Diffusion MRI: the basics

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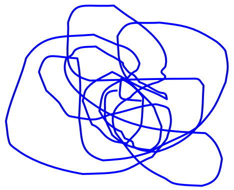
Basic concepts

Isotropic vs Anisotropic Diffusion

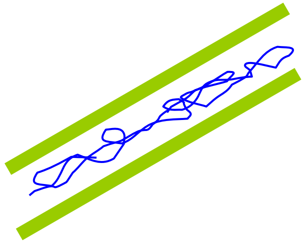
- Free diffusion (no obstacles) occurs equally in all directions. This is called **isotropic diffusion**.
- If the water diffuses in a medium having barriers, the diffusion will be uneven. Barriers can be many things (cell membranes, molecules, axons, etc), but in white matter the principal barrier is the myelin sheath of axons.
- Bundles of axons provide a barrier to perpendicular diffusion and a path for parallel diffusion along the orientation of the fibres. This is termed **anisotropic diffusion**.

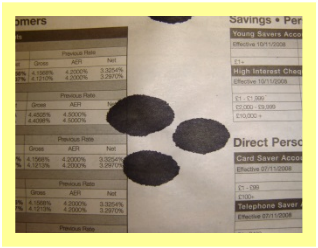
Diffusion trajectory

Isotropic Diffusion (free water)



Anisotropic Diffusion (coherent axonal bundle)





The diffusion MRI signal

- MRI signal profile as a function of the direction (θ,ϕ) of the DW gradients, $S(\theta,\phi)$:
  - isotropic voxel:
  - anisotropic voxel:

- Changing the gradient direction changes the amount of attenuation seen, depending on how much motion there is along that specific direction.

The diffusion weighting parameter (b-value)

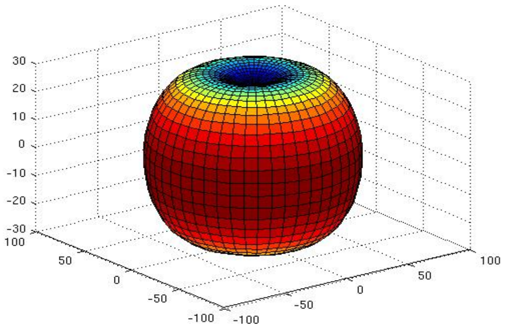
$$b = (\gamma G \delta)^2 (\Delta - \delta/3)$$

DW gradient intensity

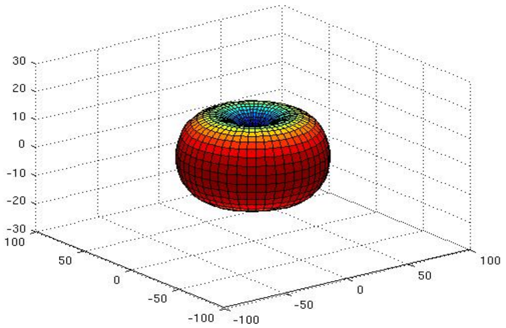
spacing between gradients

gradient duration

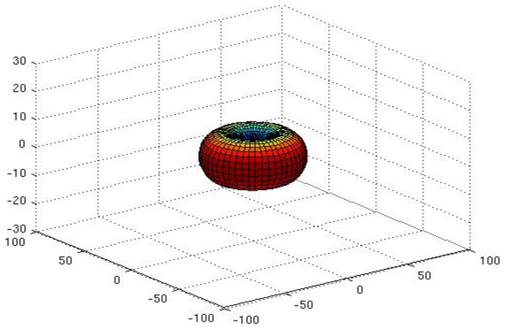
b = 1000 s/mm²



b = 2000 s/mm²

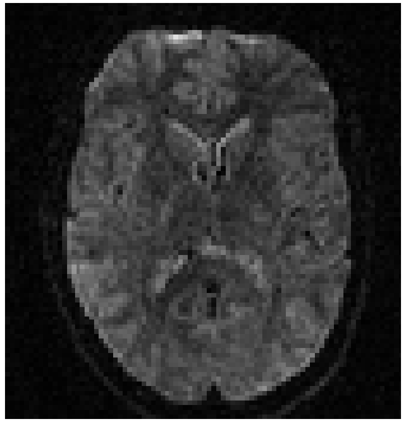


b = 3000 s/mm²

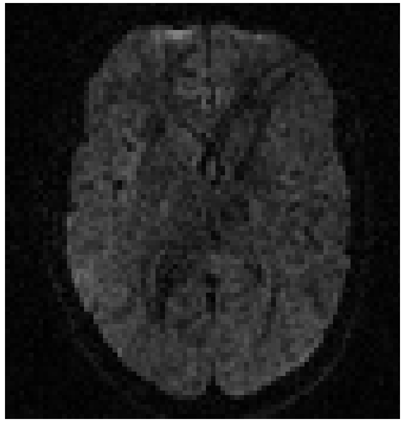


Changing the b-value in the Brain

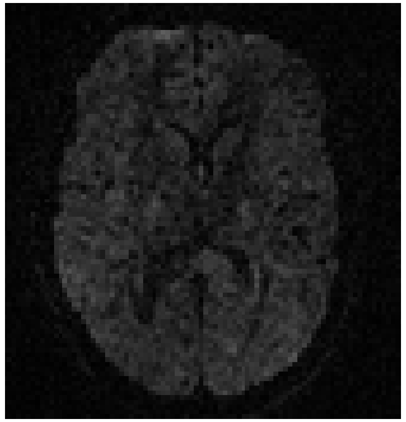
b = 0 s/mm^2



b = 400 s/mm^2



b = 800 s/mm^2



b = 1200 s/mm^2

Gaussian Modeling of the Diffusion Signal

The Diffusion Tensor Model

- Diffusion is a 3D process and water molecules mobility in tissues is not necessarily the same in all directions.

- Organized fibrous tissues, such as muscle and cerebral white matter, demonstrate anisotropic diffusion.

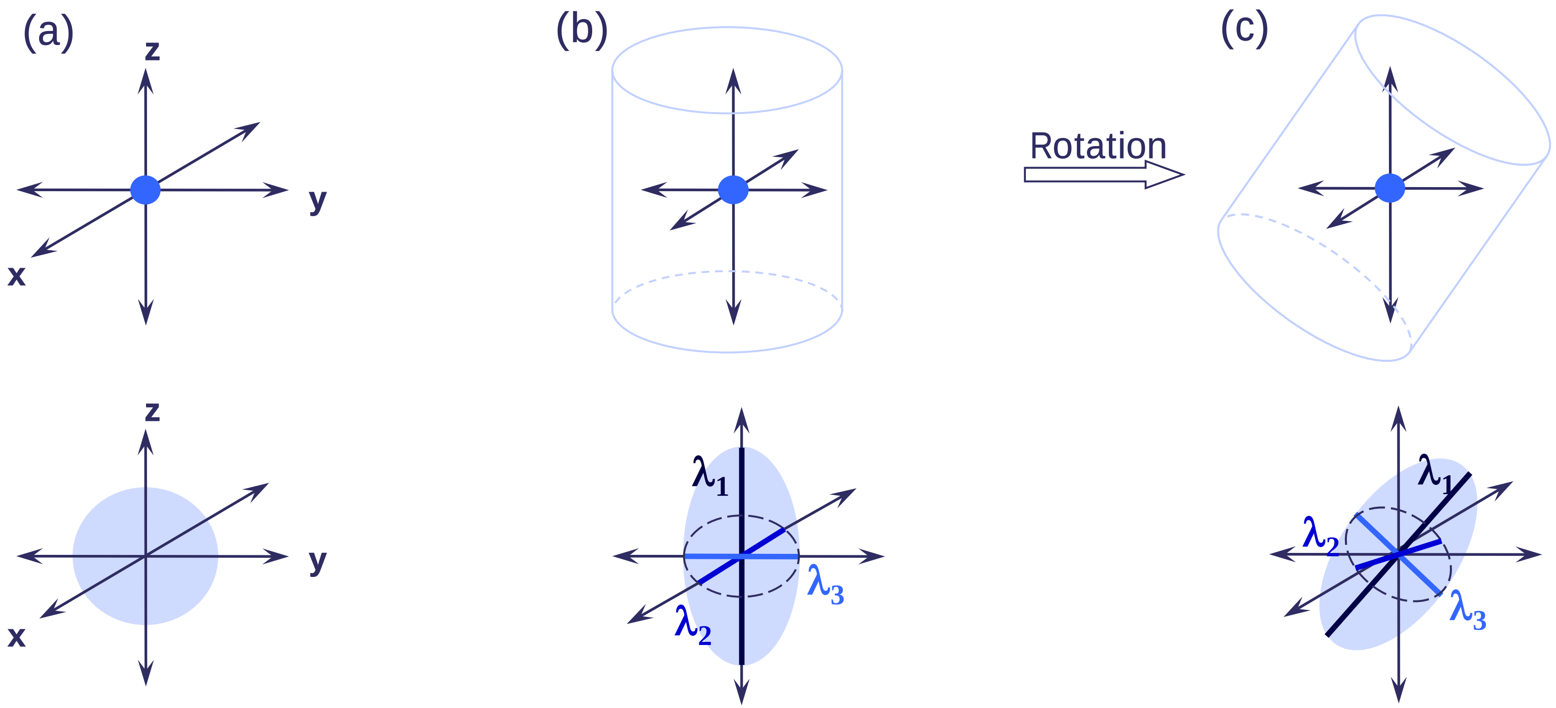
- The simplest model that can characterise Gaussian diffusion in which the displacements pert unit time are not the same along all directions is the **diffusion tensor**.

- This is a 3x3 symmetric matrix:

$$\underline{D} = \begin{bmatrix} D_{xx} & D_{xy} & D_{xz} \\ D_{xy} & D_{yy} & D_{yz} \\ D_{xz} & D_{yz} & D_{zz} \end{bmatrix}$$

- The diagonal elements correspond to diffusivities along the three orthogonal axes.

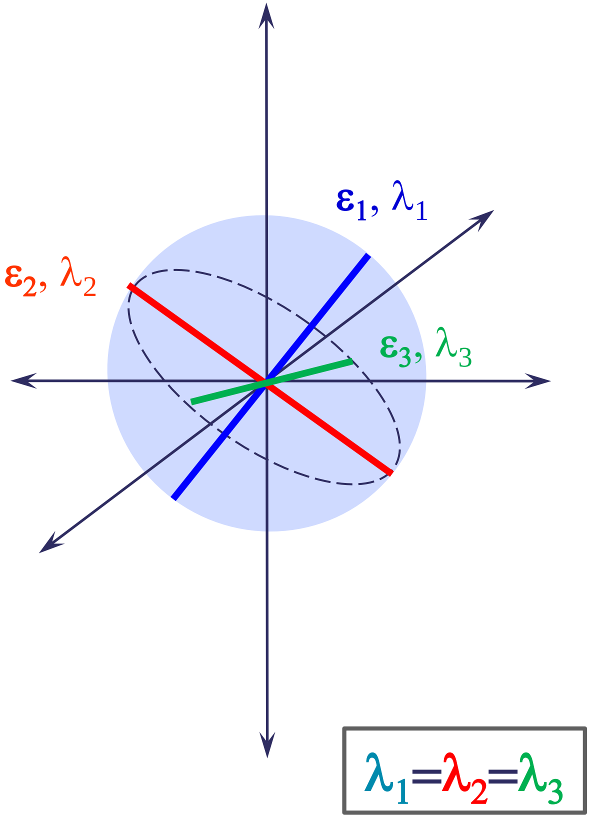
The Diffusion Ellipsoid



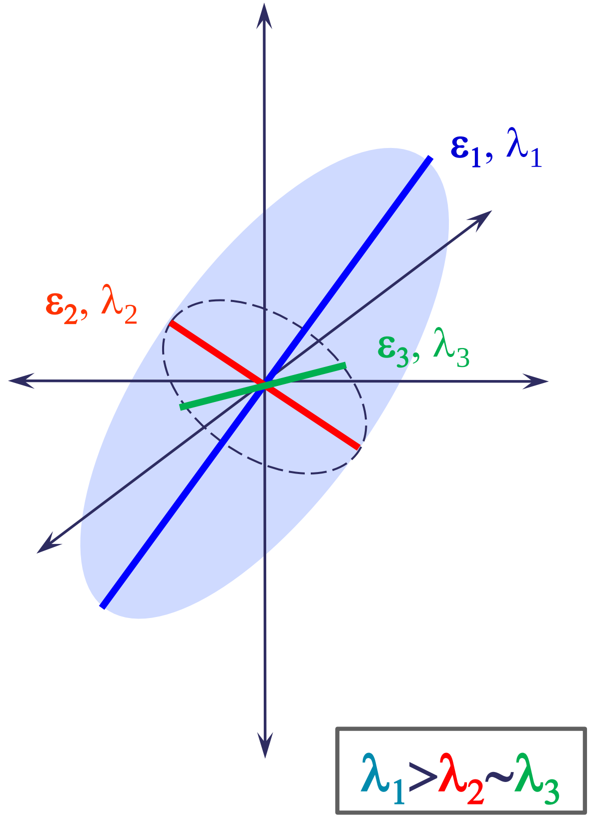
$$\begin{bmatrix} D & 0 & 0 \\ 0 & D & 0 \\ 0 & 0 & D \end{bmatrix} \qquad \begin{bmatrix} \lambda_1 & 0 & 0 \\ 0 & \lambda_2 & 0 \\ 0 & 0 & \lambda_3 \end{bmatrix} \qquad \begin{bmatrix} D_{xx} & D_{xy} & D_{xz} \\ D_{xy} & D_{yy} & D_{yz} \\ D_{xz} & D_{yz} & D_{zz} \end{bmatrix}$$

Eigenvalues and eigenvectors

Isotropic Diffusion



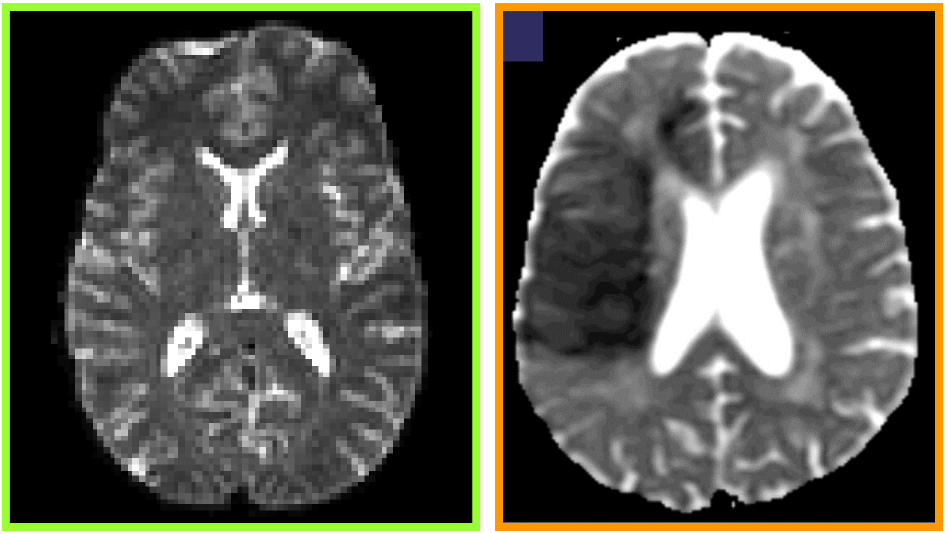
Anisotropic Diffusion



Mean diffusivity (MD)

- Measurements of the DT and its components have been found to have several applications in the human brain.

- **Mean diffusivity map:** MD is the average value of the rate of diffusion on each voxel. MD maps contain very useful information for detecting and evaluating brain ischemia and stroke.



$$MD = \frac{D_{xx} + D_{yy} + D_{zz}}{3} = \frac{\lambda_1 + \lambda_2 + \lambda_3}{3}$$

MD maps of a healthy brain (left) and a stroke patient (right).

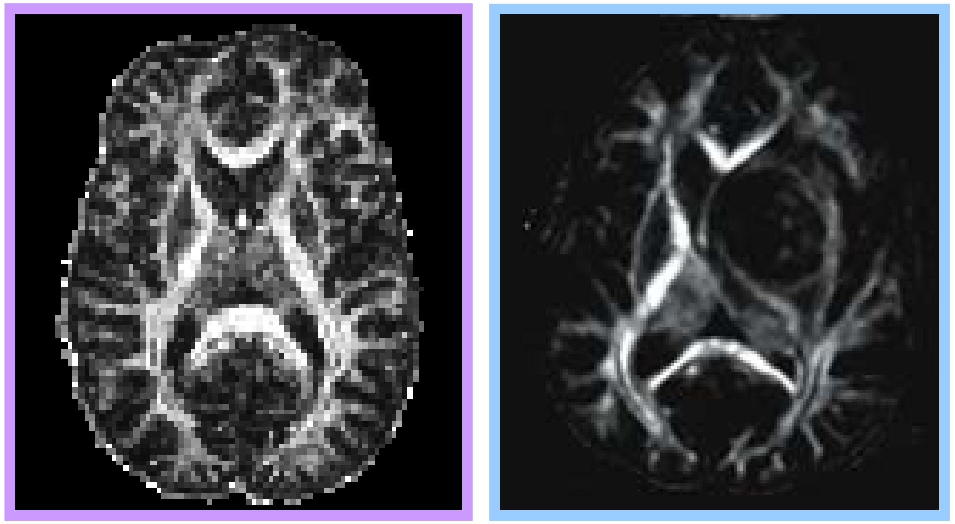
Fractional Anisotropy (FA)

- **Fractional Anisotropy map:** FA is a measure of the degree of diffusion anisotropy, and it is calculated from the diffusivity constants λ_1, λ_2, λ_3.

$$\mathrm{FA} = \sqrt{\frac{3((\lambda_1 - <\lambda>)^2 + (\lambda_2 - <\lambda>)^2 + (\lambda_3 - <\lambda>)^2)}{2(\lambda_1{}^2 + \lambda_2{}^2 + \lambda_3{}^2)}}$$

- FA produces high values for white matter (highly anisotropic) and low values for grey matter(isotropic).

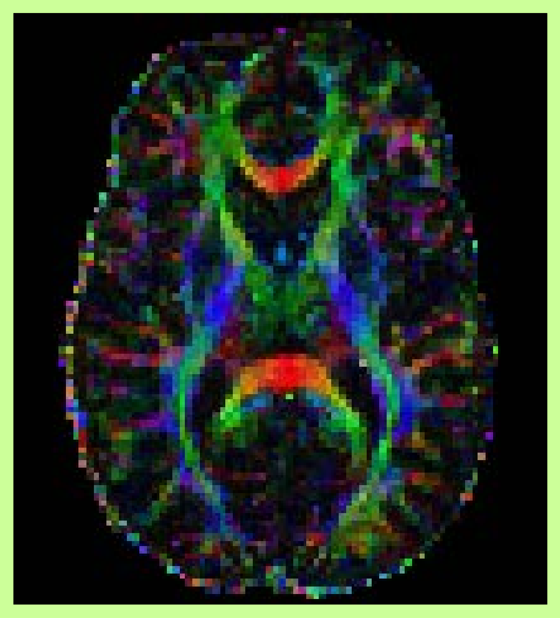
- It has been used to study white matter in terms of morphology, disease and trauma, brain development and neurosurgical planning.



FA maps of a healthy brain (left) and a brain tumour patient (right).

Colour coded FA maps

- Let ε_1 designate the longest axis of the diffusion ellipsoid.
- ε_1 can be identified with the main direction of diffusion.
- This directional information can be added to the FA map using a colour code:



Red indicates directions in the *x* axis: right to left or left to right.

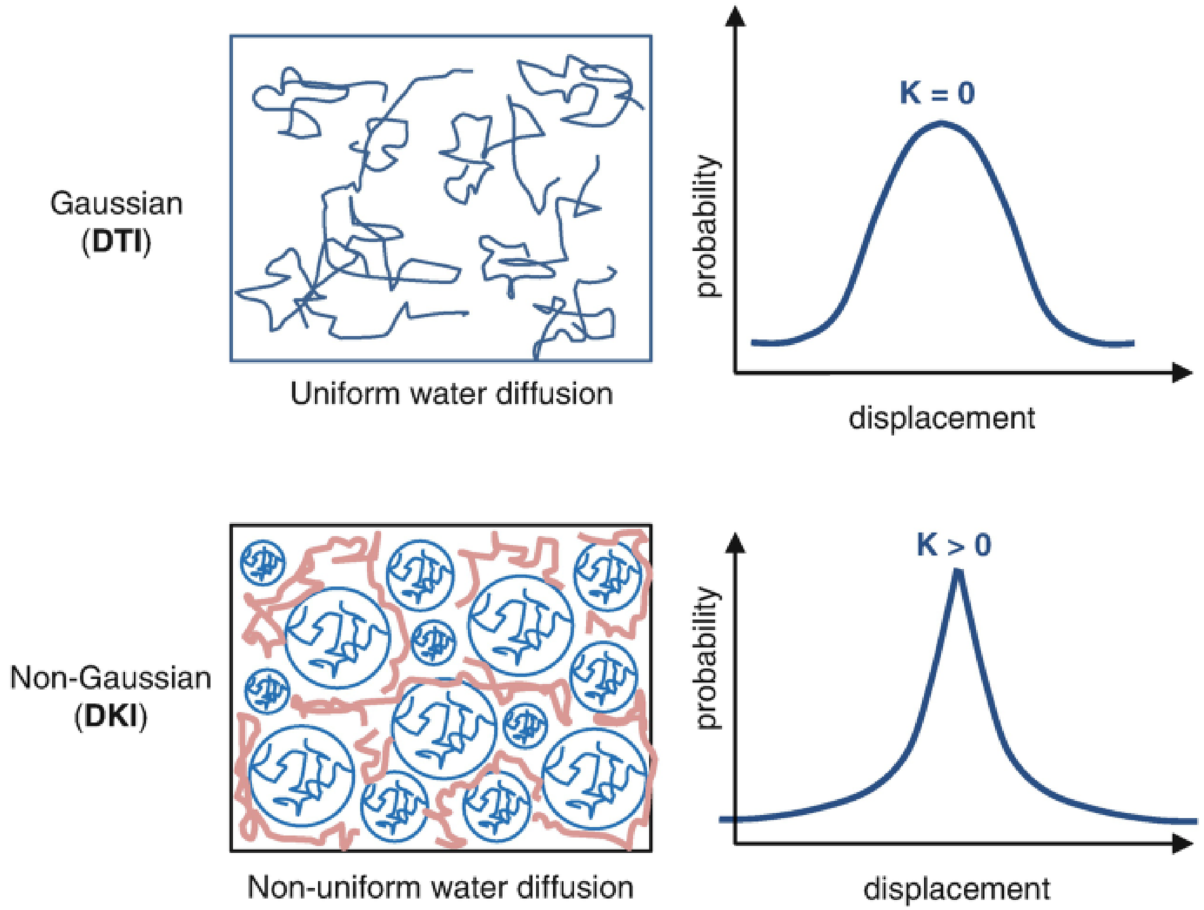
Green indicates directions in the *y* axis: front to back or back to front.

Blue indicates directions in the *z* axis: foot-to-head direction or vice versa.

Colour coded FA map.

Beyond the Diffusion Tensor Model

Diffusion Kurtosis Imaging (DKI)



From “Neuroimaging Techniques in Clinical Practice”, Springer 2020

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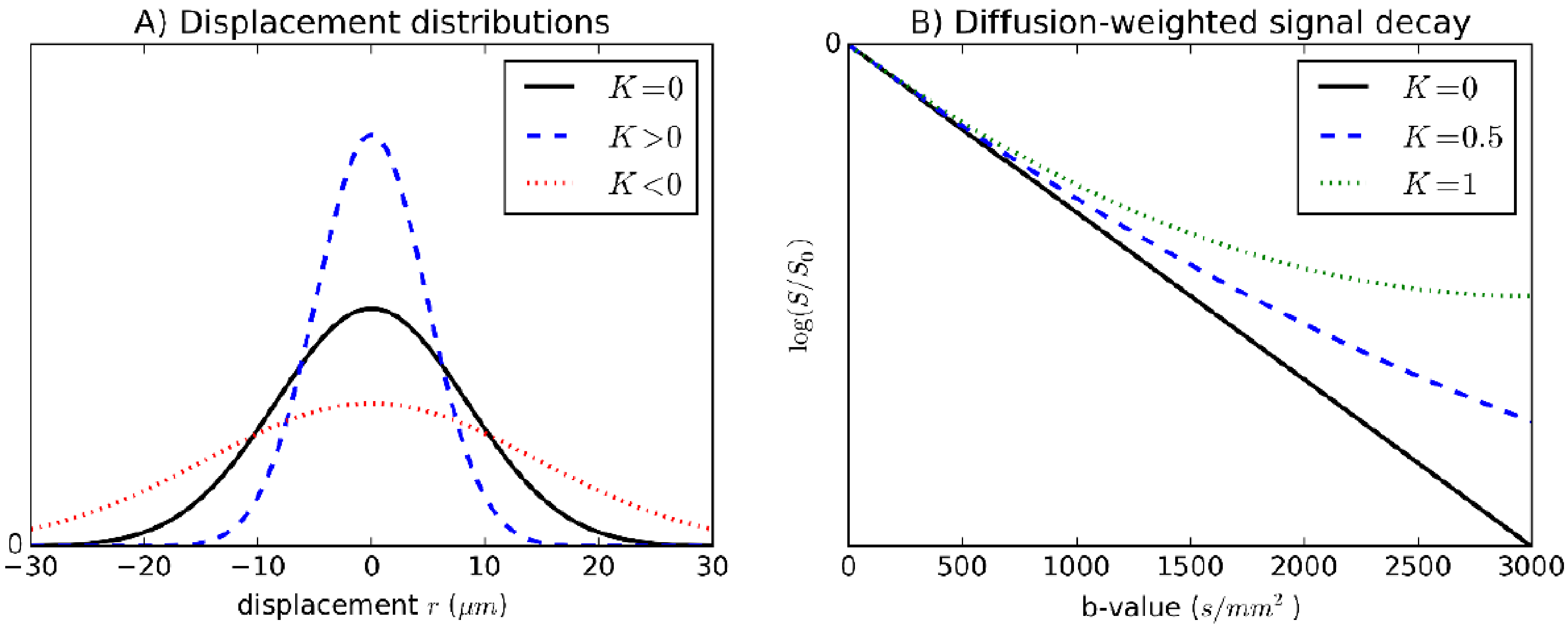
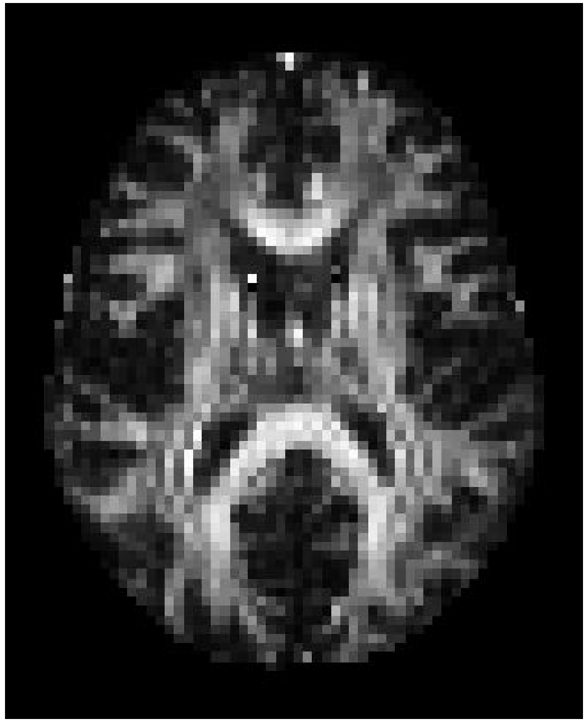


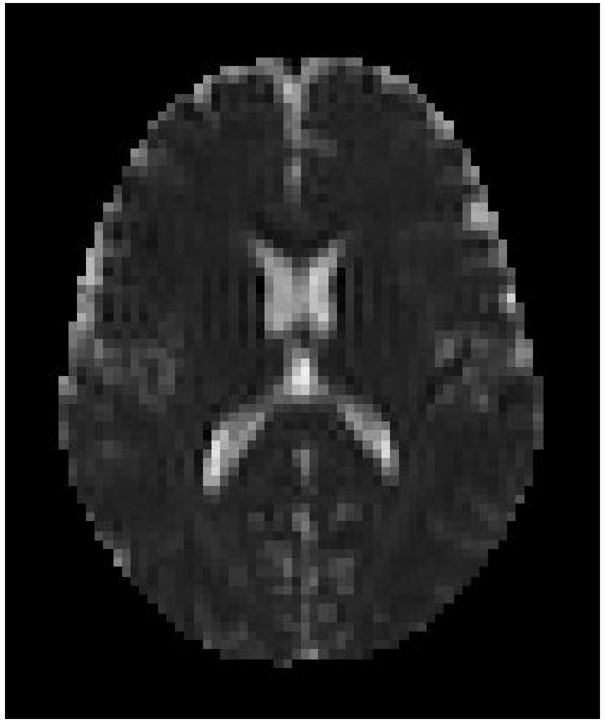
From "Advanced Methods for Diffusion MRI Data Analysis and their Application to the Healthy Ageing Brain", Rafael Neto Henriques 2017

Mean Kurtosis (MK) maps

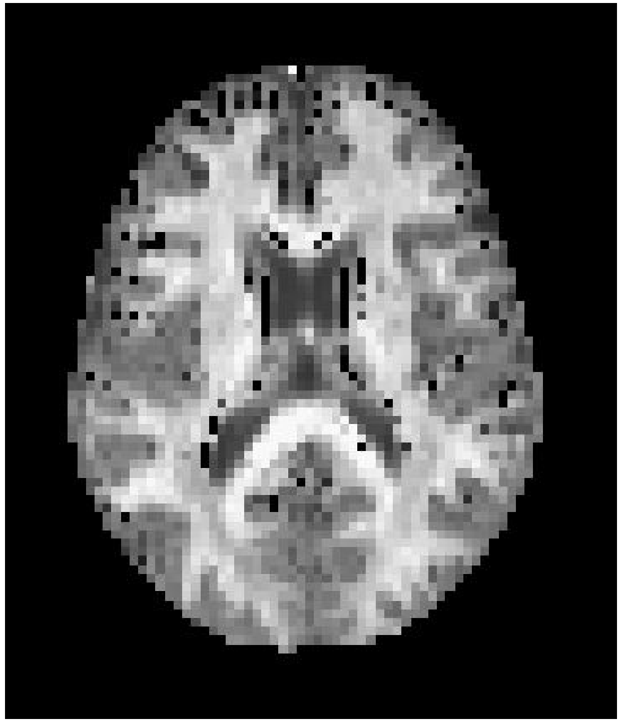
DTI FA



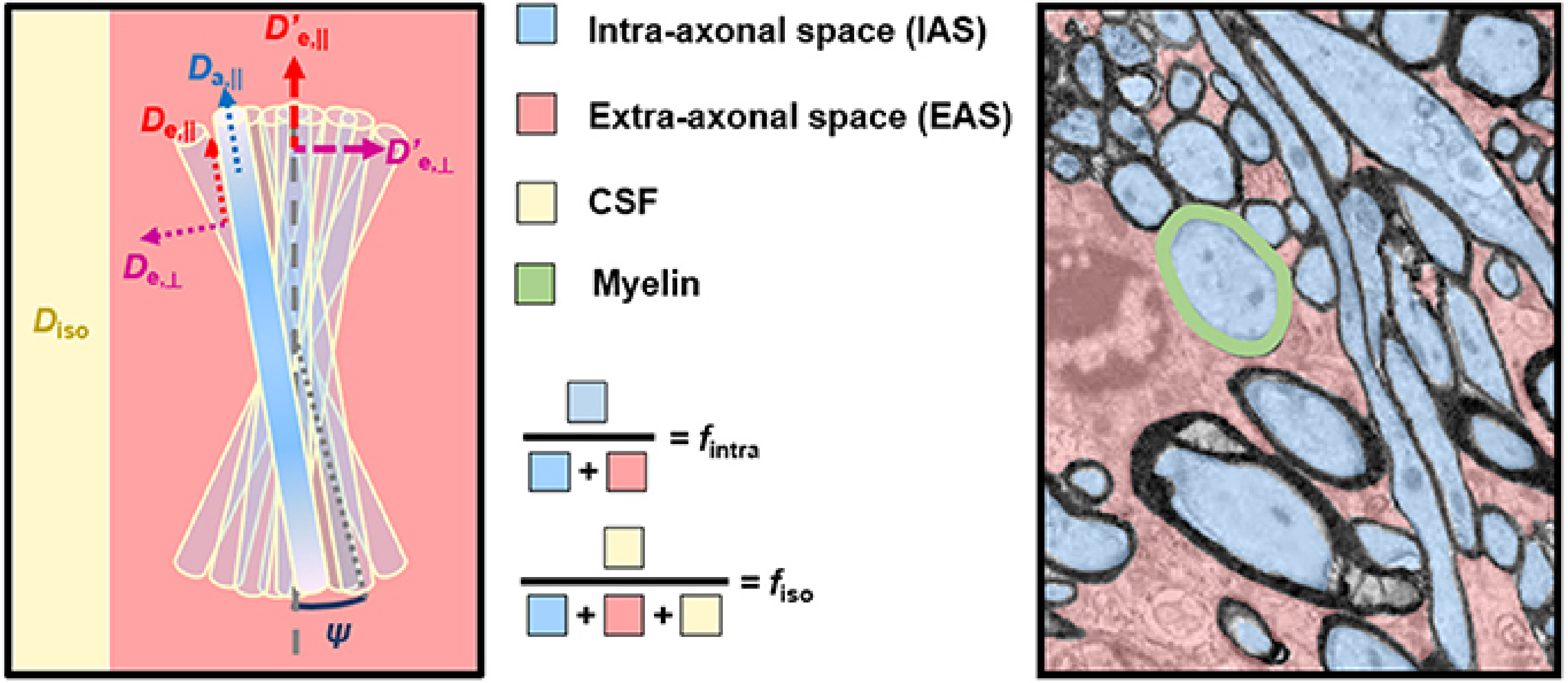
DTI MD



DTI MK



Neurite Orientation Dispersion and Density Imaging (NODDI)



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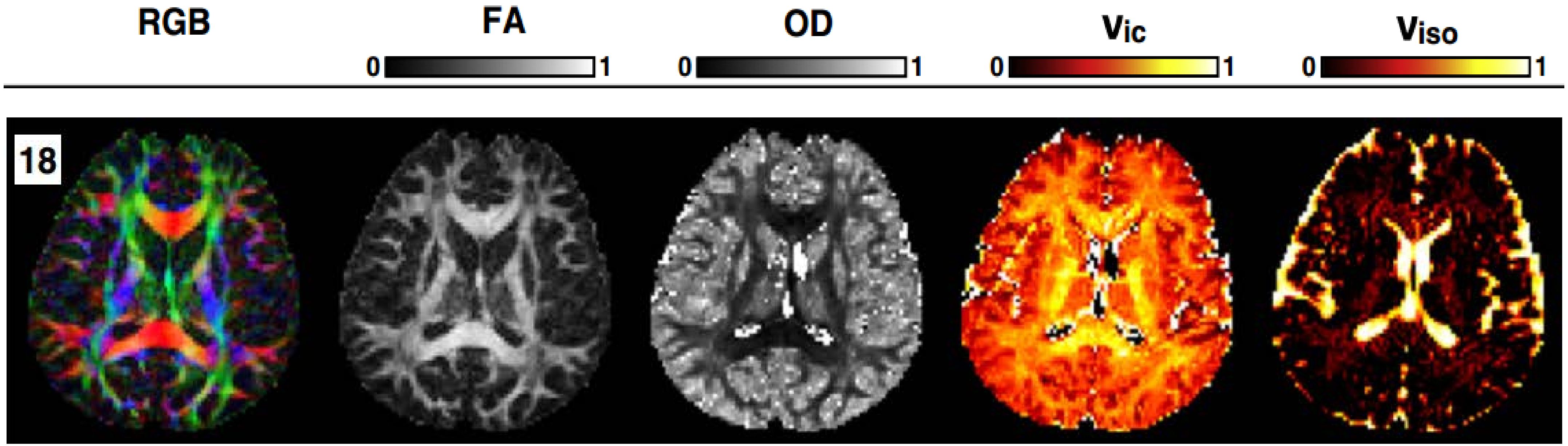

Zhang et al. (2012).

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Questions?