2]*Radiology, Duke University, Durham, NC, United States*

Purpose: Susceptibility tensor imaging (STI) (1) in the **p**-space (2) images sub-voxel magnetic field distribution and its anisotropy. It measures higher-order frequency variations within a voxel without rotating the object or the magnet. By sampling the **p**-space with pulsed field gradients or by shifted image reconstruction, a set of dipole and quadrupole susceptibility tensors can be measured (2). Simulation, *ex vivo* and *in vivo* scans have indicated that this approach may provide a powerful method for studying tissue microstructure and brain connectivity *in vivo* and non-invasively. In the shifted image reconstruction, however, when the reconstruction window is shifted outside the acquired **k**-space region, zero filling is applied. This zero filling raised concerns that the observed multipole anisotropy may originate from image artifacts associated with zero filling. In this study, multipole susceptibility was measured both with and without zero filling. It is confirmed that the previously reported multipole anisotropy is not caused by reconstruction artifacts associated with zero filling, thus further validating the **p**-space approach.

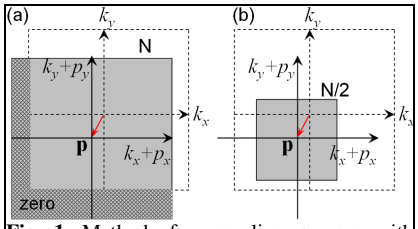

Fig. 1. Methods for sampling **p**-space with shifted reconstruction. (a) Reconstruction on size-N grid requires zero filling; (b) reconstruction on size-N/2 grid does not require zero filling.

METHODS: Phase of gradient-echo images represents the mean magnetic field within a voxel. The spatial heterogeneity within the voxel, however, is not available. If the field distribution within a voxel can be recovered, it will allow us to infer the underlying tissue microstructure. One way to recover the field distribution is to apply an external magnetic field gradient (**p**-space encoding gradient) which will modulate the resonance frequency of the spins within the voxel. Equivalently, the **p**-space can also be sampled by shifting the acquired **k**-space data. If the **k**-space data are sampled on a grid of N×N×N and **p**-space images are to be reconstructed on the same grid size, shifting the **k**-space by a vector of **p** will render part of the shifted **k**-space unsampled that has to be zero filled (Fig. 1a). To assess the effect of zero filling, we performed **p**-space reconstruction on a grid of N/2×N/2×N/2, which did not require any zero filling. Adult 10-weeks old C57BL/6 mice were anesthetized and perfusion fixed. Images were acquired on a 9.4 T (400 MHz) 89-mm vertical bore Oxford magnet with shielded coil providing gradients of 2200 mT/m. The system is controlled by a GE EXCITE MR imaging console. A 3D spoiled-gradient-recalled-echo (SPGR) sequence was used with the following parameters: matrix size = 512x256x256, field-of-view (FOV) = 22x11x11 mm^3, bandwidth (BW) = 62.5 kHz, flip angle = 60º, TE = 9.0 ms and TR = 100.0 ms.

p-space analyses were performed in three orthogonal orientations: [1 0 0], [0 1 0] and [0 0 1]. Along each orientation, N or N/2 evenly spaced image volumes were reconstructed. The 15 images on either end of any direction were discarded. For each orientation, the standard deviation of the frequency and magnitude was computed. When computing the standard deviation of the frequency, the frequency map at p = 0 was subtracted from all images.

RESULTS: Fig. 2 shows a representative slice of frequency standard deviations in three orthogonal **p**-space orientations (Fig. 2a-c) and the difference between two orientations (Fig. 2d). The overall contrast between reconstructions on N/2-grid and N-grid is similar. Specifically, white matter areas show larger frequency standard deviations than other brain regions such as the gray matter. Anisotropy in frequency standard deviations is also clearly visible in the white matter. In general, when the p-vector is parallel to the underlying white matter fibers, the standard deviation is the smallest; when the p-vector is perpendicular to the fiber, the standard deviation is the largest (arrows in Fig. 2). This anisotropic behavior is consistent between N/2-grid and N-grid. For example, the limb of the external capsule adjacent to the hippocampus exhibits the largest standard deviation when the p-vector is in the direction of [0 1 0] (Fig. 2b). As a result, the difference between (a) and (b) is negative in the external capsule (arrows in Fig. 2d). Fig. 3 shows similar contrast and anisotropy in the posterior limb of anterior commissure. Similar results are also observed in the magnitude standard deviations (data not shown). Table 1 compares the mean standard deviations in two regions of interests: the external capsule and the posterior limb of the anterior commissure. It confirms quantitatively that the multipole contrast and anisotropy does not change between N/2- and N-grid reconstruction.

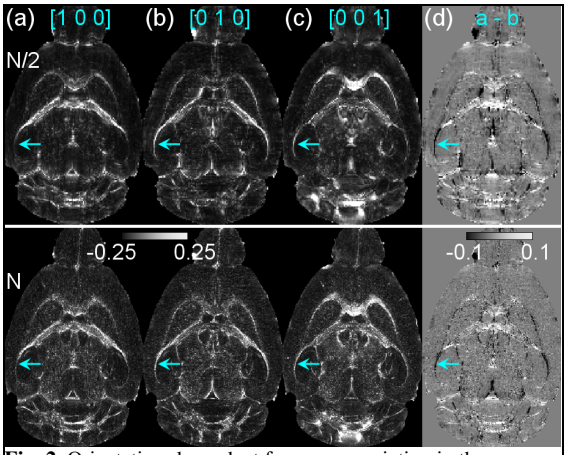

Fig. 2. Orientation-dependent frequency variation in the **p**-space. (a) Frequency standard deviation in the **p**-space direction of [1 0 0], (b) [0 10] and (c) [0 0 1]. (d) Difference between (a) and (b). The orientation dependence is clearly visible in both images reconstructed on N/2-grid (top row) and N-grid (bottom row). The external capsule (EC) adjacent to the hippocampus (arrow) exhibits the largest frequency standard deviation when perpendicular to the **p**-vector (b).

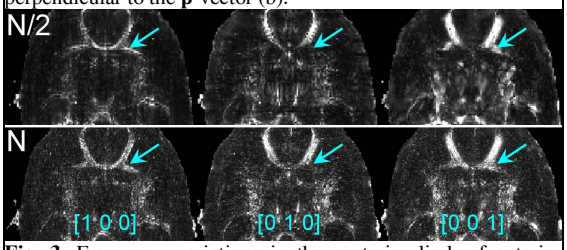

Fig. 3. Frequency variations in the posterior limb of anterior commissure (PAC) (arrows) show similar anisotropy between reconstruction on N/2 and N-grid.

Frequency variation		[1 0 0]	[0 1 0]	[0 0 1]
EC	N/2	0.067±0.03	0.21±0.07	0.13±0.05
	N	0.078±0.05	0.20±0.09	0.13±0.06
PAC	N/2	0.11±0.06	0.045±0.02	0.09±0.06
	N	0.13±0.06	0.069±0.05	0.12±0.07

Table 1. Frequency variation in three orthogonal orientations. The largest variation is observed when the white matter is perpendicular to the p-vector (shaded entries). This is independent of whether zero-filling is applied (N/2 vs. N). EC – external capsule; PAC – posterior limb of anterior commissure.

DISCUSSIONS AND CONCLUSIONS: We have demonstrated that the multipole susceptibility contrast and anisotropy detected by the method of **p**-space STI is not induced by zero filling the shifted **k**-space. While zero-filling is known to introduce ringing artifacts in individual **p**-space image, the standard deviations of frequency and magnitude are computed across many **p**-values in any given orientation. As a result, such ringing artifacts are likely suppressed and became insignificant. While the contrast and anisotropy is consistent regardless of zero-filling, N/2-grid results in higher SNR in large fiber bundles. N-grid reconstruction, on the other hand, provides better contrast for small fibers. Because **p**-space STI does not require any physical rotations, it provides MRI a means to image higher order frequency information and utilize it to elucidate tissue microstructure. We thus expect the **p**-space method to open a new avenue for studying tissue microstructure in general and brain connectivity in particular.

REFERENCES: 1. Liu, C., MRM 2010; 63:1471-1477. 2. Liu, C and Li, W. NeuroImage 2013; 67:193-202.