Diffusion Kurtosis Imaging (DKI) Reconstruction. Linear or Non-Linear?

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Declaration of Relevant Financial Interests or Relationships

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I have no relevant financial interest or relationship to disclose with regard to the subject matter of this presentation.

Introduction

- Diffusion Kurtosis Imaging (DKI)* measures the non-Gaussian behavior of water diffusion and has a great potential in providing information regarding the underlying microstructural characteristics of neural tissues.

- Two types of DKI reconstruction methods widely used:
  - Nonlinear least squares (NLS) – originally proposed (~ hours)
  - fast DKI method - uses linear fitting (~ minutes)

- Although the NLS approach may provide more accurate results, near real-time reconstruction is critical in the clinical setting and therefore linear methods are highly preferred.

* Jensen JH, et al. Magn Reson Med. 2005; 53:1432-40.

DKI Reconstruction: Method 1: *Non-linear Least Squares (NLS)**

- Step 1: Estimate $D_{app}(\mathbf{g})$ and $K_{app}(\mathbf{g})$ for each diffusion direction $\mathbf{g} = [g_1, g_2, g_3]$ through non-linear method

$$\ln(S(b,\mathbf{g})/S_0) = -bD_{app}(\mathbf{g}) + \frac{1}{6}b^2 D_{app}^2(\mathbf{g})K_{app}(\mathbf{g})$$

- Step 2: fit diffusion tensor **D** and kurtosis tensor **W** by linear least squares:

$$D_{app}(\mathbf{g}) = \sum_{i=1}^{3}\sum_{j=1}^{3} g_i g_j D_{ij} \qquad K_{app}(\mathbf{g}) = \frac{MD^2}{D_{app}(\mathbf{g})^2}\sum_{i=1}^{3}\sum_{j=1}^{3}\sum_{k=1}^{3}\sum_{l=1}^{3} g_i g_j g_k g_l W_{ijkl}$$

D_{ij}: elements of the diffusion tensor **D**
W_{ijkl}: elements of the kurtosis tensor **W**

$$MD = \frac{1}{3}\sum_{i=1}^{3} D_{ii}$$

- Reconstruction time: **slow** (~1.5 hour for whole brain)

* Jensen JH, et al. Magn Reson Med. 2005; 53:1432-40.

Method 2: *fast DKI (fDKI)**

- Only 2 b-values are used.
- Explicitly calculate D_{app} and K_{app} for each diffusion direction **g** prior to fitting diffusion tensor **D** and kurtosis tensor **W** , where

$$D_{app} = \frac{(b_3 + b_1)D^{(12)} - (b_2 + b_1)D^{(13)}}{b_3 - b_2} \qquad K_{app} = 6\frac{D^{(12)} - D^{(13)}}{(b_3 - b_2)D_{app}^2}$$

$$D^{(12)} = \frac{\ln[S(b_1)/S(b_2)]}{b_2 - b_1} \qquad D^{(13)} = \frac{\ln[S(b_1)/S(b_3)]}{b_3 - b_1}$$

- Reconstruction time: **fast** (2-3 minutes for whole brain)
- Restricted to 2 b-values and diffusion directions are assumed to be fixed for each b-value

* Jensen JH, et al. NMR Biomed. 2010. 31:741-8.

Method 3: *Fitting tensors directly (NLS_T)*

- The diffusion tensor **D** and kurtosis tensor **W** can be fitted directly from $S(\mathbf{g}, b)$:

$$\ln \frac{S(\mathbf{g}, b)}{S_0} = -b \sum_{i=1}^{3} \sum_{j=1}^{3} g_i g_j D_{ij} + \frac{1}{6} b^2 MD^2 \sum_{i=1}^{3} \sum_{j=1}^{3} \sum_{k=1}^{3} \sum_{l=1}^{3} g_i g_j g_k g_l W_{ijkl}$$

- 1 step process of 21 parameters to estimate (6 for **D** and 15 for **W**)
- Solve for D_{ij} and W_{ijkl} by non-linear least squares method
- Reconstruction time: **slow** (~1 hour for whole brain)

Method 4: *fast DKI with direct tensor fitting (fDKI_T)**

- Fit the diffusion tensor **D** and the kurtosis tensor **W** directly from $S(\mathbf{g}, b)$ using linear equations:

$$\ln\frac{S(\mathbf{g},b)}{S_0} = -b\underbrace{\sum_{i=1}^{3}\sum_{j=1}^{3} g_i g_j D_{ij}}_{D_v \cdot g_d^{\,T}} + \frac{1}{6}b^2 \underbrace{MD^2 \sum_{i=1}^{3}\sum_{j=1}^{3}\sum_{k=1}^{3}\sum_{l=1}^{3} g_i g_j g_k g_l W_{ijkl}}_{K_v \cdot g_k^{\,T}}$$

- Reconstruction time: **fast** (1-2 minutes)

* Tabesh A et al. Magn Reson Med, 2010.

Goal of this study

- To assess the performance of the linear and non-linear DKI reconstruction methods
- To assess the errors associated with each type of reconstruction in DTI and DKI parameters

Methods

- Imaging
  - DKI data collected on an adult male Sprague-Dawley rat on Bruker Biospec 7T scanner
  - 30 diffusion directions (δ/Δ=4/20 ms), 5 b-values (b = 500, 1000, 1500, 2000, 2500 s/mm^2), 5 b=0 s/mm^2.
  - FOV = 3.0 × 3.0 cm^2, matrix resolution = 128 × 128, TR/TE = 6000/50 ms, slice thickness = 1 mm with no gap, number of slices = 24, number of averages = 2.
- Datasets for testing
  - Short: A clinically practical subset with 2 b-values (b = 1000, 2000 s/mm^2)
  - Full: complete dataset with all b-values

DKI reconstruction

- Methods of Comparison:

Methods	Fitting parameters	Number of parameters	Linear or Non-linear	Data set
NLS	D_{app}, K_{app}	60	Non-linear	Short
NLS_T	**D, W**	21	Non-linear	Short
fDKI	D_{app}, K_{app}	60	Linear	Short
fDKI_T	**D, W**	21	Linear	Short
Truth	**D, W**	21	Non-Linear	Full

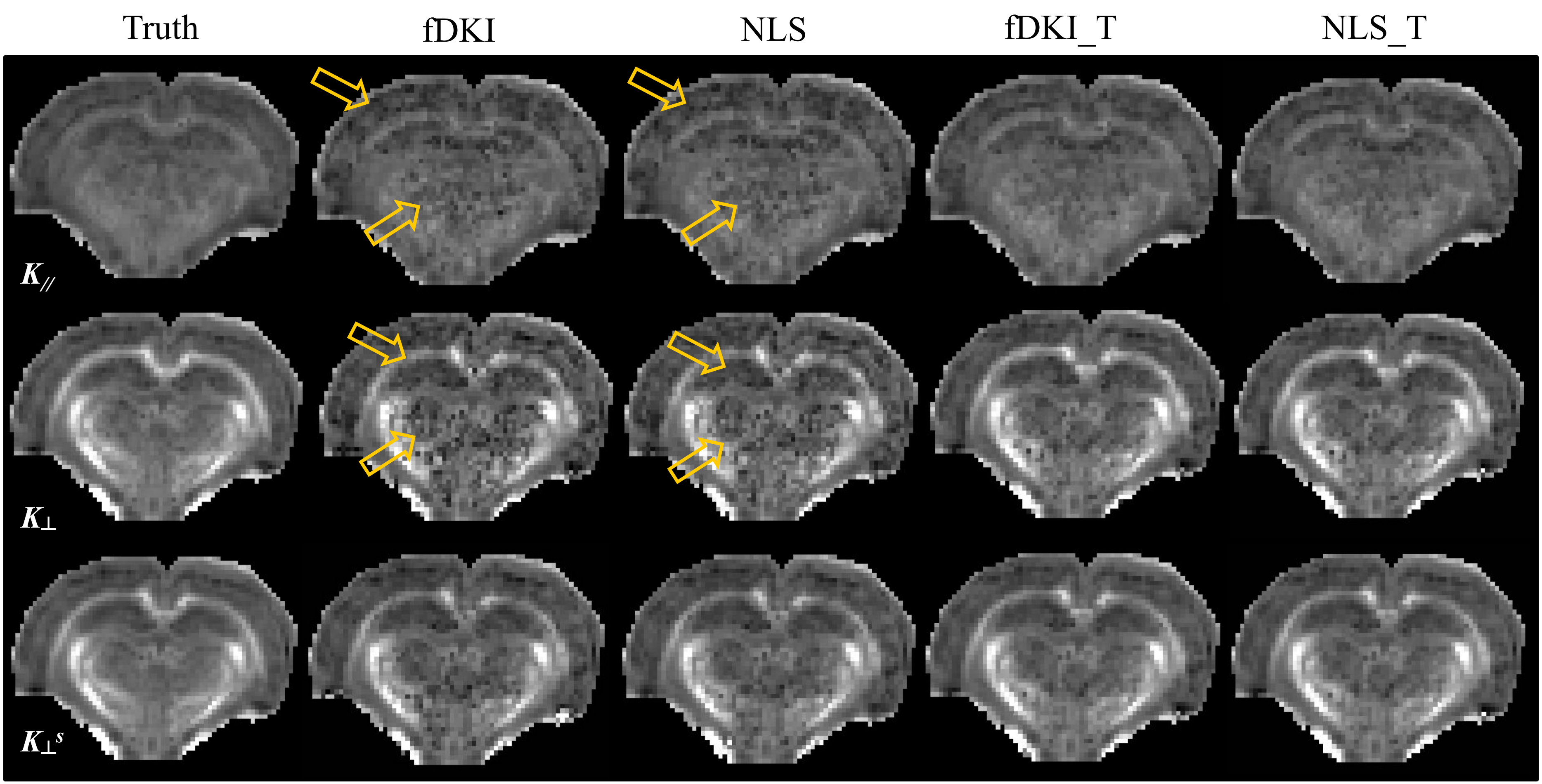
- Data preprocessing
  - Motion and eddy current correction
  - Gaussian smoothing with FWHM 0.3mm
- DKI reconstruction were performed voxel-wise.

Testing Parameters

- DTI parameters: FA, MD
- DKI parameters: MK, $K_{//}$, $K_{\perp}$
- DKI parameters calculated using surface integration*: MK^{s}, $K_{\perp}{}^{s}$

* Tabesh A et al. Magn Reson Med, 2010.

Parametric maps



- *Parametric maps are much noisier for fDKI and NLS reconstruction schemes*

Error Analysis

- Overall percentage error ***Err*** for testing parameters:

$$Err = \sum_{i=1}^{N} \left| S_i - S_i^{truth} \right| \Big/ \sum_{i=1}^{N} S_i^{truth} \cdot 100\%$$

  - N: is the total number of voxels calculated.
  - S_i and S_i^{truth} : voxel values within the parametric maps for specific method and the ground truth, respectively.

- Voxels included:

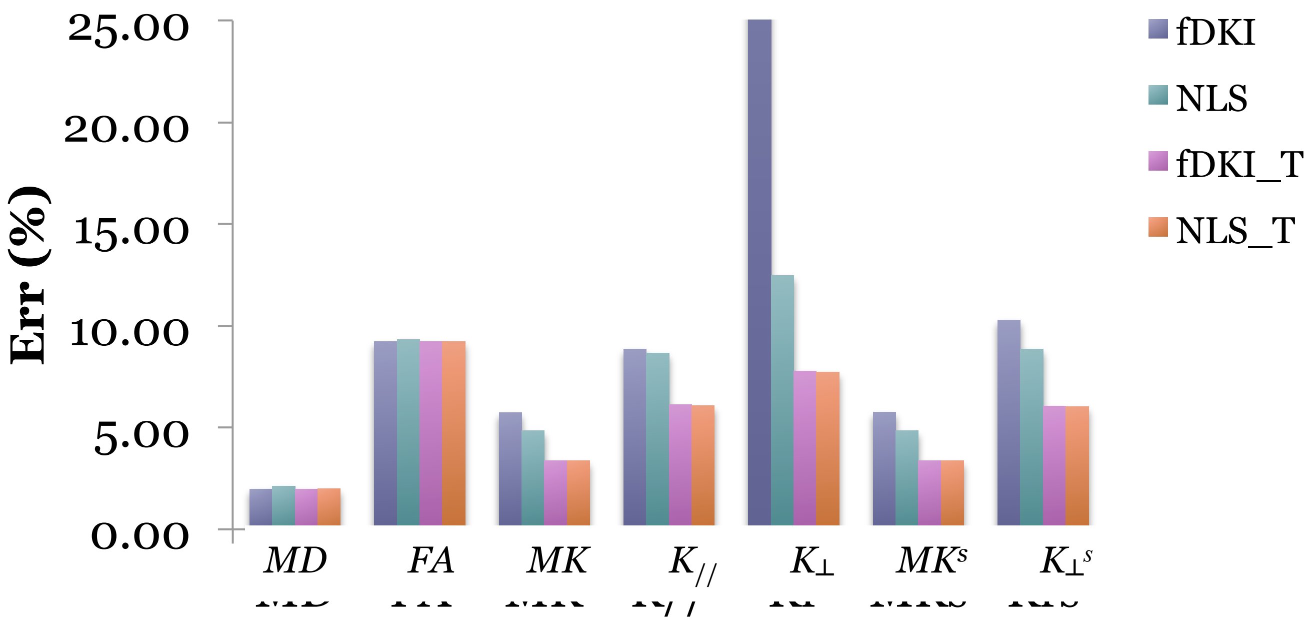
  1) Within the brain

  2) Satisfies*:

$$0 < K_{\mathrm{app}}(\mathbf{g}) < 3/(b_{max} D_{app}(\mathbf{g})) \quad \text{for all methods and } \mathbf{g}$$

*A maximum of 0.7% voxels were observed to have such kurtosis values, e.g. in $K_{\perp}$ map generated from the fDKI method

Parameter accuracy for different DKI reconstruction methods



- $Err_{fDKI} > Err_{NLS} > Err_{fDKI\_T} \approx Err_{NLS\_T}$
- $Err(K_{\perp}{}^{s}) < Err(K_{\perp})$
- $Err(MK^{S}) \approx Err(MK)$
- Errors in DTI parameters are stable for all methods considered

Discussion

- Direct tensor fitting methods (fDKI_T and NLS_T) result in fewer errors compared to conventional methods (fDKI and NLS) that require a 2-step process and need to fit many more parameters (60 parameters for 30 directions) and then reduce to tensor parameters (30 D_{app}s to fit **D** and 30 K_{app}s to fit **W**)
- Among the tensor derived methods, the linear fit (fDKI_T) performs comparable to the more time-consuming nonlinear fit (NLS_T). This may also due to the improved stability in fitting fewer parameters.
- DTI parameters are more stable across different methods because of enough redundancy in conventional methods (30 D_{app}s to fit 6 diffusion tensor parameters)
- For radial kurtosis, incorporating the more complex surface integration can provide information with increased accuracy.

Conclusion

- Using linear fit for DKI reconstruction with a tensor first approach provides comparable accuracy to nonlinear fit, hence could be the method of choice for faster and more efficient DKI reconstruction.

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