NEX or no NEX? A high angular resolution diffusion imaging study

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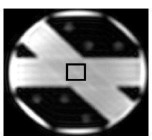
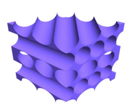
INTRODUCTION: To remove noise artifacts and enhance SNR, diffusion-weighted (DW) measurements are often repeated multiple times (NEX) along each gradient direction (typically, from 2 to 4 measurements) and each DW image is averaged. This averaging increases acquisition time considerably. It is also not clear what effects it has on the reconstructed diffusion profiles such as the orientation distribution function (ODF) [1] or fiber density orientation (FOD) function [2], also called fiber ODF (fODF) [3]. In magnitude MRI, noise is Rician-distributed [4], and is often conveniently approximated as Gaussian in high SNR regions. In the context of diffusion tensor imaging (DTI), recent attempts have been made to account for the Rician noise to regularize the DW data [5], to estimate the diffusion tensor [6], or to perform both tasks simultaneously [7]. However, among the existing methods to estimate or regularize ODF reconstructions from high angular resolution diffusion imaging (HARDI), the Rician noise bias has just started to be addressed [8,9,10,11], but the impact on the reconstructed HARDI profiles such as the ODF and fODF have not been validated yet on real data. In particular, it is important to make sure that angular resolution of HARDI is not lost when removing Rician noise. In this work, the DW images are filtered with a specific Rician-based, structure-preserving, Non-Local Means method (NLMr) [5], which recently showed to outperform other state-of-the-art methods to denoise DTI at low b-values. The filtering is applied on the raw DW images before estimating the HARDI profiles such as the ODF and the fODF. We show that multiple DW measurements and averaging can be avoided because NLMr filtering of the individual DW images can remove the Rician noise bias while preserving angular resolution. The method also produces better quality generalized fractional anisotropy (GFA) maps and more coherent ODF fields.

METHODS: To ensure that angular resolution of HARDI is not lost while removing Rician noise, a 45° ex vivo phantom [12] is filtered with NLMr (see [5,11] for details) before q-ball [1] and fODF are reconstructed with a spherical harmonic order of 12 with regularized spherical deconvolution [2,3]. The data was acquired on a 1.5T Signa MR system, TE/TR=130ms/4.5s, BW=200KHz, FOV = 32cm, matrix size of 32x32, and b-values of 2000, 4000, 6000, 8000 s/mm^2, with 4000 uniformly distributed orientations. In order to make the experiment more realistic, we have sub-sampled the data to use only 200 uniformly distributed DW images. Secondly, a human brain dataset was acquired on a 3T Siemens system using 80 encoding directions, with b = 3000 s/mm^2, TR/TE = 4 s/122 ms, 1.25 mm x 1.25 mm x 3 mm voxels and three signal averages per direction. The SNR of a single T2 image and single DW image in the white matter was estimated to SNR 6 and 2 respectively. The corresponding averaged T2 and averaged DW image have a SNR of 11 and 4 respectively. We performed NLMr on each of the three raw DWI datasets and compared the GFA maps and ODF reconstructions with the averaged dataset.

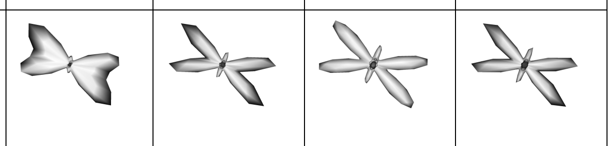
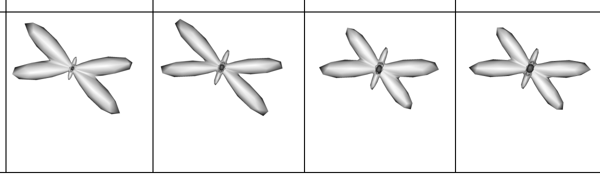
RESULTS



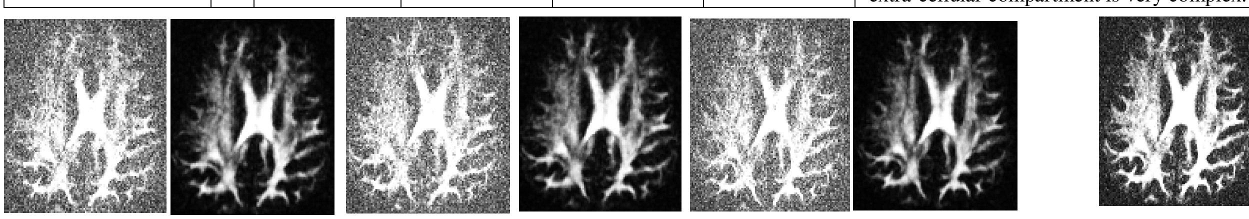
45° fast spin-echo map



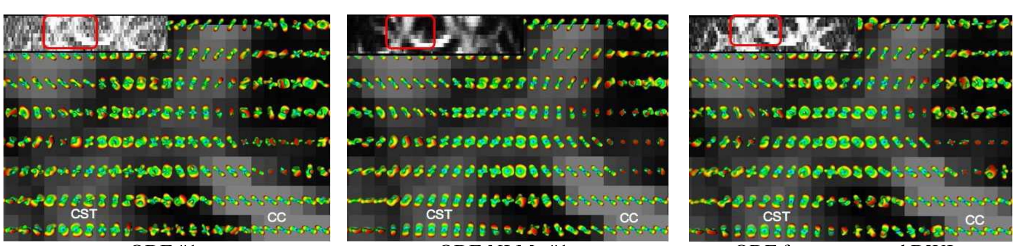
3D extra-cellular compartment

	2000 s/mm^2	4000 s/mm^2	6000 s/mm^2	8000 s/mm^2
fODF				
fODF-NLMr				

fODF reconstructions [2,3] on the 45° crossing phantom data before and after NLMr filtering. The detected separation angle between the maxima is 45.4° for all examples. This is using a simple mesh search algorithm with 1000 points for fODF values above 0.5. It is interesting to compare FODs from the lowest b-value (2000 s/mm^2), where the FOD-NLMr is sharper. NLMr can enhance fiber peaks if they are supported by the local neighborhood configuration. However, NLMr is not able to remove the small side lobes of the FODs. Note that this is probably not only due to the noise and might be present in the data. The actual anisotropy of the extra-cellular compartment is very complex.



GFA #1 GFA-NLMr #1 GFA #2 GFA-NLMr #2 GFA #3 GFA-NLMr #3 Averaged (#1,2,3) GFA



ODF #1 ODF-NLMr #1 ODF from averaged DWI

Figure 2 shows that each GFA image reconstructed after NLMr filtering of the respective dataset is better denoised than the averaged GFA image. The ODF images of order4 show a crossing region in a coronal slice between the corpus callosum (CC) and corticospinal tract (CST). ODF profiles reconstructed after filtering have less spurious peaks and are better aligned with the known anatomy. We also see that ODF profiles remain sharp and keep their multiple peak.

DISCUSSION: Our results on the phantom and real datasets suggest that NLMr filtering improves the quality of ODF and fODF reconstructions, while preserving angular resolution of HARDI. The added value is clearly seen on the filtered GFA maps computed from the real noisy datasets with SNR of 2. This suggests that NLMr filtering could be added as a restoration step in a diffusion processing pipeline before HARDI reconstruction and tractography. This restoration will become even more important for higher b-value acquisitions, where the signal is largely attenuated and Rician noise bias dominates. Therefore, the need for multiple NEX and averaging seems unnecessary. This can significantly reduce time of diffusion acquisitions multiple NEX.

References: [1] Descoteaux et al, MRM 2007. [2] Tournier et al, NeuroImage 2007, [3] Descoteaux et al, ISMRM 2007. [4] Sijbers et al, MRI 1998. [5] Wiest-Daessle et al, In Proc. MICCAI 2008. [6] Landman et al, In Proc. ICCV 2007. [7] Fillard et al, TMI 2007. [8] Assemlal et al, In Proc. ICIP 2007. [9] Aja-Fernandez et al, TMI 2008. [10] Clarke et al, TMI 2008. [11] Descoteaux et al, In Proc. MICCAI 2008. [12] Poupon et al, MRM 2008, in press.