Can we expect reproducible and unbiased information from denoised Diffusion Tensor Imaging with low SNR ?

K. R. Hahn[1], S. Prigarin[2], and K. Hasan[3]

[1]Institute Biomathematics & Biometry, gsf-National Research Center for Environment & Health, Neuherberg, Bavaria, Germany, [2]Institute Computational Mathematics, Novosibirsk, Russian Federation, [3]Diagnostic and Interventional Imaging, University of Texas Medical School, Houston, United States

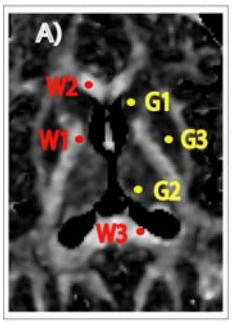
Introduction Diffusion Tensor Imaging at high spatial resolution is important in studies of the central nervous system for human beings and in studying animal models of human disease **[1,2]**. Such measurements can introduce very low signal-to-noise-ratios (SNR) in the diffusion weighted images (DWI) and need extensive denoising to minimize the pitfalls caused by nonlinear noise propagation, see e.g. **[3]**. For improving SNR or denoising we apply voxelwise averaging of the DWIs by NEX experimental replications followed by nonlinear spatial DWI filtering with bias correction as introduced in **[4]**. Denoising through temporal averaging is limited as it increases scanning time, in addition the spatial domain of the filter is restricted. This can lead to residual noise effects in the smoothed data. To quantify this effect, distributions of mean diffusivity (MD), fractional anisotropy (FA) and the main diffusion directions (α) are studied by a Monte Carlo analysis simulating denoising of 100 low SNR experiments differing only in the random-seeds of thermal noise. The simulations are based on a gold standard model of the human brain with 1x1x1 mm^3 resolution. For distributions close to unbiased Gaussians with small variance information from a single denoised experiment is reproducible and unbiased with high probability. This is best fulfilled for MD in the white and gray matter voxels of our study, for FA this is reduced in gray matter voxels, and for α only white matter voxels give satisfying results. The developed software can be helpful in preplanning of low SNR DTI experiments.

Methods and Materials The model is based on human brain DTI data with 1x1x1 mm^3 spatial resolution. Those data were denoised as outlined above, the smoothed and bias corrected DWIs define the gold standard, see **[4]** for more details about experiment and filter. Four experimental designs were simulated adding Rician noise to the DWIs of the model. In all cases we used b=1400 s mm^{-2} else we simulated the field strengths B_0=1.5 T with NEX=1 and 9, and B_0=3 T with NEX=1 and 4, producing spatially and directionally averaged SNR = 2.5, 7.5 and 5, 10 in the DWIs. For model-denoising we improved the filter proposed in **[4]** to include a locally varying noise level according to Rician statistics **[5]**. First, the filter estimates, under assumption of constant noise level, a mean of the noisy DWIs. These mean DWIs are used in a second filter application to adapt the noise level locally.

Results For six voxels in an axial slice (Fig. A) typical statistical features after denoising of a volume around corpus callosum are quantified. In Fig. B) the distributions of MD and FA for W3 and G1 are presented for all four designs, without [broken lines] and with [solid lines] bias correction (BC). For W3 the necessity of BC is apparent, the distributions with BC approach with increasing SNRs narrow unbiased Gausssian distributions. For SNR=10 (black), the range for MD is about $\pm$ 5 % of the true value (orange) and for FA $\pm$ 6 %. For G1 only MD is affected by BC, the range is minimal (black) at $\pm$ 4 % , for FA we find $\pm$ 25 %. In Table 1 for all six voxels and SNR=10 distributional means and standard deviations are given and compared with the model. A general high relative precision for MD is apparent, for FA relative precision is reduced for G1-3. For the deviations of aligned main diffusion directions $\Delta\alpha$ the voxels G1-3 show significant bias and variance indicating still too much noise for precise directional information. For white matter voxels like, W1-3, the results may be sufficient for tracking.

Discussion Denoising of low SNR DTI may only partly eliminate noise effects raising the question for reproducibility and accuracy of information based on single experiments. We find in our study a high reliability of MD measurements in all voxels and in gray matter voxels a reduction of reliability for FA and high residual arbitrariness for the main diffusion directions. Focussing on noise issues alone, prediction of reliability and bias seems to necessitate a detailed analysis. Aside of voxel depended SNRs and of peculiarities of the observables under consideration, also properties of the applied filter may be important, therefore, numerical preplanning of low SNR DTI experiments by model simulations is recommended.

References [1] Hasan K et al Proc ISMRM 14 2006 Seattle 344. **[2]** Madi S et al Mag Res Med 2005, 53 : 118-125.
[3] Hahn KR et al in Visualization and Processing of Tensor Fields, Ed. J Weickert and H Hagen, Springer, 2006, 107-119.**[4]** Hahn KR et al, Proc ISMRM13 2005 Miami 161. **[5]** Gudbjartsson H and Patz S, Mag Res Med 1995, 34:910-914.



	MD*-Model MD=0.0001 x MD* mm²/s	MD* noBC BC	FA-Model	FA noBC BC	Δα noBC BC (Δα in degrees)
W1	8.6	8.1 ± 0.02 8.6 ± 0.02	0.56	0.51 ± 0.017 0.56 ± 0.022	1.8 ± 0.95 1.7 ± 0.93
W2	9.7	8.9 ± 0.01 9.9 ± 0.02	0.78	0.64 ± 0.01 0.74 ± 0.02	1.8 ± 0.68 1.7 ± 0.97
W3	8.0	7.4 ± 0.01 8.1 ± 0.01	0.82	0.72 ± 0.01 0.81 ± 0.02	1.6 ± 0.48 0.74 ± .43
G1	8.24	8.1 ± 0.01 8.27 ± .01	0.11	0.10 ± 0.01 0.11 ± 0.01	9.3 ± 4.5 9.3 ± 4.5
G2	9.1	8.9 ± 0.02 9.0 ± 0.02	0.23	0.21 ± 0.015 0.22 ± 0.011	3.7 ± 2.3 3.6 ± 2.2
G3	9.0	8.8 ± 0.01 9.0 ± 0.01	0.1	0.08 ± 0.009 0.08 ± 0.009	10. ± 5.1 10.2 ± 5.2

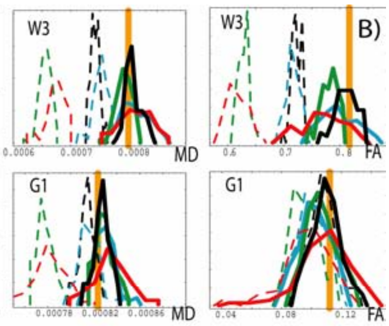


Figure A: An axial FA map of the gold standard model, three white (red) and deep gray matter (yellow) voxels are indicated. **Figure B:** MD and FA distributions in voxels W3 and G1 for 100 denoised data sets. Orange: exact model, broken lines: filtered without BC, solid lines: filtered with BC. Four experimental designs are tested; red, green: 1.5T NEX=1, 9, blue, black: 3T NEX=1, 4. **Table 1 :** MD, FA and angle deviation $\Delta\alpha$ of main diffusion directions for voxels indicated in Figure A) are given for 3T and NEX=4. Columns 3,5,6 show mean values and standard deviations after denoising without and with BC (up-down per row), columns 2,4 give model values.