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Whole-Brain Mesoscale 0.7 millimeter-Isotropic-Resolution Diffusion MRI at Ultra-High Fields: The JETS-NAViEPI Approach.

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Synopsis

Keywords: DWI/DTI/DKI, High-Field MRI

Motivation: Diffusion weighted MRI (DWI) may blur structures due to limited resolution. Increasing to submillimeter resolution reduces partial volume effects but sacrifices SNR.

Goal(s): We seek to demonstrate submillimeter isotropic DWI at 7T in 3 minutes, and enhanced high-resolution DTI maps.

Approach: Data acquisition is done via NAViEPI, enforcing consistent echo spacing between the imaging and the navigator echo, rendering minimal distortion mismatch. Image reconstruction is done using JETS, benefiting from complementary k-q-space sampling and regularization.

Results: We show a 3-scan trace acquisition with a scan time of 3:19 minutes, and offer high-resolution DTI measurement leading to Mean Diffusivity and colored Fractional Anisotropy maps.

Impact: This work demonstrates submillimeter isotropic diffusion MRI at ultra-high field 7T with improved image quality and reduced scan duration. The JETS-NAViEPI method has the potential to advance high-resolution diffusion MRI, enhancing both spatial and temporal resolution.

Introduction

Diffusion MRI plays an important role in understanding the microstructure of the brain. These structures are very small and therefore regions with more complex fiber arrangements such as crossing, fanning and branching are in a single voxel. Increasing the resolution to submillimeter-isotropic has shown to reduce partial volume effects [1-4] and it can also help detect small micro infarcts in cerebral small vessel disease[5]. Moreover, higher resolution has shown to improve brain parcellation[6-8].
However, increasing spatial resolution comes with decreasing signal-to-noise ratio which limits the ability to reconstruct the fiber tracks[9,10]. Often times, high resolution has been achieved at the expense of scan time or by using thick slices. Increasing the SNR would be possible by utilizing the dependence of SNR on the strength of B0. Imaging at 7 T has the potential to provide the necessary SNR, but it comes at the cost of artifacts from phase variations caused by B0 inhomogeneity.
In this work we show submillimeter isotropic DWI at ultra-high field 7 T with a scan time of little over 3 min as well as high resolution DTI parameter maps.

Methods

We used an adapted navigator based interleaved EPI (iEPI) method originally developed by Tan et al.[11] The primary objective of Joint Reconstruction for Shift-Encoded Navigator-based Interleaved Echo Planar Imaging (JETS-NAViEPI) is to enforce consistent effective echo spacing (ESP) between the imaging and the navigator echos. By achieving this, NAViEPI mitigates distortion discrepancies between these two echos, simplifying the correction of shot-to-shot phase variations and enabling undersampled iEPI acquisition. To maintain image quality and reduce distortions, we introduced k_y-shift encoding along the diffusion encoding direction. This approach allows for more comprehensive data sampling in k-q-space. Combined with a joint reconstruction method with overlapping locally low-rank regularization, implemented with integrated SigPY[12] and PyTorch features, this reduces noise and artifacts by exploiting signal redundancies along the diffusion encoding directions. The coil sensitivity estimation was done using ESPIRIT[13].
NAViEPI facilitates the acquisition of a large number of shots with undersampled iEPI, which enables the implementation of high-resolution mesoscale sub-millimeter protocols in a clinically feasible scan time.
We acquired diffusion data on two healthy volunteers on a clinical 7T scanner (Siemens Magnetom Terra, Siemens Healthineers, Erlangen, Germany). Using NAViEPI, we conducted a 3-scan trace acquisition with the b- value 1000s/mm^2 and a DTI acquisition with 20 diffusion encoding directions and the b-value 1000s/mm^2. The field of view covered 200x200mm^2 with 176 slices.
Two-fold in-plane acceleration and 5/8 partial Fourier with a multiband factor of 2 and a resolution of 0.7mm isotropic with 2-shot EPI were used, resulting in a scan time of 3:19 min for three diffusion encoding directions and 15 minutes for the DTI scan, respectively.
The reconstructed diffusion-weighted images were processed in DIPY[14] to generate color-coded fiber anisotropy (FA) maps.

Results

Our approach demonstrated improved signal-to-noise ratio (SNR) compared to the state-of-the-art MUSE reconstruction method[15]. Figure 1 illustrates the comparison between images reconstructed using MUSE and our JETSNAVi method, showing consistently higher SNR and overall better image quality with JETSNAVi.
In Figure 2, the DTI images, including Mean Diffusivity (MD), mean diffusion-weighted imaging (DWI), and colored Fractional Anisotropy (cFA) maps are presented. Figure 3 shows more detailed cFA maps. Notably, the FA maps reconstructed with JETSNAVi exhibited reduced noise.

Discussion & Conclusion

Obtaining 0.7 mm isotropic diffusion imaging has been a longstanding challenge, particularly due to concerns related to signal-to-noise ratio (SNR) and scan duration. Our results emphasize the potential significance of JETS-NAViEPI in advancing the pursuit of high spatial-angular-temporal resolution.
We demonstrated the ability to complete a whole brain coverage 3D diffusion weighted scan in just over 3 minutes, marking a notable improvement in scan efficiency. Importantly, JETS-NAViEPI consistently produced images with superior SNR, reduced distortion, and reduced scan time when compared to the state-of-the-art single-shot EPI and MUSE. This not only enables higher isotropic resolution but also contributes to more clinically practical scan duration.
Furthermore, our method extended to acquiring a full diffusion tensor imaging (DTI) scan with 20 diffusion encoding directions in a reasonable 15-minute time frame. The JETSNAVi method, with its focus on maintaining consistent echo-spacing between imaging and navigator echoes, significantly improved image reconstruction quality, particularly evident in the fractional anisotropy maps.
These findings underscore the potential impact of the JETSNAVi method in enhancing diffusion imaging, representing a significant step in the pursuit of higher spatial-temporal resolution in diffusion MRI.
To support open and reproducible science, our source code is available on GitHub [https://github.com/ZhengguoTan/sigpy], and interactive demonstrations are provided at [https://github.com/ZhengguoTan/demo_jets_diffusion_mri_7t].

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Figures

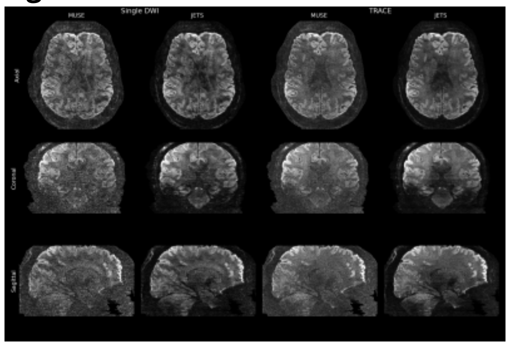

Figure 1: Single diffusion encoding direction and the corresponding TRACE images reconstructed using the MUSE and JETS methods in a 3-scan-trace dataset. The images are presented in axial, coronal, and sagittal views.

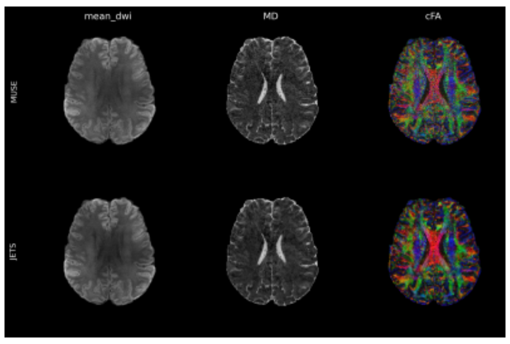

Figure 2: DTI image with a 0.7mm isotropic resolution, showing mean diffusion-weighted MRI (mean_dwi), Mean Diffusivity (MD), and colored Fractional Anisotropy (cFA) maps reconstructed using both the state-of-the-art MUSE reconstruction and the JETS reconstruction. The JETS reconstruction consistently yields images with improved signal-to-noise ratio and overall image quality compared to the state-of-the-art MUSE reconstruction.

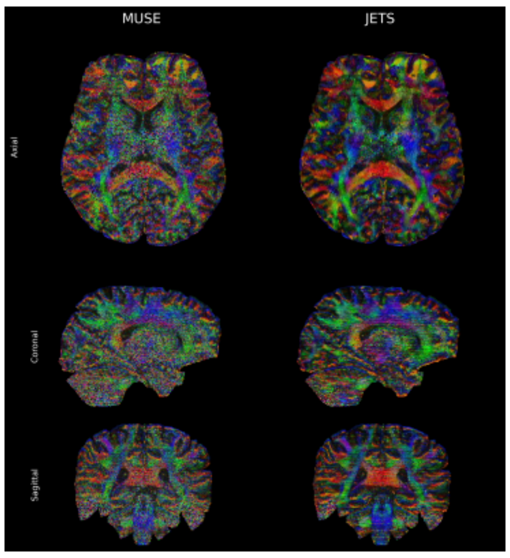

Figure 3: Fractional Anisotropy maps using both, the state-of-the-art MUSE reconstruction, and the JETS reconstruction. The axial, sagittal, and coronal views are presented. The JETS reconstruction demonstrates better Signal-to-Noise Ratio (SNR) and reveals more complex structural details.

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