Systematic Evaluation of Linear and Nonlinear DTI Estimation Methods: An Open Framework

Bennett A. Landman[a], Susumu Mori[a,b,c], and Jerry L. Prince[a,d]

[a] Department of Biomedical Engineering, The Johns Hopkins University School of Medicine, Baltimore, Maryland, United States, [b] F.M. Kirby Research Center for Functional Brain Imaging, Kennedy Krieger Institute, Baltimore, Maryland, United States, [c] The Russell H. Morgan Department of Radiology and Radiological Sciences, The Johns Hopkins University School of Medicine, Baltimore, Maryland, United States, [d] Electrical and Computer Engineering, Johns Hopkins University, Baltimore, MD, United States

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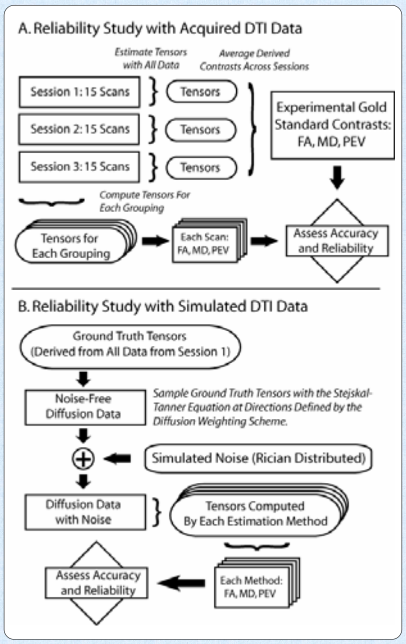
INTRODUCTION

- Diffusion tensor imaging (DTI) contrasts, including fractional anisotropy (FA) and mean diffusivity (MD), have been widely applied to characterize white matter changes in diseases and stroke
- Typical in vivo human DTI studies span a range of signal to noise ratio (SNR) where, at the low end of clinical SNR, the eigenvalues tend to systematically diverge from their true (high SNR) value, which leads to clinically significant changes in FA while MD is relatively less affected.
- Consequently, the optimization of DTI acquisitions is an important effort and previous studies have investigated the effects of noise, diffusion weighting scheme, and tensor estimation method both in simulation and *in vivo*.
- Yet, considerable uncertainty remains as to how to properly evaluate the tradeoffs between these three parameters, compare results, and ultimately select an appropriate DTI protocol.

This study provides a simple, quantitative metric to evaluate the tradeoffs made when choosing these parameters in DTI experiments.

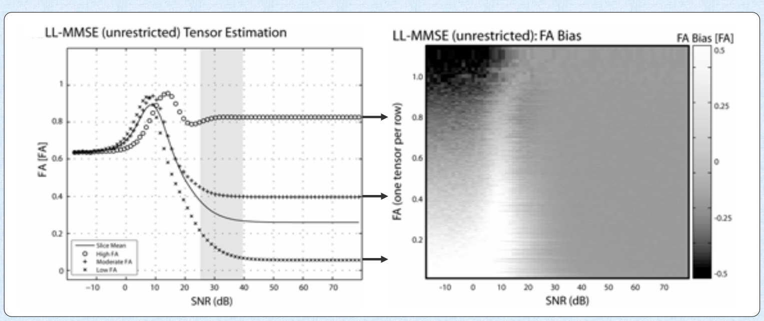
Methods

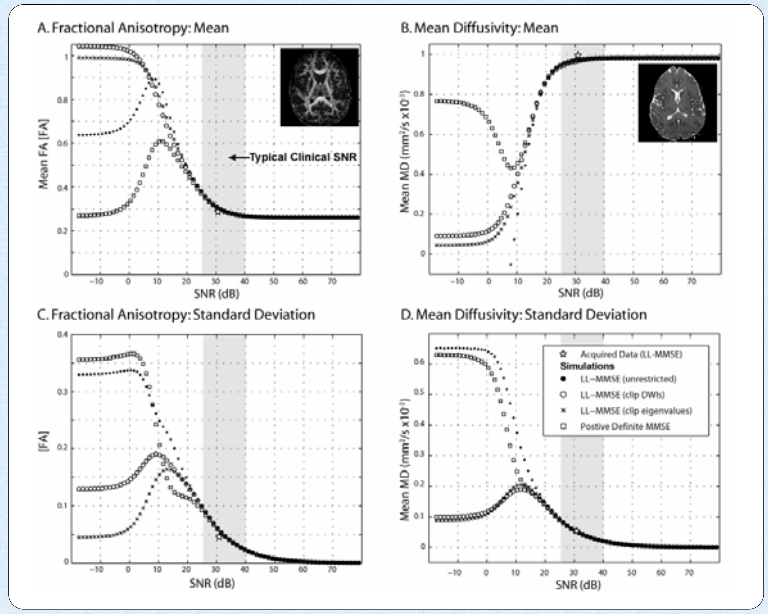
- A high resolution, high SNR dataset with 15 repetitions of 30 diffusion weighted (DW) and one scanner average of 5 minimally weighted (b0) acquisition at 1.5T was used as ground truth to assess the effects tensor estimation method.
- Simulations were performed using the Stejskal-Tanner model of diffusion, as previously described [6,7].
- An axial slice at the level of the lateral ventricles was selected to be representative of human brain anatomy.
- Four methods of tensor estimation were compared to demonstrate the practical consequences of applying a few of the many widely available choices.
  1. Direct application of the Stejskal-Tanner tensor model [8] (LL-MMSE).
  2. Replacing any DW values that were greater than the b0 value with the b0 value prior to LL-MMSE, denoted LL-MMSE (clip DWI).
  3. Replacing negative eigenvalues with zero-values, denoted LL-MMSE (clip eigenvalues).
  4. Non-linear tensor fitting method provided with the AFNI toolkit [2].
- SNR is reported relative to non-diffusion weighted (b0) volumes.



FA BIAS IS NON-MONOTONIC AND TENSOR DEPENDENT

- A common understanding is that FA "goes to 1" in very low SNR regimes (i.e. when the signal approaches pure noise) because the FA of eigenvectors chosen uniformly at random over all ℜ.
- This special case is illustrative, but the limiting value may not be valid in realistic experimental situations and does not address the potential for non-monotonic patterns of bias, and unique limiting behaviors at low SNR.
- Simulations show that the patterns of bias at low-SNR are tensor dependent (e.g., the FA of high anisotropy tensors tends lower, while that of low anisotropy tensors tends upward).
- Additionally, simulations show that the trends in FA bias may be non-monotic, especially at low SNR. In other words, FA bias may either increase or decrease with decreasing SNR as shown by the plots below.





RESULTS

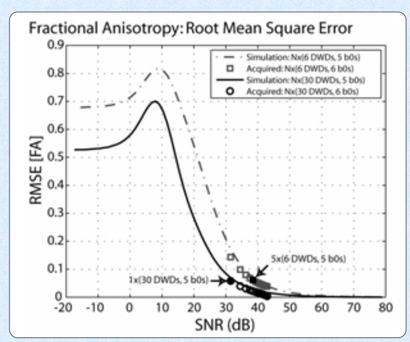
The low SNR limiting mean values of FA and MD depended on tensor estimation method. At very low SNR (<0 dB), there was little contribution from the underlying ground truth data on the estimated contrasts. At low SNR (0-20 dB), the bias in underlying contrasts rapidly increased with decreasing SNR, while the rate of change was much reduced at moderate SNR (20-40 dB). At high SNR (>40 dB), there was little change with SNR or dependence on estimation method. The positive definite method showed reduced bias in FA, but increased bias in MD. In terms of RMS error, the positive definite method out performed the three LL-MMSE methods for estimating FA, but showed reduced performance in MD estimation. The modified LL-MMSE algorithms demonstrated improvements in all FA measures over the LL-MMSE method and nominal MD improvements.

Mean Tensor Estimation Error (25 to 40 dB) (FA: [FA]x1000. MD: um²/s x 1000)

	RMS Error		Bias		Variability		CPU Time
Estimation Method	*FA*	*MD*	*FA*	*MD*	*FA*	*MD*	*Relative*
LL-MMSE	63.2	45.1	37.2	-7.97	53.8	47.4	1
LL-MMSE (clip DWI)	63.6	45.0	37.2	-7.94	53.8	47.4	1
LL-MMSE (clip evals)	63.2	45.0	37.2	-7.94	53.8	47.4	1
Positive Definite MMSE	60.0	46.1	34.4	-14.74	51.5	46.6	8

DISCUSSION

- Simulation results coincided well with in vivo experimental data and demonstrate the applicability of the simulation methodology.
- Non-monotonic trends in bias and variability, as a function of SNR, are revealed for the mean behavior of both FA and MD over a slice as well as for individual tensors.
- The choice of diffusion weighting scheme and tensor estimation method can significantly alter the accuracy and variability of DTI contrasts over a wide range of SNR including clinical regimes.
- Newly presented error metrics provide a simple, quantitative system for comparing tensor estimation methods.



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