p-space imaging: Where does the contrast come from?

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TARGET AUDIENCE – Researchers interested in the contrast seen in p-space imaging (GRE -sequence with additional gradients).

PURPOSE – In a much discussed[1,2,3,4] recent paper[5], Liu and Li proposed a new imaging approach aimed at inferring microstructural information by measuring susceptibility induced effects. They used a classical gradient echo sequence that acquires image k-space and added additional gradients before applying the k-space readout. These additional gradients sample the newly designated "p-space" simply by shifting k-space. A very similar method has been previously proposed[6,7,8,9], in which additional gradients were added to a standard spin echo sequence to investigate spin density homogeneity of nonuniform tissue such as bone[7,8,9,10,11] or labeled cells[12]. Here, we investigate the effect of the proposed p-space sampling if the magnetization is inhomogeneous within the voxel.

METHODS – Using MATLAB (Release 2013a, The MathWorks, Inc., Natick, MA, USA) the field shifts were simulated in a voxel filled with 300 myelinated axons represented by hollow cylinders[13] and assigned susceptibility values χ_I=-82 ppb for isotropic and χ_A=11 ppb for anisotropic susceptibility[14]. The field strength was chosen to be 7 T, TE=20 ms, 90° angle between the fibers and B0 field, outer radius of axons 5 µm, inner radius of axons 3.5 µm, edge length of the voxel 250 µm, and number of grid points where the field was calculated 512^2. For MRI measurements, a 2D GRE sequence was modified to acquire p-space by adding gradients in read and phase directions. Oil phantom magnitude images were acquired at 7 T (Magnetom 7T, Siemens Healthcare), with FA=15°, TR=50 ms, TE=5.5 ms, FOV=300x300 mm^2, N_{acq}=64x64, slice thickness 5 mm, and readout bandwidth 1502 Hz/px. A water phantom consisting of a 2 mm thick plastic plate immersed in deionized water was constructed. The FOV was shifted by 1 mm to obtain two different plastic-water substructures of the voxel. Water phantom phase images were acquired at 1.5 T (Magnetom Symphony, Siemens Healthcare), with FA=20°, TR=30 ms, TE=7 ms, FOV=256x256 mm^2, N_{acq}=128x128, slice thickness 5 mm, and readout bandwidth of 390 Hz/pixel.

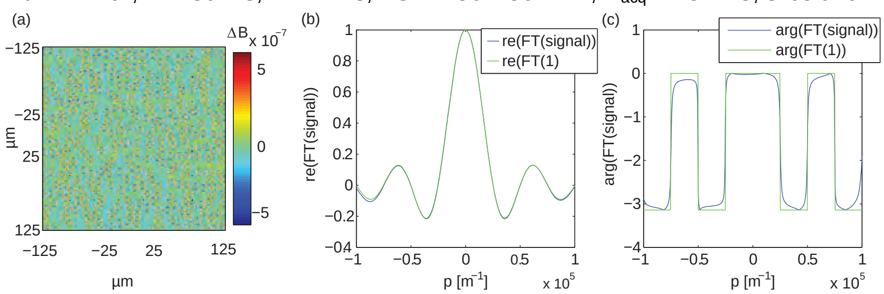

Fig. 1: MR signal for a voxel filled with axons. (a) Magnetic field shift caused by the axons. (b) Normalized real parts of the Fourier transform of the one-dimensional MR signal of the voxel filled with axons (blue curve) and of a voxel with homogeneous magnetization (green curve) over the p-space. (c) The phase corresponding to (b). p-space imaging is insensitive to this axon structure and susceptibility microstructure.

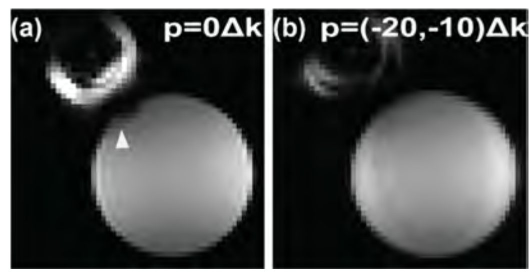

Fig. 2: Oil phantom magnitude images with and without p-gradient, $p_{(read,phase)}$=(-20,-10)Δk, applied. (a) Signal loss (arrow) due to local field gradients induced by the water phantom placed next to the oil phantom; (b) Signal is regained by applying p-space gradients which compensate for the local field gradients.

RESULTS– For the simulated MR signal (Fig. 1), we observed that the angle (only simulations for 90° are shown) between the axons and the direction of the B0 field hardly influenced the curves in Fig.1(b),(c). The curves were sinc-shaped due to the finiteness of the voxel. However, p-space gradients could recover local signal loss by compensating field inhomogeneities (Fig. 2). Moreover, when inhomogeneous magnetization and intra-voxel microstructure were present, characteristic phase patterns emerged that were indicative of the voxel substructure (Fig. 3).

DISCUSSION– p-space imaging can be used to regain signal if the direction of the gradients causing field inhomogeneities is known, similar to applying shim gradients. The simulations of a voxel filled with axons could not confirm that there is a difference between a highly substructured voxel filled with axons and a voxel of homogeneous magnetization. The quadratic curve found in[5] Fig. 2b (p. 196) is very likely the result of a truncated sinc function, which is the Fourier transform of a voxel with homogeneous magnetization due to the finiteness of the voxel. Nonetheless, p-space imaging can be indicative of subvoxel structures.

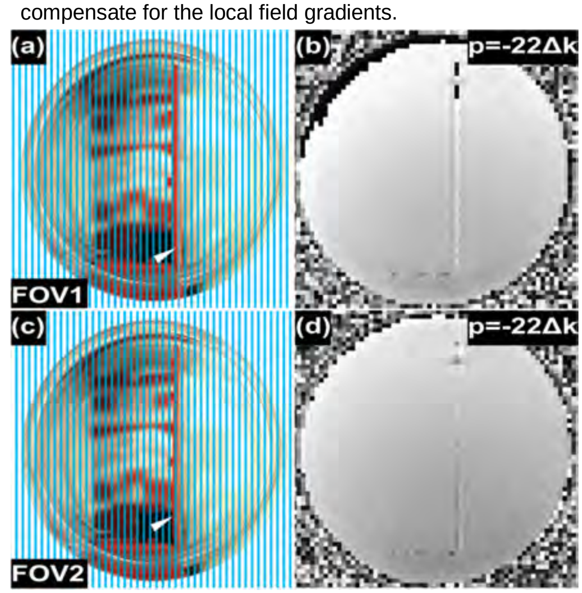

Fig. 3: Water phantom phase images with different FOV positions. (a) and (c) show a photograph of the water phantom and the position of the plastic plate (arrow) with respect to two different FOVs. (b) A p-gradient with p_{phase} = -22Δk was applied. (d) The field of view is shifted 1mm to the right in the sagittal plane, same p-gradient as in (b).

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