Impact of noise bias with parallel imaging for axon diameter estimation with q-space MRI

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Purpose. Generalized autocalibrating partially parallel acquisitions (GRAPPA) [1] enables to accelerate acquisition by undersampling the k-space in the phase-encoding direction. Missing phase lines are reconstructed by taking advantage of the redundancy of the signal from the multiple channels of a coil array. While reducing scan time and distortions in EPI, this method can introduce non-spatially uniform noise bias depending on the g-factor. This magnitude bias is particularly problematic in diffusion q-space techniques, which aim at quantifying axon diameter distribution [2], because the level of SNR can be particularly low given the large b-values that are required. The aim of this study was to compare GRAPPA with outer volume suppression reduced field of view (rFOV) technique for q-space axon diameter measure.

Methods. *Acquisition*. Experiments were done in three healthy subjects (aged 25/24/22 y.o., two males), on a 3T scanner (MAGNETOM Skyra CONNECTOM, Siemens Healthcare) equipped with a custom-made 60-channel phased array head/spine coil [3]. Single shot EPI sequence was used with the following parameters: TR ~ 2s (cardiac-gated), TE = 70ms, resolution = 0.8×0.8×5 mm^3, 4 slices covering C2 to C5 levels (20 mm gap), adaptive combined reconstruction [4]. Q-space was sampled linearly in four directions perpendicular to the spinal cord: XY, –X–Y, X–Y, –XY, G_{max} = 300*√2 = 424 mT/m, δ= [3,3,6,6,10] ms, diffusion time Δ = [20,40,20,36,30] ms. Total acquisition time was around 40 min with 1150 volumes. For each subject, the same protocol was applied with GRAPPA (R=2, matrix=128×128) and with rFOV (saturation band, matrix=70×70, outer volume suppression using two saturation bands). *Processing* included (*i*) eddy-currents correction using opposite diffusion gradients, (*ii*) slice-by-slice motion correction using polynomial regularization along z, (*iii*) Rician noise correction [5] and (*iv*) registration of final results to the MNI-Poly-AMU template [6]. *Model fitting*. Q-space data were fitted using AxCaliber [2]. Diffusion in the extra-axonal compartment was assumed Gaussian while diffusion in the intra-axonal compartment was modeled using Gaussian phase distribution [7]. *SNR calculation*. Noise was extracted for all subjects at b_{max} using manually-drawn regions in the background. Standard deviation of noise was computed by fitting a non-central chi distribution on noise histograms. Noise was found to be Rician on both GRAPPA and rFOV (k<1.2) with very little bias (η/σ_{noise}<2%) in all subjects. *Bias study*. Bias was assed by computing the signal difference inside the spinal cord, volume by volume across q-space, between GRAPPA and rFOV. A paired *t*-test (α = 5%) was done for each subject after validating Gaussianity.

Results. Figure 1 shows raw images at b=0 and b=30,770 s/mm^2 for GRAPPA and for rFOV. Visually, GRAPPA data show lower SNR and the presence of spatially-correlated noise. Table 1 shows the SNR per slice and per subject. SNR was always higher on the rFOV data (+40% in average). No significant signal bias between GRAPPA and rFOV was found for subjects #1 (p=0.38) and #3 (p=0.86), however subject #2 shows a significant bias ($p=10^{-27}$). Figure 2a shows an example of fit and Figure 2b shows the signal difference along q between GRAPPA and rFOV. The bias was smaller than 5% of the b=0 image after Rician noise correction. This bias resulted in different estimation of axon diameter ($p<10^{-11}$ using a paired *t*-test) between GRAPPA and rFOV (see Figure 2). We found a significant underestimation of axon diameter of 0.6µm +/- 1.0µm when using GRAPPA ($p<10^{-16}$), but no significant difference for the restricted water fraction (p=0.39). Figure 2 shows a map. Regarding susceptibility-distortions, no visible difference was observed with and without GRAPPA, thanks to the careful shimming in a small region and the location of the slices at the level of the mid-vertebrae.

Discussion. This study investigated the effect of GRAPPA for estimating axon diameter using q-space diffusion measurements. Reduced-FOV data using sat bands yielded significant increase in SNR. Although a signal bias existed between the two conditions, the impact on axon diameter estimation was fairly small (0.6 µm). However, we noticed that GRAPPA imaging can introduce noise patterns in some slices, whereas rFOV images were free from this type of artifact. Hence, we suggest the use of rFOV techniques for quantitative diffusion imaging of the spinal cord.

Subject	1	2	3
GRAPPA	17.8	13.1	12.9
Reduced FOV	31.2	17.3	15.4

Table 1: SNR comparison between GRAPPA and rFOV for all subjects. SNR was calculated on b=0 volumes.

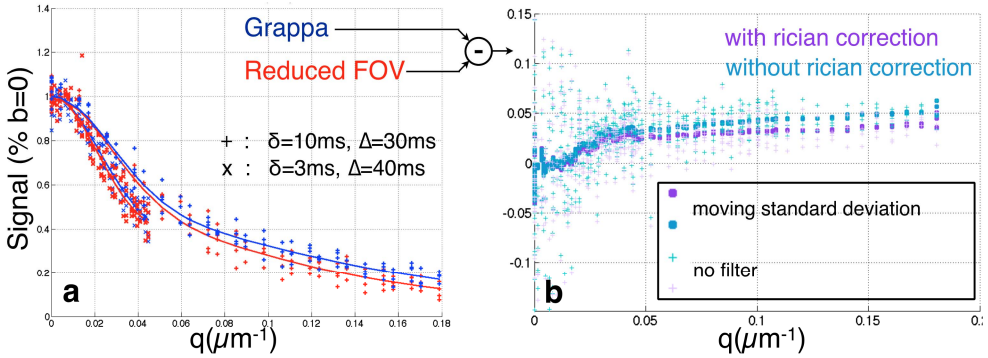

Fig 2. a. Q-space fitting comparison between GRAPPA and rFOV in one voxel of subject #2. b. Paired-Volume signal difference along q for all voxels in the spinal cord of subject #2. A moving-average filter was applied along q. GRAPPA presented an upward bias of ~5% at qmax, which was partially corrected with Rician noise correction.

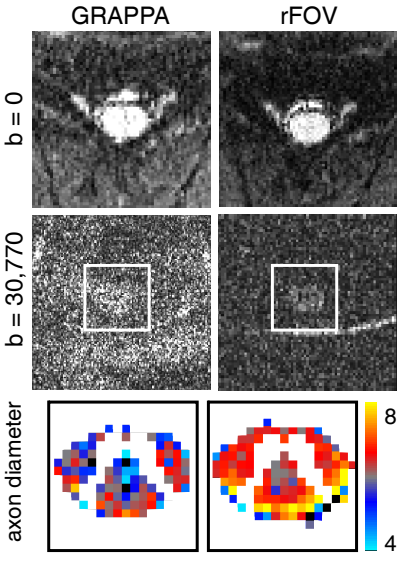

Fig 1. Raw images at b=0 and high b-value and axon diameter estimation.

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