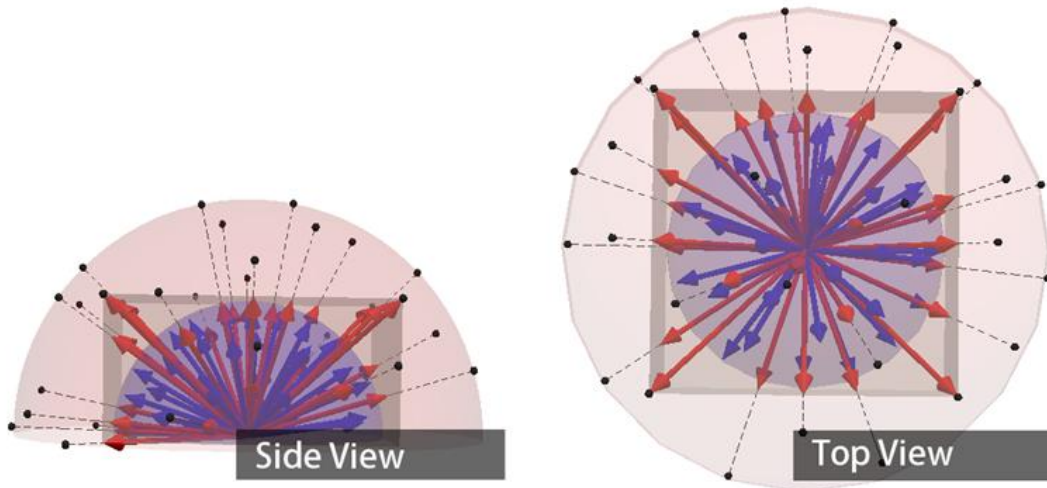


Cube and Sphere (CUSP) Diffusion Weighted Imaging

Benoit Scherrer, Maxime Taquet, Simon K. Warfield



Freely available presentation

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Introduction

Beyond Diffusion Tensor Imaging...

- A number of approach focus on characterizing the global shape of the diffusion profile

Q-Ball Imaging, Spherical Deconvolution, High order tensors, ...



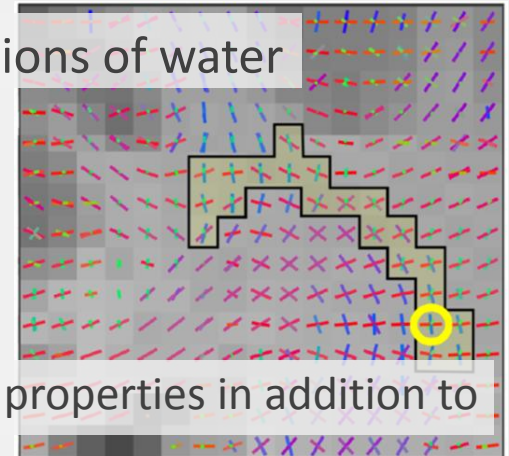
- Multi-Fascicle Models : generative models.

Represent the signal contribution from different populations of water molecules

- Signal contribution from each individual fascicle
- Signal contribution from unrestricted diffusion

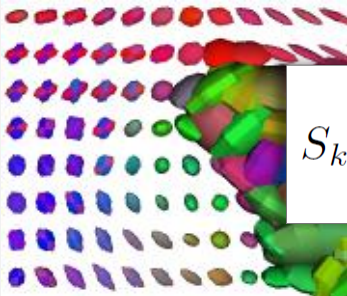
Based on underlying biological assumptions

⇒ Of great interest to characterize and compare white-matter properties in addition to the WM connectivity



Introduction

Multi-tensor representation of multiple fascicles



Fractions of occupancy

$$S_k(\mathbf{D}, \mathbf{f}) = S_0 \left(f_0 S_k^{\text{free_water}} + \sum_{j=1}^{N_f} f_j S_{k,j}^{\text{single_fascicle}} \right)$$

Signal arising from unrestricted diffusion

Signal arising from each fascicle

$$S_k^{\text{free_water}} = e^{-b_k D_{\text{iso}}}$$
$$S_{k,j}^{\text{single_fascicle}} = e^{-b_k \mathbf{g}_k^T \mathbf{D}_j \mathbf{g}_k}$$

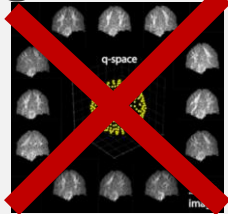
⇒ Enables compensation for partial voluming (fractions of occupancy)

⇒ Comparison between individuals (fascicle integrity, unrestricted diffusion – inflammation/edema)

Were known to be numerically challenging and unstable

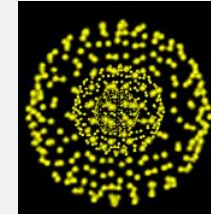
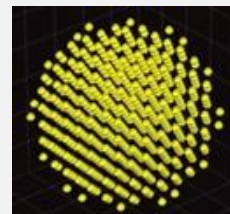
[Scherrer and Warfield, ISBI2010, PLoS ONE 2012] : *Theoretical* demonstration that multiple b-values are required. Single non-zero b-value : collinearity in the parameters

Single-shell HARDI



Single non-zero b-value

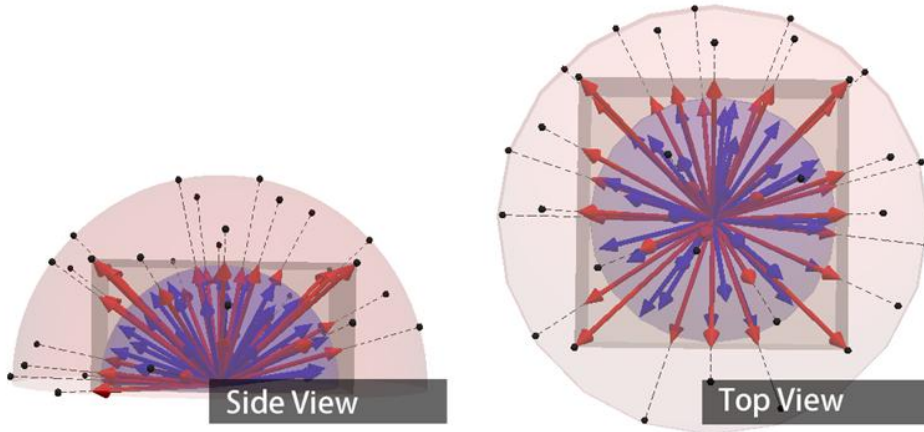
DSI, Multi-shell HARDI



Introduction

Multi-tensor representation of multiple fascicles

CUSP



CUbe & SPHERE Diffusion Imaging

$$e^{-b_k D_{\text{iso}}} = e^{-b_k \mathbf{g}_k^T \mathbf{D}_j \mathbf{g}_k}$$

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Single non-zero b-value



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- ⇒ Comparis

Were know

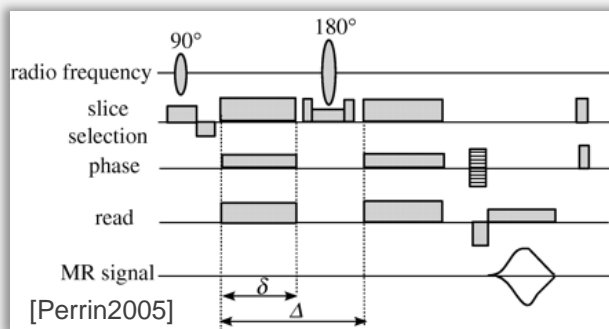
[Scherrer an
multiple b-v

Multiple b-values imaging

How to image multiple b-values?

Expression of the b-value

Pulsed-gradient spin echo (PGSE) sequence



$$b_{\text{applied}} = \gamma^2 \delta^2 (\Delta - \delta/3) G^2 \|\mathbf{g}\|^2$$

$$b_{\text{nominal}} = \gamma^2 \delta^2 (\Delta - \delta/3) G^2$$

G Scanner gradient strength

$\|\mathbf{g}\|$ diffusion sensitizing gradient norm

$$|g_k^X| \leq 1, |g_k^Y| \leq 1, |g_k^Z| \leq 1$$

γ proton gyromagnetic ratio

δ duration of the diffusion gradient pulses

Δ time between diffusion gradient RF pulses

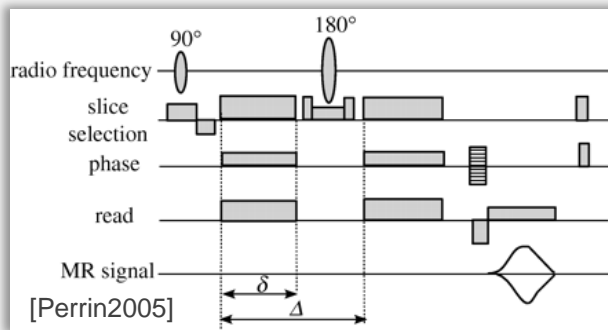
Imaging multiple b-values: modification of Δ , δ or $\|\mathbf{g}\|$

Multiple b-values imaging

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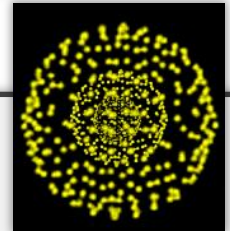
δ duration of the diffusion gradient pulses

Δ time between diffusion gradient RF pulses

Imaging multiple b-values: modification of Δ , δ or $\|\mathbf{g}\|$

Multi-shell HARDI

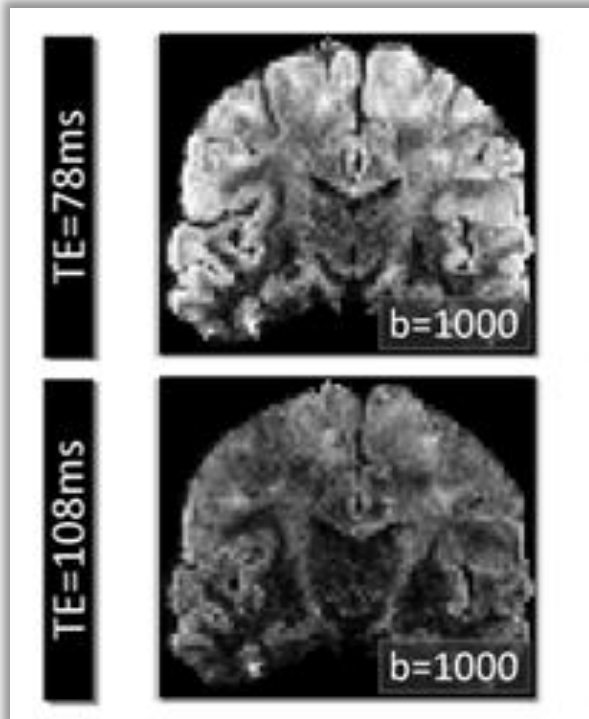
- Fixed timing parameters Δ and δ (=setting the 'nominal b-value')
- Full spherical sampling : requires $\|\mathbf{g}\| \leq 1$
 - ⇒ The largest shell must be described with $\|\mathbf{g}\|=1$, other shells with $\|\mathbf{g}\| < 1$
- Achieving a large b-value with $\|\mathbf{g}\|=1$: **requires long Δ and δ**
 - ⇒ Long TE ⇒ **signal drop-out due to T2 relaxation, for all the shells**



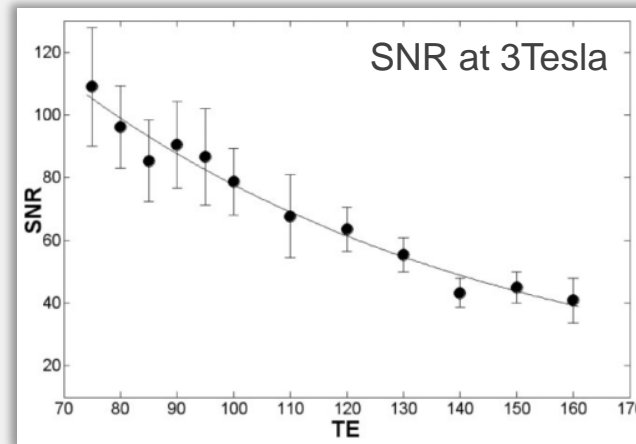
$$S = S_0 e^{-TE/T_2} e^{-b_{\text{applied}} D}$$

Multiple b-values imaging

Signal drop-out due to T2 relaxation



$$S = S_0 e^{-TE/T2} e^{-b_{\text{applied}} D}$$



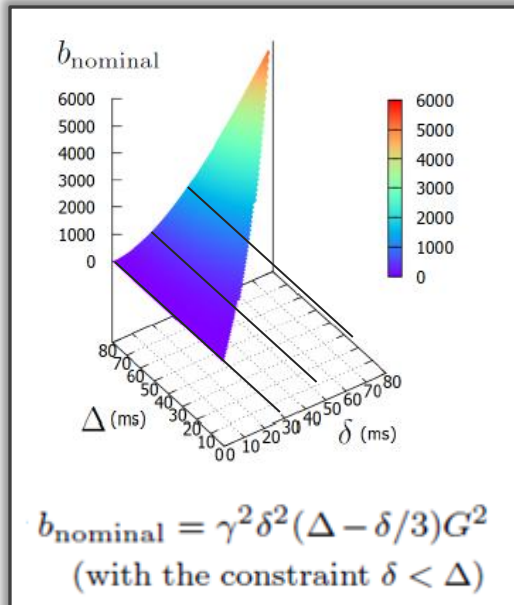
[Qin2009]

CUSP acquisition scheme

How to satisfy the requirement of multiple b-values?

Remark on the choice of Δ and δ

$$b_{\text{applied}} = \gamma^2 \delta^2 (\Delta - \delta/3) G^2 \|g\|^2$$



- Increase in δ has much more impact than increase in Δ
- Approaches such as Q-Ball, DSI, ...
Consider that: $\delta \ll \Delta$ (Narrow pulse approximation)
- However, in practice, on a clinical scanner:
 $\delta \approx \Delta$ to reduce TE and minimize the signal dropout due to T2 decay

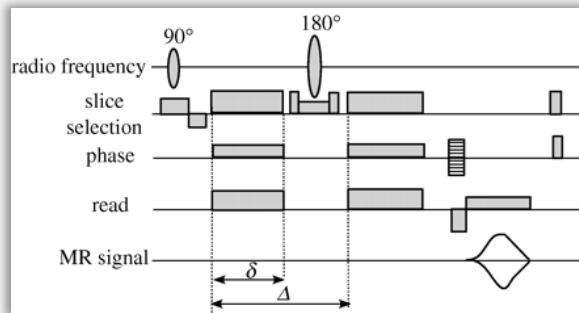
⇒ $\delta \ll \Delta$ is not verified

Multiple b-values imaging

How to image multiple b-values?

Expression of the b-value

Pulsed-gradient spin echo (PGSE) sequence



[Perrin2005]

$$b_{\text{applied}} = \gamma^2 \delta^2 (\Delta - \delta/3) G^2 \|\mathbf{g}\|^2$$

$$b_{\text{nominal}} = \gamma^2 \delta^2 (\Delta - \delta/3) G^2$$

G Scanner gradient strength

$\|\mathbf{g}\|$ diffusion sensitizing gradient norm

$$|g_k^X| \leq 1, |g_k^Y| \leq 1, |g_k^Z| \leq 1$$

γ proton gyromagnetic ratio

δ duration of the diffusion gradient pulses

Δ time between diffusion gradient RF pulses

Novel Cube and Sphere (CUSP) acquisition

Utilizing fixed Δ and δ and $\|\mathbf{g}\| > 1$ while respecting $|g_k^X| \leq 1, |g_k^Y| \leq 1, |g_k^Z| \leq 1$ to image multiple b-values without increasing the TE.

Example : $\mathbf{g}=(1,1,1) \Rightarrow b_{\text{applied}} = 3 b_{\text{nominal}}$

If $b_{\text{nominal}}=1000 \Rightarrow b_{\text{applied}}=3000$ without any cost in TE (but only four tetrahedral gradients...)

CUSP acquisition scheme

CUSP imaging : utilizing $||g|| > 1$

to image multiple b-values while achieving a short duration TE.

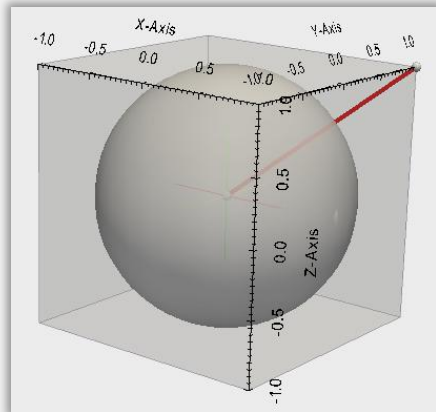
$$b_{\text{applied}} = \gamma^2 \delta^2 (\Delta - \delta/3) G^2 ||g||^2$$

$$|g_k^X| \leq 1, |g_k^Y| \leq 1, |g_k^Z| \leq 1$$



Set of gradients that can be imaged with fixed Δ and δ : corresponds to a cube whose size is fixed by δ and Δ

Cube of constant TE

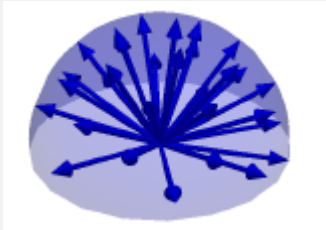
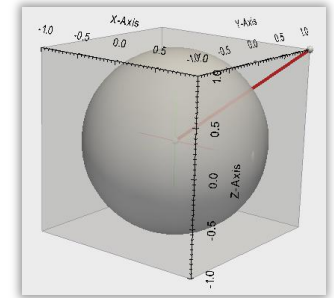


- Any gradient inside the cube can be imaged without modifying δ or Δ by modulation of $||g||$
- Any gradients outside of the cube: requires modification of δ or Δ

Cube and Sphere diffusion imaging

CUSP

Combines both spherical and cubic sampling in q-space



(A) First consider a single shell HARDI at b_{nominal}

⇒ Uniformly samples q-space

⇒ B_{nominal} chosen to provide optimal SNR.
Determines δ and Δ

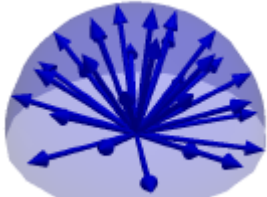
$$b_{\text{optimal}} = 1.11/\text{ADC} \text{ (Conturo et al., 1995; Jones et al., 1999)}$$

$$b_{\text{optimal}} = 1000\text{s}/\text{mm}^2 \text{ for an adult brain and } b_{\text{optimal}} = 800\text{s}/\text{mm}^2 \text{ for a pediatric brain}$$

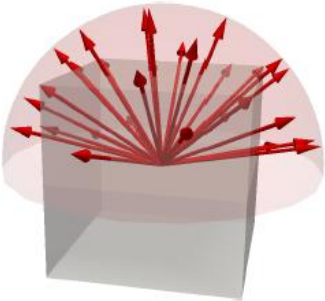
Cube and Sphere diffusion imaging

CUSP

Combines both spherical and cubic sampling in q-space



(A) Spherical sampling at optimal B_{nominal}



(B) Consider a second shell at $3 B_{\text{nominal}}$

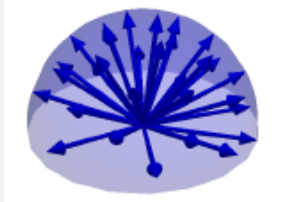
⇒ Choose optimally separated gradient directions not imaged by the inner shell [Cook et al., 2007]

BUT: gradients outside of the cube of constant TE, cannot be imaged without modifying TE

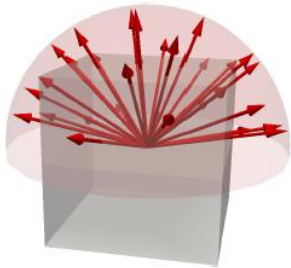
Cube and Sphere diffusion imaging

CUSP

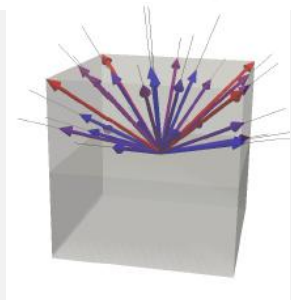
Combines both spherical and cubic sampling in q-space



(A) Spherical sampling at optimal B_{nominal}



(B) Consider a second shell at $3 B_{\text{nominal}}$

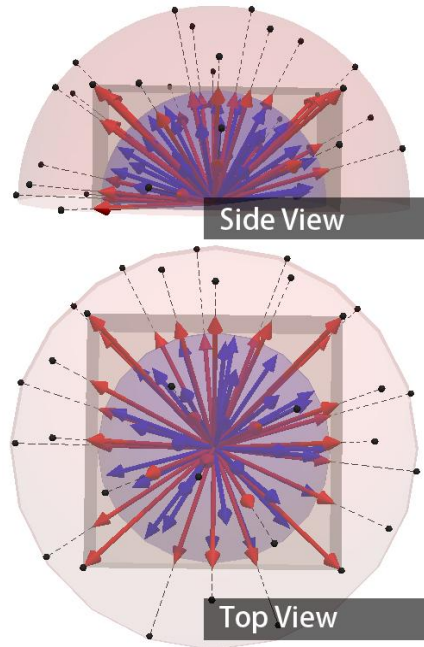


(C) Projection to the faces of the cube of constant TE
Reduce the gradient strength to lie in the cube of constant TE

Cube and Sphere diffusion imaging

CUSP

Combines both spherical and cubic q-space sampling



- Satisfies the need for multiple b-values for MFM estimation
- Introduces high b-values
- **Does not increase the echo time**
- Better SNR than a multishell HARDI
- Contains conventional $b=1000$ single shell Cube sampling as an 'add-on'
Makes clinicians happy (ADC, etc...)

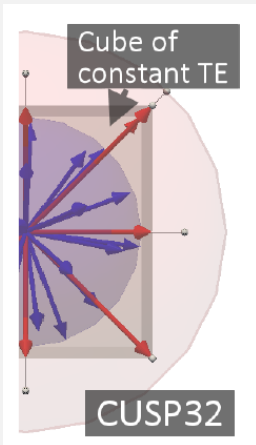
High SNR DW imaging

Short acquisition duration compatible with clinical practice

Enables the estimation of the full multi-tensor model

ISBI Challenge

CUSP32



Inner-shell ($||g||=1$)

22 gradients uniformly distributed, $b=1000$

Cube ($||g||>1$)

6 Hexahedral gradients $(0, \pm 1, \pm 1)$, $(\pm 1, \pm 1, 0)$, etc.

4 Tetrahedral gradients $(\pm 1, \pm 1, \pm 1)$

=32 DW images

- Restoration of each DW image

with optimized non-local means denoising filter

Coupe, P., Yger, P., Prima, S., Hellier, P., Kervrann, C., Barillot, C.: An optimized blockwise nonlocal means denoising filter for 3-d magnetic resonance images. *IEEE Trans Med Imaging* 27(4), 425–441 (2008)

- Diffusion model : multi-tensor model

with unrestricted diffusion and maximum of $m=3$ fascicles

$$S = S_0 \left(f_0 e^{-bD_{iso}} + \sum_{i=1}^m f_i e^{-bg^T D_i g} \right)$$

- Estimation with MAP formulation [Scherrer and Warfield, PLOS One 2012]

Considering a model of gradually increasing complexity.

Method

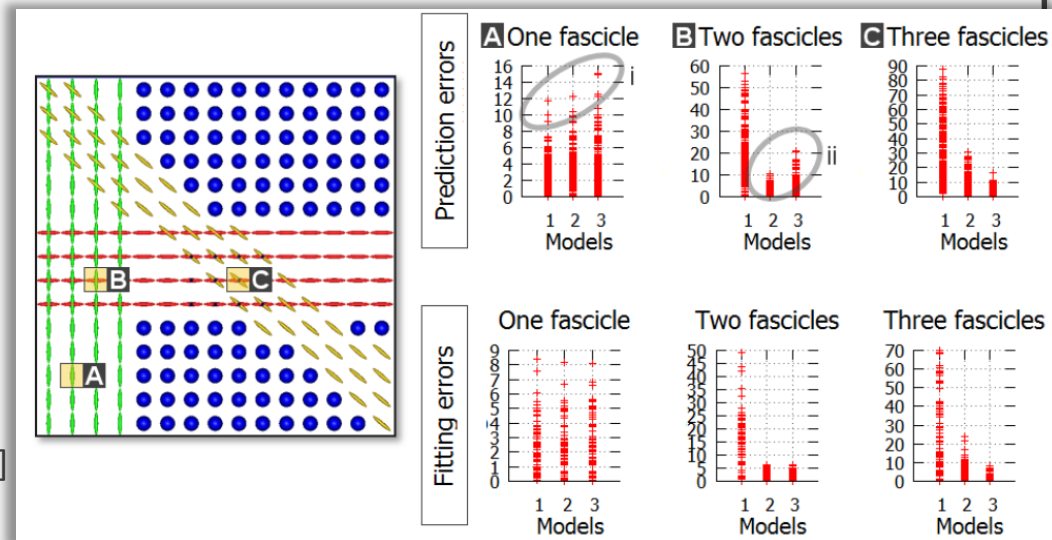
Model order selection

- Novel approach: minimization of the generalization error (GE)
Scherrer, B., Taquet, M., Warfield, S.K.: Reliable Selection of the Number of Fascicles in Diffusion Images by Estimation of the Generalization Error, IPMI, 2013
- Not fitting error + penalization of complex models as in F-Test, BIC, ARD !
- Generalization error = error on data not used for estimation
 - Too simple model \Rightarrow large generalization error ;
 - Too complex model \Rightarrow overfitting, poor generalization error

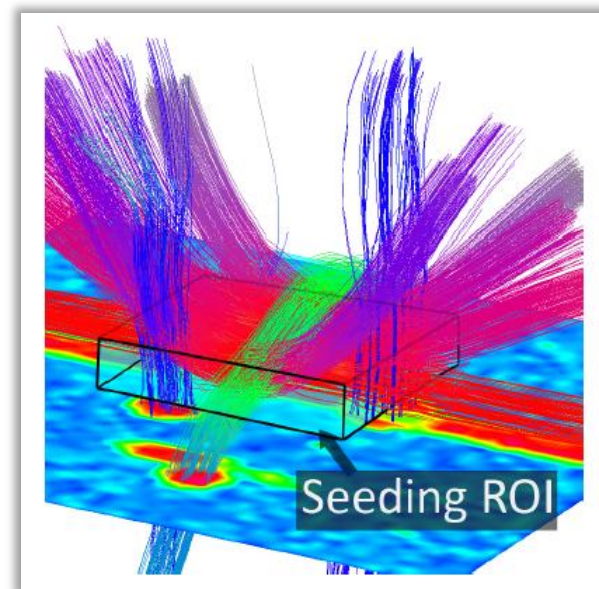
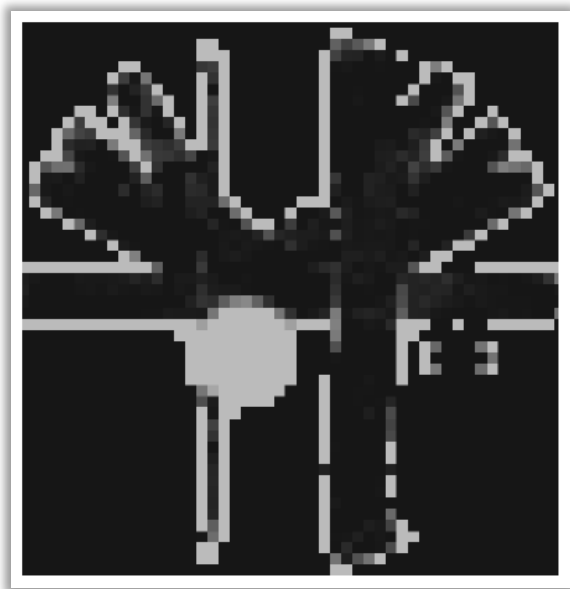
How to estimate the GE?

- Leave-one-out : high variance
- K-fold cross validation: reduces the variance but higher bias

\Rightarrow IPMI2013: Estimation with the bootstrap 632 approach [Efron1984]
Low bias and low variance



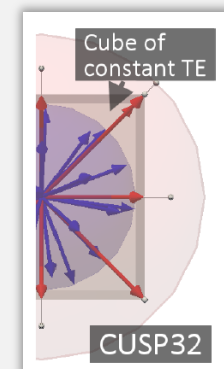
Results



Method

Conclusion

- Acquisitions with a very low number of DW images
Great interest for routine clinical practice
 - Challenging for both
 - Model parameters estimation
 - Model order selection
- ⇒ Arguably needs carefully consideration of :
- Image acquisition process
 - Image pre-processing
 - DW signal modeling
 - Estimation strategy



- We considered here:

(1) CUSP (Multiple b-values with high SNR)

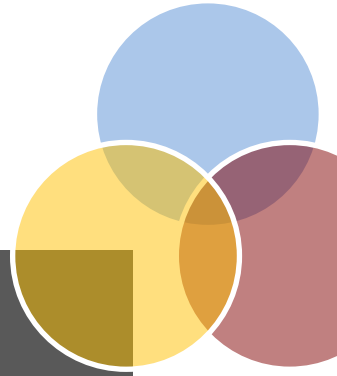
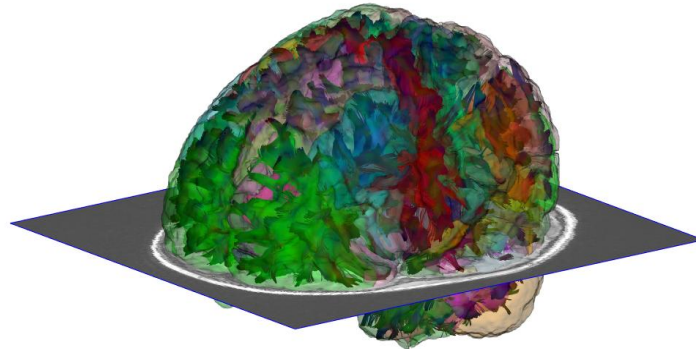
(3) a multi-tensor model ...

and (5) model order selection based on the minimization of the generalization error.

(2) non-local means denoising

(4) ... whose parameters are estimated via a MAP formulation

Thank you for your attention,



Questions?

This investigation was supported in part by NIH grants R01 RR021885, R01 EB008015, R03 EB008680, R01 LM010033 and UL1 RR025758-03.