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Acquisition Optimization of Ultra-High Resolution Diffusion MRI for the Next-Generation 7T scanner

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Synopsis

Keywords: Diffusion Acquisition, Diffusion Acquisition

Motivation: To realize the NexGen 7T's full potential for ultra-high resolution diffusion MRI.

Goal(s): To explore, optimize, and share best practices for ultra-high resolution diffusion imaging on the NexGen 7T.

Approach: We systematically optimized multiple acquisition approaches starting from a SAR and artifact reduction perspective (via optimization of fat saturation and coil combination approaches) and then moved on to optimization of SNR (via optimization of slice order, slew rate of diffusion gradients, and other SNR enhancing techniques).

Results: The cumulative gains in SNR and reduction in SAR and artifacts allow for fast, high-quality, high-resolution diffusion imaging (≤ 0.6mm).

Impact: Our study sheds light on the complex and often opaque diffusion acquisition parameter space to help the diffusion community more readily achieve mesoscale diffusion imaging, which would facilitate better characterization of complex crossing fibers as well as cortical-depth-dependent brain connectivity.

Introduction

The faster, stronger gradients of the NexGen 7T significantly reduce diffusion encoding times for up to a 3-fold improvement SNR while also reducing total scan time[1]. However, the complex acquisition parameter space can result in unanticipated barriers to achieving high-quality, ultra-high-resolution, diffusion imaging. In this study, we systematically optimize multiple acquisition approaches starting from a SAR and artifact reduction perspective and then move on to optimize SNR; allowing for fast, high-quality, ultra-high-resolution (≤ 0.6mm) diffusion imaging.

Methods

The NexGen 7T (Siemens Healthcare) includes the PNS-optimized Impulse head gradient coil and achieves a Gmax of 200 mT/m and max slew rate of 900 T/m/s[1]. Subjects were scanned using an 8-channel pTx, 64-channel Rx array. The CMRR C2P Diffusion sequence with FLEET reference scan was used for time-efficient robustness to motion. Acquisition parameters were optimized using a 0.9 mm DWI protocol: 152-156 axial slices, GRAPPA3, MB2, PF6/8, TR~5500ms. Diffusion encoding gradient rise-time (specified on scanners SBBDiffusion.ini file) was updated from 16 us/(mT/m) to 6 us/(mT/m). We also evaluated: Standard CHESS fat-saturation, gradient reversal, and a low SAR method[2,4] using custom RF-pulse durations (5, 7, and 10 ms). SENSE1[3] and Sum of Squares (SoS) coil combination methods were evaluated. tSNR was calculated from scans of 10 b=0 s/mm^2 images. The 0.6 mm protocol includes: 118 axial slices, GRAPPA3, PF5/8, SLIDER2, TR12000ms, TE49.4ms, b=800s/mm^2 (64-directions), AP/PA phase encoding, TA=25 mins. The 0.6mm data were processed[5,6] using denoising[7], and corrections for Gibbs ringing artifacts[8], eddy current, EPI distortions, and subject motion, using the T2-weighted scan as a structural target for co-registration.

Results and Discussion

Consistent with prior work[2,4], Figure 1A shows that gradient reversal fat-saturation at 7T is spectrally too aggressive resulting in B0 dropout in the orbital frontal and ventral temporal lobes. This dropout can be avoided with standard CHESS fat-saturation or alternatively by just setting the excite pulse duration to half of the refocusing pulse which resulted in good fat-suppression and SAR performance. Importantly, not using CHESS improves tSNR and SAR by ~30% (Fig 1B) resulting in higher-quality fractional anisotropy maps (Fig 1CD).

Figure 2 shows the signal-void artifact with SENSE1 coil combination method[9] can be quite pervasive with the higher channel-count coil used. These artifacts are prominent around phase singularities (Fig 2CD) but can be avoided using SoS coil combination (Fig 2AB) at the cost of elevating the noise floor[3].

Figure 3 shows the effect of number of slices on slice order and tSNR. In the presence of imperfect slice profiles, maximizing time between excitation of adjacent slices becomes important. The standard interleaved slice order excites adjacent slices ~TR/2 apart. However, to avoid temporally adjacent excitations at the MB slice stack interface when the number of shots (Nshots=Nslices/MB) is even and Nshots/2 is odd, the CMRR C2P utilizes an interleaved pattern where adjacent slices are excited only ~TR/4 apart[10]. This can result in spin history instabilities and significantly reduced tSNR.

Table 1 shows the SNR improvements from shorter TEs afforded when fully utilizing the Impulse gradient's PNS performance. The original Impulse Gradient settings utilized a body-PNS limited diffusion gradient rise-time of 16 us/(mT/m) (slew rate = 62.5 T/m/s) while the updated settings utilize a rise-time of 6 us/(mT/m) (slew rate = 167 T/m/s), resulting in a 7.2ms TE reduction and SNR gain of 17% for our 0.6mm protocol.

The cumulative gains in SNR and reduction in SAR and artifacts allow us to push the resolution to 0.6 mm (more than 4x finer in volumetric resolution compared to HCP 7T diffusion data[2]). Figure 4 shows the detail afforded in the 10-TR averaged b=0 s/mm^2 image. The primary diffusion direction map overlayed onto FA for this 0.6 mm data reveals dark bands of FA not seen at lower resolutions[2]. The dark bands tend to be strongest along sulcal banks (red arrows; where white matter fibers turn sharply into cortex).

Summary and Conclusion

We have demonstrated the optimized acquisition protocol for ultra-high-resolution diffusion imaging on the NexGen 7T. The increases in SNR, due to the novel Impulse gradients, allow for substantially higher spatial resolutions than in prior 7T studies. We hope that these best practices will be incorporated in future C2P releases (in addition to an improved SENSE1 algorithm and an increase to the 4096x4096 mosaic size limit which prevented us from extending slice coverage of the 0.6 mm protocol).

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Figures

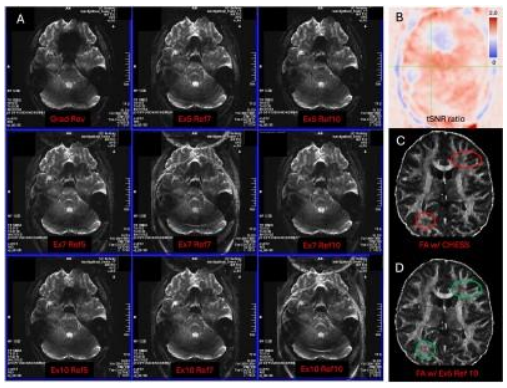

Figure 1. Evaluation of fat suppression methods for diffusion MRI on the NexGen 7T. A) Gradient reversal (upper left) is compared against low SAR fat-sat (for 5, 7, and 10 ms RF-pulse durations). B) tSNR ratio between gradient reversal and CHESS shows a ~30% tSNR improvement without CHESS. C) FA map w/ CHESS. D) FA map w/ low SAR fat-suppression. Red circles show areas of substantial degradation in FA estimation quality w/ CHESS.

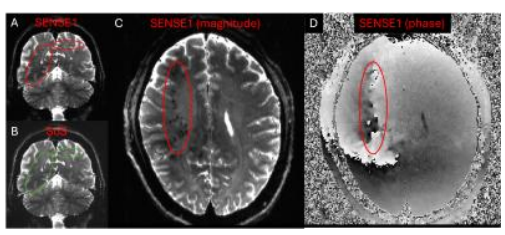

Figure 2. Evaluation of coil combination methods for diffusion MRI on the NexGen 7T. The SENSE1 coil combination method can result in pervasive signal void artifacts on the NexGen 7T due to the higher channel count coils used (red circles). These artifacts, which come from destructive interference in a complex sum of coil signals, are prominent around phase singularities but can be avoided using the SoS coil combination method (green circles) at the cost of an elevated noise floor.

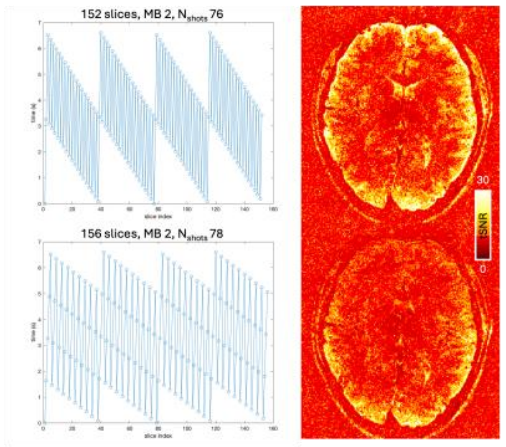

Figure 3. The effect of number of slices on slice order and tSNR. To avoid temporally adjacent excitations at the MB slice stack interface, when Nshots = Nslices/MB is even and Nshots/2 is odd, the CMRR C2P utilizes an interleaved pattern where adjacent slices are excited ~TR/4 apart as opposed to the standard ~TR/2. This can result in spin history temporal instabilities and significantly reduced tSNR. Top row) Nshots = 76. Bottom row) Nshots = 78.

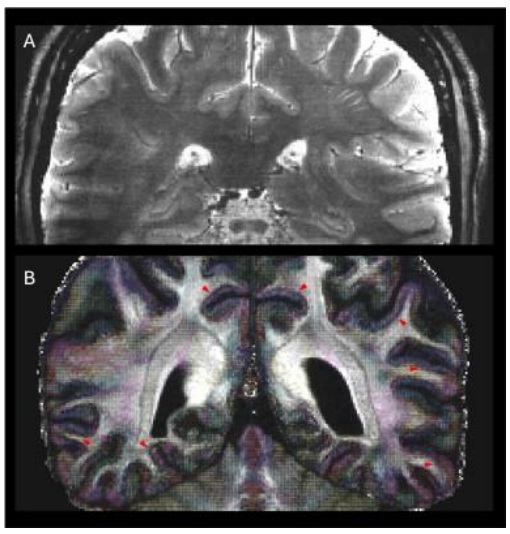

Figure 4. Example of 0.6 mm isotropic diffusion imaging. A) Coronal cross-section of a 10 TR average b=0 s/mm² image showing fine anatomical details of the hippocampus and perivascular spaces. B) The primary diffusion direction map overlayed onto FA reveals dark bands of FA strongest along sulcal banks (red arrows).

	b=800 s/mm² (0.6 mm iso)	b=2500 s/mm² (0.9 mm iso)	b=10000 s/mm² (0.9 mm iso)
Impulse Gradients (new)	TE = 49.4 ms	TE = 47.2 ms	TE = 58.6 ms
Impulse Gradients (original)	TE = 56.6 ms	TE = 53.8 ms	TE = 61.6 ms
Relative SNR gain	1.17	1.15	1.07

Table 1. Minimum Echo Times for b=800, 2500, and 10000 s/mm². Relative SNR gain is calculated as: exp(TE1/T2)/exp(TE2/T2), using a white matter T2 of 46 ms (Yacoub et al 2003). New Impulse Gradient settings utilize a diffusion encoding rise time of 6 us/(mT/m) (slew rate = 167 T/m/s) while the original settings utilized a body-PNS limited rise time of 16 us/(mT/m) (slew rate = 62.5 T/m/s). Both settings utilized a Gmax of 190 mT/m for diffusion encoding.

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