High-Resolution Multi-Shot Spiral Diffusion Tensor Imaging with Inherent Correction of Motion-Induced Phase Errors

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Introduction: Multi-shot spiral imaging is a promising alternative to single-shot echo-planar imaging for diffusion tensor imaging (DTI) because it can achieve a higher spatial resolution and signal-to-noise ratio (SNR), but is challenging because subject motion causes phase errors among different shots, leading to signal loss and aliasing artifacts in the reconstructed images as well as subsequent errors in the DTI metrics.

Existing multi-shot spiral DTI techniques use a variable-density spiral trajectory[1] or a navigator echo[2] to estimate and correct for these phase errors, but result in a longer scan time. Another method[3] can inherently correct for such errors with no scan time penalty, but requires a long computation time and only corrects for spatially linear phase errors due to rigid-body motion, not for nonlinear phase errors due to nonrigid motion.

Here, we compare two alternative reconstruction methods for multi-shot spiral DTI designed to both inherently and efficiently correct for linear and nonlinear phase errors.

Methods: The first method simply consists in reconstructing a *magnitude* image from the k-space data of each shot, by using a sensitivity encoding (SENSE) reconstruction algorithm[4], and averaging the resulting images from all shots. Since each image is only reconstructed from one shot, it is not affected by phase errors among different shots, but suffers from an SNR loss due to the g-factor penalty inherent in parallel imaging.

The second method consists in reconstructing a *phase* image from the k-space data of each shot, also by using SENSE[4], to estimate the motion-induced phase error (**Fig. 1**). Since these errors are spatially slowly varying, only the central k-space of each shot is used for the SENSE reconstruction, such that the phase images have a twice lower spatial resolution but a higher SNR, resulting in a more robust phase estimation. The phase maps are then unwrapped, smoothed, and interpolated to the full resolution.

Once estimated, the motion-induced phase errors ϕ are combined with the coil sensitivity profiles *s* to form composite sensitivity profiles that vary with each shot. The full k-space data and composite sensitivity profiles of all shots are then supplied to an iterative conjugate gradient (CG) algorithm[1], similar to the SENSE algorithm for arbitrary k-space trajectories[4], to correct for the phase errors and reconstruct the final image.

Multi-shot spiral DTI data were acquired on healthy volunteers on a 3T MR750 GE scanner using a 32-channel head coil and a single spin-echo, 6-shot, constant-density spiral sequence with TR = 5.2 s, TE = 51 ms, FOV = 20.8 cm, matrix = 208$\times$208, slice thickness = 3 mm, 44 slices, *b*-factor = 800 s/mm^2, 15 diffusion directions, and NEX = 1. Images were reconstructed with the SENSE or CG method and blurring artifacts due to susceptibility effects and eddy currents were corrected with dynamic B_0 mapping[5].

Results: Even though the subjects were instructed to remain still and their head was restrained with padding, residual motion still causes extensive signal loss and aliasing artifacts in the uncorrected diffusion-weighted images as well as subsequent errors in the uncorrected fractional anisotropy (FA) maps throughout the brain (**Fig. 2**).

Results obtained with the SENSE method are not affected by such artifacts, but suffer from a low SNR due to the g-factor penalty. In contrast, results obtained with the CG method are also free from artifacts, but have a substantially higher image quality and SNR (up to 50% in the center of the FOV). The total reconstruction time on a Linux cluster was 20 and 12 min for the SENSE and CG methods, respectively.

Discussion: These results demonstrate that the proposed CG method can inherently, effectively, and efficiently correct for motion-induced phase errors in multi-shot spiral DTI and provide high-quality, high-resolution FA maps, revealing fine anatomical details typically not seen in DTI data acquired with single-shot echo-planar imaging at 3T.

As expected, this method is superior to the SENSE method, which is limited by a low SNR. It also benefits from significant advantages over existing methods[1–3], since it does not increase the scan time, is not limited by a long computation time, and can correct for both linear and nonlinear phase errors due to rigid and nonrigid motion.

Conclusion: The proposed CG method can correct for motion-induced phase errors in multi-shot spiral DTI with no scan time or SNR penalty. It should thus facilitate a wider adoption of high-resolution multi-shot spiral DTI in basic and clinical neurosciences.

References: 1. Liu C et al. MRM 2005;54:1412–22. 2. Van AT et al. IEEE Trans Med Imaging 2011:30:1933–40. 3. Truong TK et al. MRM 2012;68:1255–61. 4. Pruessmann KP et al. MRM 2001;46:638–51. 5. Truong TK et al. NeuroImage 2011;57:1343–47.
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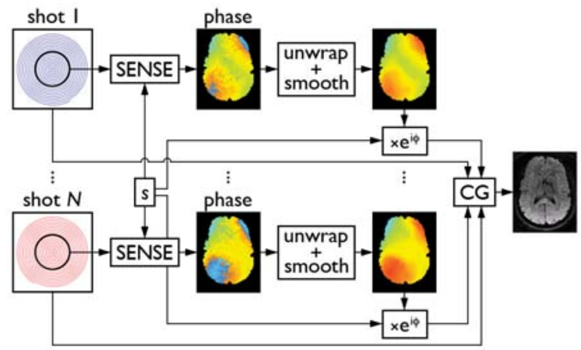

Fig. 1: Schematic diagram of the proposed CG method.

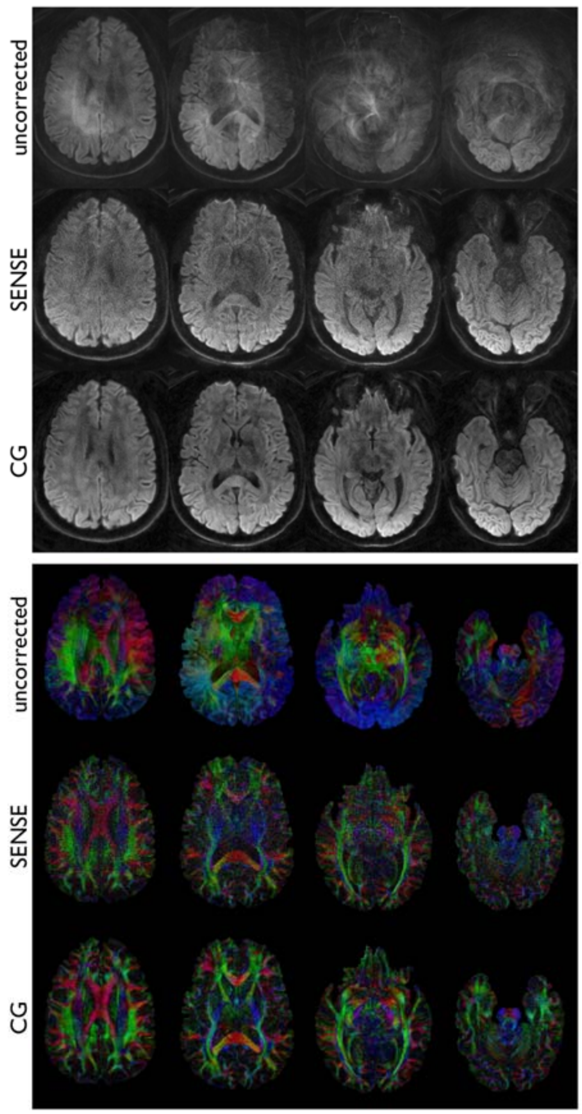

Fig. 2: Diffusion-weighted images and color-coded FA maps.