# Selecting the number of fibers in a Multi-Fiber Model from CUbe and SPhere (CUSP) Diffusion Imaging


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## INTRODUCTION.

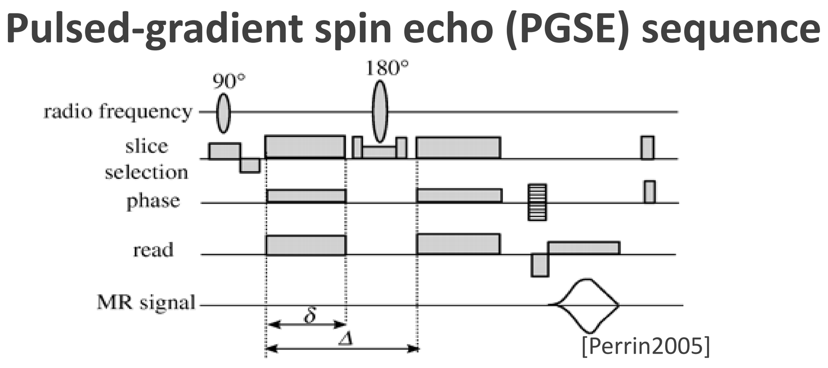
Multi-tensor models enable representation of multiple white matter fiber fascicles. However, a single fiber bundle is known to be better characterized by a single tensor. In this work, we propose a novel *acquisition-based* approach to select between the one- and the two-tensor models at each voxel. It is based on characterizing the diffusion signal at multiple diffusion scales by considering multiple b-values. We employ the recently proposed CUbe and SPhere (CUSP) acquisition scheme which achieves multiple non-zero b-values without increasing artifacts such as the geometric and intensity distortion. We show that our approach enables the selection of the number of tensors at each voxel. It is to our knowledge the first model selection approach taking into account the underlying properties of the diffusion signal generation.

## CUSP (CUbe and SPhere q-space sampling)

[Scherrer and Warfield, ISMRM2010]: theoretical demonstration that the full multi-tensor model estimation problem requires multiple b-values.

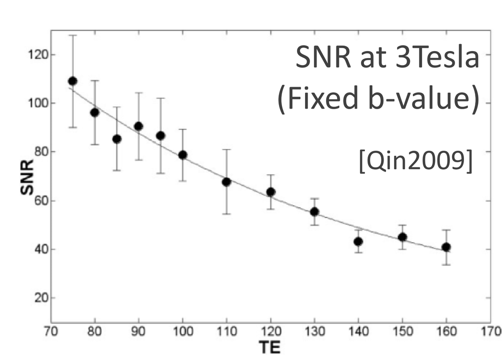
### *HOW TO SATISFY THIS REQUIREMENT?*

**Pulsed-gradient spin echo (PGSE) sequence**




$$b_{\text{nominal}} = \gamma^2 \delta^2 (\Delta - \frac{\delta}{3})$$
$$b = b_{\text{nominal}} G^2$$
$$b \approx \gamma^2 G^2 \frac{TE^3}{12}$$ [Jones DK1999]

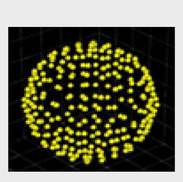
$G$ diffusion sensitizing gradient norm EACH COMPONENT MAX MAGNITUDE: 1
$\gamma$ proton gyromagnetic ratio
$\delta$ duration of the diffusion gradient pulses
$\Delta$ time between diffusion gradient RF pulses




$$S = S_0 e^{-TE/T_2} e^{-bD}$$

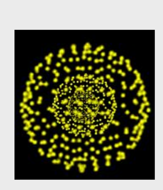
**HOW to image with multiple b-values?**

**(1) Modify the timing parameters (Δ, δ)**



Multiple single-shell HARDI
⇨ different TE for each shell
⇨ different distortion patterns

**(2) Modify the gradient strength (G)**



Multi-shell HARDI: Describes multiple full shells with varying G (**requires** G≤1)
⇨ Require to set $b_{nominal}$ = b-value for the largest shell
⇨ Increased TE ⇨ Increased acquisition time & distortion, lower SNR for all the measurements

**OUR SOLUTION: CUbe and SPhere q-space Sampling**

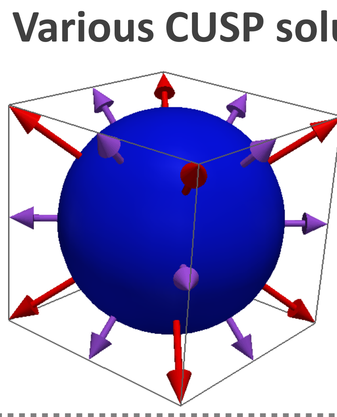
Inspired by [Conturo96], [Pierpaoli96], [Peled2009]

The magnitude of each component (Gx,Gy,Gz) of G has to be ≤ 1 (~electricity in each coil)
Describes the enclosing cube of the sphere of radius 1.
⇨ Any gradient in this region can be acquired *without* modifying the TE by choosing the appropriate G
⇨ Corresponds to a **"Cube of Constant TE"**

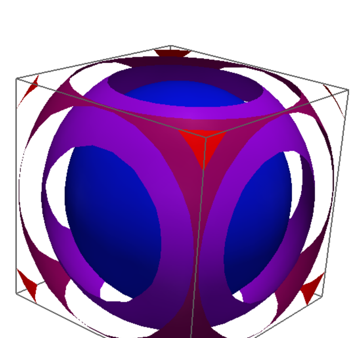
CUSP : Combines a single-shell HARDI (because the diffusion is symmetric) with gradients in the cube of constant TE (enclosing cube)

⇨ Provides multiple non-null b-values without modifying the TE
⇨ Introduces high b-values (up to three times larger than the nominal b-value for G=(1,1,1) ) known to better characterize MFMs
⇨ Does not increase the imaging time or the distortion

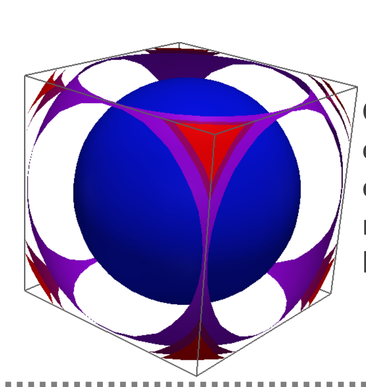
**Various CUSP solutions:**



CUSP-CURVE: A shell with the hexa- and tetra-hedral gradients Similar to CURVE-Ball, [Peled2009]



CUSP-UNI : portions of shells contained in the cube of constant TE, with uniformly spaced radius



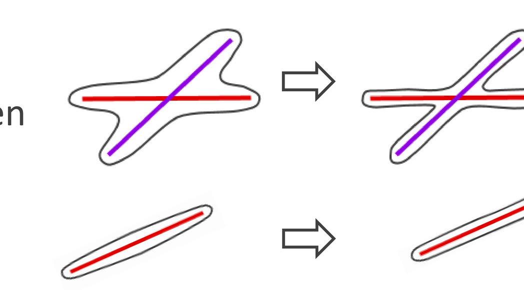
CUSP-X : portions of shells with exponentially spaced radius, to achieve better SNR

## MOSE (MOdel SElection)

Increasing the b-value : probes the diffusion signal at a smaller diffusion scale

Our hypothesis:

- In voxels containing multiple fiber bundles: An Increased b-value leads to a sharper diffusion profile in the space between the fiber bundles
- In voxels containing a single fiber bundle: The diffusion profile is more homogeneous among diffusion scales.



CUSP-MOSE : Characterization of the voxel complexity by assessing the homogeneity of the diffusion profile at multiple diffusion scales.

**1** We consider each voxel to be composed of a single fiber bundle

Estimation of the one tensor solution $D_{1T}$ **from the low b-values** with a least squares fit.

**2** Evaluation of the Prediction Performance (PP) of $D_{1T}$ **for the high b-value measurements**

*How well does the one-fiber model predict the signal for higher b-values?*

$$\tau = \frac{1}{\#H} \sum_{k/b_k \in H} \left[ S_0 e^{-b_k \mathbf{g}_k^T \mathbf{D}_{1T} \mathbf{g}_k} - \mathbf{y}_k \right]^2$$

H: Set of high b-values
#H: Number of high b-values
S0: Signal with no diffusion gradient applied
$g_k$: Gradient direction associated with the b-value $b_k$
$y_k$: Measured signal

Estimation of the typical Prediction Performance for a *known* one-fiber region

- Automatic segmentation of the body of the Corpus Callosum from $D_{1T}$ (red component), FA map and largest component analysis
- Estimation of the mean and variance ($\mu_{1T}, \sigma_{1T}$) of the PP in the body of the Corpus Callosum

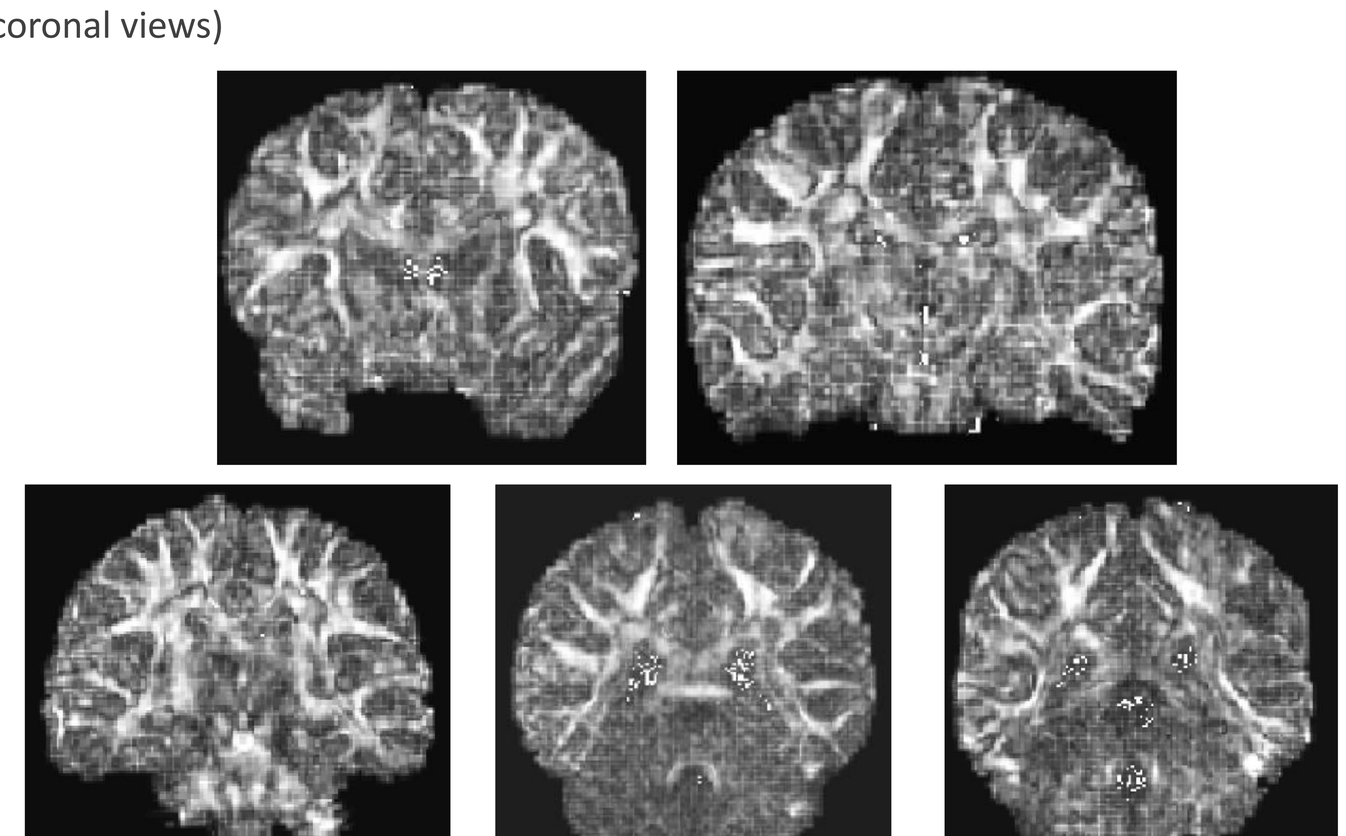
**3** Labelling of the two-fiber voxels

Large value of τ ($\tau > \mu_{1T} + 2\sigma_{1T}$)

⇨Indicates a substantial heterogeneity of the measured signal across different diffusion scales
⇨Indicates the selection of the two-tensor model

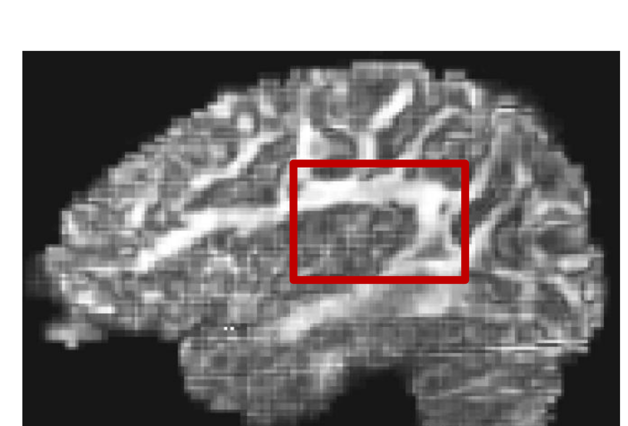
## RESULTS

One-tensor prediction performance for various subjects
(coronal views)



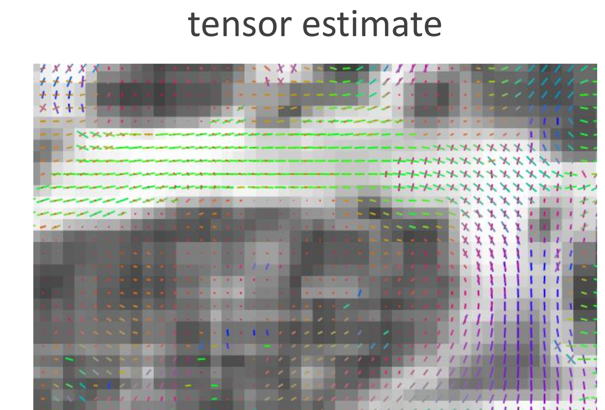
CUSP-CURVE45: 5B=0s/mm2, 20 directions on the hemisphere, 2xhexahedral gradients, 2xtetrahedral gradients

CUSP-MOSE
Model-selection with CUSP-MOSE
Multi-tensor estimation with CUSP-MFM

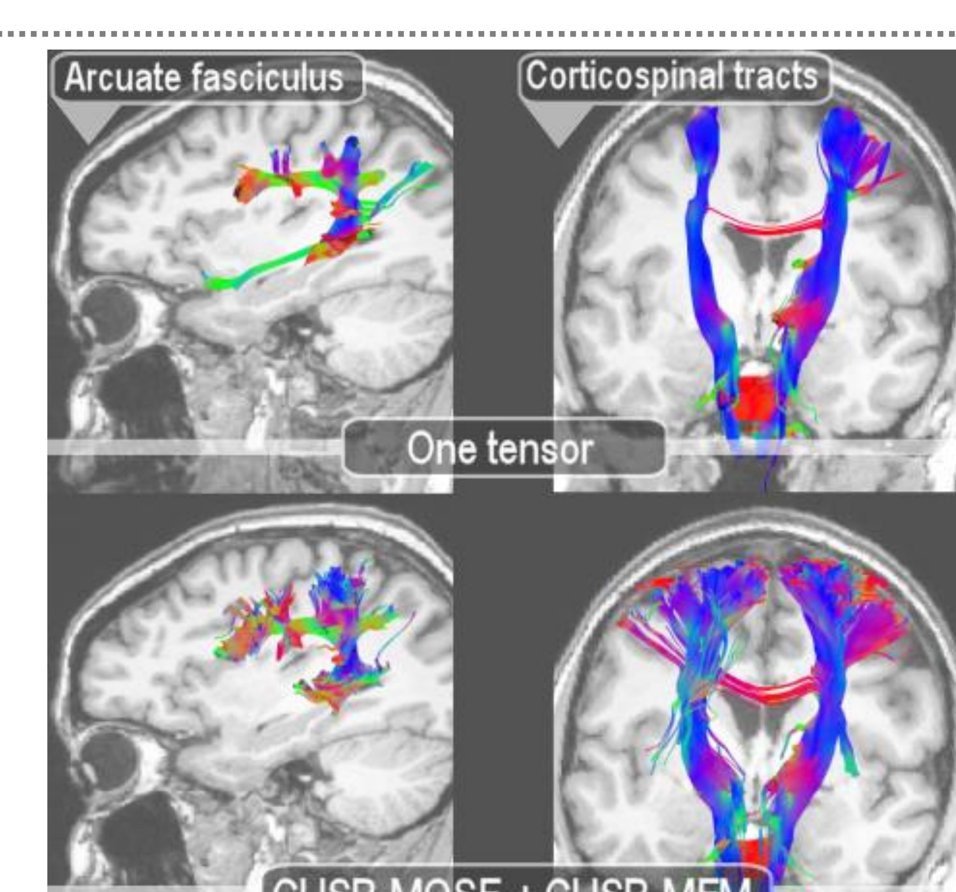


Prediction Performance
(sagittal view)

P.P. overlaid with the one-tensor estimate



P.P. overlaid with the multi-tensor estimate




Tractography with the one-tensor estimate (top) and CUSP-MOSE + CUSP-MFM (bottom)

## CONCLUSION.

Assessing the prediction performance of the diffusion signal among multiple diffusion scales provides information about the voxel complexity. The use of multiple b-values, which is required to fully estimate multi-tensor models, can also be employed for the model selection. This approach can be easily extended to more than two tensors. Future work will include a detailed evaluation of the optimal CUSP acquisition parameters for a specified imaging time, and comparison of various model selection approaches to CUSP-MOSE.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