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Progress in the use of SQUASHER for Diffusion weighted imaging

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Synopsis

The applicability of SQUASHER to EPI, along with a k_z -dependent reconstruction approach for highly-accelerated 3D segmented EPI in dMRI

Introduction

High-resolution diffusion MRI (dMRI) remains challenging due to low SNR and long scan times. Several approaches have been proposed for high-resolution dMRI, including segmented acquisitions (1) and echo volumetric imaging (2). However, the increased scan time in the former, and the increased T2 blurring and signal loss in the latter have hindered their utility. An alternative line of work aims at imaging thicker slices multiple times, and resolving them at a higher resolution in the reconstruction (3,4). The original SLIDER approach (3) images slices with sub-voxel spatial shifts, which was shown to have unfavorable noise amplification (5). Subsequently, this was replaced with gSLIDER (4), which uses different RF excitation profiles to image the same slice/slab to improve the conditioning of the reconstruction. In order to avoid the sharp transitions of the RF profiles in gSLIDER, an alternative 3D encoding method called SQUASHER (Slice quadratic phase with HSn encoding and reconstruction) was also proposed (6), in which a quadratic phase is imposed on the slab, which spreads its k -space spectrum. In this work, we investigate the applicability of SQUASHER to EPI, along with a k_z -dependent reconstruction approach for highly-accelerated 3D segmented EPI in dMRI.

Methods

SQUASHER 3D-EPI: A 3D-EPI acquisition with slice and phase-encoding segmentation using frequency swept pulses for excitation and refocusing(4) was implemented to image thin slabs of less than 10 slices. A single navigator was used across all segments. Diffusion weighting was achieved using the spoiler gradients. Fast imaging by sub-sampling in the k_z direction was evaluated with retrospective undersampling.

Reconstruction: Navigator correction was performed with linear phase-difference estimated from the navigator, and applied channel-specific. To evaluate the robustness of sub-sampling in k_z direction, both a conventional 3D-GRAPPA algorithm(5) and a k_z -dependent 3D-GRAPPA algorithm(7) were implemented. The latter builds on an earlier modified GRAPPA approach(6), and utilizes a region-specific 3D kernel for different slice encoding locations.

Phantom imaging, A single-shot partition segmented diffusion weighted SE-EPI with TE/TR=143/4000ms, 1.5mm³ isotropic resolution, 8 slices/slab, 25% slab oversampling was used. This was used to compare the spectrum of the SQUASHER 3D-EPI against a standard implementation with a SINC RF-pulse. The SQUASHER data was retrospectively sub-sampled at rate 4×2 ($k_y \times k_z$), and reconstructed using single-kernel and k_z -dependent 3D-GRAPPA approaches.

In-vivo imaging was performed on a 3T Prisma, equipped with a 32 channel receiver coil. For GRAPPA kernel estimation, an ACS reference scan with 1 segment in the phase-encoding direction was acquired with TE/TR=129/800ms, 1.5×1.5×1mm³ resolution, 8 slices/slab, 25% slab oversampling, matrix size=128×128×10 and matched RF to the accelerated acquisition. For accelerated acquisitions, phase-encoding segmentation (two) was used, with TE/TR=91/800ms, FOV and resolution matching the reference scan. These acquisitions were repeated both with and without diffusion weighting.

Results

Fig. 1 shows the signal energy of the acquisitions using SQUASHER and SINC encoding pulses, in the x - y - k_z plane following a root-sum-squares combination across coils. SINC encoding exhibits a fast decay in energy in the k_z direction, which hinders segmentation due to the low SNR in the high-frequency components. On the other hand, SQUASHER exhibits a slow decay in the k_z direction, which may be favorable for slice segmentation correction.

Fig. 2 depicts a phantom reconstruction with 4×2 undersampling. Single-kernel reconstruction (b) suffers from residual aliasing and signal variation, whereas the k_z -dependent kernels (b) enable a distortion-free image at this high acceleration rate. The signal variation in a reformatted view (d) shows the superiority of the k_z -dependent kernels in maintaining the signal variations across slices in this thin slab.

Fig. 3 shows the application of these techniques to human brain imaging for a single slice from a 3D acquisition at 4-fold k_y acceleration, with 2 different diffusion weightings, and with 1mm through plane resolution and 1.5×1.5mm in-plane resolution.

Discussion

The use of SQUASHER and the k_z -dependent GRAPPA algorithm allows for a higher SNR acquisition and better reconstruction. These provide a flexible, scalable approach for high resolution imaging with 3D-acquisitions of thin slabs.

For 3D thin-slab high resolution imaging, one of the challenges for the slice-segmentation is that the acquired k_z slices have low signal. The low signal was previously addressed with the gSLIDER technique (4) where a Hadamard type encoding with n different RF pulses was used with n slices having coherent RF phase for increased signal. In contrast, SQUASHER requires a single RF encoding shape, while maintaining the conventional Fourier slice and phase encoding, but instead modifies the properties of the k -space signal for better segmentation.

In this study, we have shown the feasibility of combining SQUASHER and the k_z -dependent GRAPPA for accelerated 3D EPI diffusion weighted imaging. Higher-resolution acquisitions and combination with SMS will be explored in future studies for faster whole brain coverage.

Acknowledgements

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References

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Figures

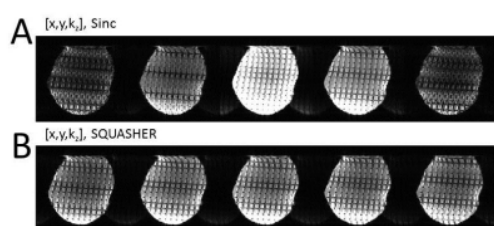


Figure 1 The signal in $[x, y, k_z]$ for SINC and SQUASHER encoding

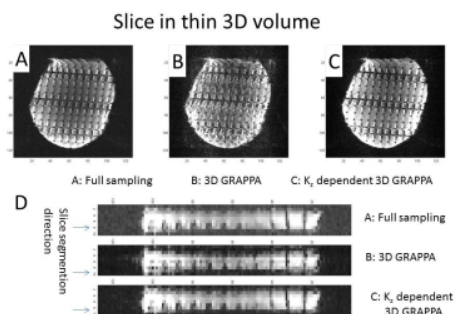


Figure 2 A single axial slice from the 3D volumes are shown in A (fully sampled k-space), B (3D reconstructed with 3D GRAPPA), C (reconstructed with k_z dependent GRAPPA).

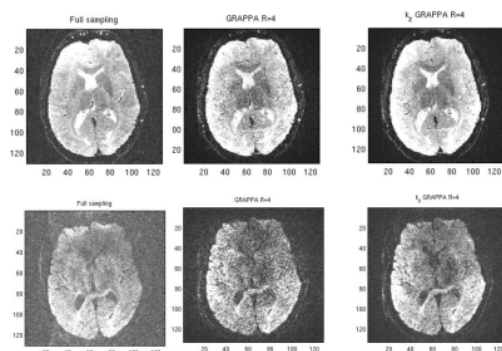


Figure 3: Axial images from 3D diffusion weighted SE-EPI. Top row is with ($b=0$), and the bottom row is with diffusion weighting. The second column is for a reconstruction with $R=4$, using the 3D GRAPPA reconstruction and the third column is with the k_z 3D GRAPPA reconstruction.

