Isotropic High-Resolution 3D Diffusion Weighted SSFP Imaging with Spiral Projection Imaging

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INTRODUCTION – The conventional spin preparation for DWI, the single-refocused spin echo, requires a large percentage of the TR reducing scan time efficiency. The Diffusion-Weighted Steady State Free Precession sequence (DW-SSFP), however, can have high diffusion sensitivity with diffusion gradients that are short relative to those required by the spin echo sequence for similar diffusion sensitivity. This is because the DW-SSFP signal arises from multiple echo pathways that can have long diffusion times. Consequently the diffusion attenuation of DW-SSFP depends not only on the geometry of the diffusion weighting pulse, but also on T_1, T_2, diffusion coefficient, TR, and flip angle. These dependences have been described in detail by Kaiser *et al*. [1], and more recently Wu and Buxton [2] and Freed *et al*. [3]. Previous demonstrations of DW-SSFP imaging have used the TURBINE sequence [4] and the 3D projection sequence [5]. To use the gradient system more efficiently, spiral projection imaging (SPI) readout is used to achieve whole brain coverage and to allow phase navigation by batching interleaves acquired in similar cardiac phases (over an RR-interval) similar to the methods presented by Miller [6].

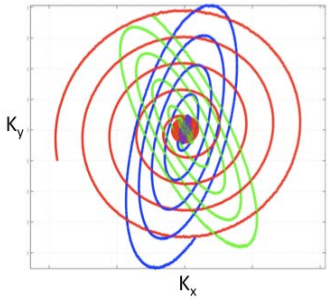

Fig. 1 - *The k-space trajectory. 3 successive spiral interleaves are shown in separate colors. Note the densely sampled central navigator region.*

METHODS – • *MRI:* DW-SSFP SPI was performed on a volunteer using a 1.5T scanner (Signa HDX, GE Healthcare) with 8-channel head coil. The k-space trajectory was a bi-density spiral-in with a fully sampled central region for phase navigation and a radially under-sampled outer spiral. To cover the full 3D k-space sphere the spirals were rotated in 3D with the normal vector to the spiral plane following a 2D *golden angle sampling* pattern [7]. Sequence parameters included: isotropic 1.4 mm^3 resolution, 280 mm^3 FOV, TR 23.4 ms, scan time 2 min per direction for 3 diffusion directions, 5000 spiral interleaves per volume, diffusion gradient width 5.5 ms with 1ms ramps, and diffusion gradient strengths 5, 2.5, 1, and 0.5 G/cm

• *Recon:* Reconstruction was performed by retrospectively binning the data into 10 cardiac phases using pulse oximeter waveforms. For each spiral interleave, corresponding 16^3 pixel navigators were reconstructed from each cardiac phase and used to reconstruct the images with a phase-corrected iterative SENSE algorithm [8]. K-space trajectories were measured on a phantom using the Duyn method [9]. Density compensation was performed using the algorithm of Pipe and Menon [10] and code from Johnson [11]. For comparison, standard gridding reconstruction was also performed.

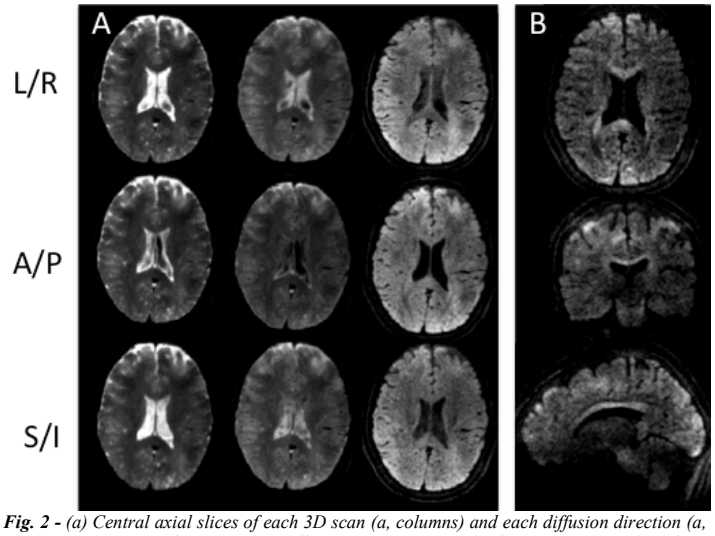

Fig. 2 - *(a) Central axial slices of each 3D scan (a, columns) and each diffusion direction (a, rows). Scans were performed with a diffusion gradient strength of 0.5, 1, and 2.5 G/cm (from left-to-right); (b) axial, sagittal, and coronal views from the 5 G/cm scan with A/P diffusion encoding.*

RESULTS AND DISCUSSION – Central axial slices for the SENSE-reconstructed images are given in Fig 2 for each diffusion weighting strength and direction. As expected the contrast changes from T_2-like to diffusion- weighted as the diffusion gradient strength increases from left to right (Fig 2a). Note that in the higher diffusion-weighting (Fig 2a last column) there are residual phase errors due to phase inconsistencies between shots. These are more apparent in the S/I direction and L/R direction. Figure 2b shows 3 orthogonal slices through the acquired volume using the maximum gradient strength of 5 G/cm and demonstrating the isotropic 3D full brain coverage of the technique. Figure 3 shows the signal recovery achieved by using the cardiac phase binning and SENSE reconstruction (white arrow, b) compared to the standard gridding reconstruction and without considering the cardiac phase (white arrow, a).

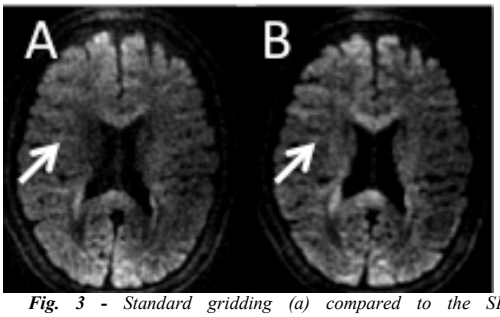

Fig. 3 - *Standard gridding (a) compared to the SENSE reconstruction (b). The SENSE reconstruction restores signal around the ventricles (white arrows).*

CONCLUSION – The demands for DTI are clearly pointing towards isotropic 3D resolution to facilitate tractography and VBM. Reducing the slice thickness for 2D acquisitions bears diminishing returns. While most other approaches have focused on thin slab 3D approaches with excessive averaging, here a 3D isotropic high-resolution DW-SSFP technique for multiple diffusion weightings and directions is demonstrated that covers the whole brain. The use of the cardiac gated SENSE reconstruction in combination with golden angle scanning was able correct a significant portion of the non-linear phase errors and led to considerably better image quality than regular gridding reconstruction. However, the 16^3 navigator resolution appears to be insufficient to resolve all phase error terms, which is reflected in some residual subtle shading artifacts. Future work will therefore leverage parallel imaging to increase the navigator resolution and focus on removing residual random phase errors.

References: [1] Kaiser et al J Chem Phys 1974. [2] Wu and Buxton. JMR 1990. [3] Freed et al. J Chem Phys. 2001. [4] Mcnab et al. MRM 2010. [5] Jung et al JMRI 2009. [6] Miller and Pauly. MRM 2003. [7] Chan et al. MRM 2009. [8] Liu et al MRM 2005. [9] Duyn et al JMR 1998. [10] Pipe and Menon MRM 1999. [11] http://www.public.asu.edu/~kojohnso/research.html

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