Navigated PSF Mapping for Distortion-Free High-Resolution In-Vivo Diffusion Imaging at 7T

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Target Audience: This work will be of high interest for high-resolution diffusion-weighted imaging and its applications at ultra-high field such as 7T.

Objective: High-resolution diffusion-weighted imaging (DWI) is used for microstructural characterization of human brain in basic research as well as clinical applications. Although single-shot echo-planar imaging (EPI) is a most popular tool for DWI, it might not be suitable for high-resolution DWI due to severe T2 blurring and susceptibility- and eddy-current-induced geometric distortions along the phase-encoding (PE) direction, especially at ultra-high field (UHF). Several multi-shot approaches including readout-segmented [1,2] and interleaved EPI [3] have been proposed to mitigate such effects. In this study, a point-spread function (PSF) based EPI-DWI approach is newly proposed. In contrast to the previous approaches [1-3], this method can yield an image without any T2 blurring and geometric distortions, and enables a clear demonstration of the detailed structure in the human brain *in-vivo*.

Methods: ***Undistorted image from the 3D PSF data:*** In the PSF method, the integral of the 3D PSF data $I(x,y,s)$ along the distorted coordinates (y) yields an undistorted image $I_{undistorted}(x,s)$ [4-6]:

$$I_{undistorted}(x,s) = \int I(x,y,s)dy, \qquad (1)$$

where x (EPI readout), y (EPI-PE), and s (PSF or spin-warp PE) represent coordinates in image space with negligible and severe distortion, and without distortion, respectively. Therefore, a distortion-free image $I_{undistorted}(x,s)$ can be obtained from PSF data using Eq. 1. Furthermore, while T2 decay occurs along the EPI-PE acquisition (Δk_y), the signal is constant in the PSF-PE dimension (Δk_s), corresponding T2 blurring does not appear in the final undistorted image.

PSF mapping with navigator echo: The multi-shot nature of the PSF sequence causes shot-to-shot motion-related phase errors sensitized by strong diffusion gradients, which result in ghost artifacts in the undistorted image. To avoid such artifacts, a 2D navigator echo is acquired after each PSF phase-encoded 2D acquisition (Fig. 1a). To reduce specific absorption rate (SAR), the navigator echo was acquired without refocusing (180°) RF pulse.

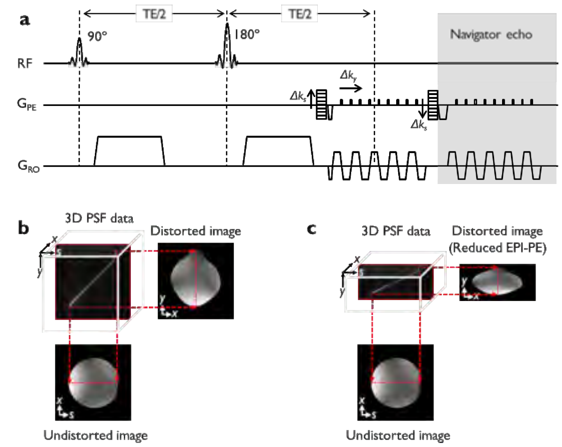

Fig. 1 A PSF-based diffusion sequence diagram with navigator echo (a) and corresponding reconstructed 3D PSF data without (b) and with a reduced EPI-PE resolution (c).

Acceleration through reduced resolution in the EPI-PE coordinate: As shown in Eq. 1 and Fig. 1, the PE resolution of the final undistorted image is determined only by that of the undistorted coordinate (s). The resolution of the distorted coordinate (y) is not relevant due to integration. By reducing the resolution of the EPI-PE coordinate, the use of a minimized (echo time) TE is possible. Therefore, sufficient signal can be achieved within the PSF phase-encoded as well as navigator echo acquisition window even in very high-resolution imaging at UHF, where T2 decay is relatively short. The EPI-PE is only needed to map the PSF in this dimension.

Experiments and post-processing: PSF scans with and without diffusion gradients were performed at 7T (Siemens Healthcare, Erlangen, Germany) using a 32-channel head coil (Nova Medical, Wilmington MA, USA). The imaging protocols were: TR/1st TE(PSF acquisition)/2nd TE(navigator echo)=2170/54/78ms, partial Fourier 6/8 and GRAPPA factor 3 in the EPI-PE dimension, 20 slices, slice thickness 2.8mm, readout bandwidth 1048Hz/pixel, image FOV 224^2, matrix size 320^2 (=0.7mm^2 in-plane resolution), 13 PSF scans with one b-value=0, and 12 b-value=1000s/mm^2. Each PSF data set was acquired with an acceleration factor of 5 in the PSF-PE dimension (corresponding to 64 repetitions or averages) [4] and with a reduced resolution factor of 4 in the EPI-PE dimension (resulting in a matrix size of 80 in the EPI-PE coordinate). No cardiac gating was used and the total scan time for all PSF scans was about 30 minutes.

A 2D phase correction was applied to all PSF phase-encoded images (x,y,k_s) after 2D inverse Fourier transformation (iFT) in k_x and k_y. Each navigator echo was windowed in k-space by a triangular function in both the readout and PE directions prior to FFT [1]. The shot-to-shot phase incoherencies were calculated by subtraction between each navigator echo and the averaged echo. An additional iFT in k_s yields the 3D PSF data and a final undistorted image can be obtained by Eq. 1 from the PSF data. After rigid body motion correction (with six degrees of freedom) of all the reconstructed images, a color-coded fractional anisotropy (FA) map was calculated using FSL software package [7].

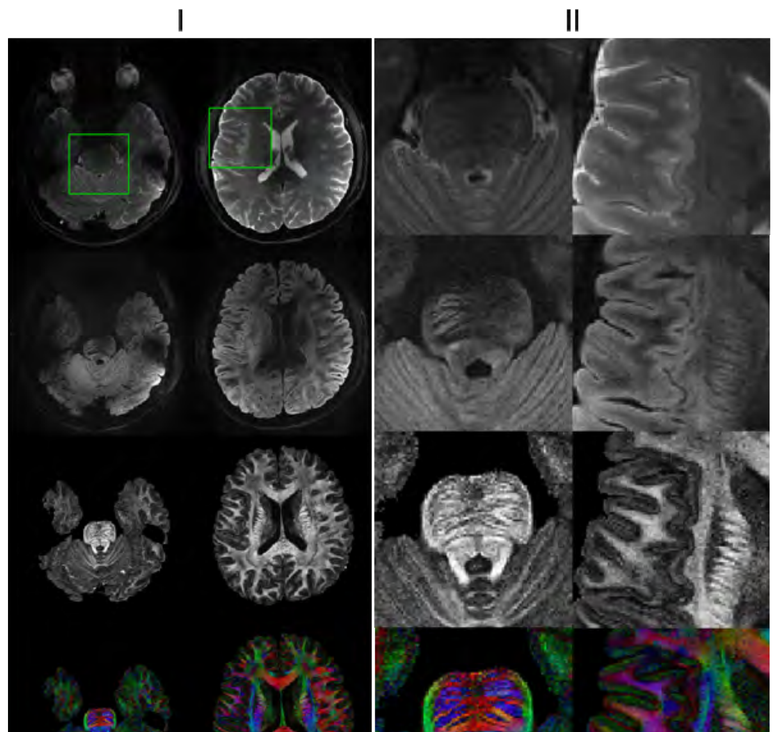

Fig. 2 Two reconstructed DW images (1st and 2nd columns) for b-value = 0 (1st row) and 1000 s/mm^2 (2nd row), corresponding FA map (3rd row), and color-coded FA maps (4th row). A region of interest, as a green box drawn over the full FOV image (I) with b-value = 0 s/mm^2, is enlarged in (II). The acquisition voxel size is 0.7×0.7×2.8mm^3.

Results and Discussion: As shown in the DW images (Fig. 2, 2nd row) obtained by the proposed method, very stable imaging is possible without cardiac gating. The color-coded FA maps demonstrate that the proposed high-resolution DWI shows very detailed structures in brainstem (Fig. 2II, 1st column) without geometric distortions and depicts a clear interface between white and gray matter (Fig. 2II, 2nd column) due to the absence of T2 blurring. Since PSF acceleration is generally limited by the strength of geometric distortions [4], longer scan time is required for each PSF scan although it acts as averaging to increase the signal to noise ratio (SNR) of the acquired image.

Conclusion: The results demonstrate that very high-resolution DWI without any geometric distortions and T2 blurring effects is possible with the proposed method, which results in a clear delineation of brain and cortical structures. Therefore, this technique can be a tool to characterize *in-vivo* human brain anatomy and connectivity for basic research as well as clinical applications.

References: [1] SJ Holdsworth et al., Eur J Radiol 2008;65:36-46 [2] DA Porter and RM Heidemann, MRM 2009;62:468-75 [3] H-K Jeong et al., MRM 2012; 69:793-802 [4] M Zaitsev et al., MRM 2004;52:1156-66 [5] JY Chung et al., MAGMA 2011;24:179-90 [6] MH In and O Speck, MAGMA 2012;25:183–192 [7] http://fsl.fmrib.ox.ac.uk/fsl/

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