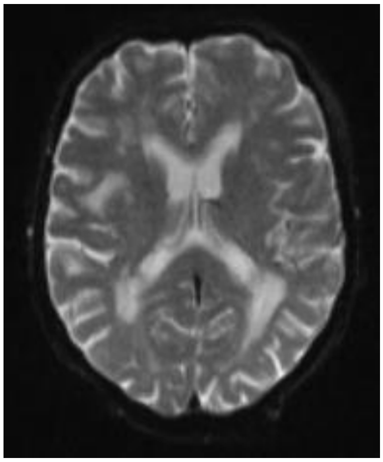
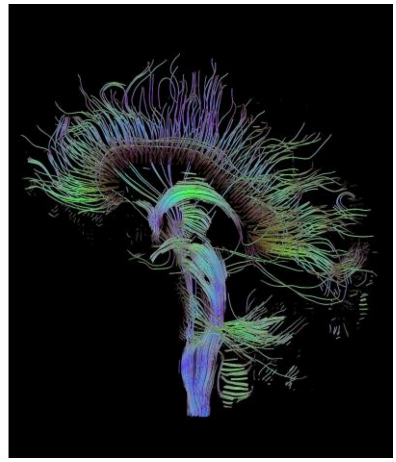

DWI/DTI

Jatta Berberat

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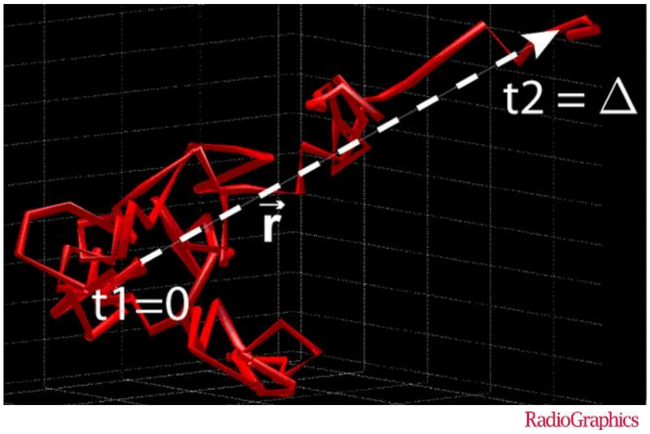
Context

- DWI
  - DWI general
  - Diffusion
  - Parameters: b, D
  - ADC
  - T2-shine through
  - Stroke
  - DWI summary

- DTI
  - DTI general
  - Diffusion tensor
  - FA
  - Clinical cases
  - DTI phantom
  - DTI summary

Diffusion



Diffusion-driven random trajectory (red line) of a single water molecule during diffusion. The dotted white line (vector **r**) represents the molecular displacement during the diffusion time interval, between $t_1 = 0$ and $t_2 = \Delta$.

•Molecular diffusion is the random movement of water molecules within tissues propelled by thermal energy.

Hagmann P *et al*. Radiographics 2006;26:S205-S223

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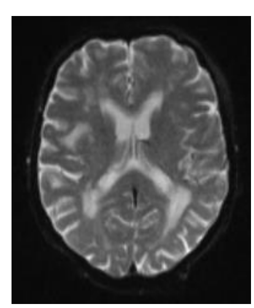
DWI

- Diffusion MRI is a method that produces images of biological tissue weighted with the local microstructural characteristics of water diffusion
- In Diffusion Weighted Imaging (DWI), each image voxel has an image intensity that reflects a single best measurement of the rate of water diffusion at that location
- sensitive to early changes after a stroke
- DWI is most applicable when the tissue of interest is dominated by isotropic water movement e.g. gray matter in the cerebral cortex and major brain nuclei
  -> the diffusion rate appears to be the same when measured along any axis



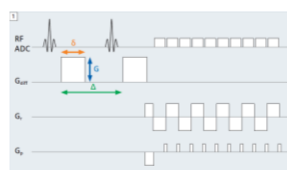
DWI

- image-intensities at each position are attenuated, depending on the
  - strength (b-value)
  - direction of the so-called magnetic diffusion gradient
  - local microstructure in which the water molecules diffuse

- The more attenuated the image is at a given position, the more diffusion there is in the direction of the diffusion gradient

- In order to measure the tissue's complete diffusion profile, one needs to repeat the MR scans, applying different directions (and possibly strengths) of the diffusion gradient for each scan

DWI-Sequence



- DWI is a pulsed gradient spin echo method (90 degree pulse followed by a large gradient; then a 180 degree pulse and another large and equal gradient)

- The homogeneity of magnetic field is varied linearly by a pulsed field gradient

- Since precession is proportional to the magnet strength, the protons begin to precess at different rates, resulting in dispersion of the phase and signal loss

- Another gradient pulse is applied in the same direction but with opposite magnitude to refocus or rephase the spins

- The refocusing will not be perfect for protons that have moved during the time interval between the pulses, and the signal measured by the MRI machine is reduced

DWI

- This reduction in signal due to the application of the pulse gradient can be related to the amount of diffusion that is occurring through the following equation (Stejskal and Tanner):

$$\frac{S}{S_0} = exp[-\gamma^2 G^2 \delta^2 (\Delta - \frac{\delta}{3}) D]$$

where

S_0 is the signal intensity without the diffusion weighting
S is the signal with the gradient
γ is the gyromagnetic ratio
G is the strength of the gradient pulse
δ is the duration of the pulse
Δ is the time between the two pulses and
D is the diffusion constant

DWI

- As the pixel signal intensity, S, is related to the b-value and the diffusion coefficient, D, the equation from Stejskal and Tanner has two unknowns:
  - The signal intensity from b = 0 (S_0)
  - D

$$\vec{S} = S_0 e^{-\vec{b}D}$$

- Therefore at least two measurements need to be made, each at <u>different b-value</u> to calculate D

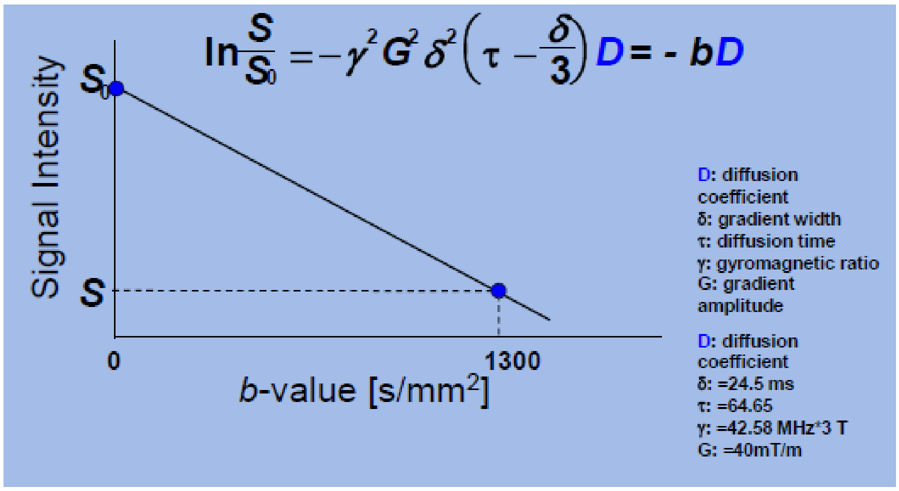
b-value

- The gradients and the timing elements are part of the b-value where we can control the degree of weighting of the DWI.
- B-value is the gradient duration and amplitude.
- B-values are important because they control the weighting of the DW images and can control the contrast of how bright an edema-related area will appear on both the DWI and ADC map.
- A b-value of zero delivers a T2-weighted EPI image for anatomical reference
- The proper b-value has approximately 80% of the reciprocal ADC value of normal background tissue.

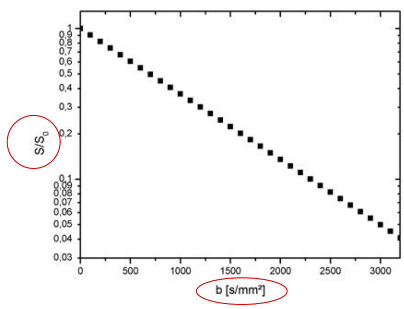
Example of b-values

- **Brain:** b-value of 0 and 1000 s/mm²
  - Low b-values serve as anatomical reference
- **Prostate/liver:** b-value of 50 and 1000 s/mm²
  - The selection of a low b-value larger than zero provides suppression of large vessels which makes lesions more conspicuous

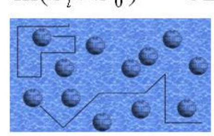
Diffusion attenuation- equation



Exponential signal decay



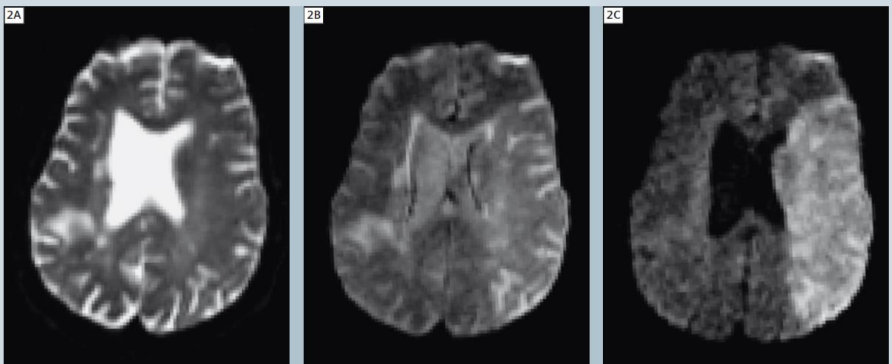
$$\ln(S_i / S_0) = -bD$$



optimal b-value: b·D=1
D=1µm/ms in tissue → b=1000 s/mm²

Take care: signal in diffusion weighted images must be larger than image noise

Diffusion weighting



2A b = 0. No diffusion weighting, low-resolution T2 image.

2B b = 500. Intermediately diffusion-weighted image.

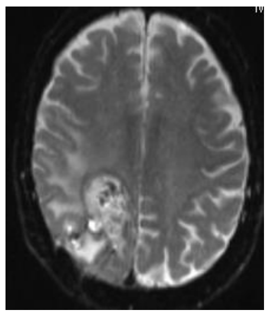
2C b = 1000. Strongly diffusion-weighted image.

D

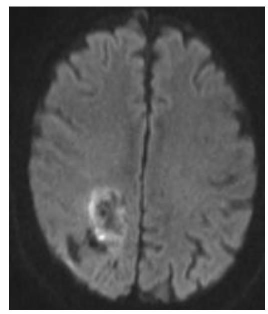
- diffusion coefficient characterizes the viscosity of the medium with which molecules are displaced
- The diffusion coefficient for water at 37°C is approximately $D = 3 \cdot 10{-}9\ m^2/sec$
- The longer the diffusion time interval, the larger the variance, because there is more time in which molecules may be displaced

DWI

- <u>Gray matter:</u>
  isotropic diffusion, D appr. 2.5 times smaller as in pure water
- <u>White matter:</u>
  anisotropic diffusion, D varies a lot



b = 0

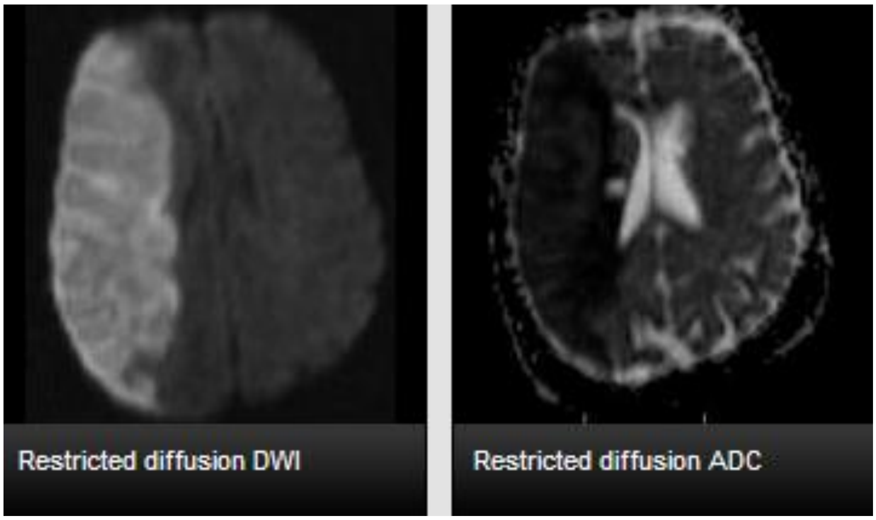


b = 1000

ADC

- expresses diffusion, relaxation effects on image contrast and cell density.
- The amount of signal intensity loss that can be measured in each voxel is determined by the apparent diffusion coefficient (ADC) in that voxel.
- If white matter tracts (WMT) are disrupted or the permeability of axonal membranes is increased, the ADC will increase.

T2-Restricted diffusion: stroke



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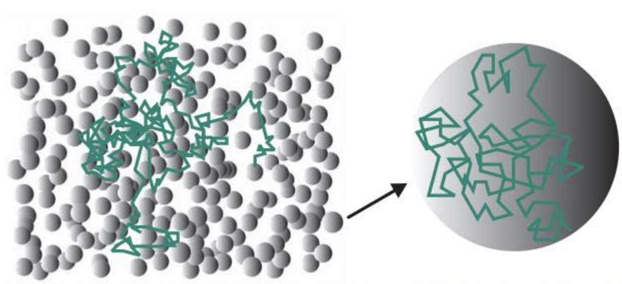
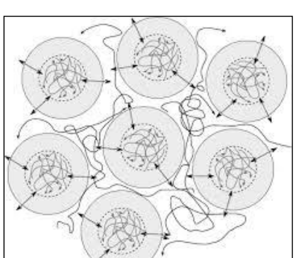


FIGURE 1.7 Biological cells may hinder the Brownian motion of extracellular water molecules (left). Inside each cell, diffusion may be envisioned to be restricted by the cellular membranes (right).



The bigger the cells,
the fewer the space to move

Diffusion- summary

	Restricted Diffusion of molecules appears:	**Normal Diffusion of molecules appears:**
On DWI	Bright (More spins stuck in one area = more signal) =hyperintense	Dark (Less/No spins = No signal)
On ADC map	Dark (Traffic Jam) =hypointense	Bright (Highway without traffic)

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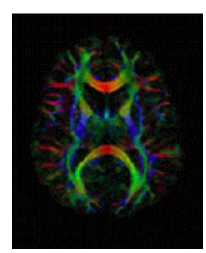
Diffusion tensor imaging (DTI)

- The measured rate of diffusion will differ depending on the direction from which an observer is looking
- In DTI, each voxel has one or more pairs of parameters:
  - a rate of diffusion
  - a preferred direction of diffusion (described in terms of three dimensional space)
  - The properties of each voxel of a single DTI image is usually calculated by vector or tensor matrix from several different diffusion weighted acquisitions, each obtained with a different orientation of the diffusion sensitizing gradients.



Color FA

DTI

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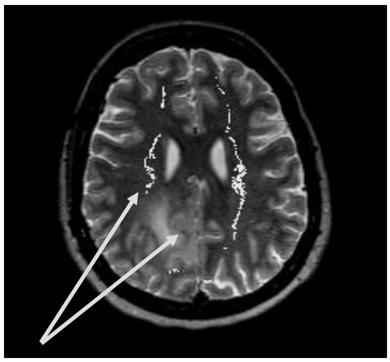
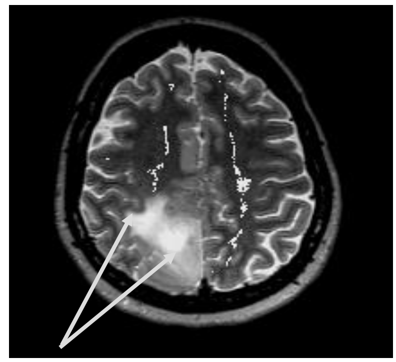
Tractography





Destruction of the tracts
because of the tumor
„Tractus corticospinalis"

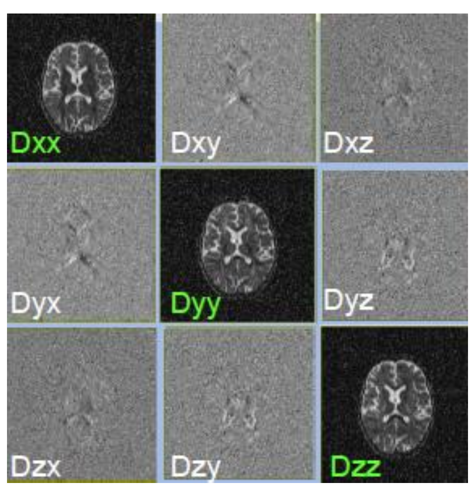
DTI

- Diffusion weighted MRI applications are increasingly used in clinical practice
  - neuronavigation
  - novel radiation therapy planning for brain tumours
- It is crucial to be able to show the anatomically correct extensions of fibers

DTI

- Diffusion Tensor Imaging (DTI) based fiber tracking reveals the main direction of the fibers in a voxel by voxel based analysis
- Fiber mask is overlaid onto the 3D anatomical magnet resonance imaging (MRI) data set
  - enables an accurate anatomical image enhanced with
    - rate
    - preferred direction of diffusion

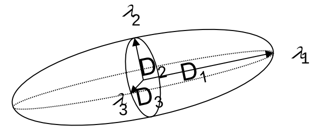
What is Diffusion Tensor D?



D = diffusion tensor in a symmetric, square matrix form (3x3)
D = Diffusion in 6 principal directions: Dxx, Dxy, Dxz, Dyy, Dyz, Dzz

=Diffusion gradient direction vector

$$\vec{S} = S_0 e^{-\vec{b}D}$$



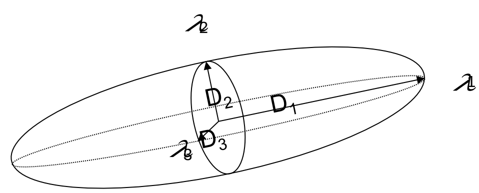
The diffusion tensor elements (Dxx, Dxy, Dyz,…) are patient-orientation-dependent. To eliminate this dependency, the diffusion tensor matrix can be diagonalized to the following form:
Lab reference form

This is equivalent to using a new coordinate system that is aligned along the three axes of the diffusion ellipsoid at each spatial encoding.

The elements D1, D2 and D3 are known as characteristic values or eigenvalues (λ) of the matrix.

$$D = \begin{bmatrix} Dxx & Dxy & Dxz \\ Dyx & Dyy & Dyz \\ Dzx & Dzy & Dzz \end{bmatrix} \xrightarrow{\text{From lab reference to ellipsoidal cordinate change}} D = \begin{bmatrix} D_1 & 0 & 0 \\ 0 & D_2 & 0 \\ 0 & 0 & D_3 \end{bmatrix}$$

Eigenvalues



Where
D = diffusion tensor in a symmetric, square matrix form (3x3)
D1,2,3 = the eigenvector, a vector corresponding to an orientation (3x1)
λ = the eigenvalue, a scalar constant

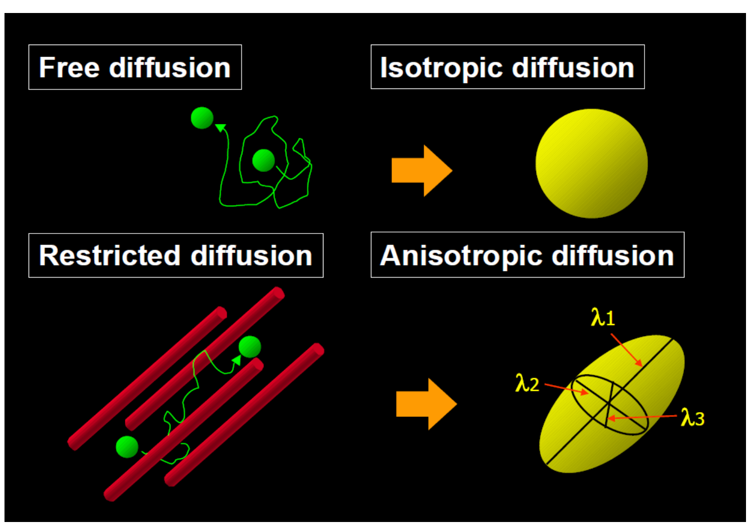
FA

- Fractional anisotropy (FA) gives information about the shape of the diffusion tensor at each voxel:

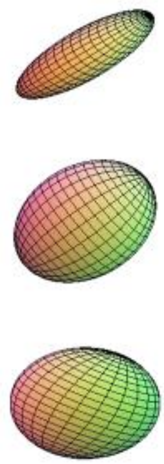
$$FA = \sqrt{\frac{3}{2}\left(\frac{(\lambda_1 - \bar{\lambda})^2 + (\lambda_2 - \bar{\lambda})^2 + \lambda_3 - \bar{\lambda})^2)}{\sum_{i=1}^{3} \lambda_i^2}\right)}$$

- FA is based on the normalized variance of the eigenvalues (λ_1, λ_2, λ_3) reflecting
  - isotropic (0) and
  - linear (1) diffusion

FA



FA



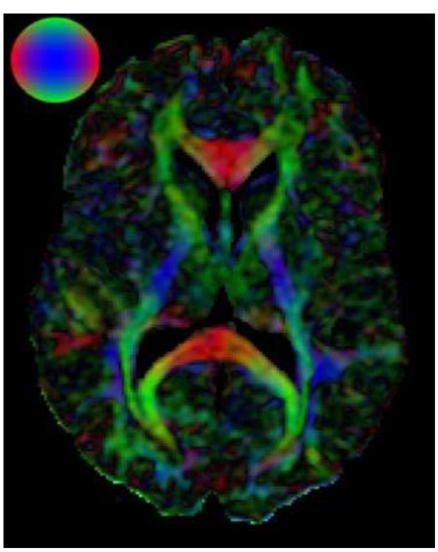
$\lambda_1 >> \lambda_2 ; \lambda_3=0$ FA~1

$\lambda_1 > \lambda_2 ;\lambda_3$~0 FA<<1

$\lambda_1 = \lambda_2 = \lambda_3$ FA=0

*

DTI



• Pixel colour represents the direction of the eigenvectors

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Clinical cases about DTI

- Disturbance of fiber systems by tumorous lesions
- Disturbance of fiber systems by trauma, ischemia, inflammation, degeneration, metabolic disorder
- Exploring the developing brain
- Exploring the activation tracks in epilepsy

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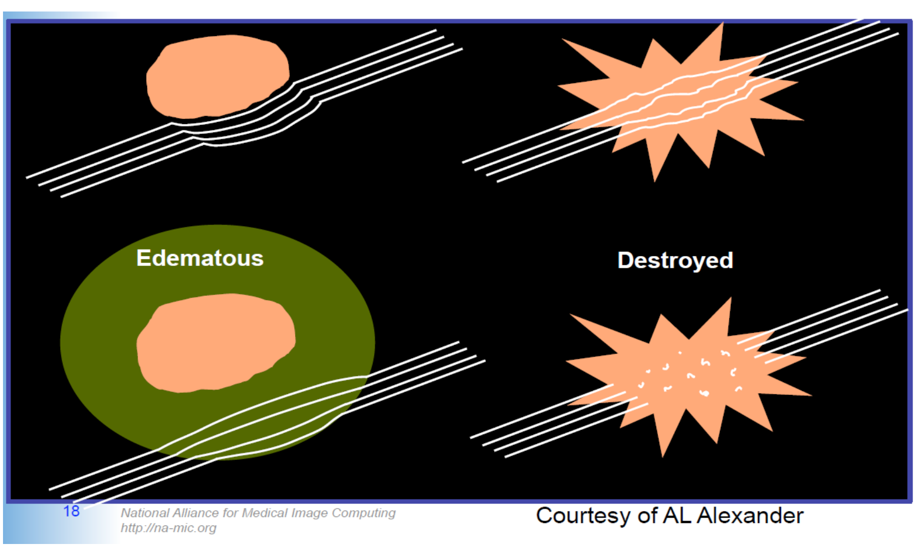

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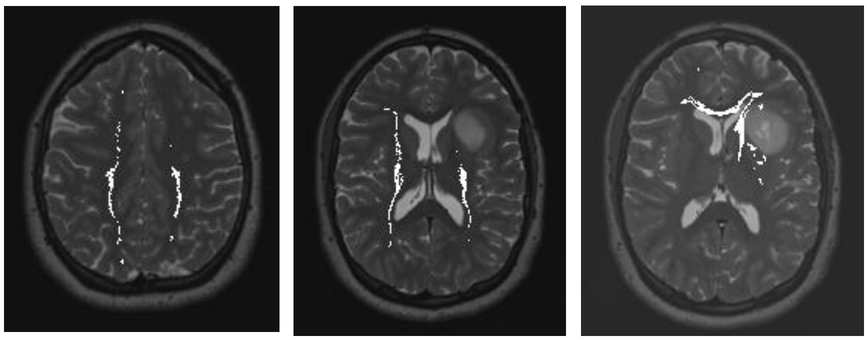

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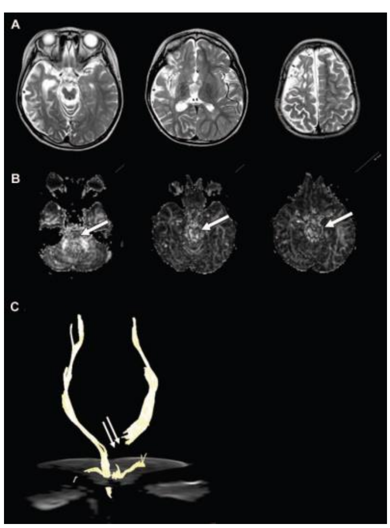
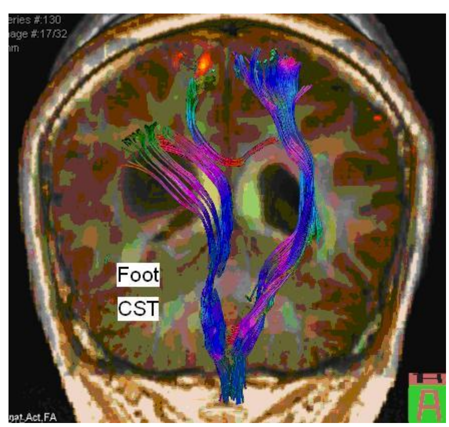

A
B
C


Foot
CST

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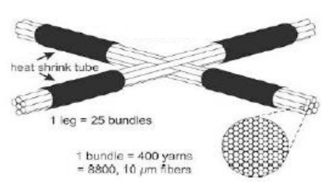
DTI- example

- A hardware phantom containing fibers crossing at a sub-voxel level was used for the QA [2]

3 tubular anisotropic orthogonal fiber bundle tube
1 crossing fiber bundle set @ 60o



1 tube
220 000 10µm fibers

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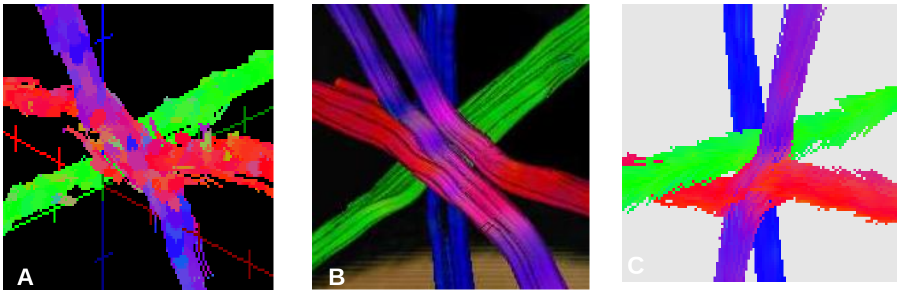

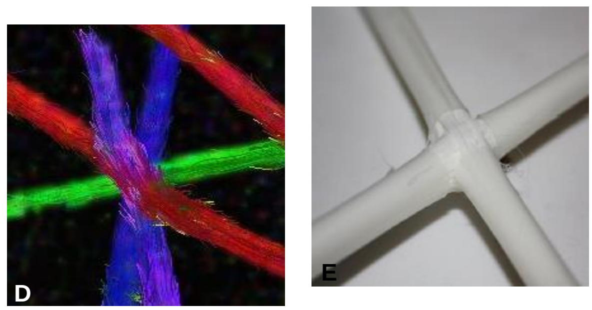

(A)Brainvoyager

(B)Neuro-3D

(C)MedInria

(D)StealthViz

(E)The known intersection of purple and red fibers

DTI-summary

- Technique based on diffusion weighted imaging

- A method to
  - isolate the white matter tracts in the brain
  - Identify which bits of brain are connected to each other
  - Estimate the degree of interconnection between brain regions

- Machine and user-dependent factors must acknowledged

- Diffusion tensor imaging (DTI) is limited in resolving complex white matter architecture

- Visualisation of the tracts is dependent on
  - imaging data quality
  - tracking algorithm
  - its predefined parameters


THANK
YOU