## A Simple Retrospective Noise Correction for Diffusional Kurtosis Imaging

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**TARGET AUDIENCE:** This work demonstrates a weighted linear least squares algorithm for tensor estimation in diffusional kurtosis imaging (DKI) that substantially reduces the noise bias. It is relevant for those using DKI data having a low signal-to-noise ratio (SNR), as may occur in high resolution acquisitions.

**PURPOSE**: For diffusion MRI (dMRI), low SNR often leads to a positive signal bias in the magnitude images that are typically analyzed. This is evident in high resolution DKI and diffusion tensor imaging (DTI) datasets, which have inherently noisy signals, or when imaging anatomical regions with short T2 values, such as the globus pallidus. This study investigates the effects of noise on DKI parameters for noisy phantom data. A simple noise correction scheme is presented and applied to the images, and the calculated DKI parameters are compared to reference results obtained with high SNR.

**METHODS**: A previously validated dairy cream phantom<sup>1</sup> was imaged with a protocol adapted to increase the effects of noise. The phantom was scanned using a 3T Siemens MAGNETOM Tim Trio system (Siemens Medical Solutions, Erlangen, Germany) with a transmit/receive head coil. Diffusion weighted images were acquired for b = 0, 1000, and 2000 s/mm<sup>2</sup> diffusion weighting along 30 different gradient directions using an echo planar imaging sequence with repetition time (TR) = 2 s, echo time (TE) = 143 ms, field of view = 256 x 256 mm<sup>2</sup>, acquisition matrix = 128 x 128, and bandwidth = 2298 Hz/voxel. Parallel imaging, fat suppression, and partial Fourier imaging were all turned off, and the sequence was modified for both magnitude and phase reconstruction. Slice thicknesses were varied from 2 to 10 mm to alter SNR. Scans were repeated 3 times at each slice thickness, and 16 scans were acquired at 2, 4, and 10 mm slice thicknesses for complex averaging. DKI parameters

were calculated in a region-of-interest (ROI) drawn in the intersection of the fat and water signals in the phantom (composite region) in which a significant kurtosis is expected.<sup>1</sup> The noise was assumed to obey a Rician distribution<sup>2</sup> with a second order moment of  $\eta^2$  in air, found in the image background. The true, unbiased signal was estimated by  $S = (M^2 - \eta^2)^{1/2}$ , where *M* is the measured signal.<sup>3</sup> A weighted linear least squares fit was employed, where the weights account for the effects of noise as well as log-signal transformation on measurement error. The cost function minimized was:

$$C \equiv \sum_{i} \frac{(M_{i}^{2} - \eta^{2})^{2}}{2M_{i}^{2} - \eta^{2}} \cdot \left[ \ln(M_{i}^{2} - \eta^{2}) - \ln(M_{0}^{2}) + 2\boldsymbol{\alpha}_{i} \cdot \boldsymbol{x} \right]^{2} \Theta(M_{i}^{2} - \eta^{2}),$$
(1)

where  $M_i$  is the i<sup>th</sup> measured signal,  $\alpha_i$  is a known vector defined by the experiment,  $x_i$  is a vector of parameters to be estimated, and  $\Theta$  is the Heaviside step function to zero out terms where  $M_i^2 \leq \eta^2$ . Eq. (1) was applied to the composite region ROI with acquisitions across all gradient directions being averaged over each b-value. As a reference, uncorrected diffusion parameters were also calculated from the magnitude images by minimizing Eq. (1) with  $\eta = 0$ . For complex averaging, magnitude and phase images were used



(B) after arithmetic average of 10 independent b = 0 image, not (A) the original, (C) after complex averaging of 16 real and imaginary images. Only complex averaging reduces the mean background noise.

to calculate real and imaginary images and an average real and imaginary image was obtained. The magnitude image was obtained from the average real and imaginary images, and the DKI parameters were then estimated from Eq. (1) with  $\eta = 0$ . Sample images are shown in Fig. 1. The ground truth DKI parameters were estimated in the dataset with the highest SNR (defined here to be the ratio of b = 0 signal magnitude in phantom to background signal mean), which was that with 10 mm slice thickness after complex averaging.

**RESULTS:** By increasing the slice thickness from 2.0 to 10.0 mm, SNR improved from 3.6 in to 20.6. Complex averaging improved SNR to 73.3 in the 10.0 mm dataset. The effects of varying the SNR on the diffusional kurtosis are demonstrated in Fig. 2, which shows the kurtosis values for different slice thicknesses as obtained from the uncorrected and corrected magnitude images, as well as from the complex averaged data. Decreasing slice thickness increased mean kurtosis estimates for the uncorrected analysis from  $0.972(\pm 0.003)$  to  $1.261(\pm 0.043)$  in the 10.0 mm and 2.0 mm datasets, respectively. Ground truth for the mean kurtosis was found to be 0.949, which differed from the 2.0 mm estimate by 33%. The mean kurtosis estimates following noise correction differed by no more than 2.7% from the ground truth.

**DISCUSSION:** The noise correction technique demonstrated provides a convenient and straightforward method for removing the majority of noise bias in DKI. It may be particularly useful for datasets when high resolution images are acquired. The consistency of the results obtained from application of Eq. (1) with the background noise parameter  $\eta$  with those obtained from complex averaging supports the accuracy of this technique. The corrected signal of  $S = (M^2 - \eta^2)^{1/2}$  has been previously described for magnitude MR images<sup>3</sup> but not, to our knowledge, the corresponding weighting factors in Eq. (1). In this experiment, parallel imaging was not



employed allowing  $\eta$  to be estimated from the background signal in air. With parallel imaging, Eq. (1) may still be used even if the noise follows a non-central  $\chi$  rather than a Rician distribution.<sup>2</sup> However,  $\eta$  would then no longer be spatially uniform and should be calculated from a noise map. Eq. (1) is also applicable to diffusion parameter estimates obtained with DTI and other dMRI techniques.

**CONCLUSION:** The noise correction scheme based on minimizing the cost function of Eq. (1) can substantially reduce the noise bias in DKI parameter estimates due to the use of magnitude images. This method may find application to high resolution and accelerated DKI for which SNR is inherently poor.

**REFERENCES:** (1) Fieremans E, Pires A, and Jensen, JH. A simple isotropic phantom for diffusional kurtosis imaging. *Magn Reson Med.* 2012; 68: 537–42. (2) Koay CG, Basser PJ. Analytically exact correction scheme for signal extraction from noisy magnitude MR signals. *J Magn Reson.* 2006; 179: 317-22. (3) McGibney G, Smith MR. An unbiased signal-to-noise ratio measure for magnetic resonance images. *Med Phys.* 1993; 20: 1077-8. **FUNDING:** This project was supported by the South Carolina Clinical & Translational Research (SCTR) Institute, NIH/NCRR Grant number TL1 TR000061 and the NIH/MSTP Predoctoral Fellowship Training Grant GM08716.