Steady-State Free Precession (SSFP) Diffusion Imaging Using 3D Rotating Spirals (3DRS)

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INTRODUCTION 3D diffusion imaging has been an appealing but challenging topic over the last decade. It provides good properties such as isotropic resolution, higher SNR efficiency, and less inflow effect. However, it also suffers from long scan time and consequently more severe motion artifacts. Compared with traditional spin-echo diffusion weighted imaging (DWI) method, steady-state free precession (SSFP) DWI [2, 3, 4] yields strong diffusion sensitivity with much shorter imaging time. On the other hand, although signal in SSFP-DWI is composed of both spin echo and multiple stimulated echoes, experiments have shown that motion induced artifacts in SSFP-DWI can still be reduced by correcting navigated phase errors or averaging multiple DWI scans [3, 4]. In this work, we will present a SSFP 3D rotating spiral (3DRS) method for fast DWI and diffusion tensor imaging (DTI) acquisition, which is based on our previously reported 3D-SNAILS technique [1]. By combining SSFP-DWI and 3DRS readouts in this approach, high quality diffusion weighted volumes can be rapidly acquired with very high SNR efficiency and low sensitivity to motion artifacts.

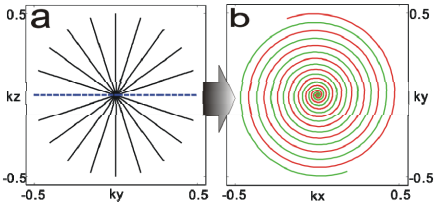

Figure 1: 3DRS: (a) k-space is fully sampled by radial planes rotating along kx; (b) each of these planes is sampled by interleaved VD-spirals.

METHODS Rotating variable density (VD) spiral trajectories are used, as shown in Fig 1. The whole 3D k-space is radially sampled by 2D planes along kx-axis, with each plane sampled by interleaved VD-spirals. The 3D navigator part in 3D-SNAILS [1] is removed here to shorten the readout time of the SSFP sequence. This 3DRS interleaving strategy offers several advantages over EPI and radial readouts. First, every echo is acquired at k-space center and samples near k-space origin can be utilized for phase correction. Next, dense sampling of k-space center provides high SNR efficiency, thus it usually requires fewer NEX and total scan time to achieve desired SNR. Finally, this oversampling also improves image quality by reducing its sensitivity to subject motions. Fig 2 shows the SSFP-3DRS pulse sequence. VD Spiral-in trajectories are used to acquire the strongly diffusion-weighted M^- signal. Diffusion sensitizing gradients can be altered into different directions to acquire tensor images.

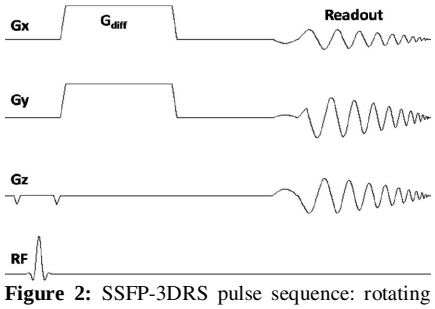

Figure 2: SSFP-3DRS pulse sequence: rotating spiral-in trajectories are interleaved to acquire the M^- signal.

In vivo DTI scans were performed on a healthy volunteer at a 3T GE-DV750 scanner with an 8-channel head coil. The following parameters were used: TE/TR = 23ms/35ms, FA = 50, FOV = 24cm, matrix size = 128x128x128, BW = 125kHz. The voxel size was thus 1.8mmx1.8mmx1.8mm isotropic. 12 in-plane spiral interleaves and 200 rotating spiral planes were generated with a readout length of 12ms. Each single DWI volume was acquired with a scan time of 1.5 minutes. Two DTI experiments were implemented with different b-values (b_{eff}=600 and 1000 respectively [2, 3]). For each experiment, six diffusion gradient directions, [0.910, 0.416, 0], [0, 0910, 0.416], [0.416, 0, 0.910], [0.910, -0.416, 0], [0, 0.910, -0.416] and [-0.416, 0, 0.910] (D1 to D6), were applied to acquire diffusion tensor volumes [6]. A non-diffusion-weighted volume (b=0) was also acquired, during which a small diffusion gradient ([0, 0, 0.1]) had to be turned on to avoid banding artifacts [5]. A two-stage 2D-gridding reconstruction approach was used to reconstruct each DWI volume, as presented in [1]. For each interleaf, samples near k-space center were used to estimate the 0-th order phase error and this error was subtracted out before combining all interleaves. A naive exponential diffusion model was used to calculate ADC values without quantitative T1 and T2 measurements [2].

RESULTS Fig 3 shows the acquired axial DWI slices. For these prescription parameters, a single NEX appears to be yielding high enough SNR. Hence, it takes only 10.5 minutes for a whole brain DTI acquisition. Diffusion anisotropies can be observed for both DTI experiments from Fig 3. ADC traces and FA maps were also calculated for each experiment. Example coronal and axial slices are shown in Fig 4.

DISCUSSION AND CONCLUSION In this work, we have demonstrated the acquisition of diffusion-weighted whole brain volumes using a SSFP-3DRS sequence. Compared with other diffusion techniques, our approach can achieve much higher SNR with desired diffusion weighting and limited imaging time. The 3DRS sampling strategy also benefits from reduced sensitivity of subject motion. However, since only the 0th order phase error term can be extracted and corrected, images may still be contaminated by residual motion artifacts, especially for high b-values, as shown in Fig 3 and Fig 4. A proper 3D navigator should help further improve the image quality, which is still under investigation. Furthermore, with its high SNR efficiency, SSFP-3DRS can be feasibly applied to acquire DTI volumes under even higher resolution, which is usually desirable for tractography..

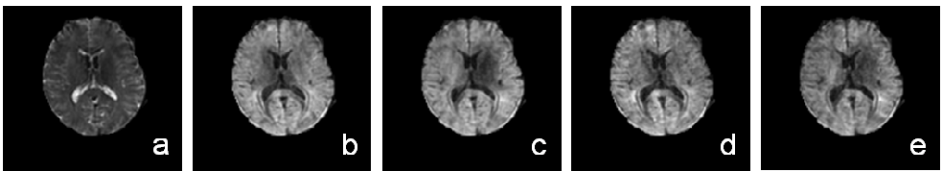

Figure 3: Diffusion weighted volume slices acquired by SSFP-3DRS sequence with different b values and tensor directions: (a) b=0; (b) b=600, D1; (c) b=600, D4; (c) b=1000, D1; (d) b=1000, D4.

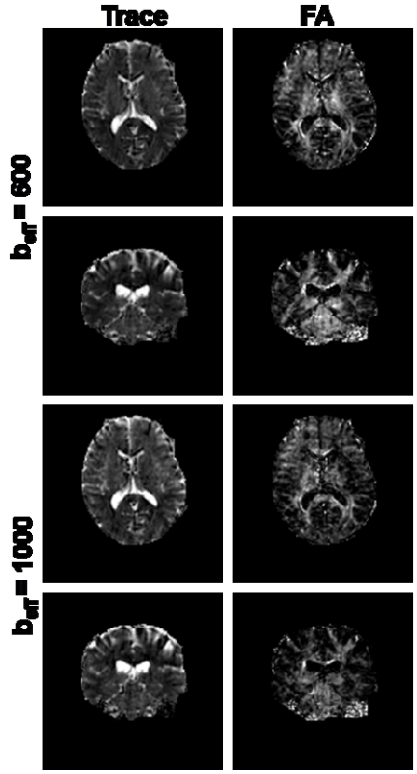

Figure 4: Trace of ADC and FA maps of axial and coronal slices for different b-values.

REFERENCES 1. Zhang J et al., ISMRM 2007, p9; 2. Buxton R., Magn Reson Med, 29, 235-243, 1993; 3. Mille K., et al., Magn Reson Med, 50, 343-353, 2003; 4. Bosak E., et al., J Magn Reson 12, 167-176, 2001; 5. Zur Y., et al., Magn Reson Med, 6, 175-193, 1988; 6. Skare S., et al., J Magn Reson 147, 340-352, 2000.

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