Self-Navigated Diffusion Tensor Imaging with Interleaved Variable Density Spiral Acquisition

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INTRODUCTION: Subject motion is a major source of image distortion and artifacts in diffusion-weighted (DW) MRI. Phase error induced by bulk motion has so far limited the use of multi-shot echo planar imaging (EPI) approach. However, single-shot EPI results in relatively long readout time and low bandwidth per pixel, which can lead to a limited image resolution, blurring and geometric distortions. To compensate for eddy current, reduce motion artifacts, and improve phase navigation capabilities, we have implemented a twice-refocused spin echo sequence (TRSE) (1, 2) using a variable density (VD) spiral waveform design (3, 4). With reduced eddy current, the actual k-space trajectory prescribed by the scanner hardware is less distorted than conventional EPI. The VD spiral was designed such that the center of the k-space is excessively oversampled and served as an effective self-navigator. Here, we show high resolution (256x256) *in vivo* diffusion tensor images with high SNR, great contrast, and significantly reduced geometric distortions.

MATERIALS AND METHODS: The twice-refocused spin echo sequence is known to give a reduced artifact level when combined with EPI or conventional spiral readout (1-2). An improved version of our TRSE sequence (2) was implemented on a GE 1.5T and 3T whole body system: a simple analytical method was used to design the interleaved variable density spiral readout trajectory (3). For a given FOV, the desired resolution and number of interleaves, a minimum-duration trajectory has been designed such that it is realizable on the gradient hardware of the system. Because of the limitation of the gradient strength, this normally results in a combined use of both a slew-rate-limited and an amplitude-limited waveform design. Interleaved acquisition is then achieved by rotating the same trajectory interleave by interleave in the waveform memory of the spectrometer unit. By increasing the number of interleaves, the readout time can be shortened as desired. This design method is flexible and enables real-time prescription on the scanner.

In vivo diffusion measurements were performed on healthy volunteers. The following parameters were used: TR/TE = 3s/63ms, G_{max} = 50mT/m, b = 900 s/mm^2, FOV = 24cm, acquisition matrix size = 256x256, BW = ±100 kHz, NEX = 6, and 16 interleaves. The duration of the four diffusion gradients was: $\delta_1 = \delta_3$=7.1ms and $\delta_2=\delta_4$=11.2ms. The readout time was 16.4 ms for each interleave. In total, six diffusion gradient directions [(-1 -1 0), (1 0 1), (0 1 -1), (-1 1 0), (0 1 1), (1 0 -1)] were applied to acquire the diffusion tensor. The scan time for acquiring six DW images plus an unweighted image was 5.7 minutes per NEX. All images were reconstructed using a gridding algorithm without any retrospective motion correction or gating.

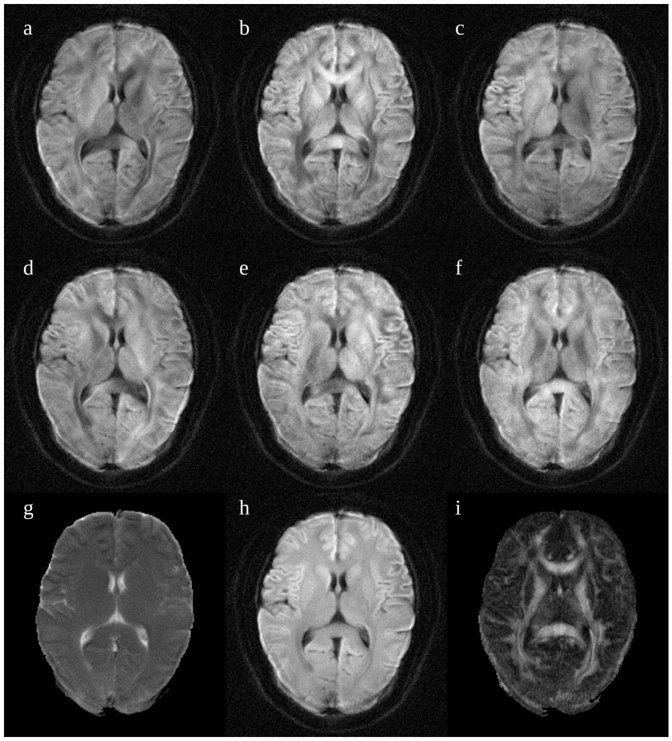

Fig. 1 – *in vivo* high resolution (256x256) DTI results acquired with a VD spiral TRSE sequence. (a)-(f) Diffusion-weighted images with different diffusion gradient directions. (g) Trace map of the diffusion tensor. (h) Isotropic diffusion-weighted image. (i) Fractional anisotropy map.

RESULTS: Fig. 1a-f shows the six diffusion weighted images with diffusion gradients played out along the aforementioned gradient directions. Due to the self-navigating capability of the variable density spiral readout trajectory, there was a tremendous reduction of motion artifact in the DW images. Another great advantage of the interleaved spiral readout is that there are no geometrical distortions in the DW images. No fat-sat technique was used here and, hence, fat appears slightly bright near the edge of the brain because of the relative short TE. Nevertheless, fat signal does not cause major artifacts due to the high resolution acquisition. By using the six independent diffusion-weighted images, the diffusion tensor was calculated. Fig. 1g-i shows the trace map, the isotropic-weighted image, and the fractional anisotropy (FA) map. A color coded FA map was also created by using the directions of the three eigenvectors (Fig. 2). Red indicates the anterior-posterior direction; green indicates left-right direction; and blue indicates the cephalo-caudal direction. Orientation of the white matter tracts can be clearly identified in the colored FA map.

DISCUSSION: We have demonstrated the acquisition of high resolution diffusion-weighted images using a VD spiral TRSE sequence. The resultant images have high SNR and great contrast between white matter and gray matter. As a result, fine structures, such as the layers of the tapetum in the optic radiation, can be observed in both the DW images and the FA map. The VD spiral acquisition of DW images has a substantial benefit in reducing the sensitivity to subject motion. VD spiral acquisition is a self-navigated technique in the sense that the center of k-space is excessively oversampled, and consequently the motion-induced phase error can be effectively averaged out. This is a similar feature shared by PROPELLER MRI (5). Because of the similarity, similar post-processing techniques can be employed for VD spiral.

Furthermore, the sequence is virtually immune to image warping due to eddy currents, which is a severe problem for single-shot EPI DWI. The latter usually causes severe misregistration with conventional structural images that impair image coregistration in functional studies. The radial nature of a spiral trajectory enables to spread artifacts evenly among all directions. It is also very flexible to change the sampling density of the spiral trajectory and prescribe the desired number of interleaves. The interleaved acquisition shortens the readout time, therefore helps to reduce the distortions that result from the spins that are off-resonant.

There is an increase in scan time using interleaved spiral acquisition of DW images. This is the necessary tradeoff in order to achieve higher resolution and better SNR simultaneously. The scan time, however, can be reduced by adding parallel-imaging techniques (6). In conclusion, it is feasible to acquire high resolution DW images of high SNR and great contrast by using a VD spiral readout trajectory.

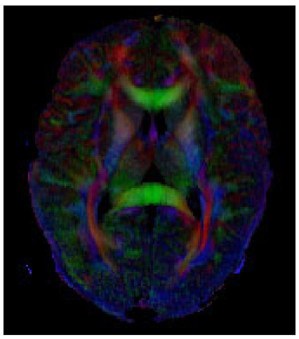

Fig. 2 – Color coded FA map. Red: anterior-posterior. Green: left-right. Blue: cephalo-caudal.

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