Diffusion Tractography

- Goal of tractography
- Estimating Fibre Orientations - BEDPOSTX
- Probabilistic Tractography - PROBTRACKX
- ProbtrackX outputs
- Tractography limitations
Principal Diffusion Direction

Assumption:

Direction of maximum diffusivity (in anisotropic voxels) is an estimate of the major fibre orientation.
But is WM always coherently organised within a voxel?

Unfortunately not, complex fibre patterns (e.g. crossings) are very common at the voxel scale.

Williams, Gluhbegovic, and Jew, "The Human Brain: Dissections of the Real Brain", Virtual Hospital, University of Iowa, 1997
Predictions from the tensor model
no crossing fibres

One orientation

Measured
Signal
Shape

Predicted
Signal
Shape

DTI
Ellipsoid

Prediction & Measurements in 2D
Predictions from the tensor model crossing fibres

Two orientations

Measured Signal Shape

Predicted Signal Shape

DTI Ellipsoid

Prediction & Measurements in 2D
Predictions from the tensor model crossing fibres

Three Orientations

Measured Signal Shape

Predicted Signal Shape

DTI Ellipsoid

Prediction & Measurements in 2D
How good is the DTI Model in regions with crossing fibres?

- In voxels containing two crossing bundles, the tensor ellipsoid is pancake-shaped (oblate, planar tensor).
- In voxels containing three crossing bundles, the tensor ellipsoid is spherical.

- In these areas, DTI $\mathbf{v}_1$ is meaningless.

Prolate Tensor

$\lambda_1 >> \lambda_2, \lambda_3$

Oblate Tensor

$\lambda_1=\lambda_2 >> \lambda_3$

Spherical Tensor

$\lambda_1=\lambda_2=\lambda_3$
Uncertainty on DTI Fibre Orientation Estimates

Repeat an acquisition many times and obtain the variability in $v_1$ from the different datasets.

Uncertainty Sources
- Modelling errors
- Noise

Cones of uncertainty on DTI $v_1$

Jones, 2002
Do we have to use the DTI model to estimate orientations? Not really, many models exist.

**DTI model (dtifit)**

**Ball & sticks model (bedpostx)**

\[
s_j = s_0 \left[ (1-f) \exp(-b_j d) + f \exp(-b_j d(x_j^T v)^2) \right]
\]

- Measured Signal for Gradient \( j \)
- Unit vector representing the direction of gradient \( j \) (known)
- Diffusivity (unknown)
- Anisotropic Volume Fraction (unknown)
- Fibre Orientation (unknown)
- b-value for gradient \( j \) (known)
Ball & Sticks Model
Unlike the DT model, it can represent many orientations

- Anisotropic tensors (sticks) with isotropic background (ball)
- Fibre Orientations modelled explicitly and separated from isotropic partial volumes

\[ s_j = s_0 \left[ (1 - \sum f_n) \exp(-b_j d) + \sum f_n \exp(-b_j d (x_j^T v_n)^2) \right] \]

- Measured Signal for Gradient \( j \)
- Unit vector representing the direction of gradient \( j \) (known)
- Anisotropic Volume Fractions (unknown)
- Diffusivity (unknown)
- Max number of sticks (user-defined)
- Fibre Orientation (unknown)
- \( b \)-value for gradient \( j \) (known)
Predictions from the ball and sticks model crossing fibres

Two orientations

Measured Signal Shape

Prediction & Measurement in 2D

Three orientations

DTI

Ball & sticks
Markov Chain - Monte Carlo (MCMC) Sampling

Model Predicted Signal

Measured Signal

5000 iterations per voxel

Output samples
Output in Each voxel = Distributions of Parameters

- WM
  - Orientation Distribution
  - DTI ellipsoid

- GM/CSF
  - Orientation Distribution
  - DTI ellipsoid
Ball & Sticks Model Selection

- Model selection problem: One, two or more fibres within a voxel?

- Automatic Relevance Determination: Only estimate complexity that is supported by the data
Modelling Complex Fibre Architectures
Automatic Relevance Determination (A.R.D.)

• No benefit from including a 2nd fibre => 2nd volume fraction goes to zero

- - - Measured Signal
  Model Predicted Signal

Model with one stick       Model with two sticks

Signal for one fibre configuration

ARD1
- After running BedpostX all voxels will have estimated parameters for the maximum number of sticks requested.

- But due to ARD, the sticks that are not supported in a voxel will have an almost zero volume fraction.

- We use a threshold (e.g. >5%) to exclude sticks with tiny volume fraction.
Ball & Sticks Orientations

All sticks, with secondary ones thresholded ($f_n > 5\%$)

Orientations RGB-colour coded
DTI vs Ball & Sticks Orientations

DTI

Ball & Sticks
A large portion of the WM supports crossing fibres

Coherence in orientations shows that we are not over-fitting (the ARD works)
Multi-Shell Diffusion Acquisitions
Why bother?

One Orientation

Two Orientations

Three Orientations

Signal at different $b$ values (s/mm$^2$)

- $b=1000$
- $b=2000$
- $b=3000$
- $b=4000$
- $b=5000$

Higher $b$ value gives us more angular contrast!!!
Multi-Shell Diffusion Acquisitions
Why bother?

One Orientation  Two Orientations  Three Orientations

Signal at different b values (s/mm²)
b=1000
b=2000
b=3000
b=4000
b=5000

But SNR goes down very quickly with b… 😞
Generalised Ball & sticks Model
Gets best of both worlds

- Multi-shell model (or model=2) in Bedpostx options.
- Allows representation of multiple diffusivities within a voxel (rather than just one).
- More accurate model for multi-shell data & partial volume effects.

Human Connectome Project Data

*Jbabdi, Sotiropoulos et al, MRM 2012
*Sotiropoulos, Jbabdi et al, NeuroImage 2013
Faster bedpostx on GPUs

50x-150x Speedup using GPUs

Hernandez et al, Plos One 2013