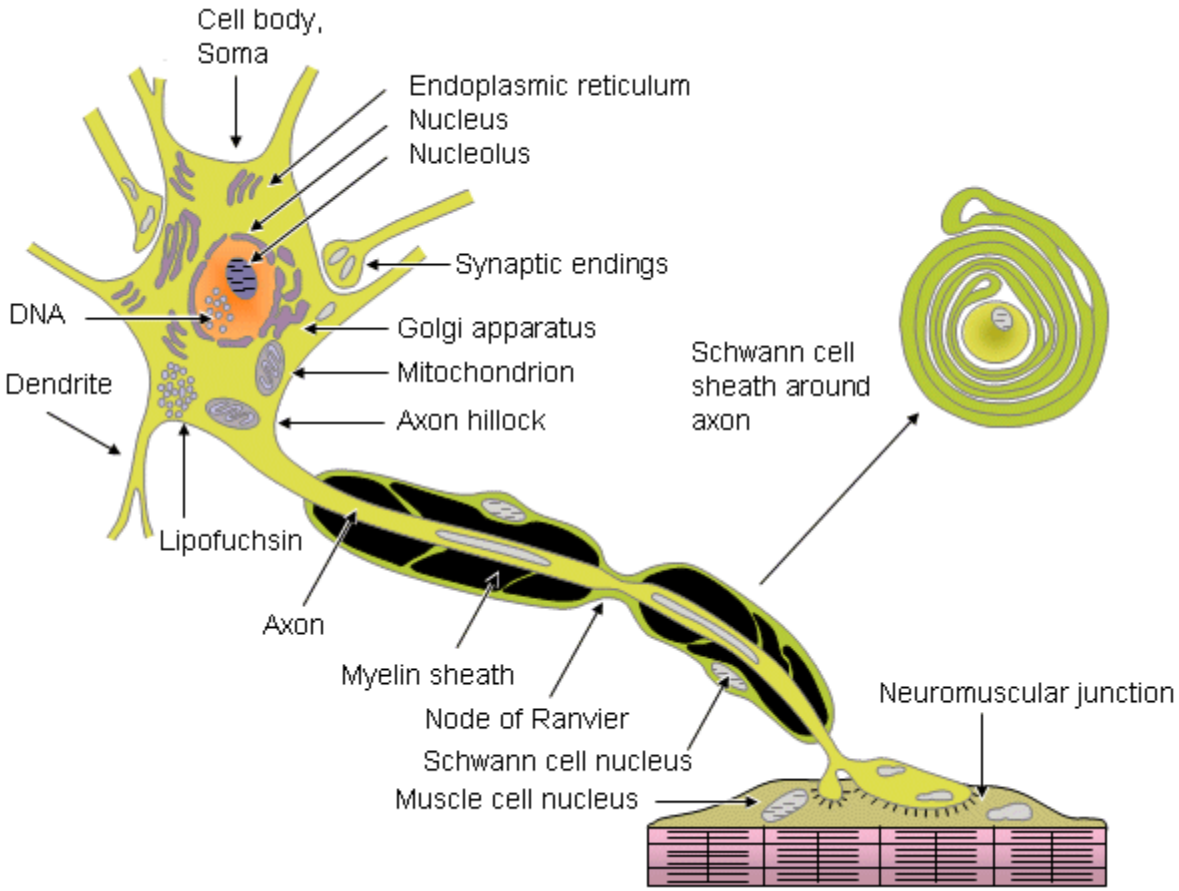
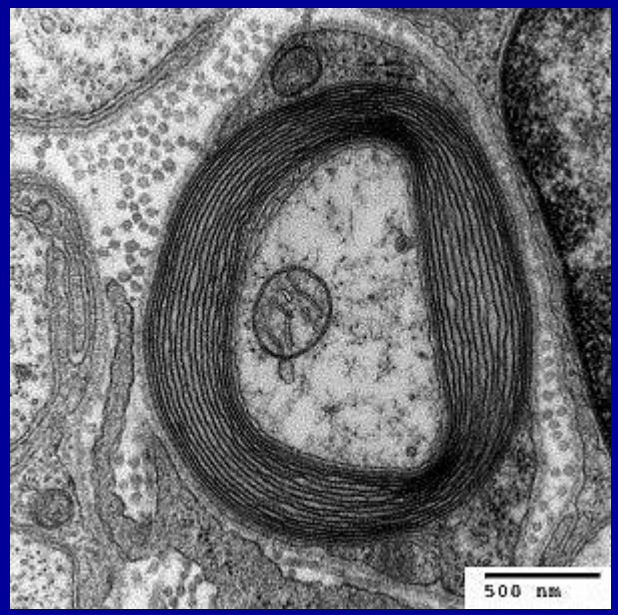
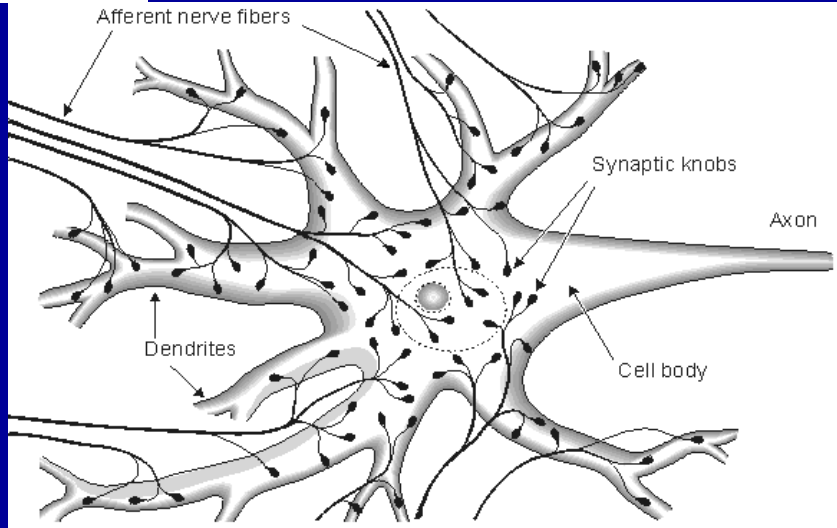
Diffusion and DTI principle (Basic)

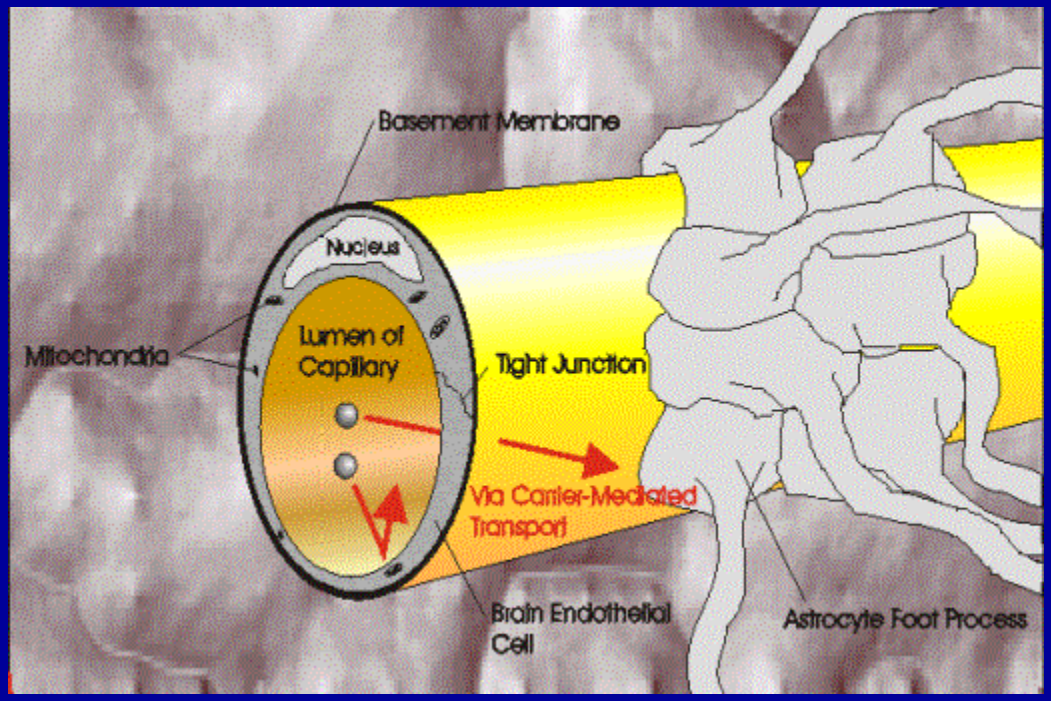
M A Oghabian

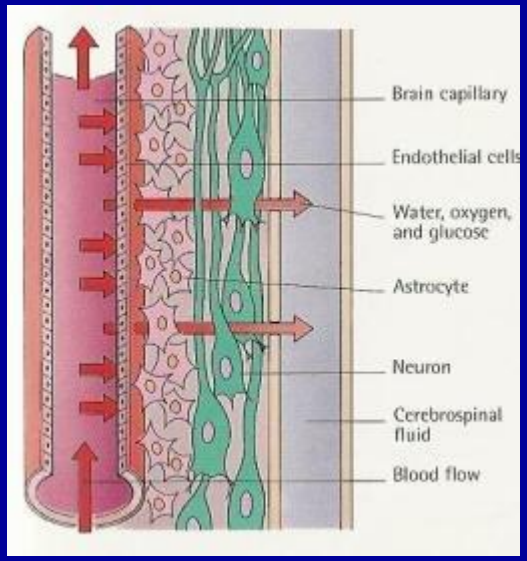

Cell body,
Soma
Endoplasmic reticulum
Nucleus
Nucleolus
Synaptic endings
DNA
Golgi apparatus
Mitochondrion
Dendrite
Axon hillock
Schwann cell
sheath around
axon
Lipofuchsin
Axon
Myelin sheath
Node of Ranvier
Schwann cell nucleus
Muscle cell nucleus
Neuromuscular junction


500 nm

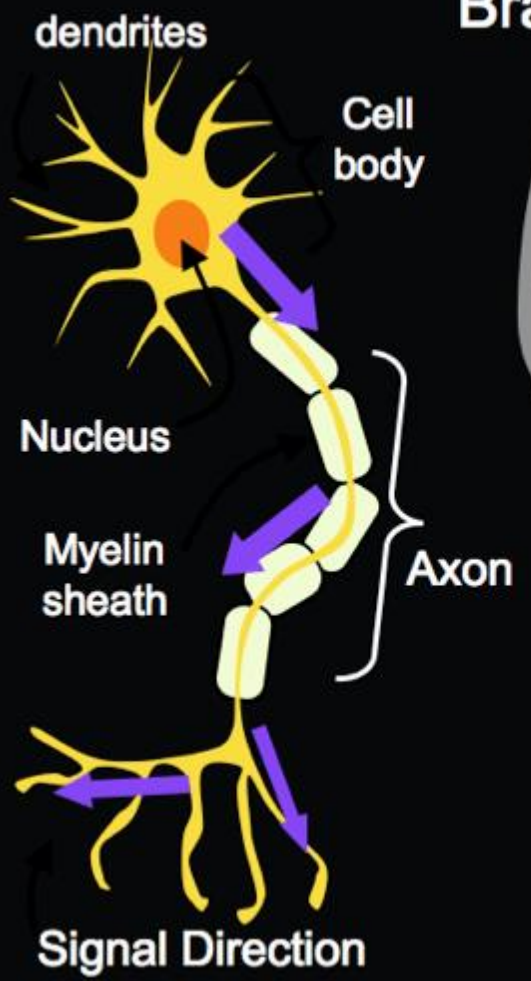

Afferent nerve fibers
Synaptic knobs
Axon
Dendrites
Cell body

Blood brain barrier

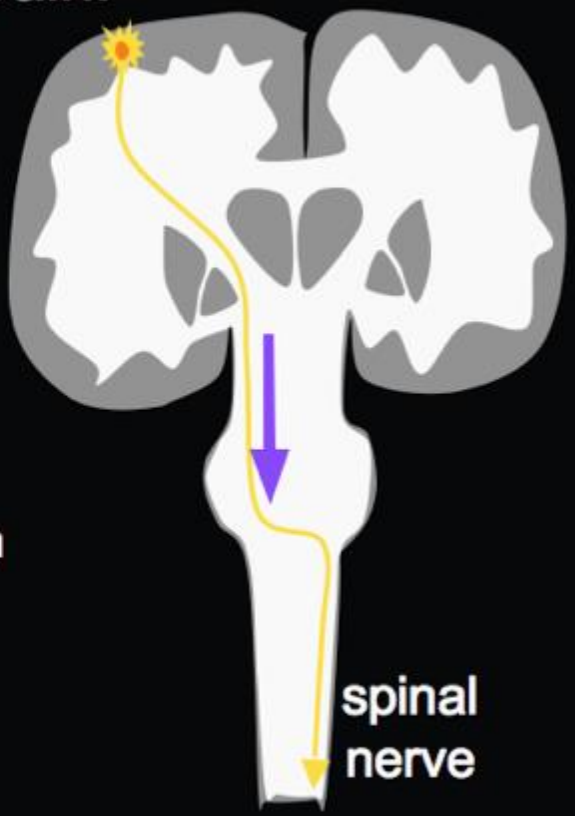




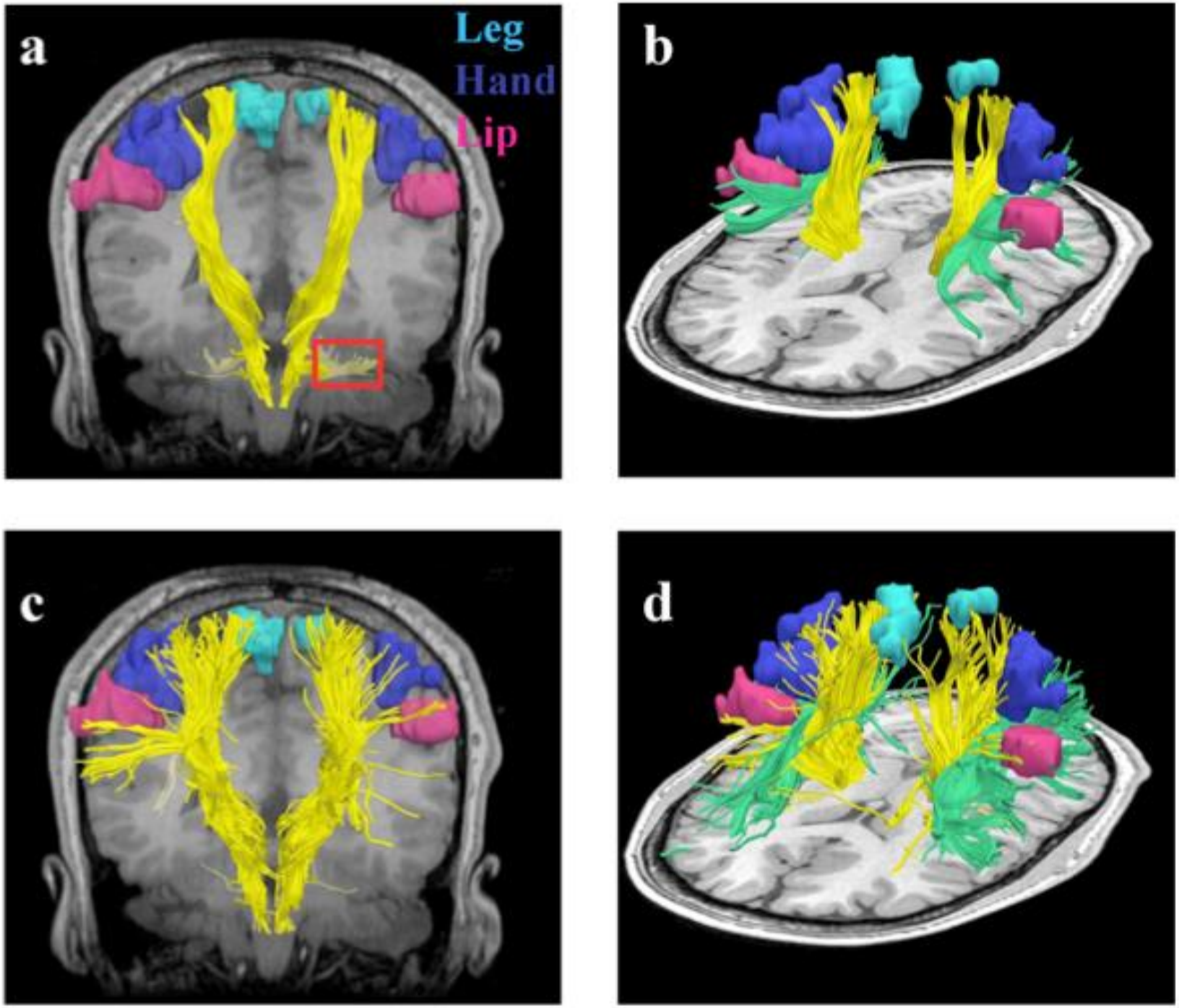
Neuron:



Brain:

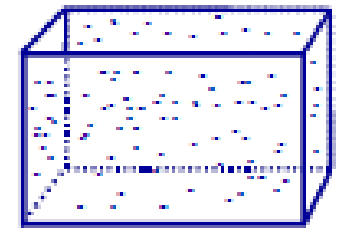


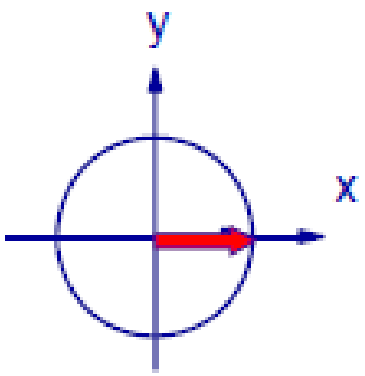
- Gray matter (cortex + nuclei): cell bodies
- White matter: axons
- Myelin sheath speeds signal conduction
- Axon + sheath = nerve fibers
- Major white matter pathways aggregate many fibers into bundles


a
Leg
Hand
Lip
b
c
d

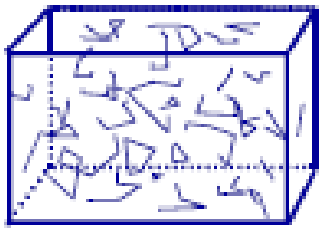
The MR signal

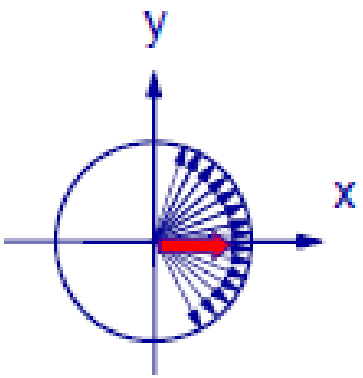
Stationary



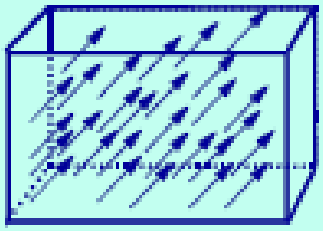


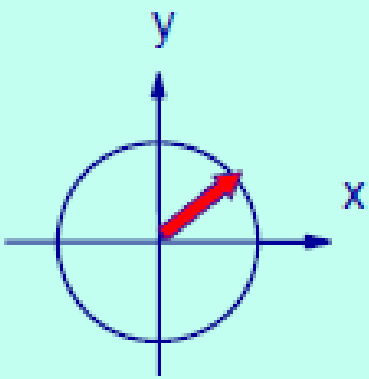
Diffusion

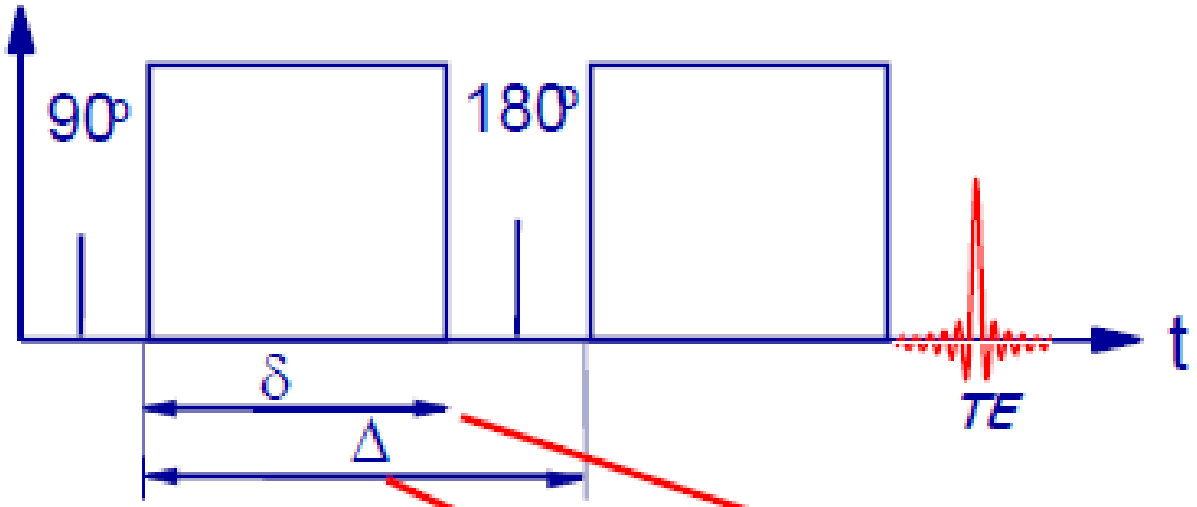


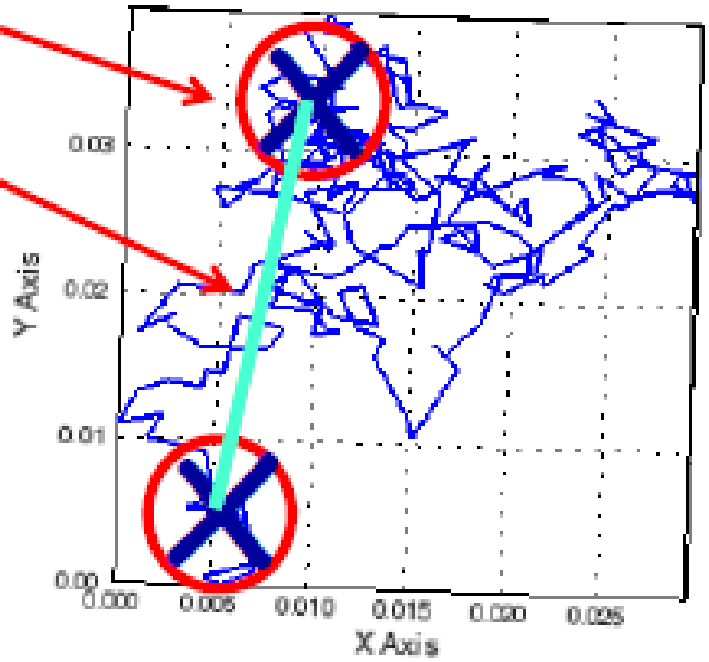


Constant flow



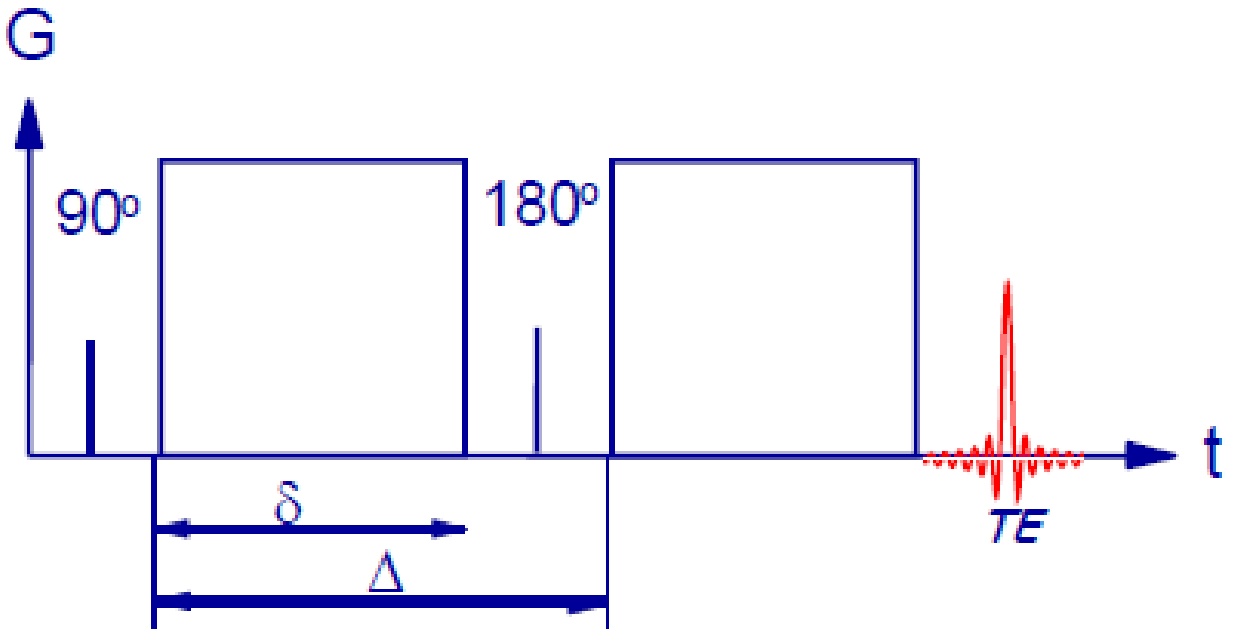






$$\text{Diffusion rate} = \frac{\text{Distance}}{\text{Time}}$$

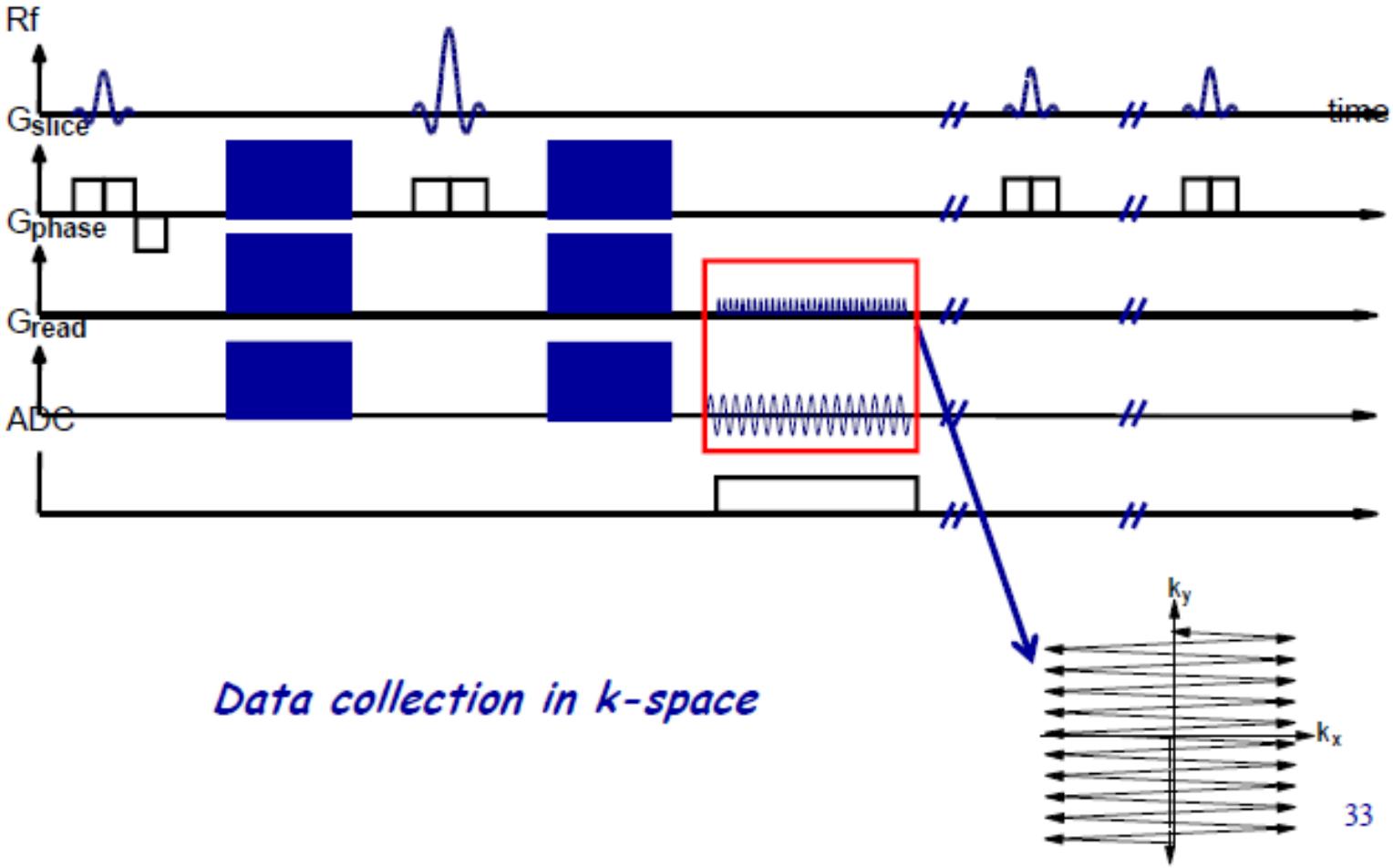
The Stejskal-Tanner sequence



- **b-value (sensitivity)** $b = \gamma^2 \delta^2 G^2 T_D \quad [\mathrm{s/m^2}]$
- **Diffusions time** $T_D = (\Delta - \delta/3) \quad [\mathrm{s}]$

The most commonly used sequence...

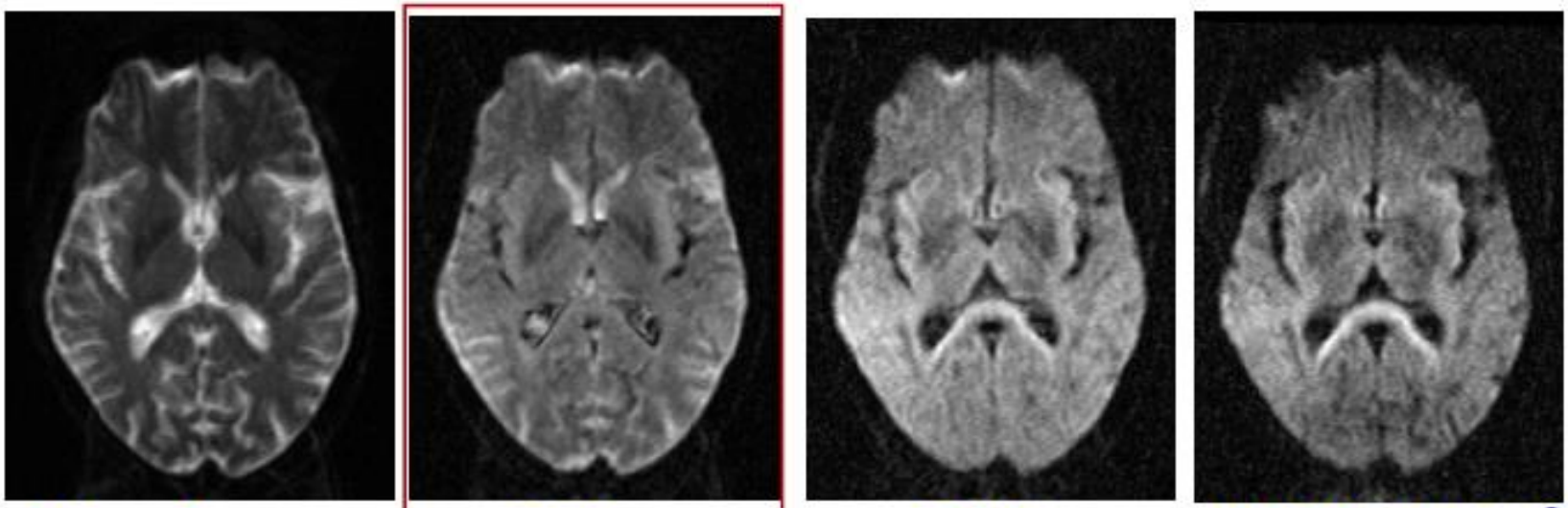
- ***The EPI pulse sequence…..***



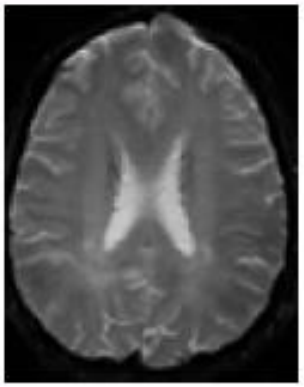
Data collection in k-space

Some snap-shots

$$S = S_0 \cdot e^{-TE/T2} \cdot e^{-b \cdot D}$$



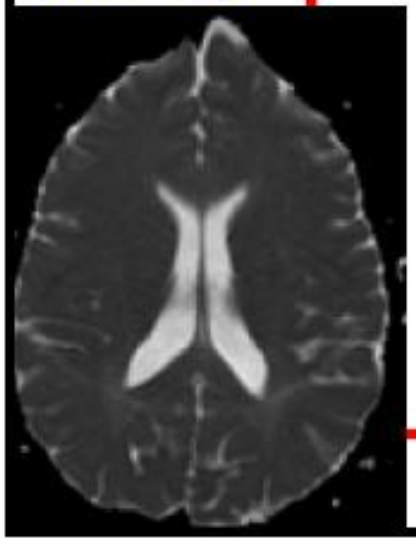
ADC-map –"speed"



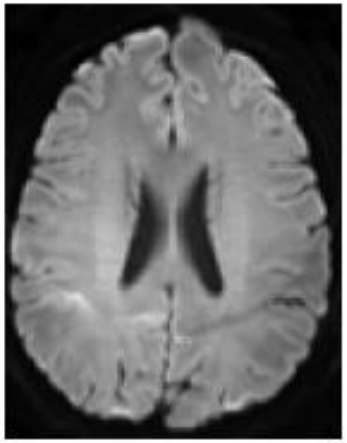
T2W (b=0)

ln(Signal)

ADC
(mm^2/s)



Diffusion weighted
(ex b=1000 s/mm^2)



$$ADC = \ln(S / S_0) / b$$

Sensitivity

APPARENT DIFFUSION COEFFICIENT (Diffusion Speed; mm^2/s^{-1})

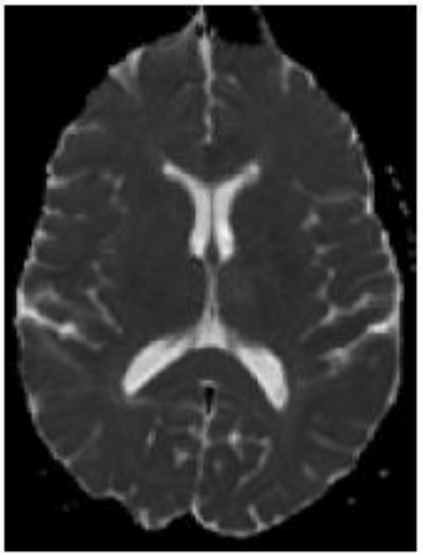
$$ADC = \ln(S / S_0) / \bar{b}$$

Mean ADC in ventricles = 3.0 x 10^{-3} mm^2s^{-1}

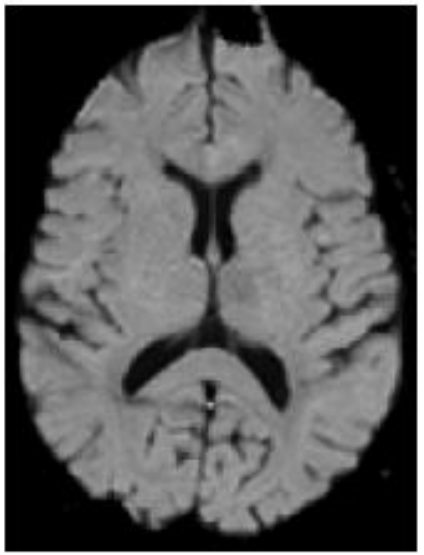
Mean ADC in parenchyma = 0.7 x 10^{-3} mm^2s^{-1}

Iso weighted diffusion / "Exponential ADC"

$$S_{iso-DW} = S_{0,TE}\, e^{-(Mean\ ADC)\cdot b}$$

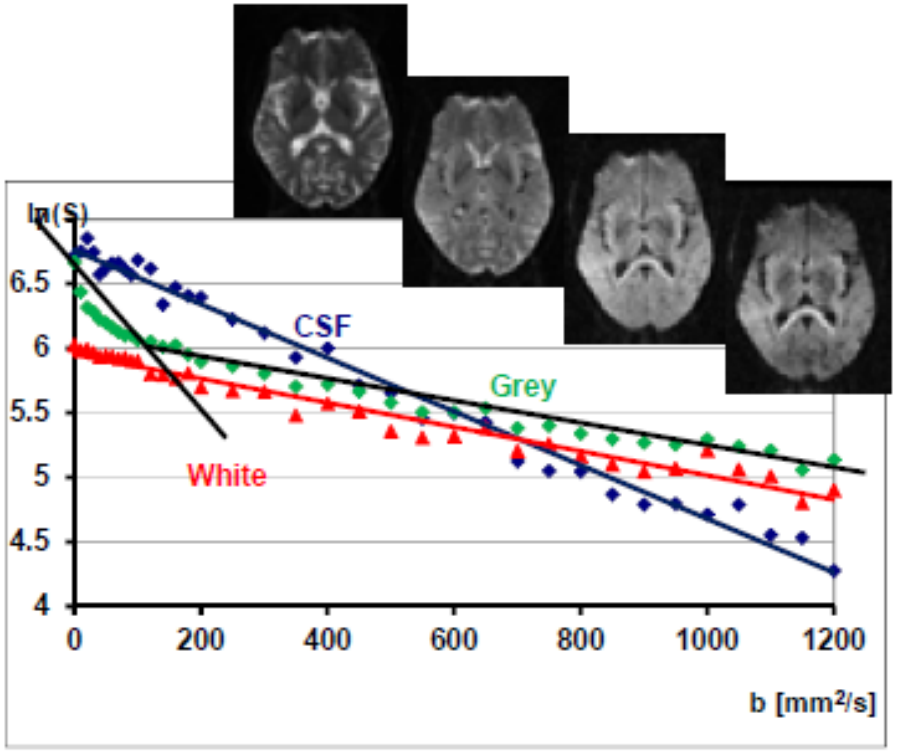


Mean ADC

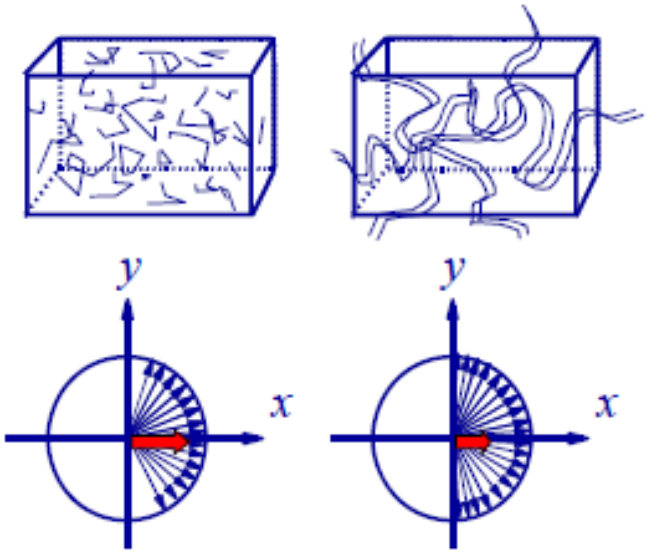


Iso diffusion weighted without T2 effects

Perfusion – pseudo diffusion

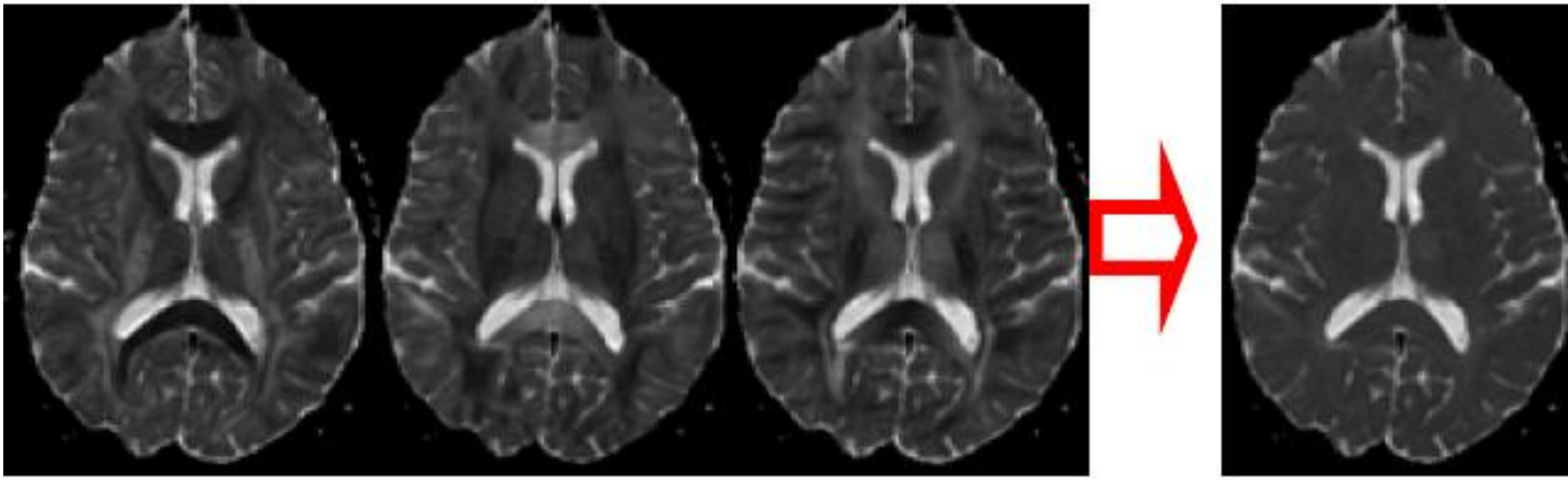


5% capillaries
D~ 0.004 mm²/s



Mean Diffusion ~ Trace

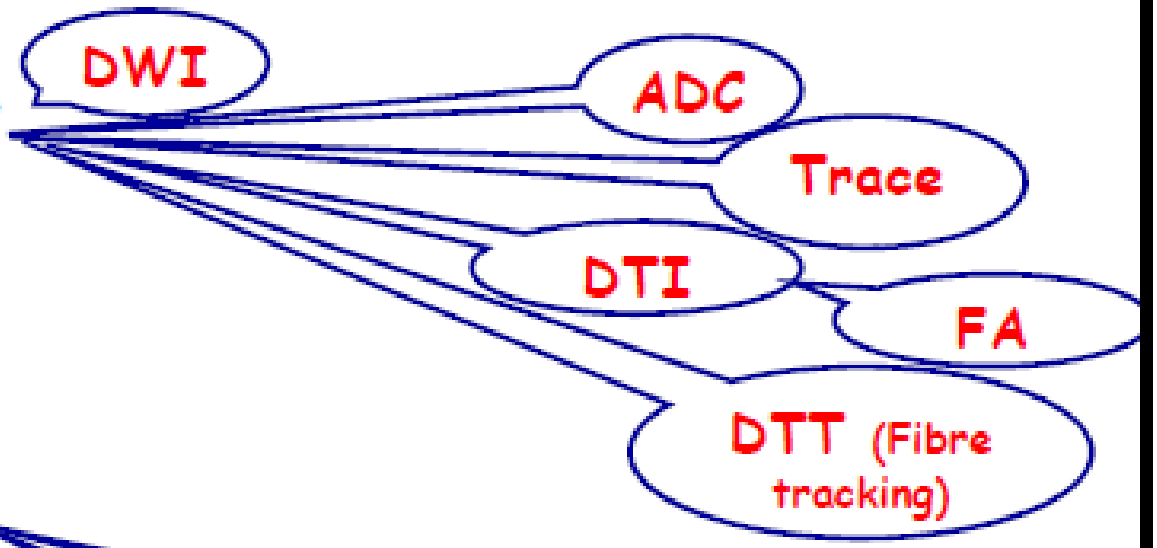
Slice Read Phase "Trace"



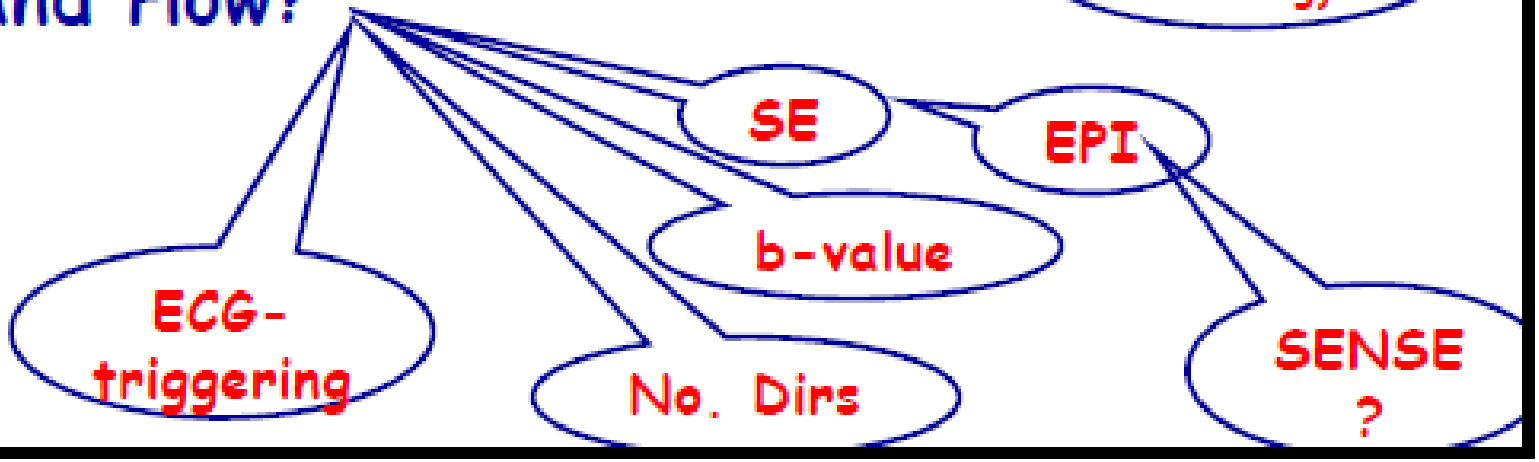
$$\frac{ADC_{zz} + ADC_{yy} + ADC_{xx}}{3} \quad ADC_{mean}$$

Diffusion MRI

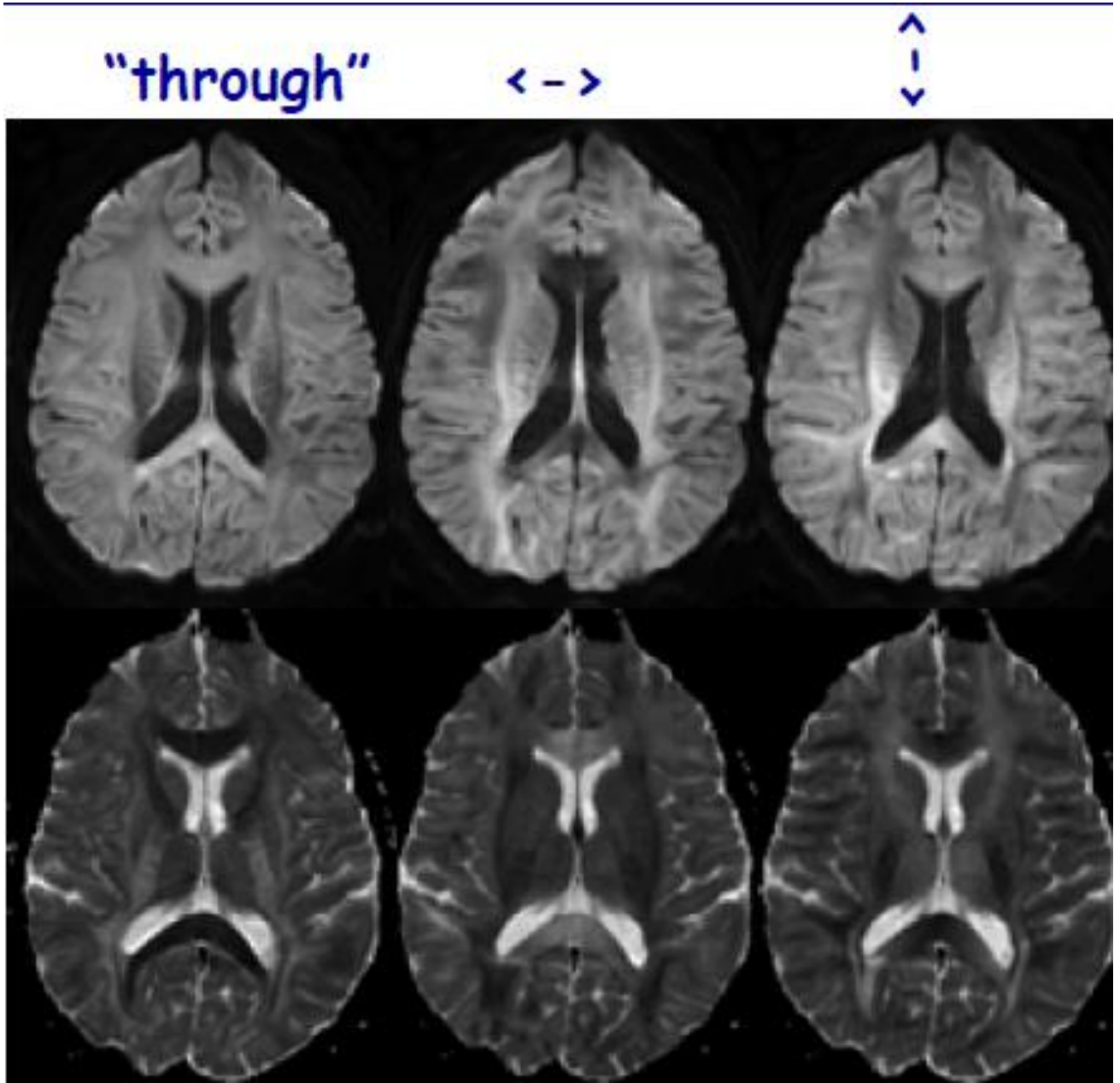
- Terminology



- And How?

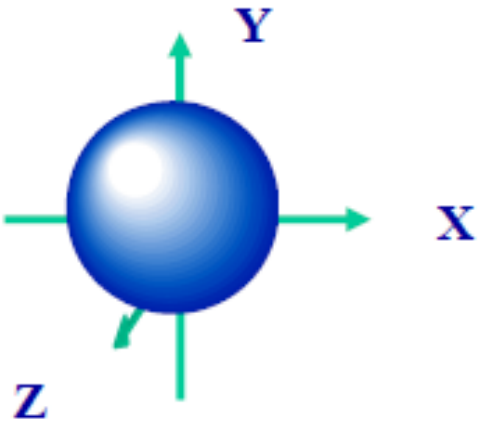


Directional Dependant Diffusion



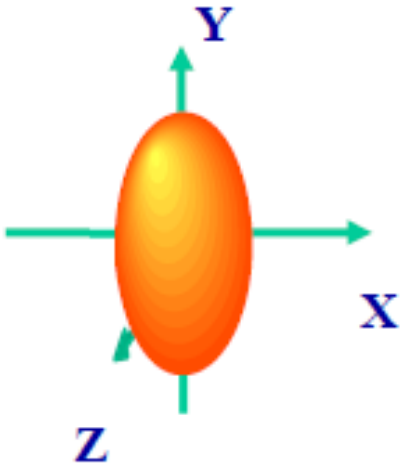
Isotropy vs anisotropy

- **Isotropic diffusion**



$ADC_X = 1\ [m^2/s]$
$ADC_y = 1\ [m^2/s]$
$ADC_Z = 1\ [m^2/s]$

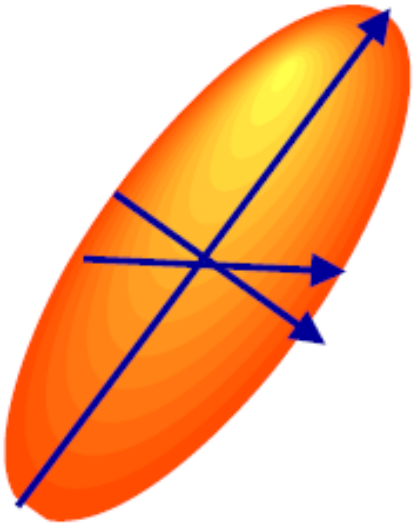
- **Anisotropic diffusion**



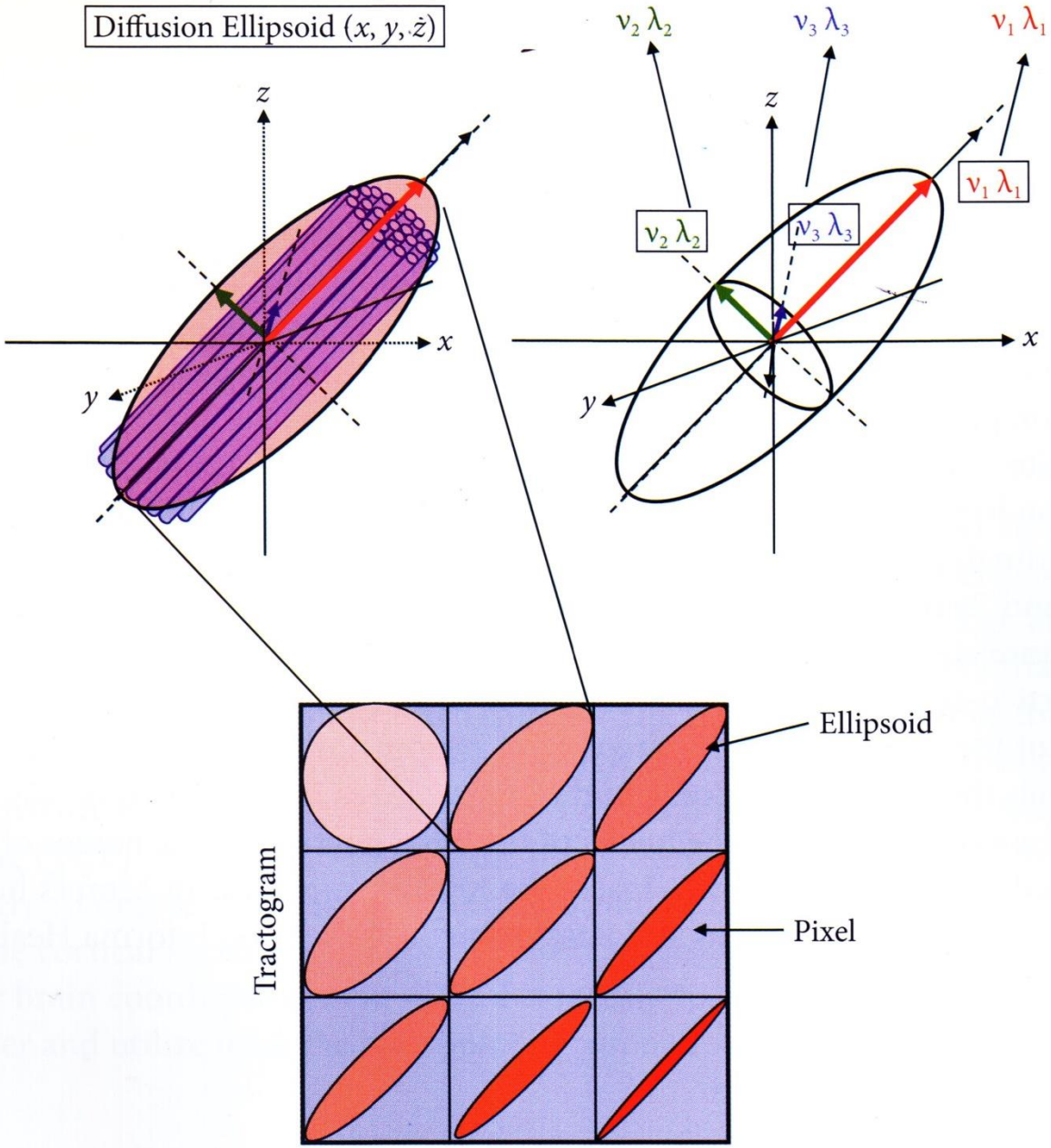
$ADC_X = 0.6\ [m^2/s]$
$ADC_y = 1.8\ [m^2/s]$
$ADC_Z = 0.6\ [m^2/s]$

$ADC_{mean} = 1$

Diffusion Tensor Imaging (DTI)

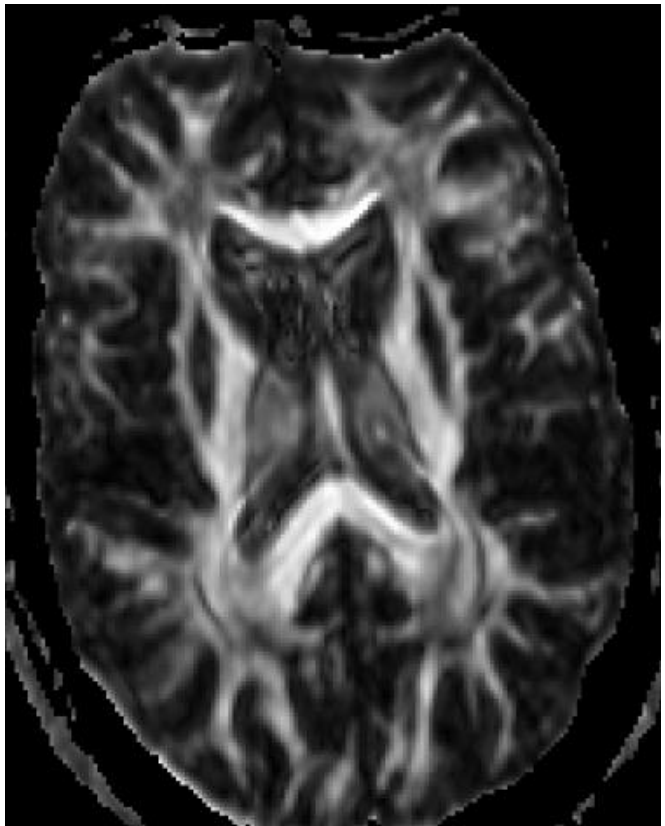


- The ellipsoid is described by
  The shape: 3 vectors
  The orientation: 3 angles
- Requires measurements in 6 directions (or more!)

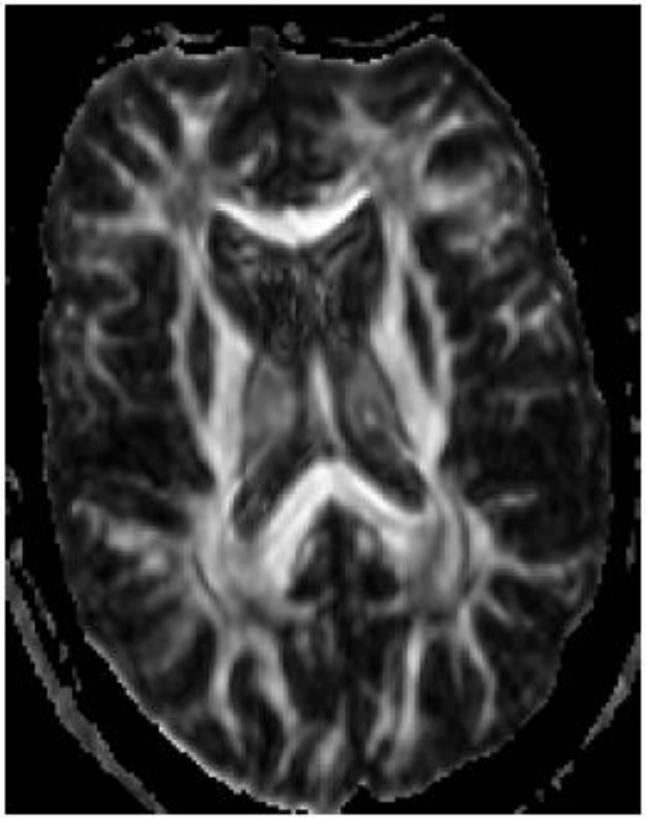

Diffusion Ellipsoid (x, y, z)
z
x
y
ν2 λ2
ν3 λ3
ν1 λ1
Tractogram
Ellipsoid
Pixel

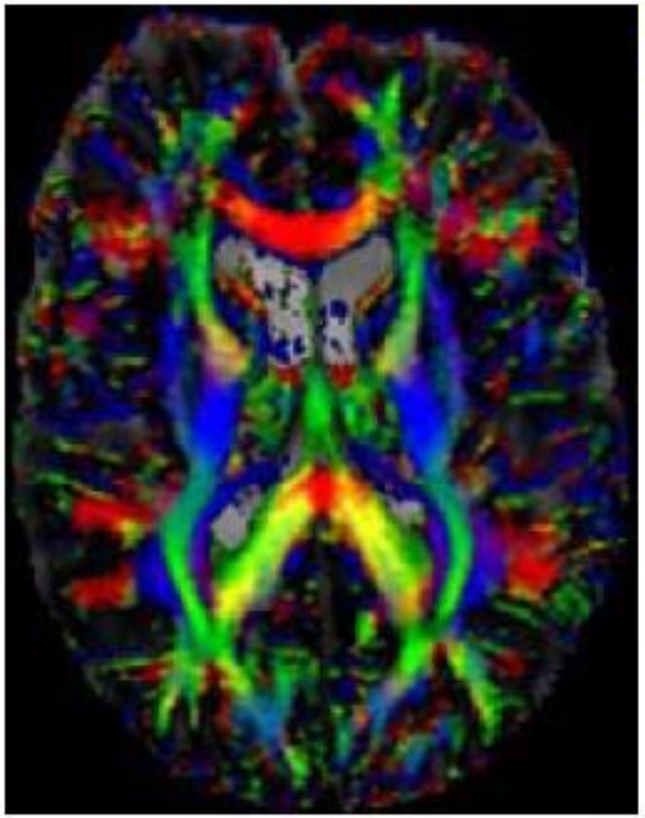
Fractional Anisotropy (FA)

$$\mathrm{FA} = \sqrt{\frac{3}{2}} \frac{\sqrt{\frac{1}{3}((\lambda_1 - \lambda_2)^2 + (\lambda_2 - \lambda_3)^2 + (\lambda_3 - \lambda_1)^2}}{\sqrt{\lambda_1^2 + \lambda_2^2 + \lambda_3^2}} = \sqrt{\frac{3}{2}} \frac{\sqrt{3\,\mathrm{Var}(\lambda)}}{\sqrt{\mathrm{Tr}(\overline{\mathbf{D}^2})}}$$



Fractional Anisotropy





Blue = HF
Green = AP
Red = RL

Relative Anisotropy:

Normalize by mean diffusivity

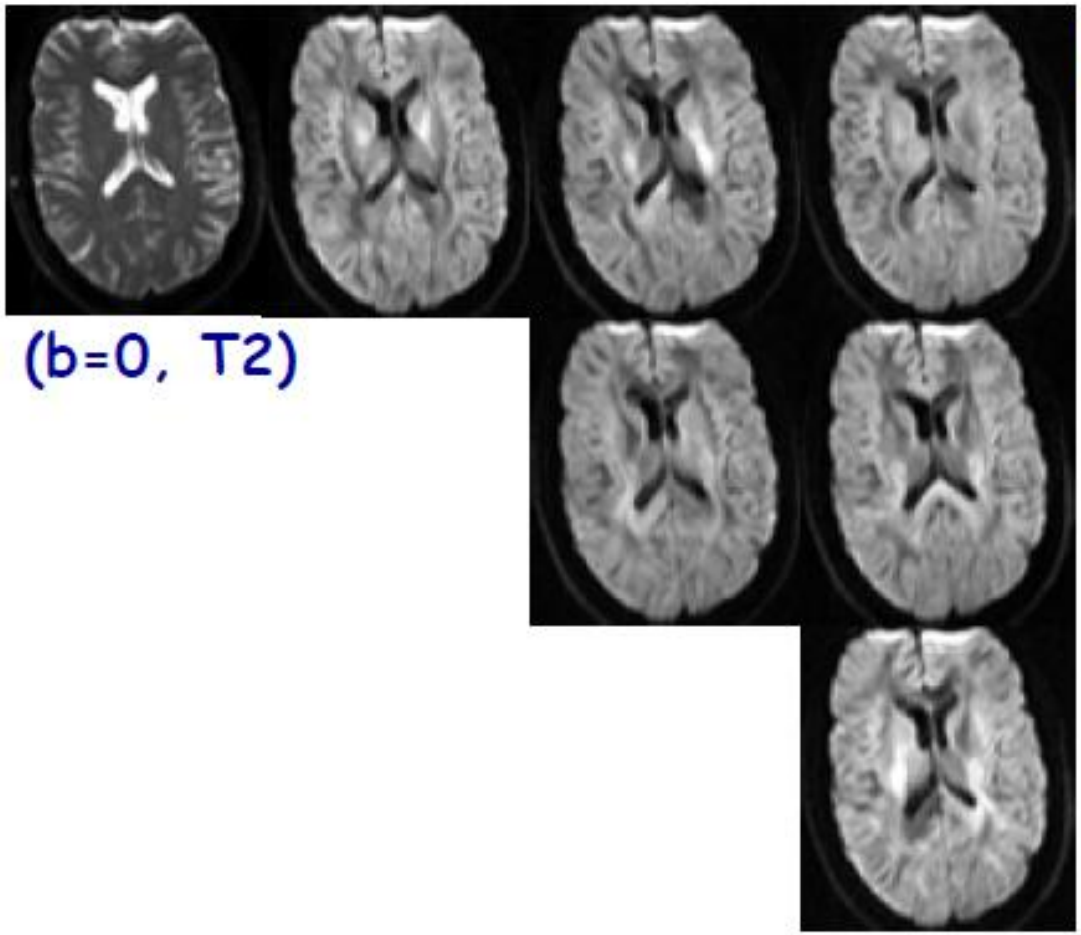
$$RA = \alpha \frac{\sqrt{(\lambda_1 - \langle\lambda\rangle)^2 + (\lambda_2 - \langle\lambda\rangle)^2 + (\lambda_3 - \langle\lambda\rangle)^2}}{\lambda_1 + \lambda_2 + \lambda_3}$$

Standard Deviation and Mean of Eigenvalues

$$\sigma_\lambda = \sqrt{\frac{(\lambda_1 - \langle\lambda\rangle)^2 + (\lambda_2 - \langle\lambda\rangle)^2 + (\lambda_3 - \langle\lambda\rangle)^2}{3}}$$

$$\langle\lambda\rangle = \frac{(\lambda_1 + \lambda_2 + \lambda_3)}{3}$$

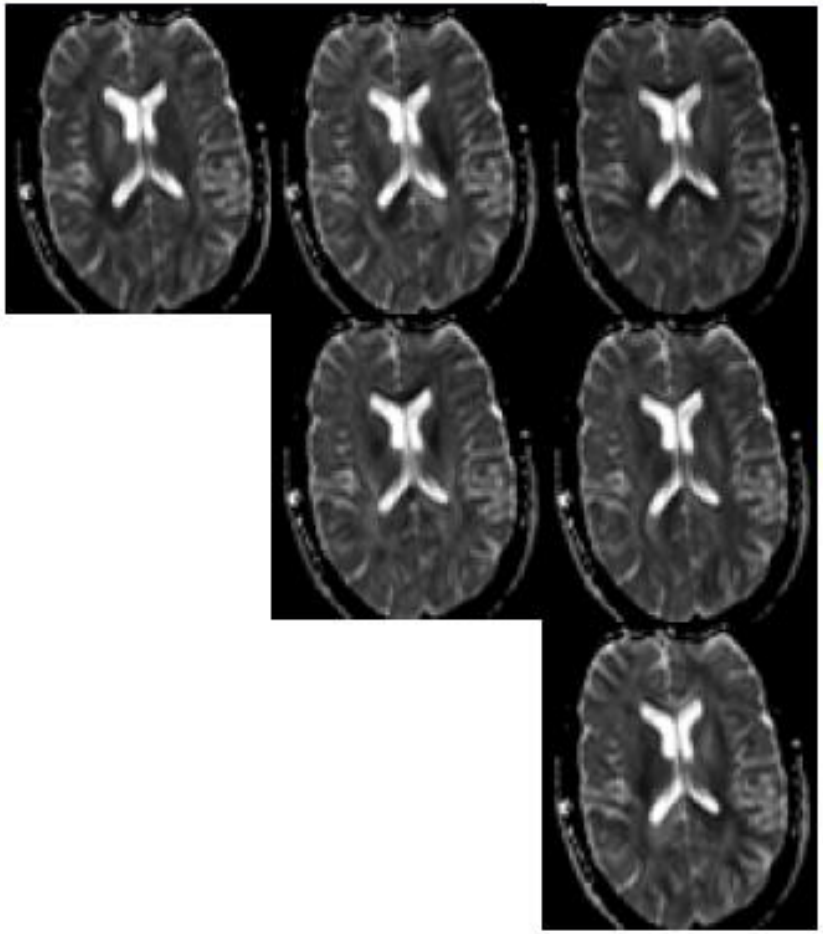
The measurments



(b=0, T2)

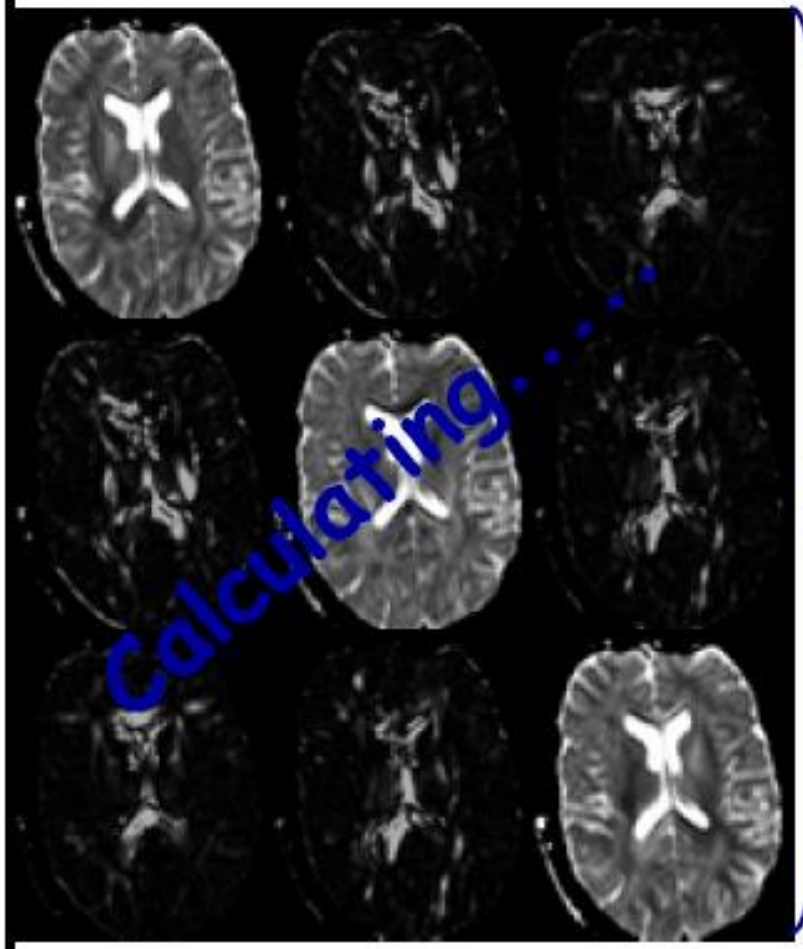
$(DW_{xx}, DW_{xy}, DW_{xz}, DW_{yy}, DW_{yz}, DW_{zz})$

Calculations (I)



$(ADC_{xx}, ADC_{xy}, ADC_{xz}, ADC_{yy}, ADC_{yz}, ADC_{yy})$

Calculations (II): the Diffusion tensor



Calculating.....

Diagonalisation

Eigenvalues

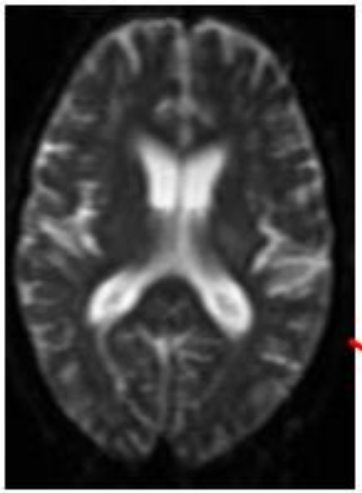
λ_1

λ_2

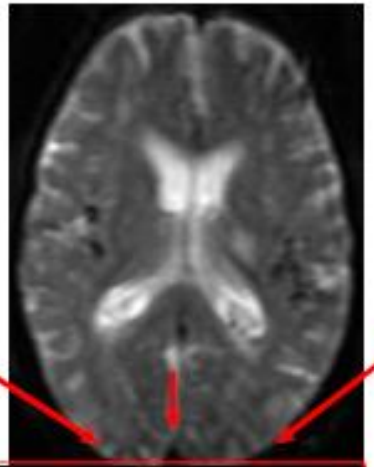
λ_3

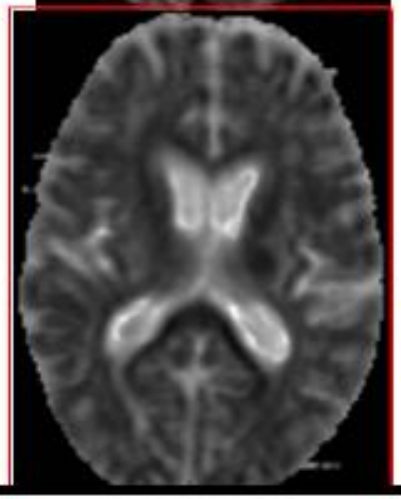
Diffusion and DTI Application

Stroke

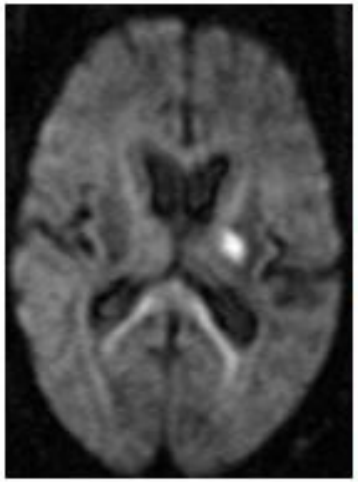


T2

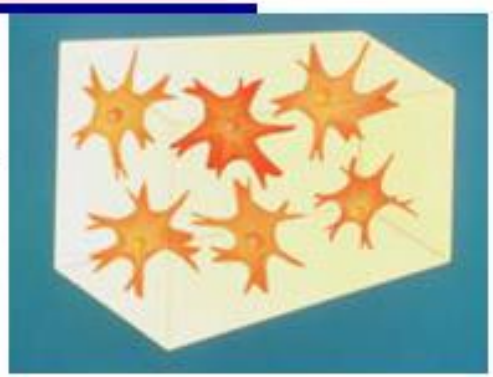


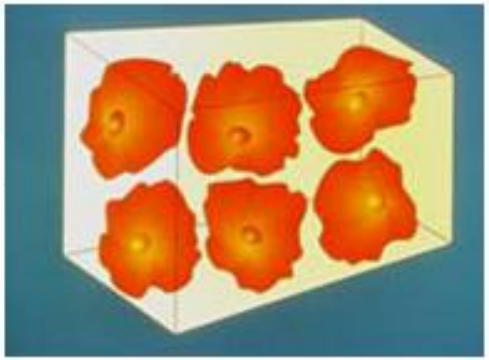


ADC (Speed)

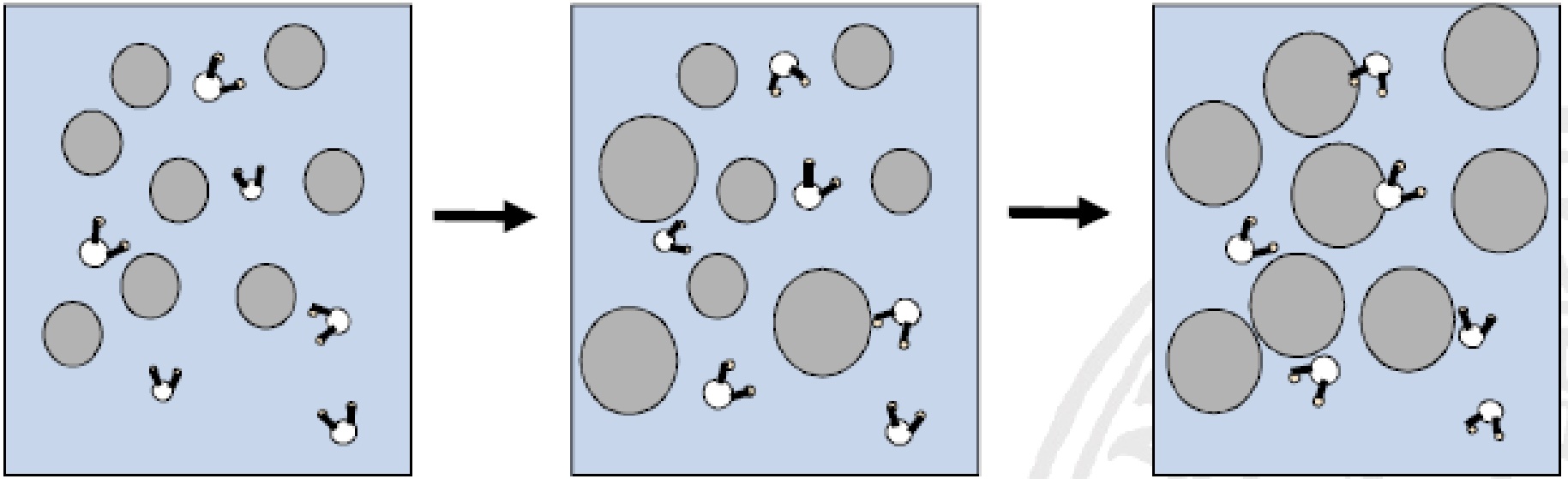


DW



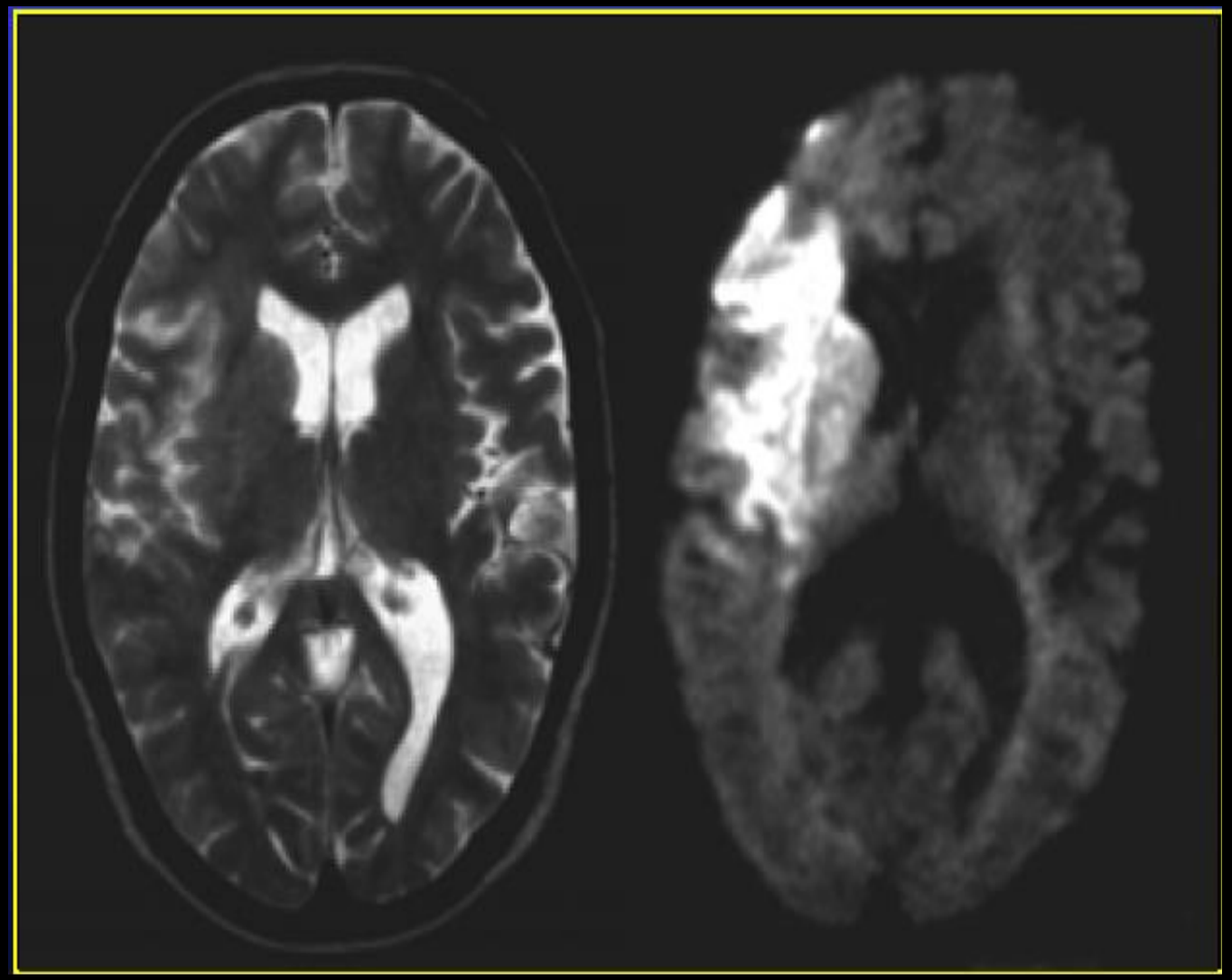


Diffusion in Stroke: Early phase



Progressive cytotoxic edema ⟹ diffusion decrease

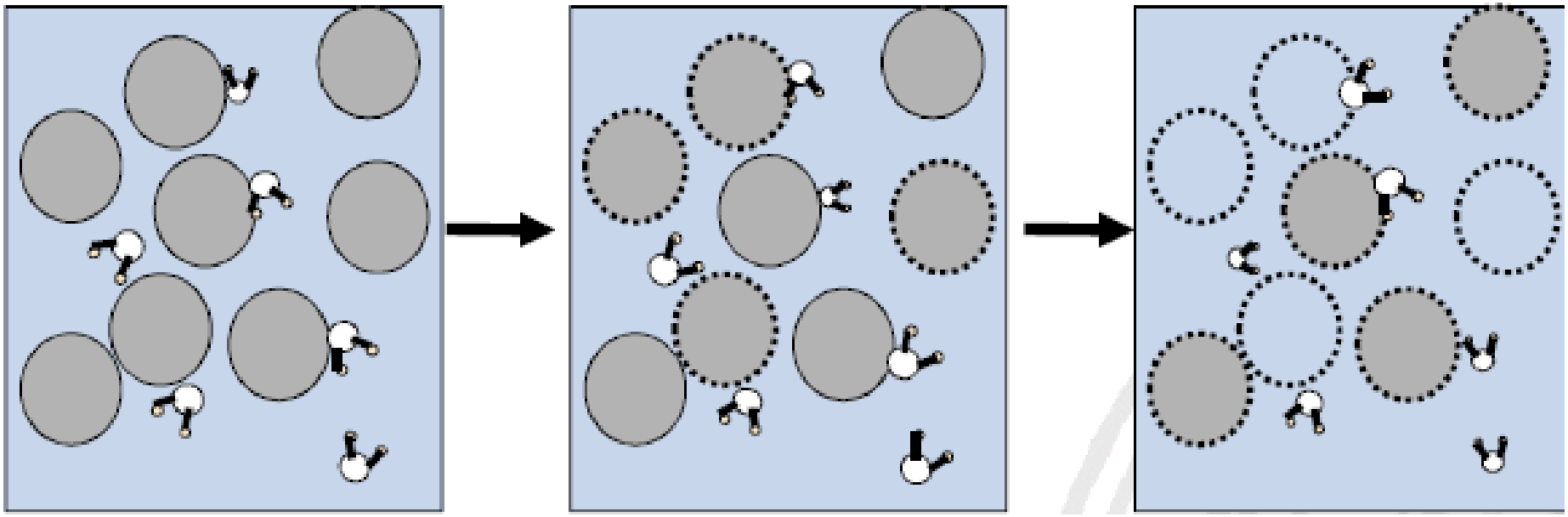
Acute Ischaemia



T2 – Weighted

Diffusion-Weighted

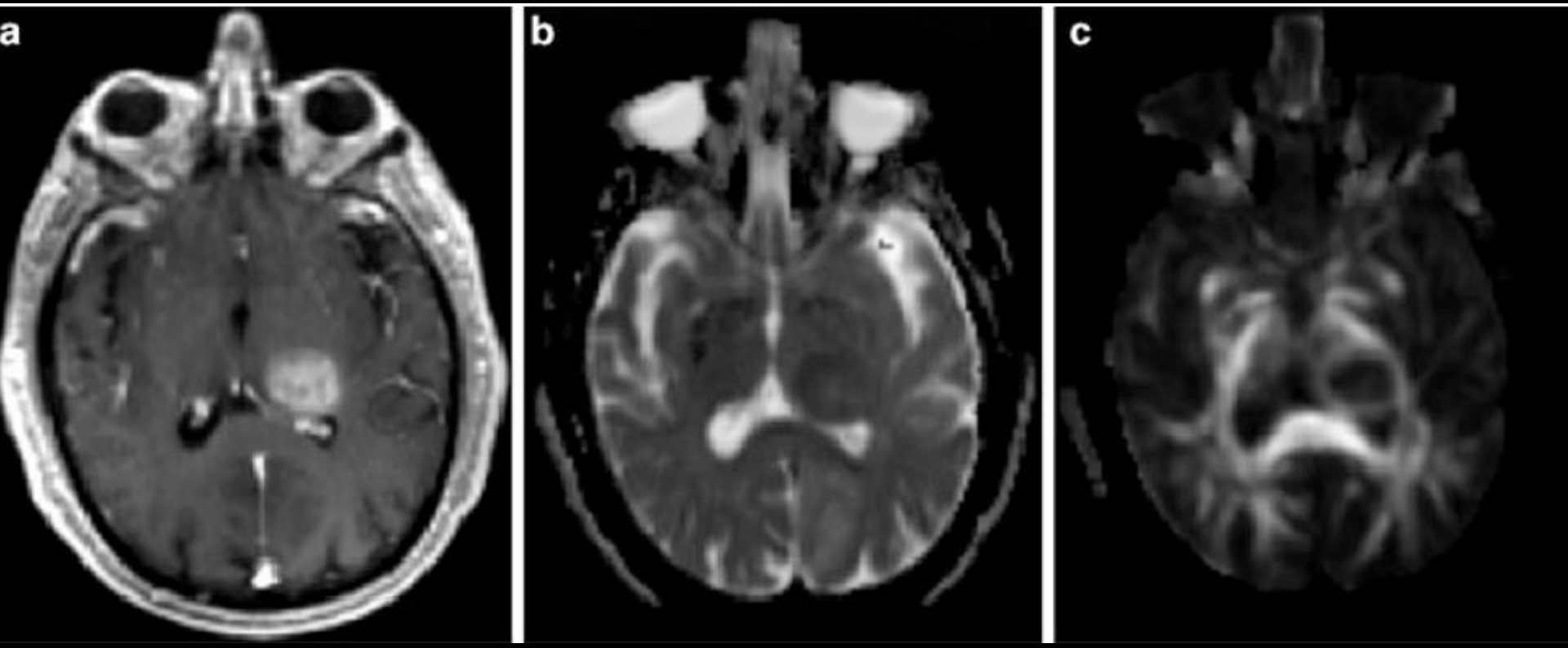
Diffusion in Stroke: Late phase



rogressive cell membrane Lyses + vasogenic edema

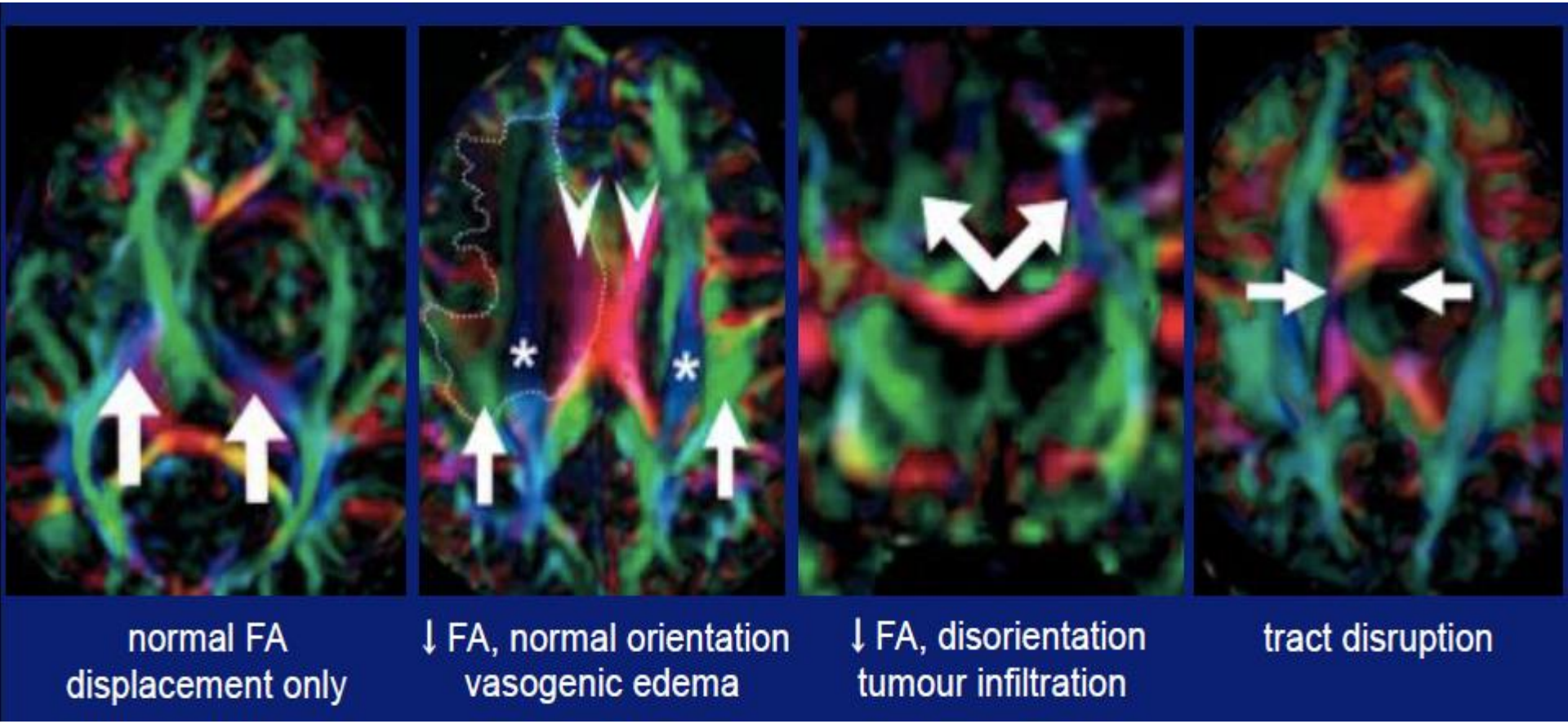
diffusion increase

Glioblastoma in *left thalamus.*



CE T1-weighted image **(a)** **MD map (b) shows restricted diffusion** **FA (c)**

Tract Integrity



Diffusion Tensor Imaging group analysis in MS

FA decreases in MS

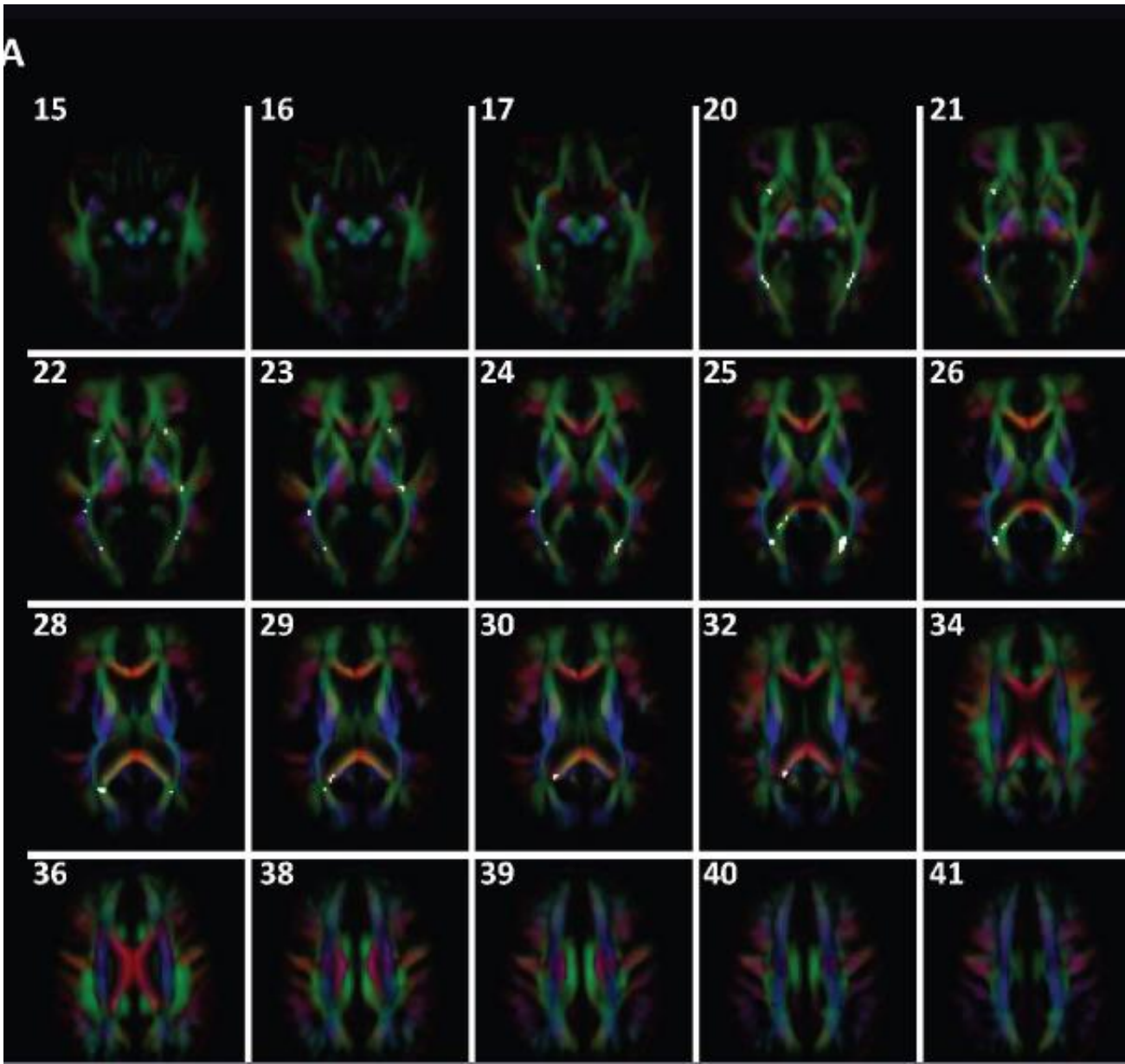
Also effects of chemotherapy,

bipolar disorder, autism,

s c h i z o p h r e n i a &

alzheimer, …

Van Hecke et al. 2010

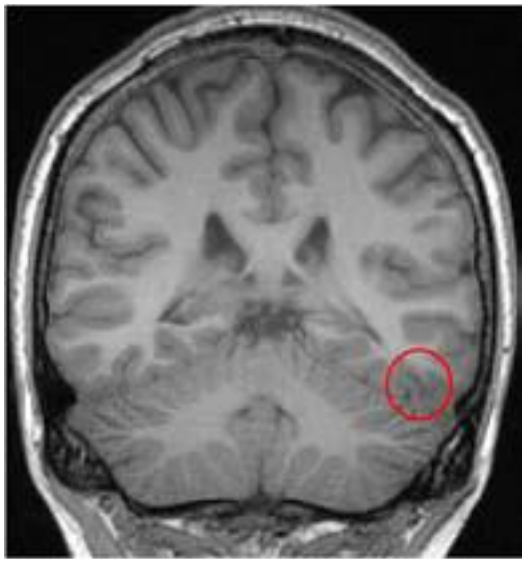


Focal Cortical Dysplasia

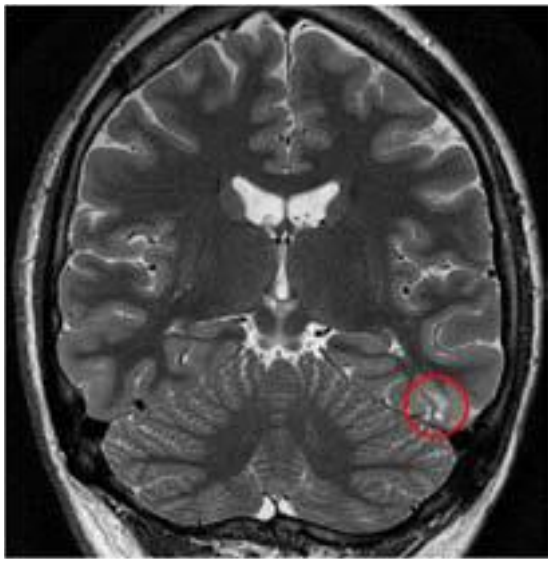
T1-weighted

intracellular volume fraction

Focal Cortical Dysplasia

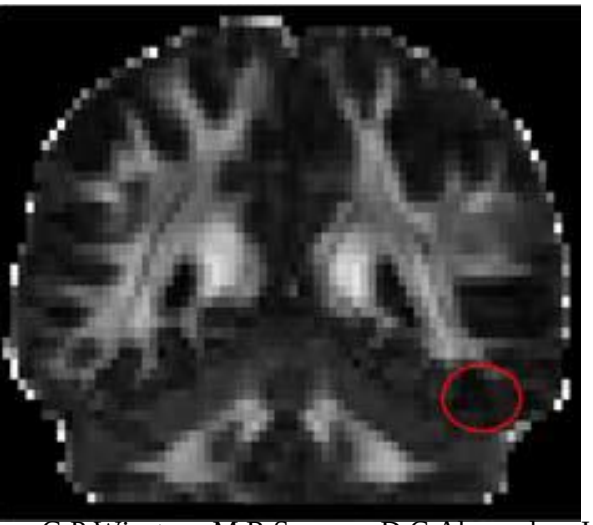


T1-weighted

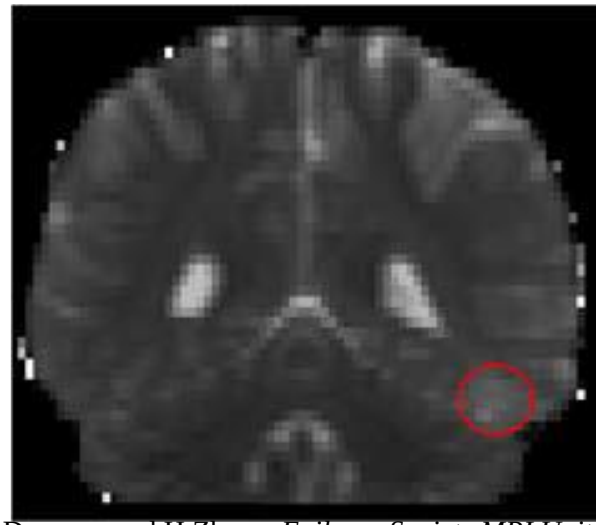


T2-weighted PROPELLER

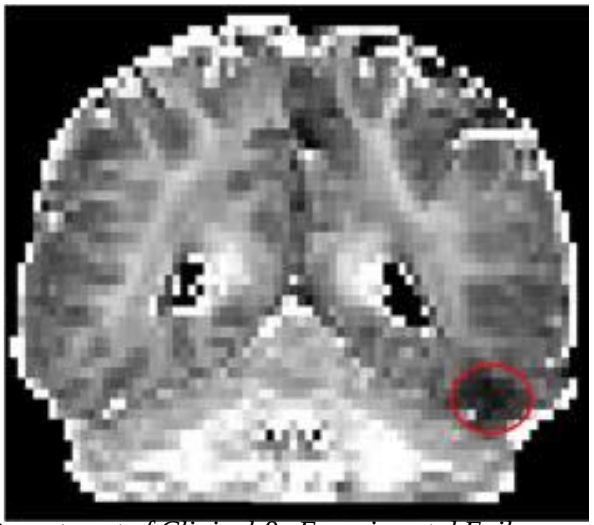
standard DTI (FA)



mean diffusivity (MD)

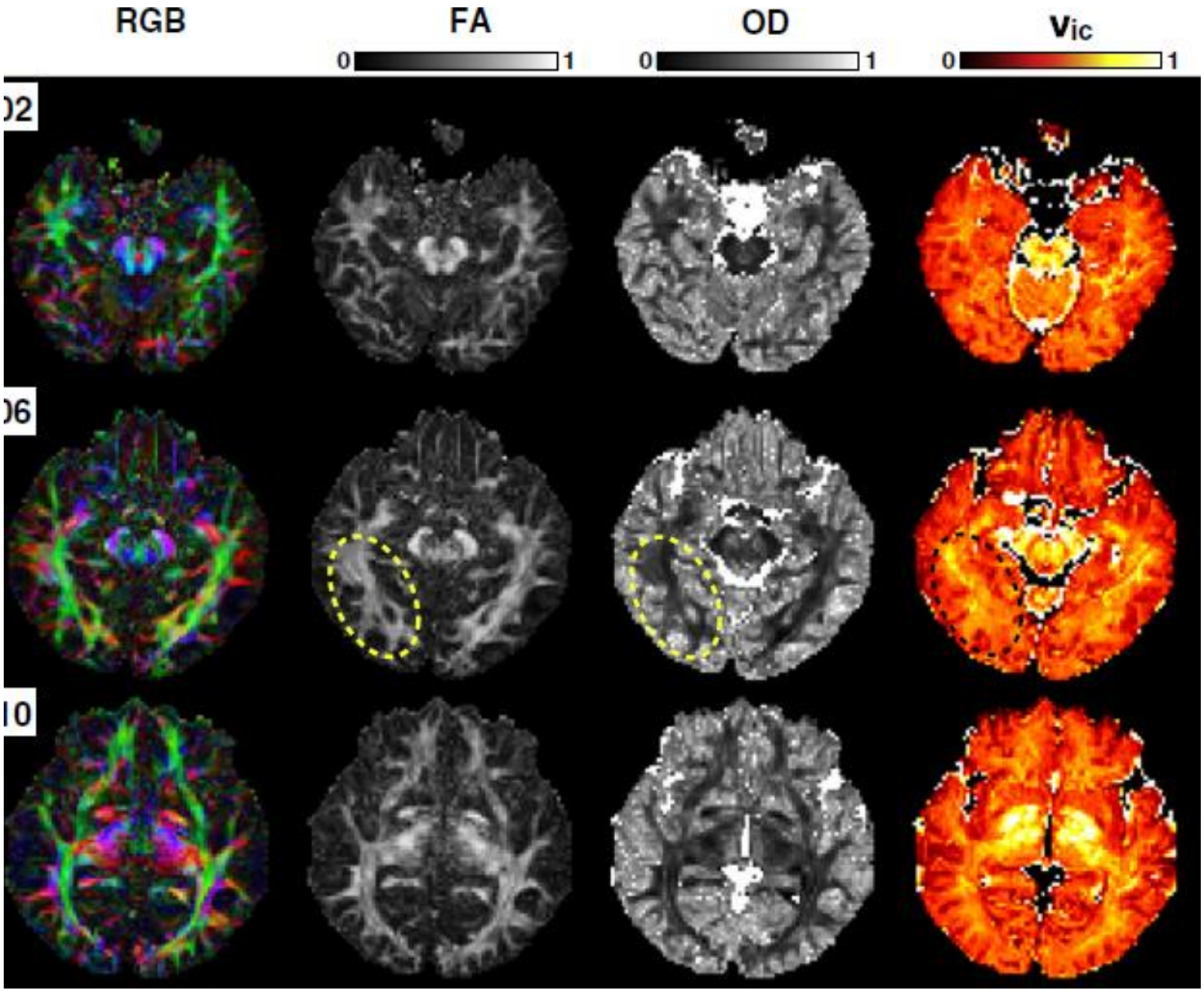


intracellular volume fraction (IVF)



G P Winston[1], M R Symms[1], D C Alexander[2], J S Duncan[1], and H Zhang[2] [1]*Epilepsy Society MRI Unit & Department of Clinical & Experimental Epilepsy,*

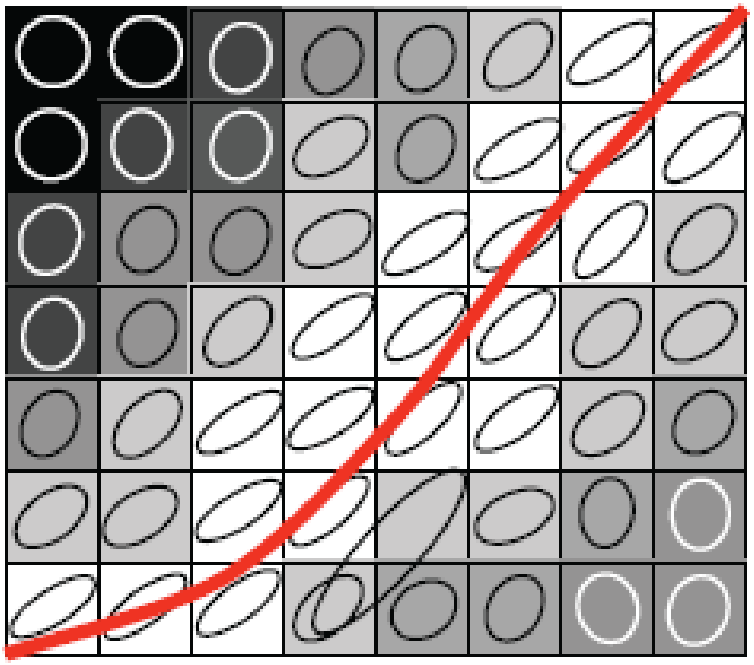
NODDI: Neurite orientation dispersion and density imaging

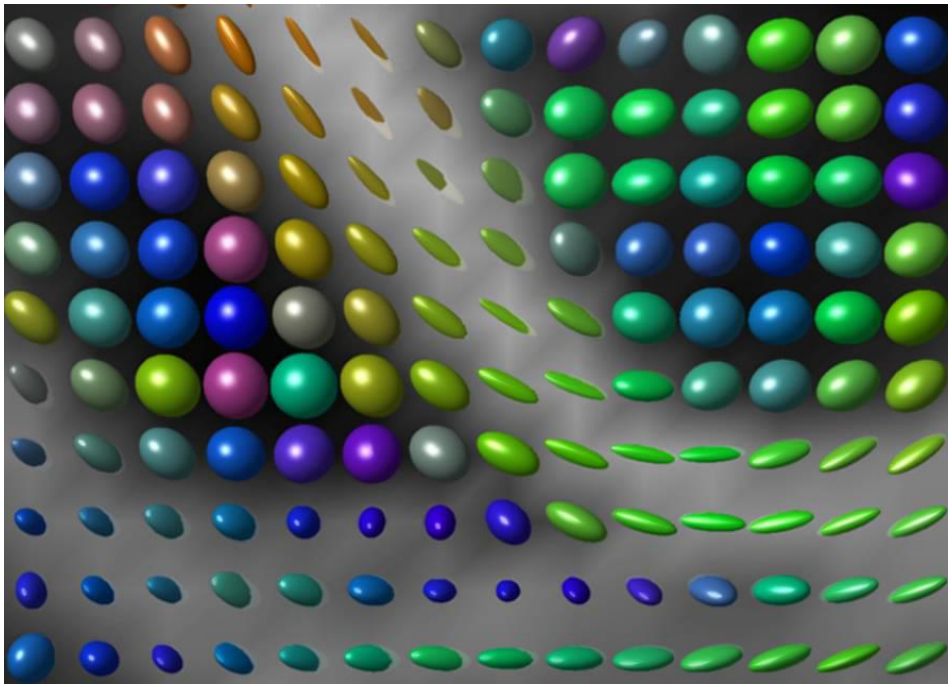


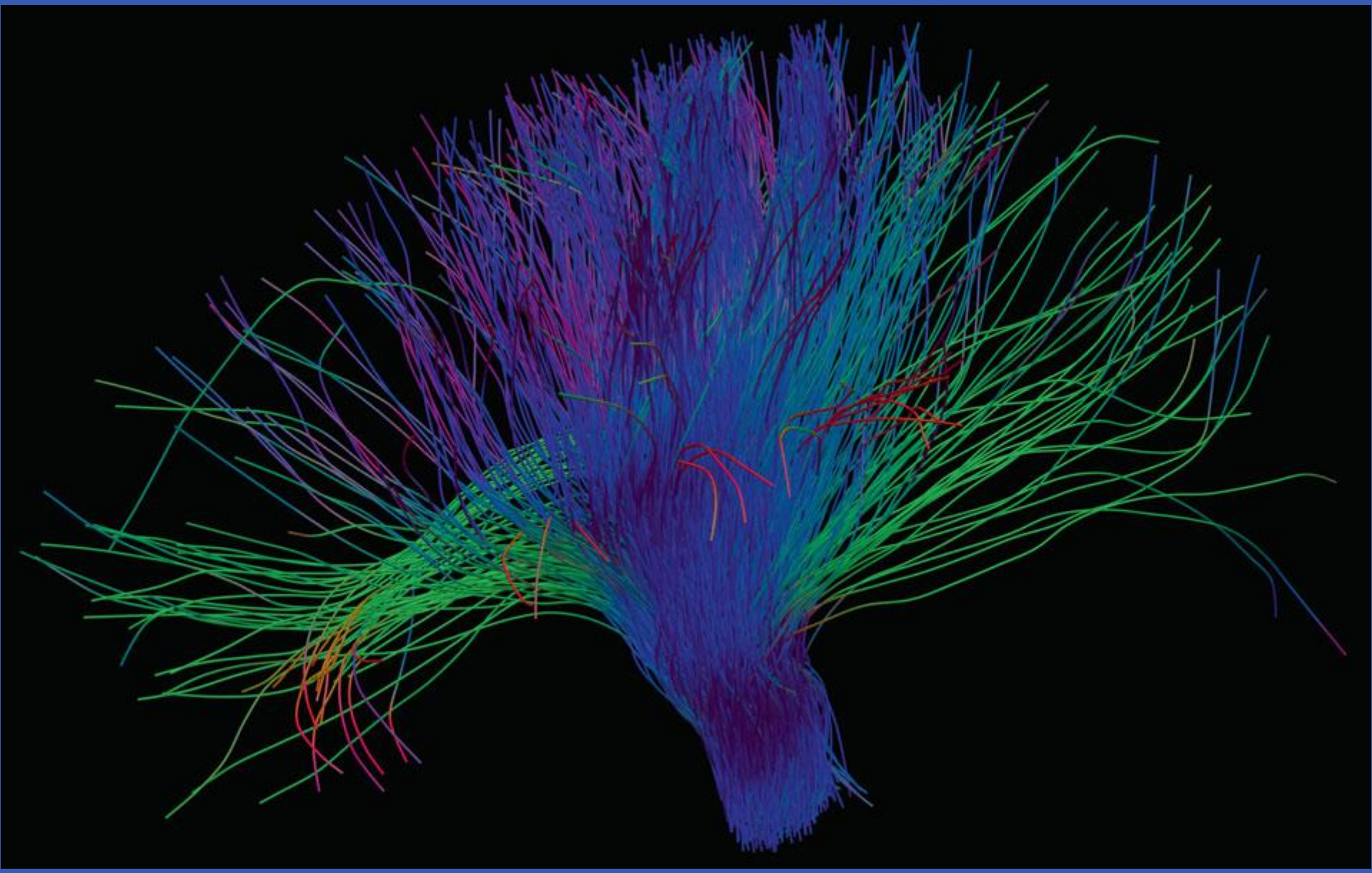
Maps of RGB-encoded principal direction μ, FA, orientation dispersion index OD, intra-cellular volume fraction vic

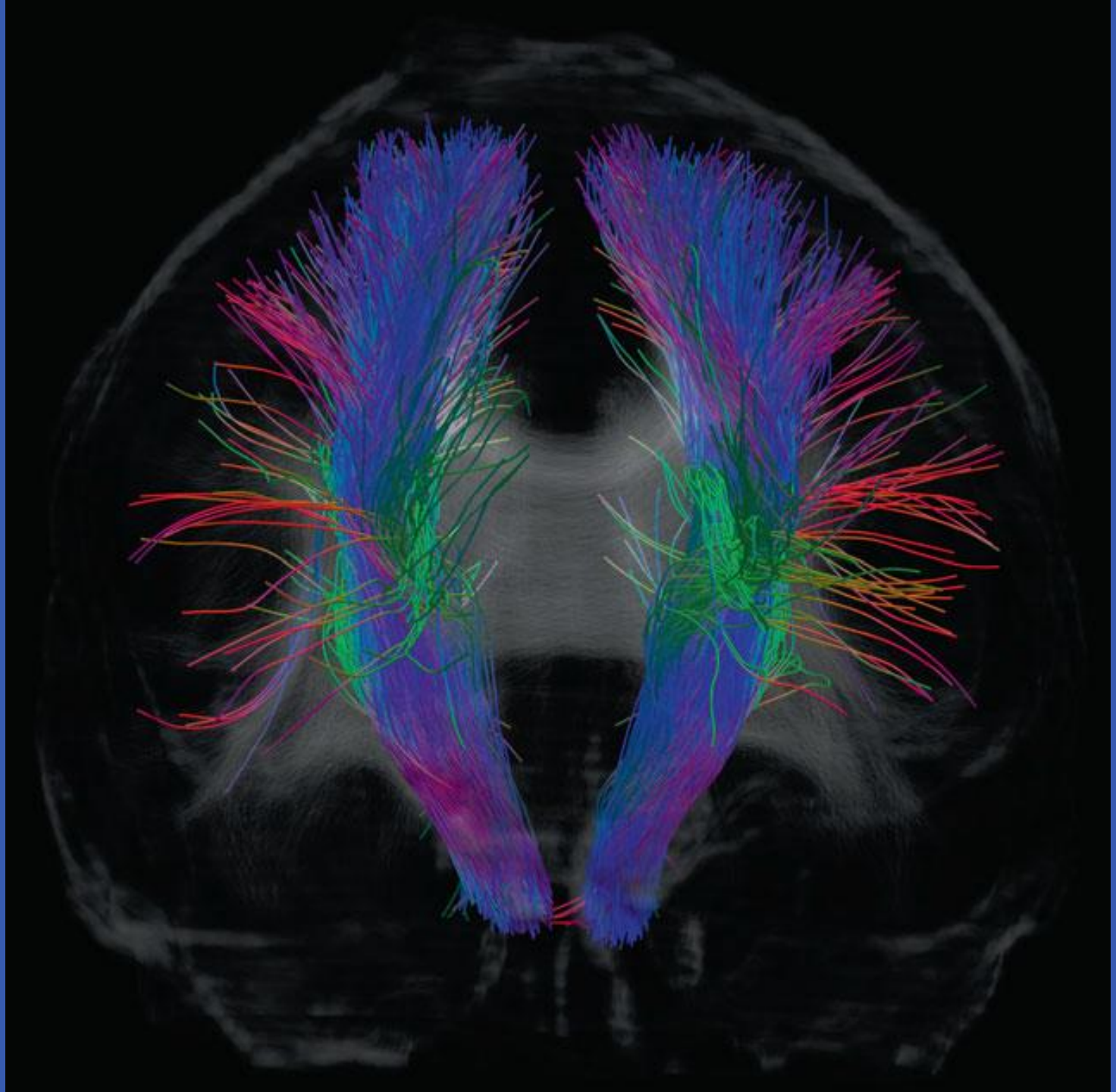
Tractography - Overview

- Voxels are connected based upon similarities in the maximum diffusion direction
-

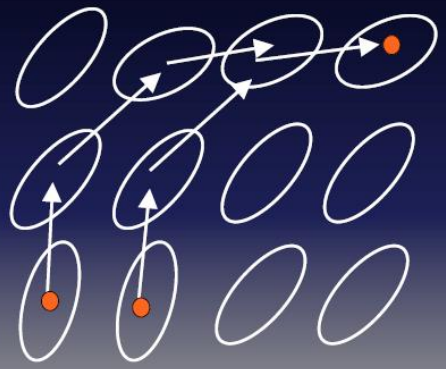




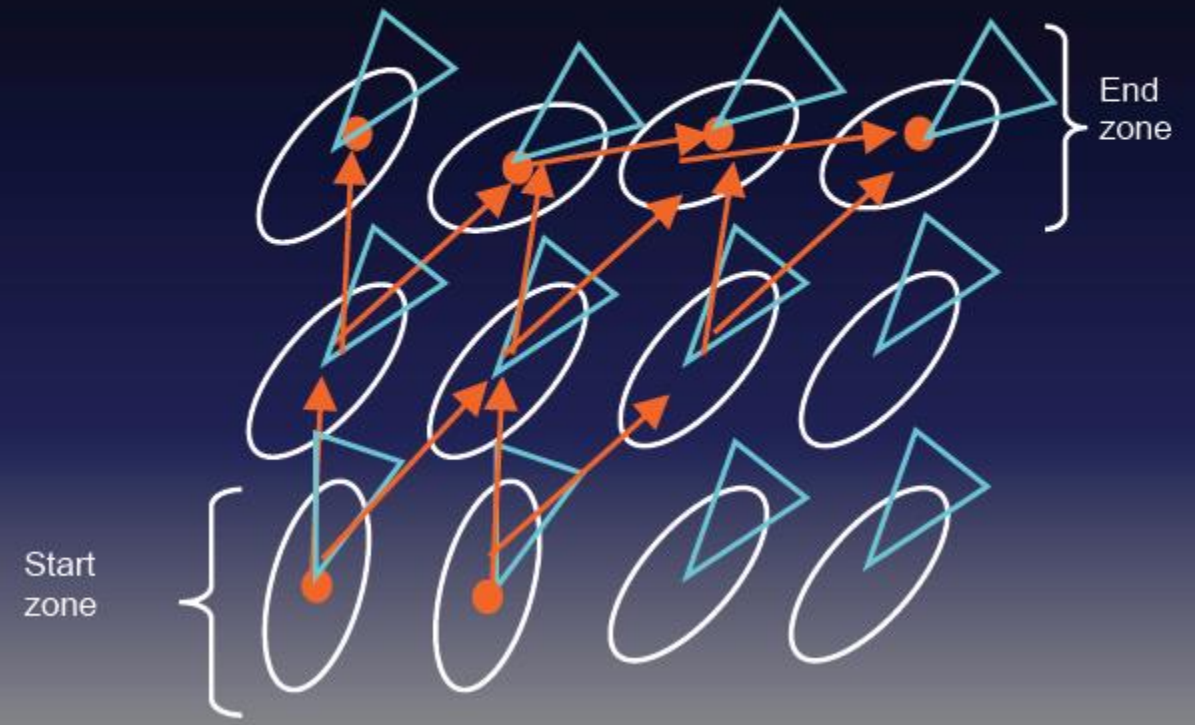




Example of Streamline Tracking



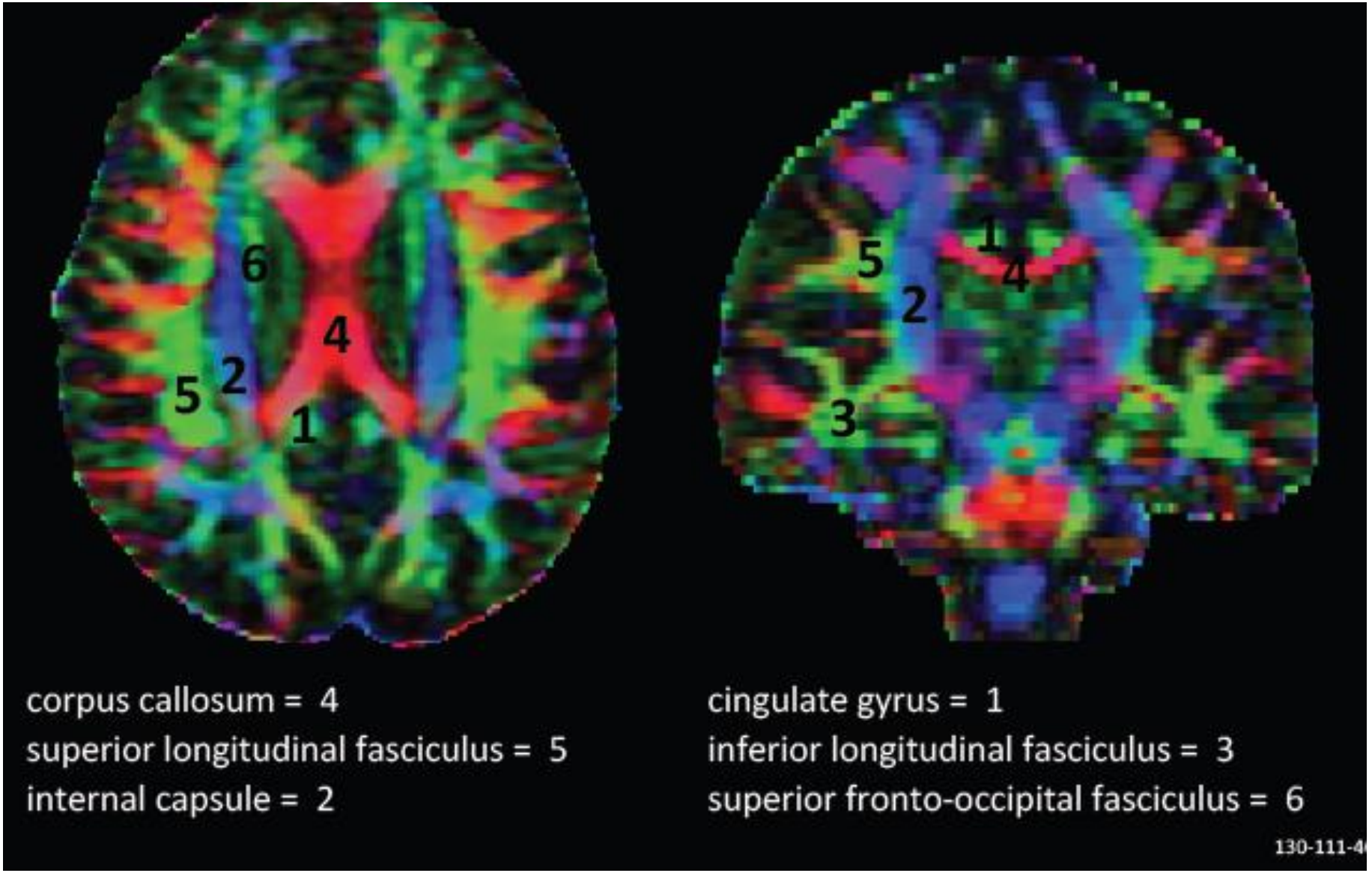
Probabilistic Tracking

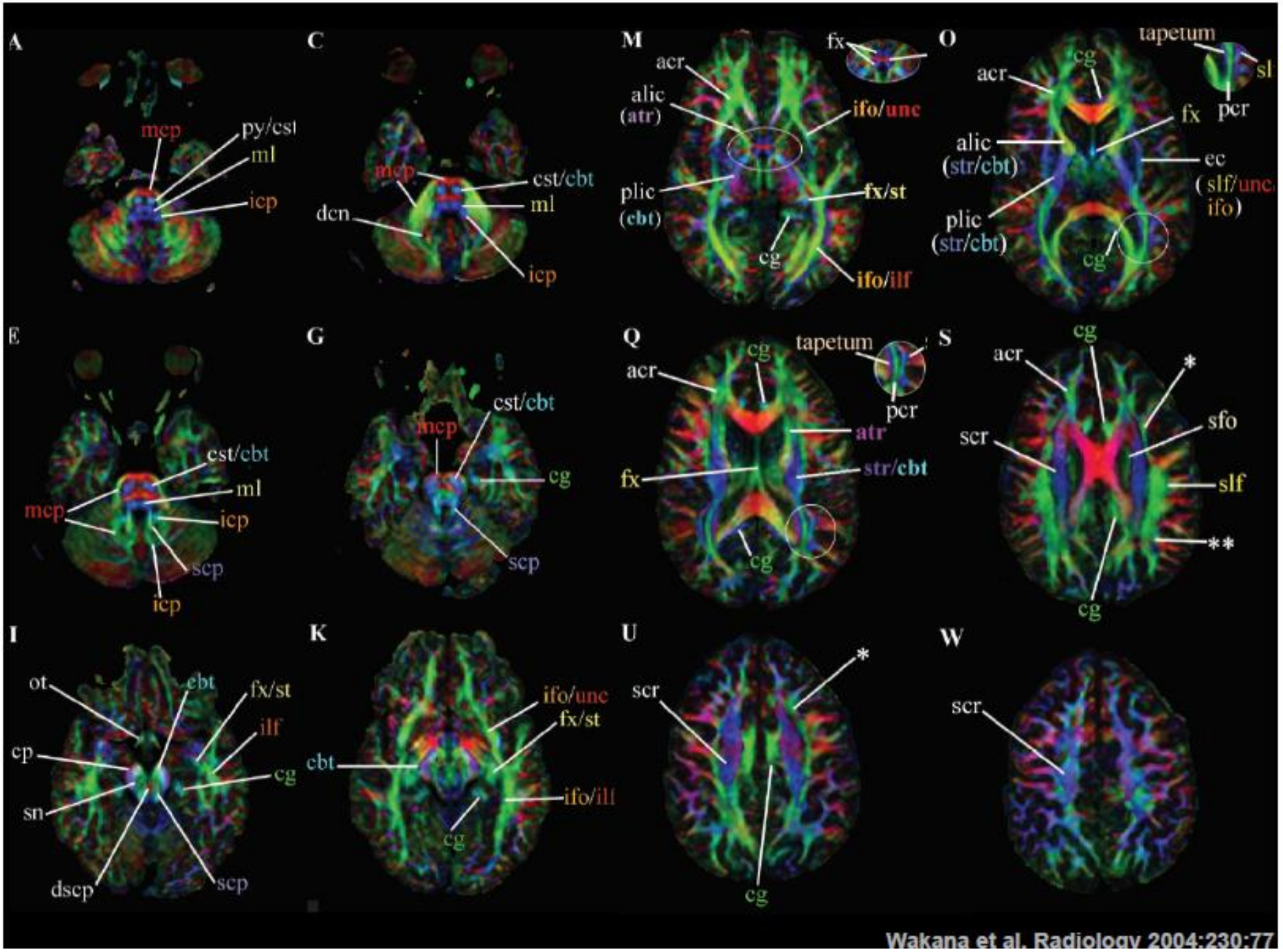


Anatomy for Pre-surgical Planning

- White matter tract assessment requires anatomical knowledge
  - placement of seed/target ROIs for fiber tracking
  - presumed location of ‘eloquent’ white matter tract.
  - ROI size
  - thresholds (angular, FA)
  - order of ROI placement.
- Attempts to standardize ROI placement, no consensus

How to identify white matter tracts





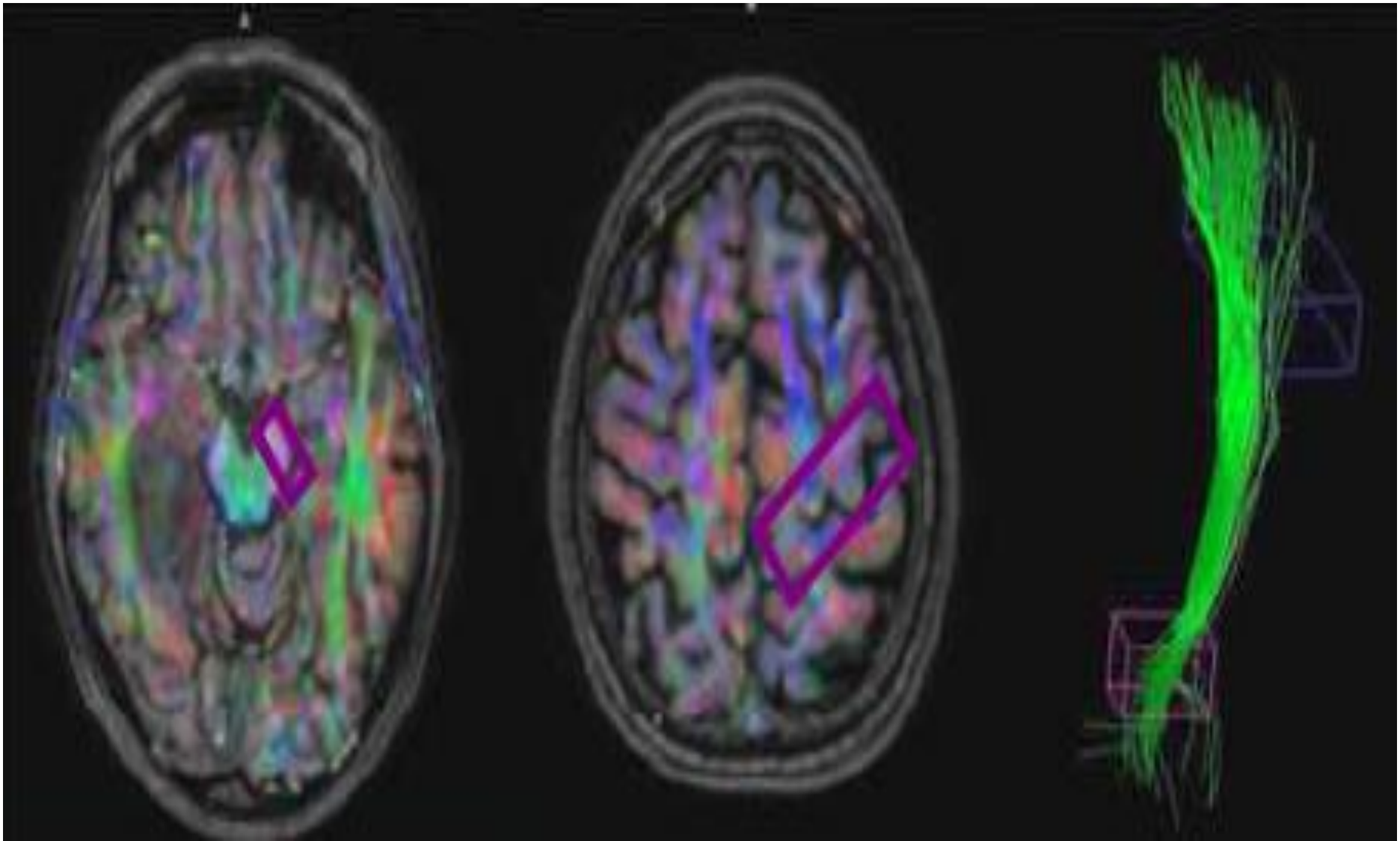
Wakana et al. Radiology 2004;230:77

RCMCI
مرکز تحقیقات تصویربرداری سلولی و مولکولی

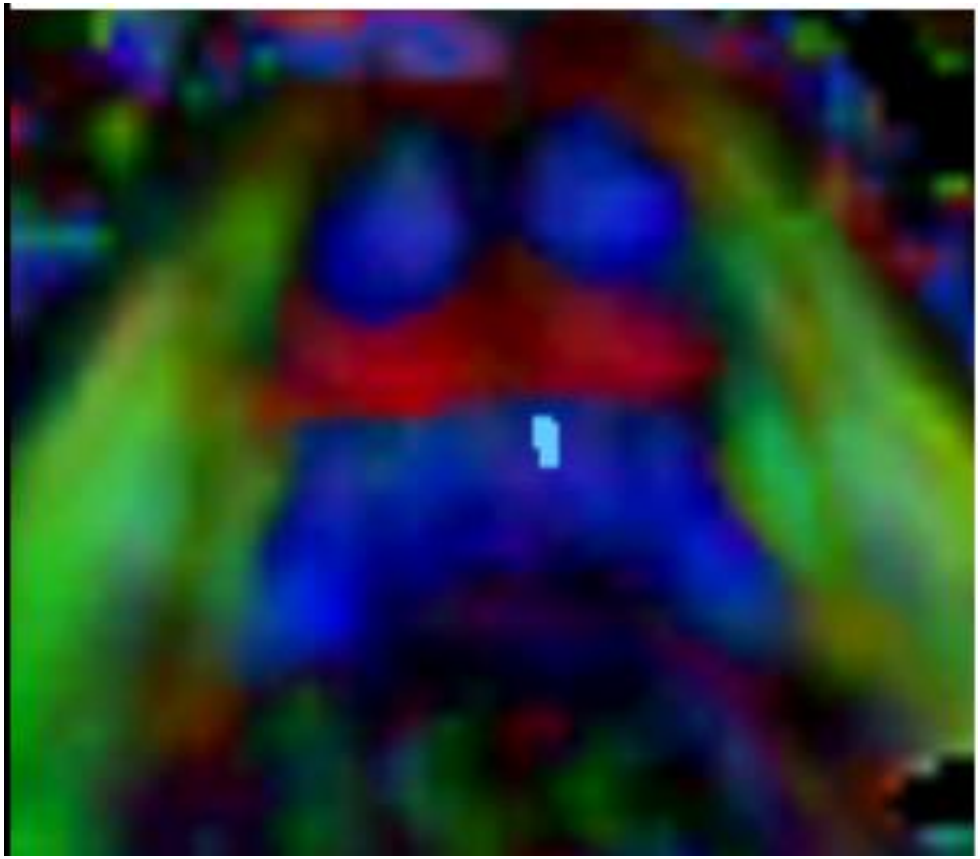
بسم الله الرحمن الرحیم

دانشگاه علوم پزشکی تهران

DTI Motor

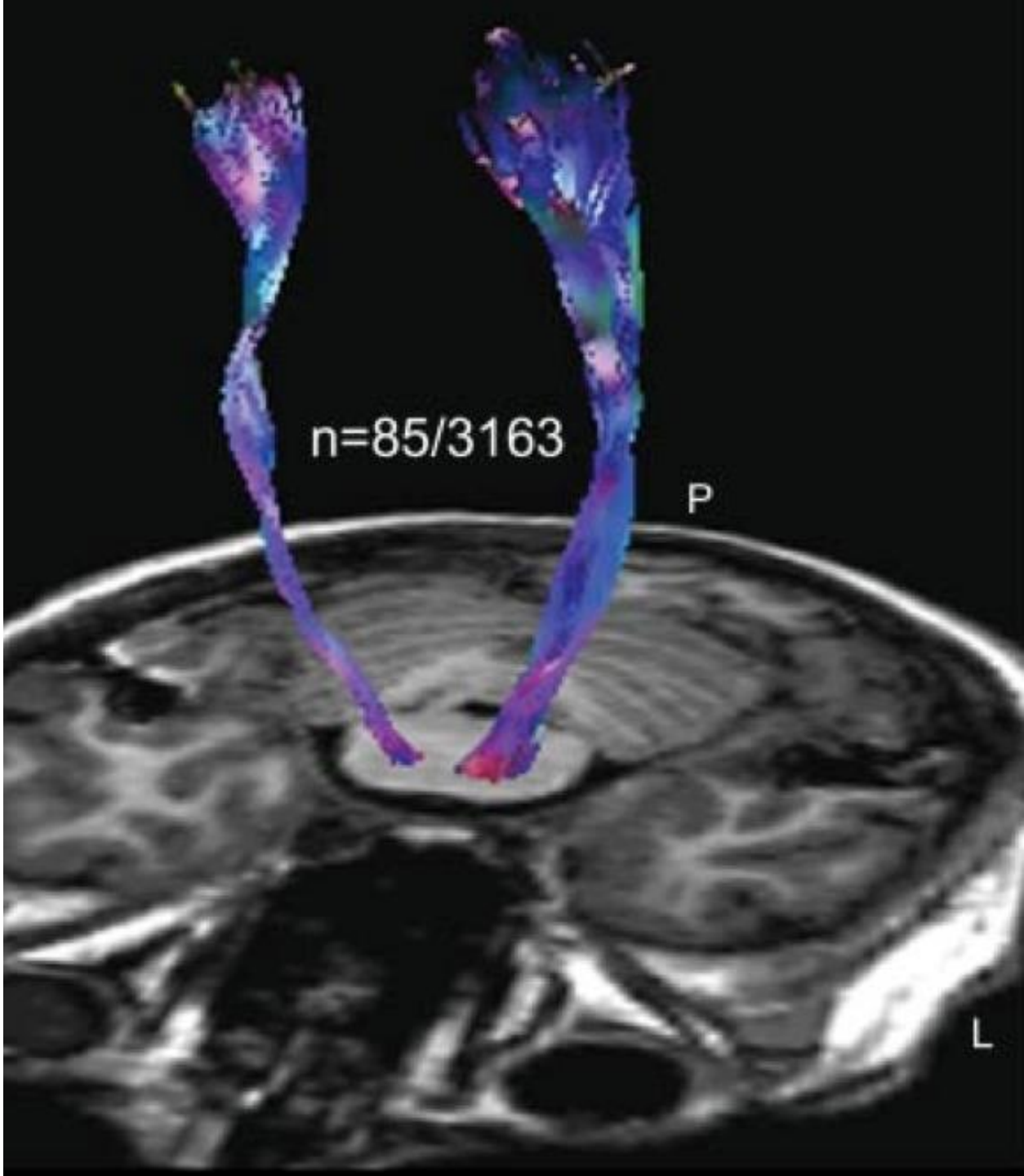


Brain Stem Anatomy

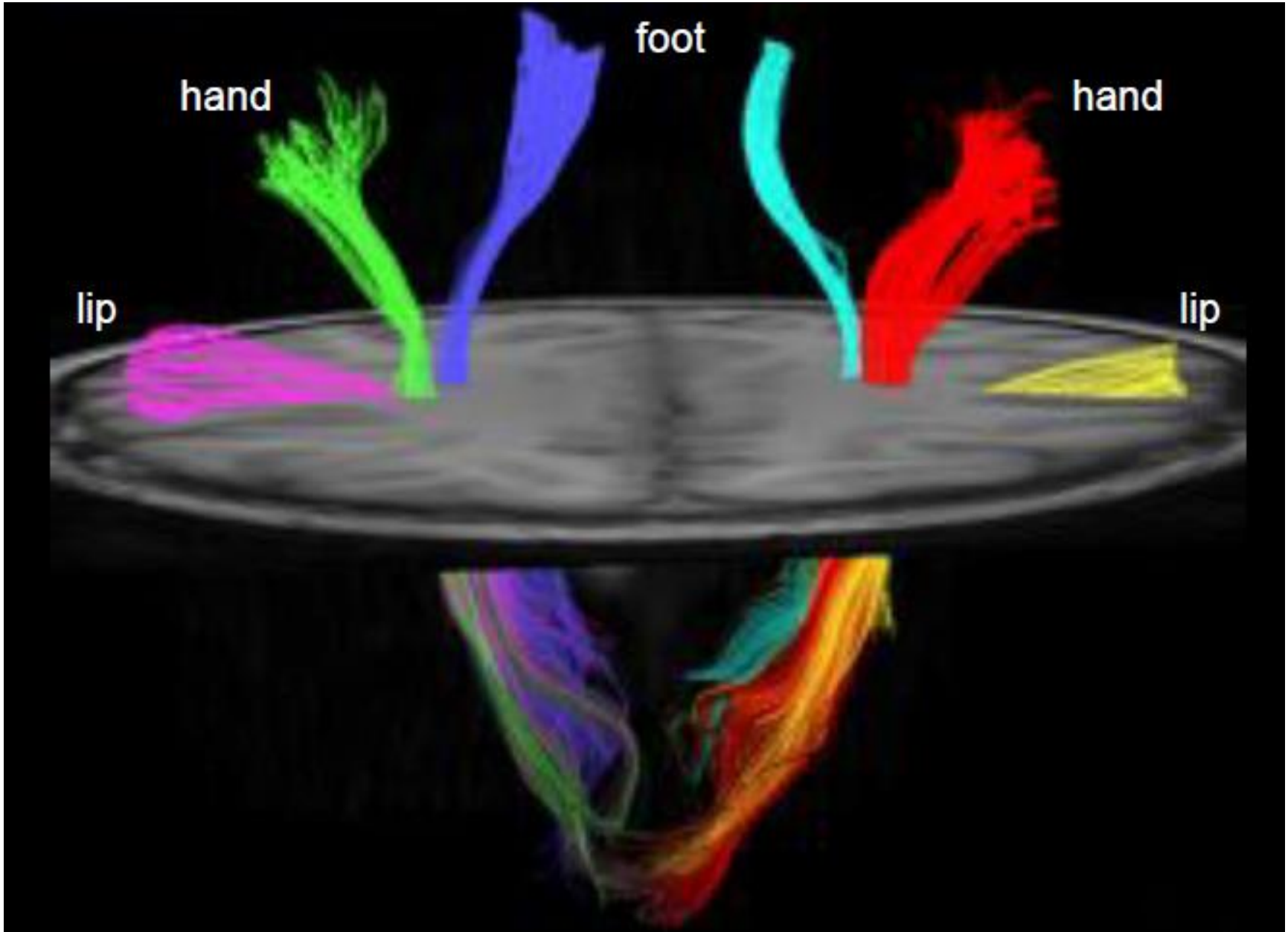


Brain Stem Anatomy

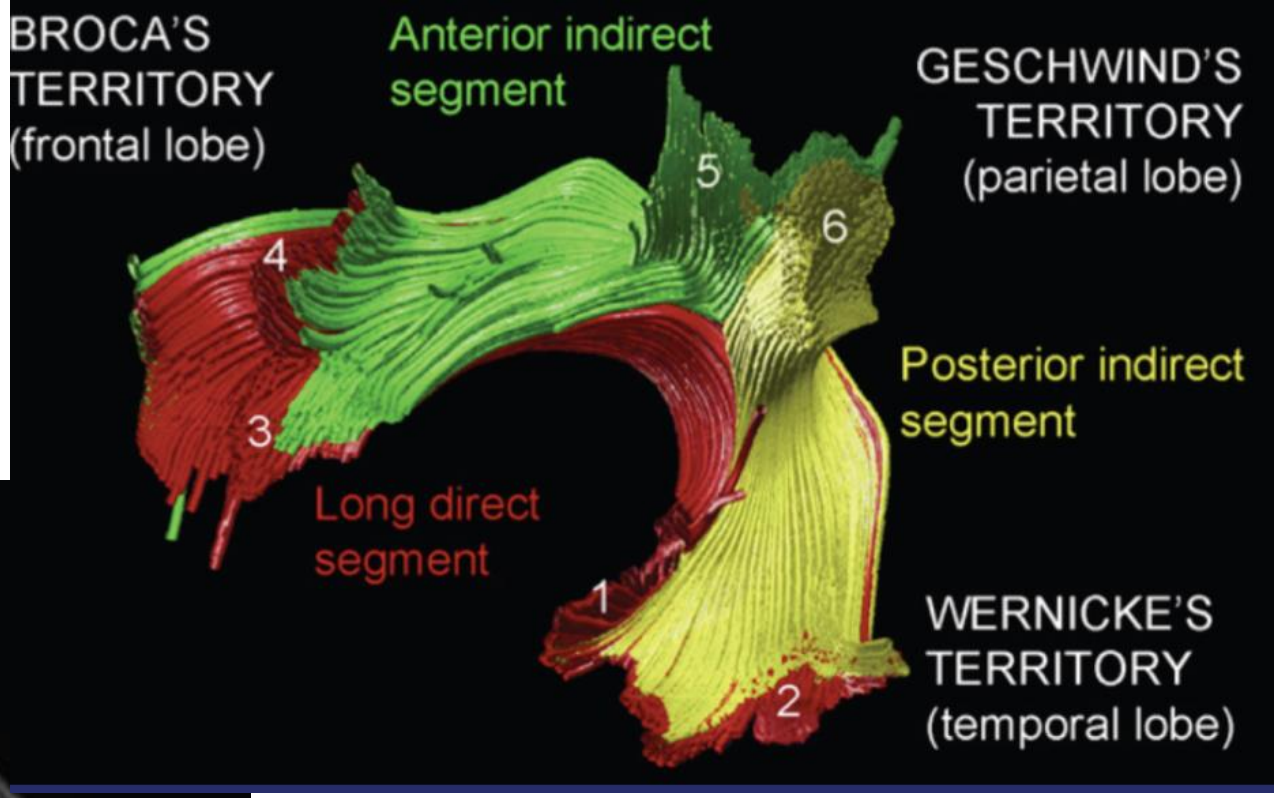
CST

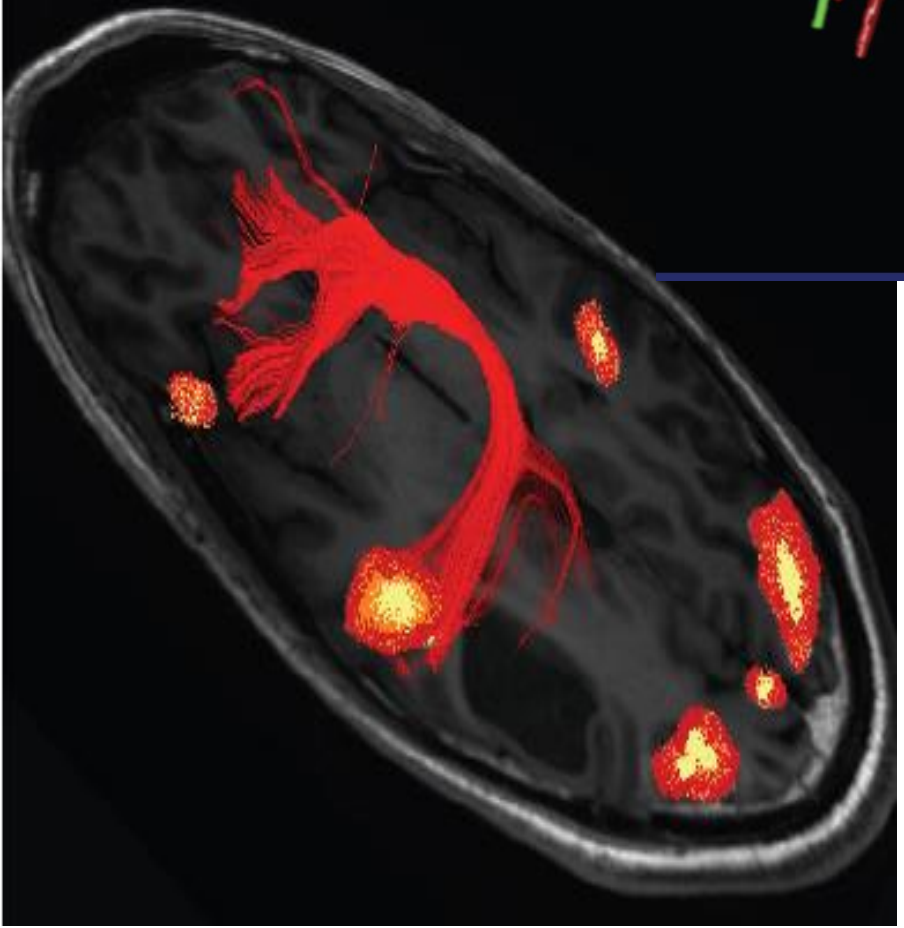


Tracking CST using fMRI masks



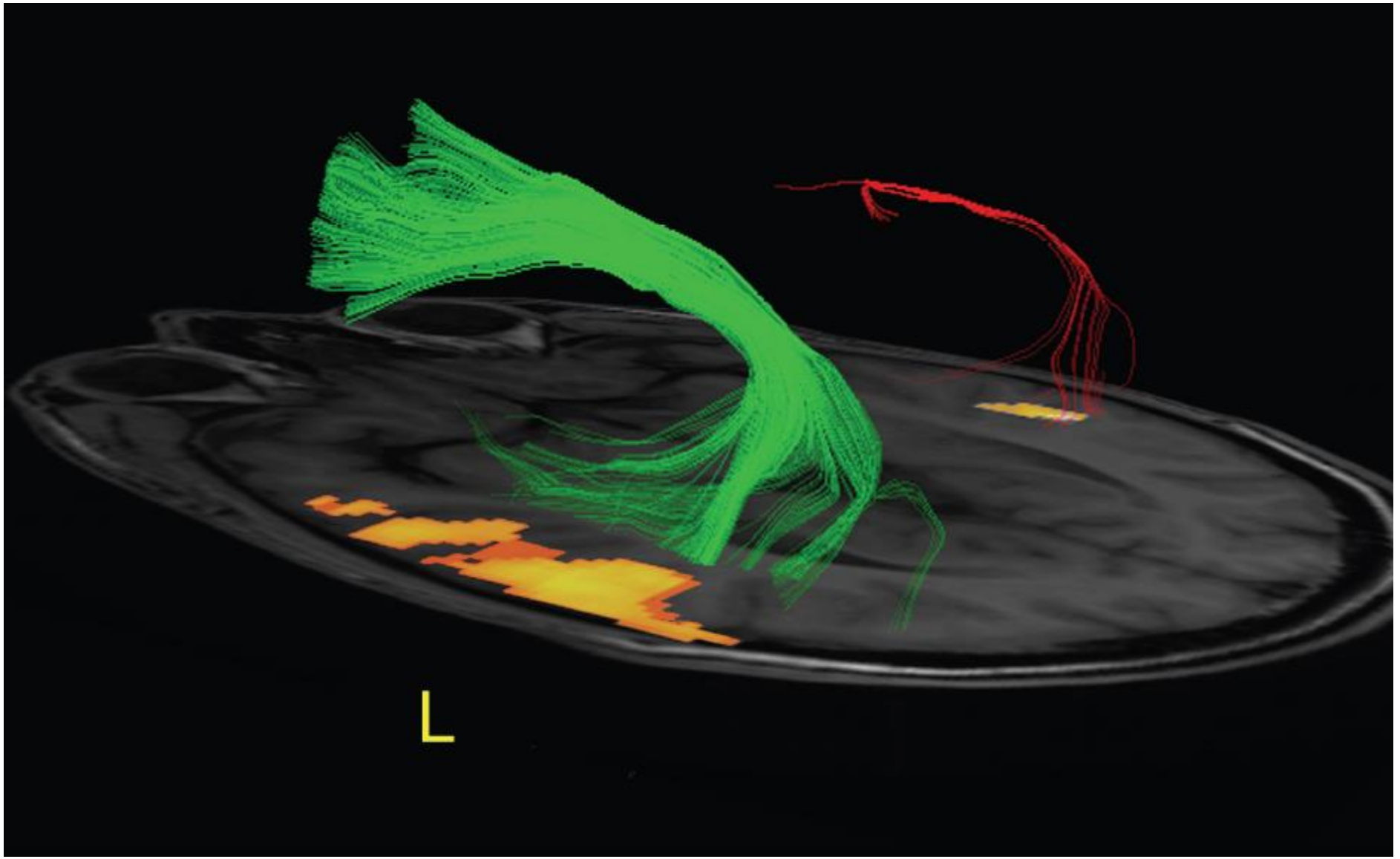
DTI – LANGUAGE



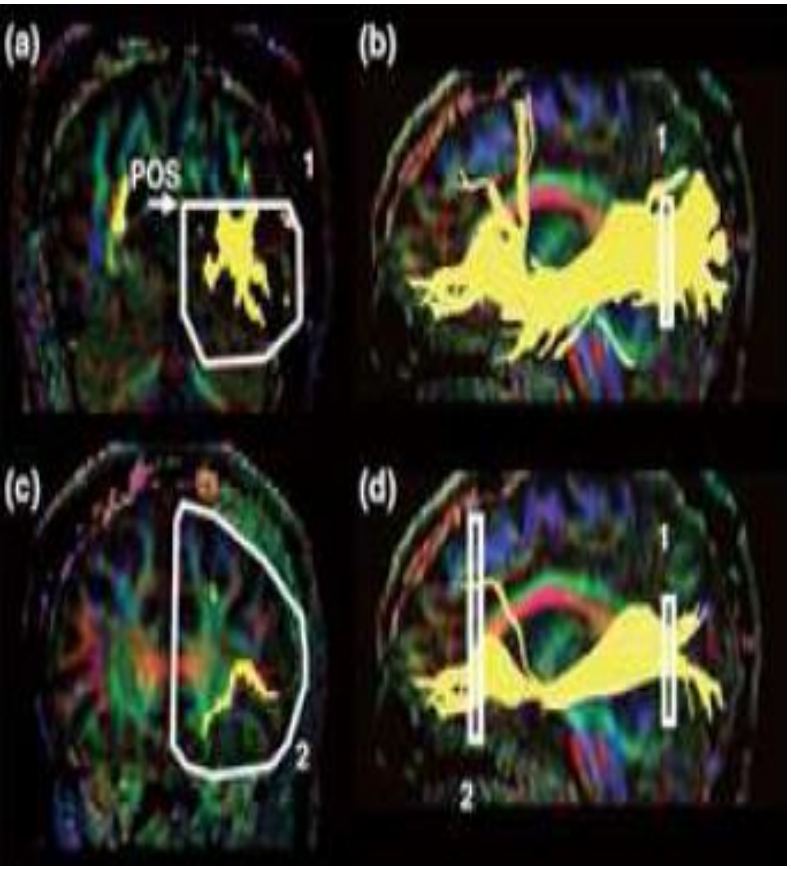


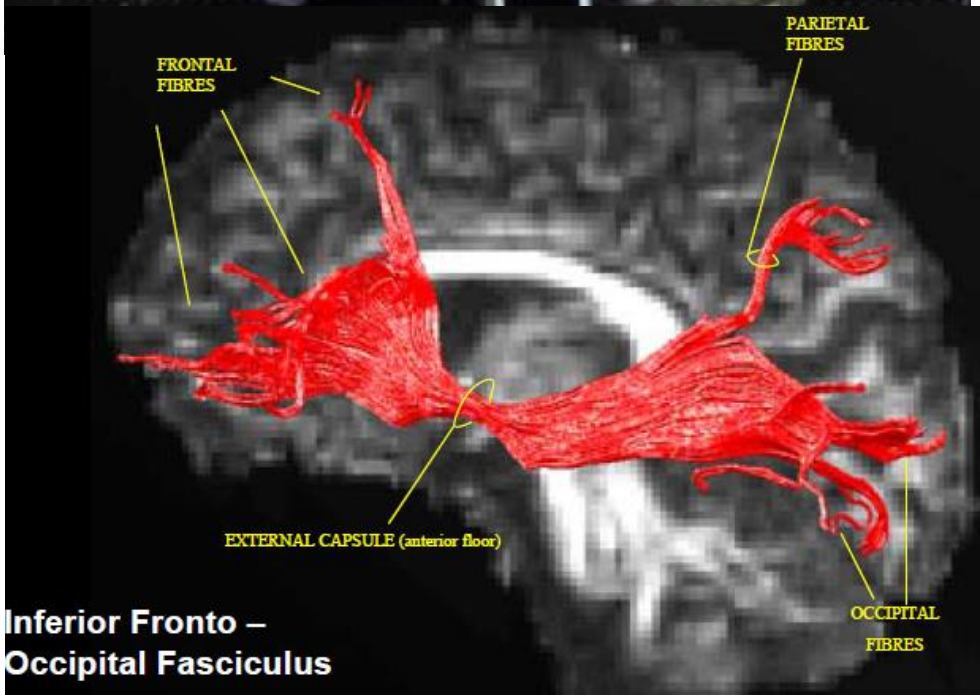
ARCUATE FASCICULUS

Asymmetry in AF due to physiological Lateralization



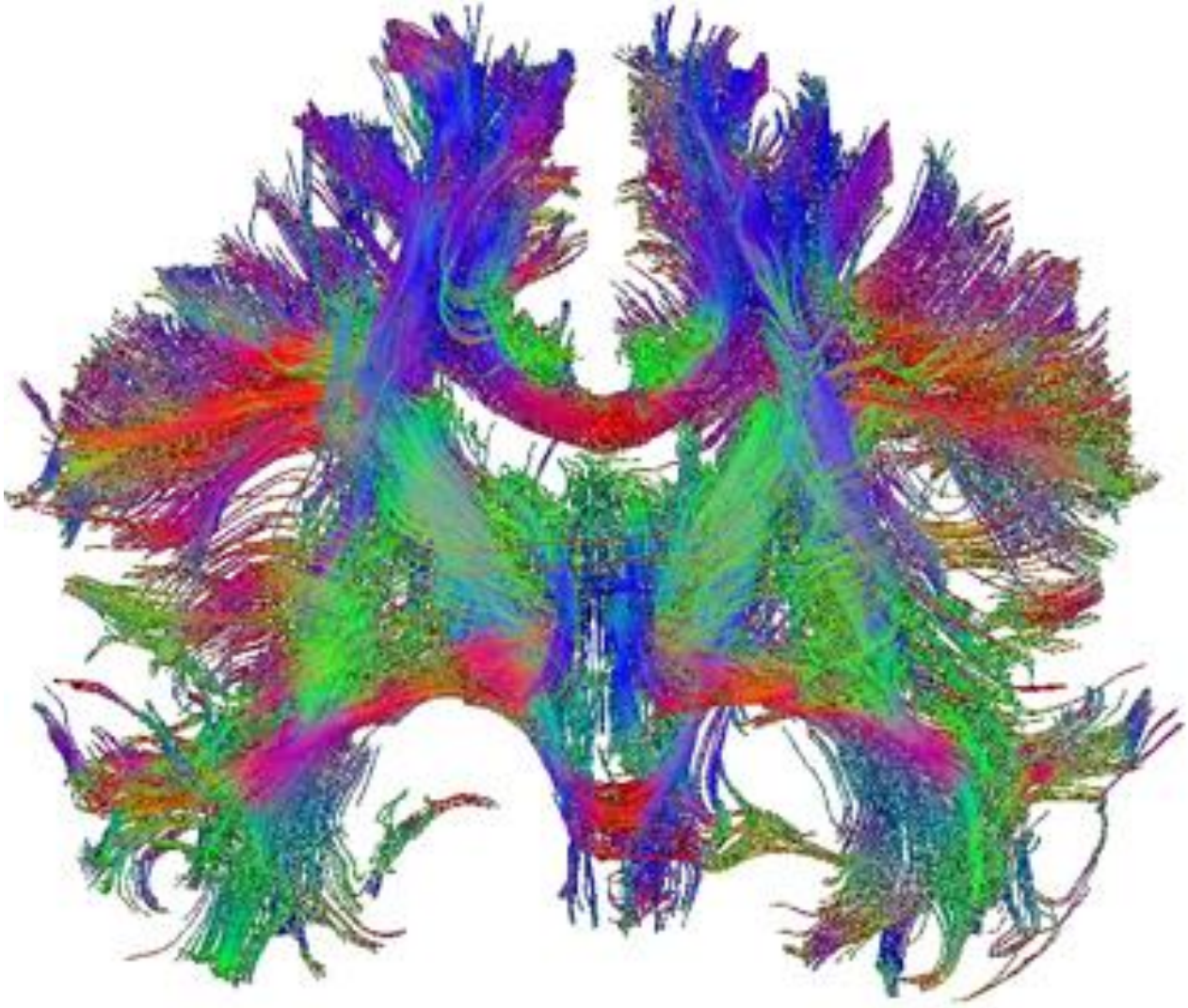
DTI – LANGUAGE

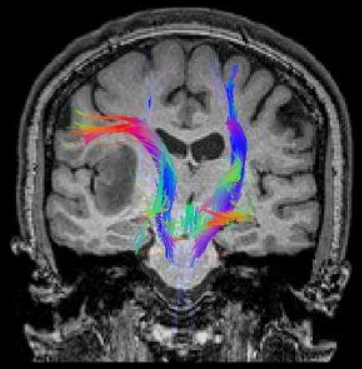


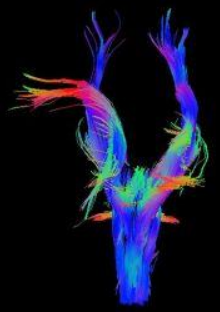


inferior fronto-occipital fasciculus (IFOF)

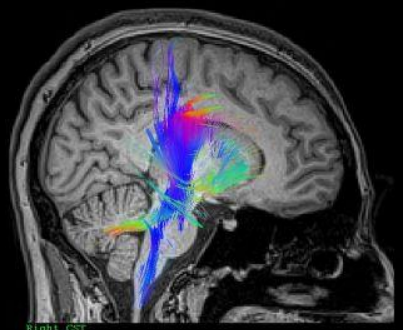
Main problem- Crossing Fibers

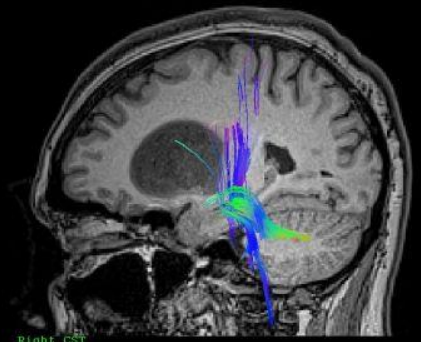




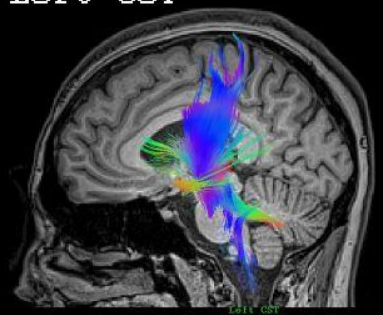


Right CST



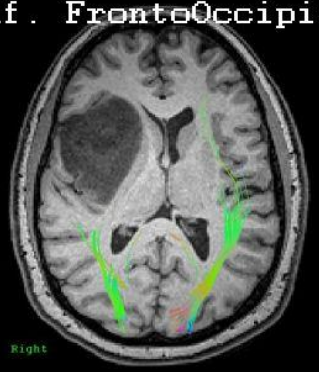


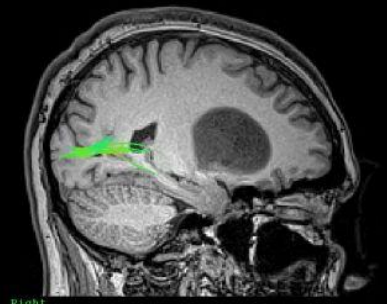
Left CST

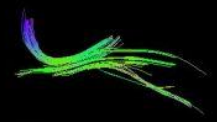


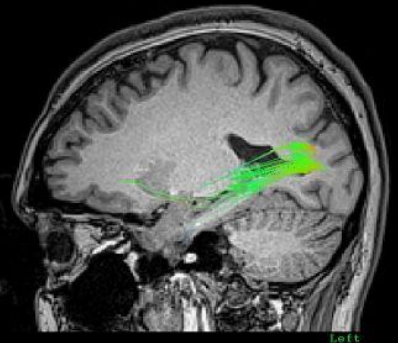
[redacted]
2014-08-03
CorticoSpinal Tract

[redacted] 2014-08-03
Inf. FrontoOccipital Faciculus









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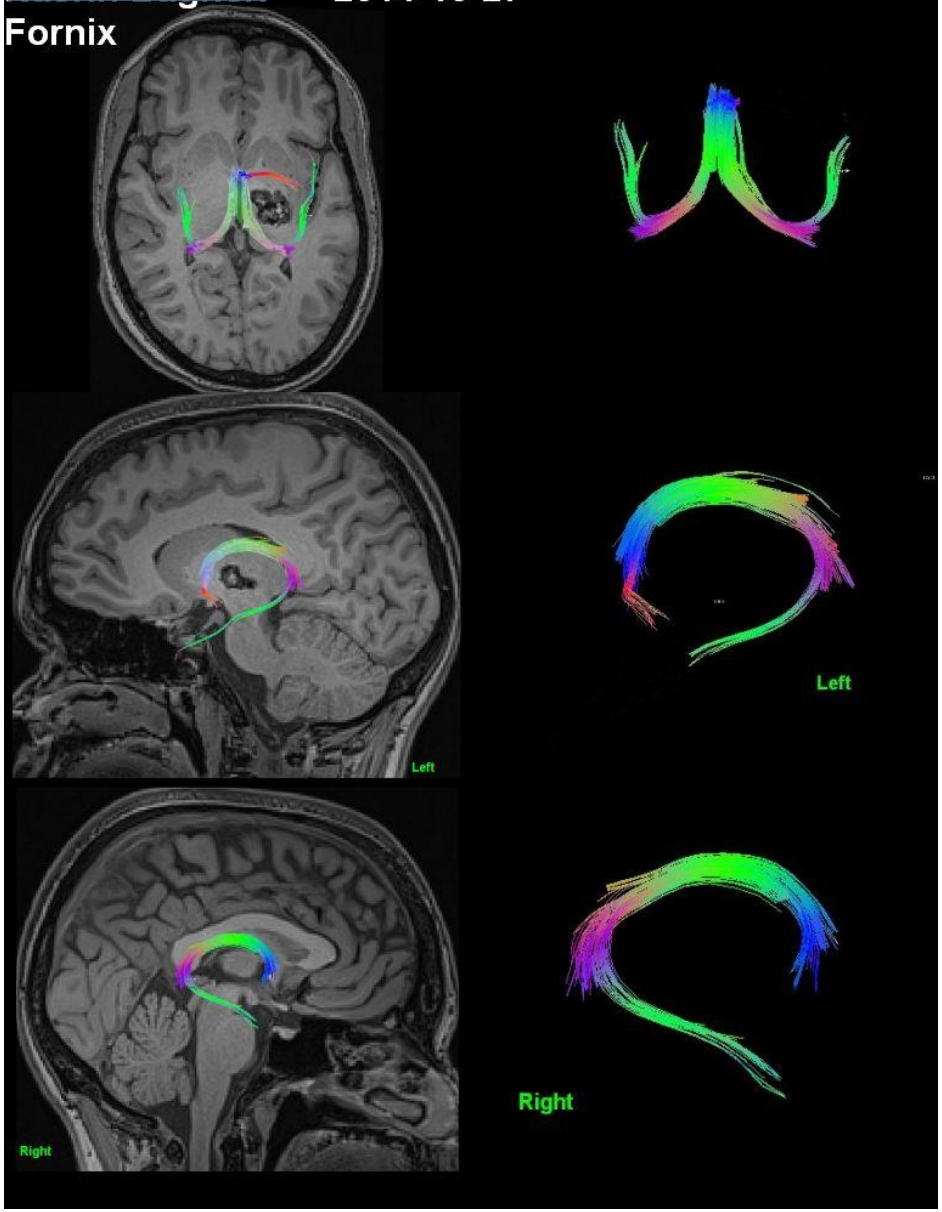
Fornix



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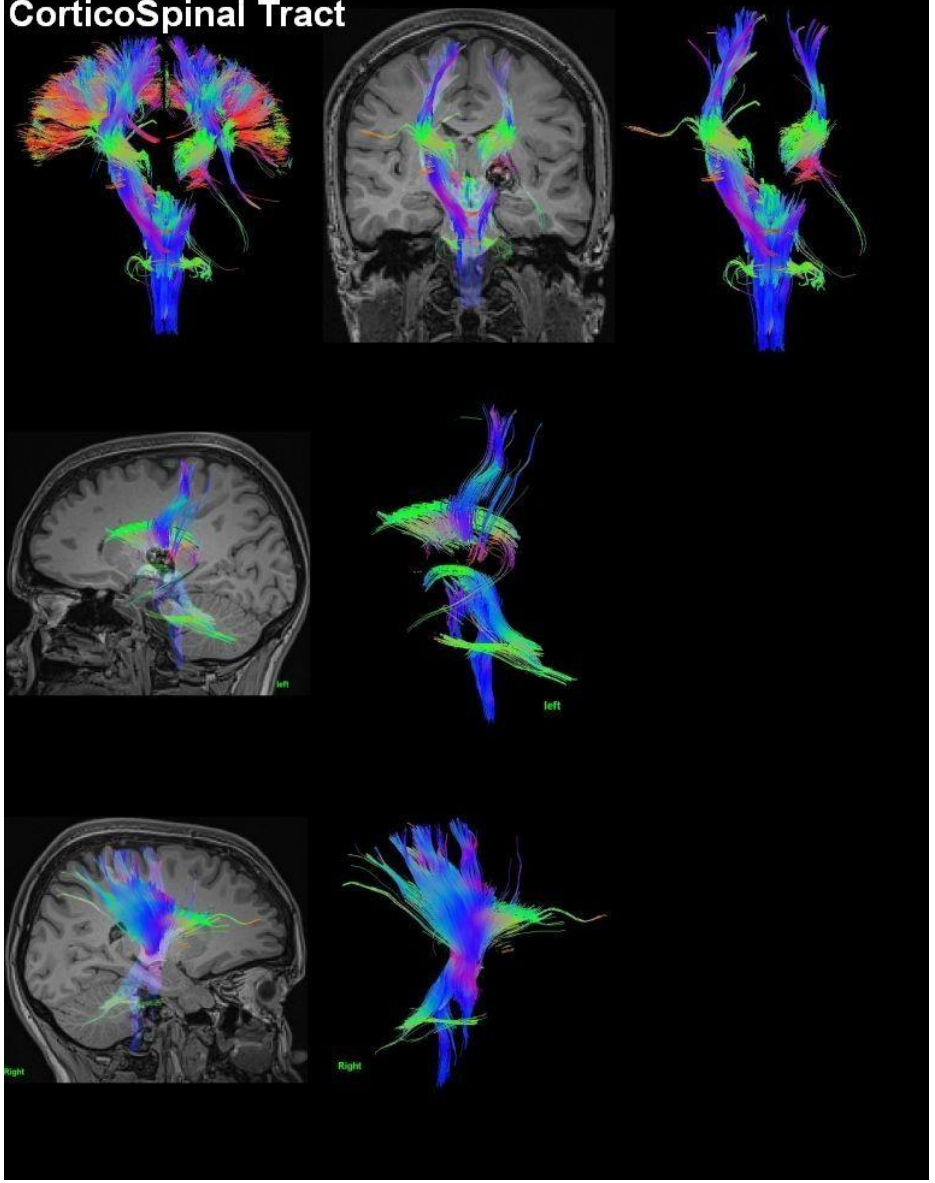
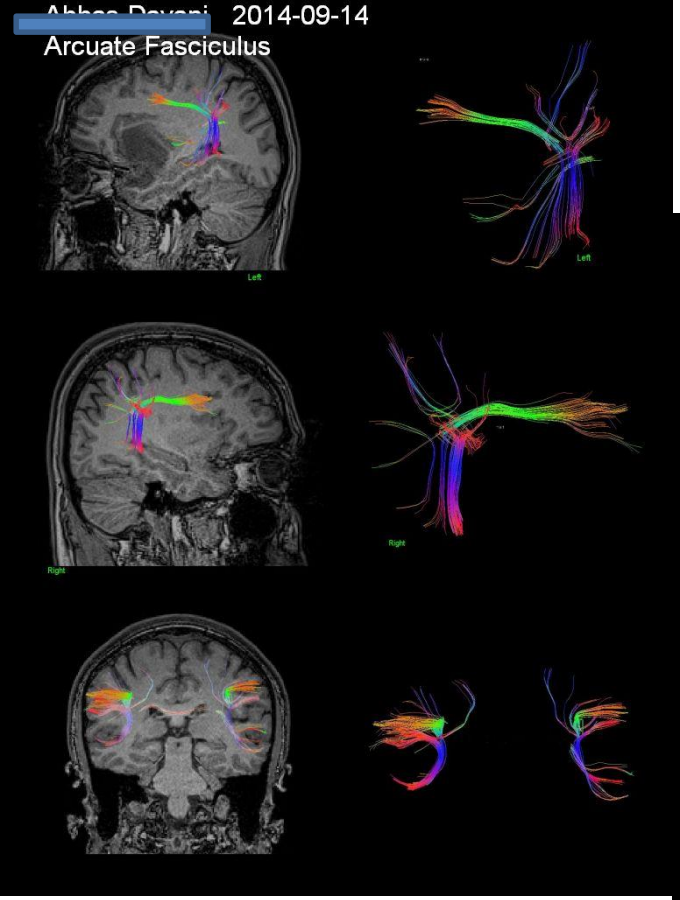
CorticoSpinal Tract



[redacted] 2014-09-14

Arcuate Fasciculus



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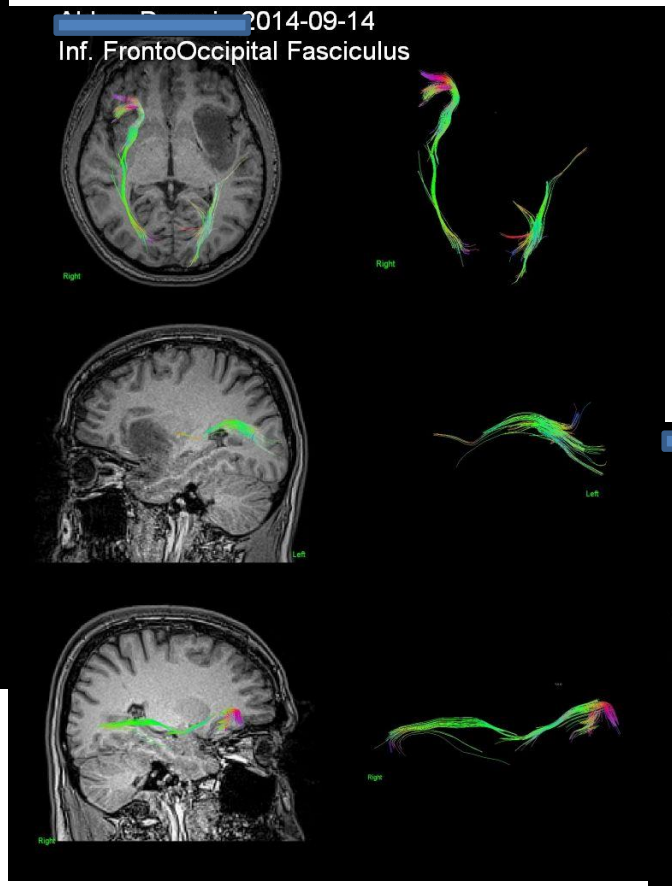
Inf. FrontoOccipital Fasciculus



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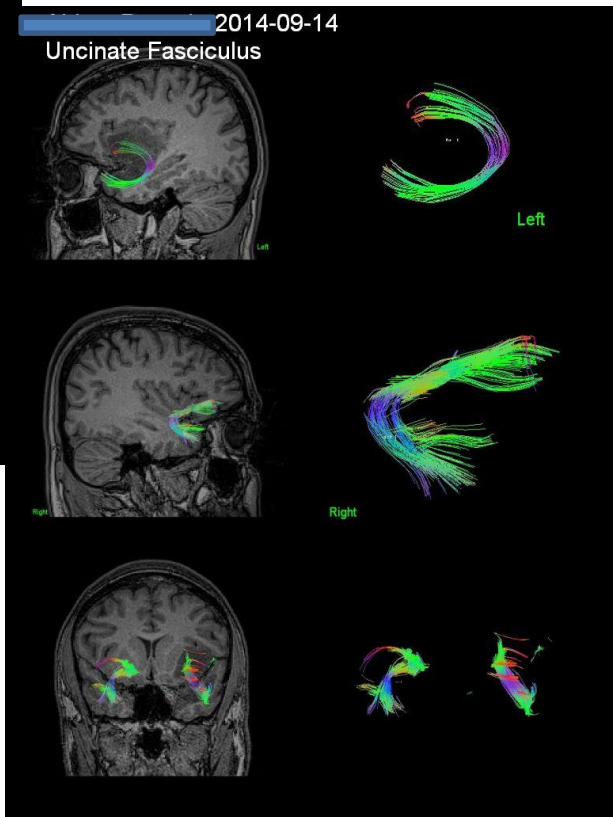
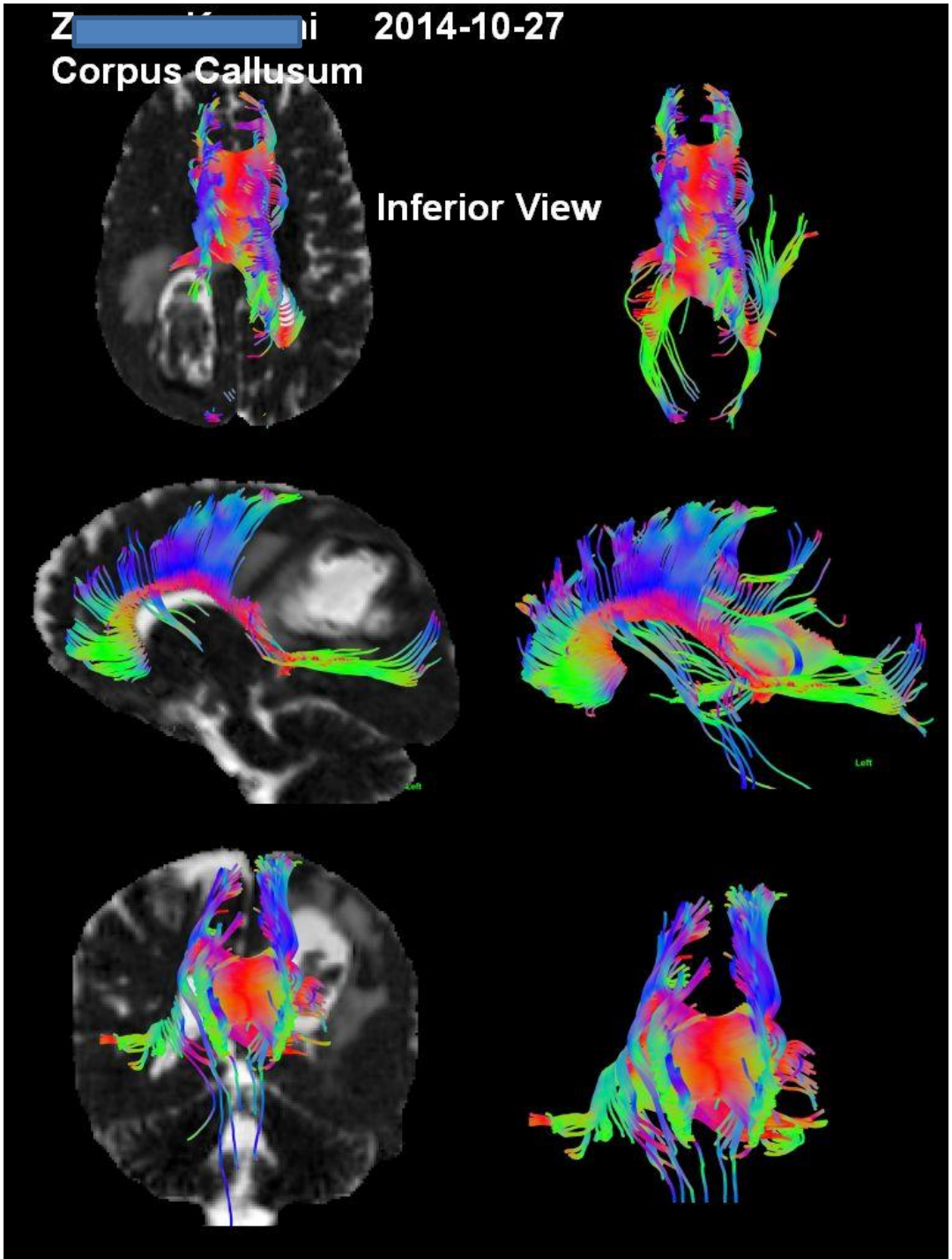
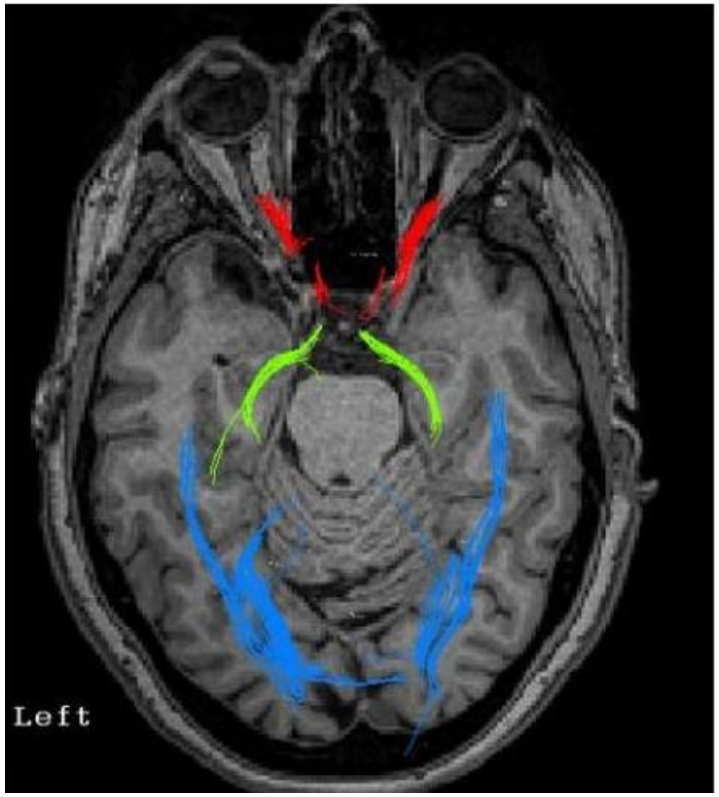
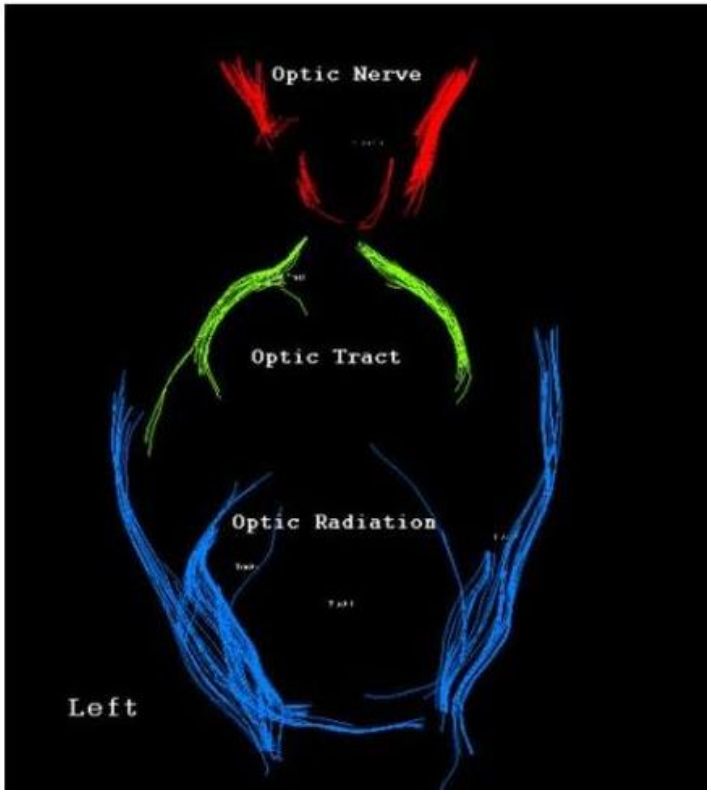
Uncinate Fasciculus

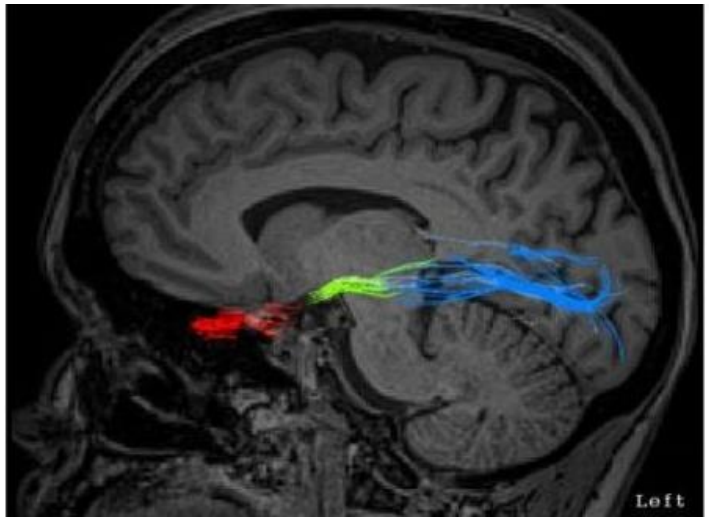


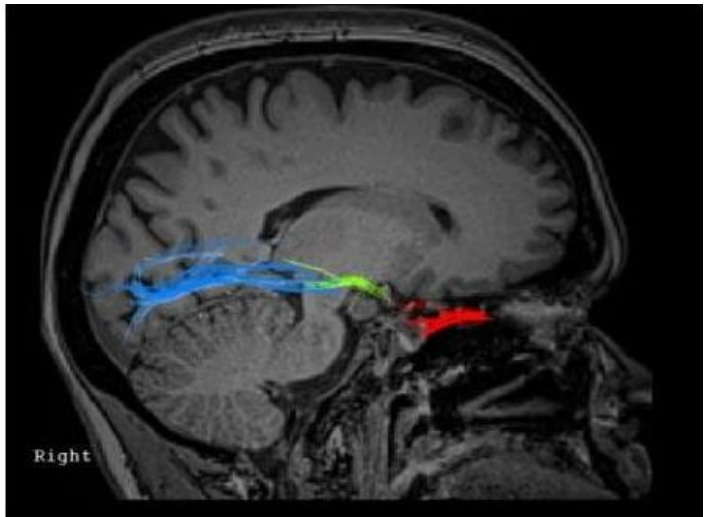

Z [redacted] i 2014-10-27
Corpus Callusum
Inferior View

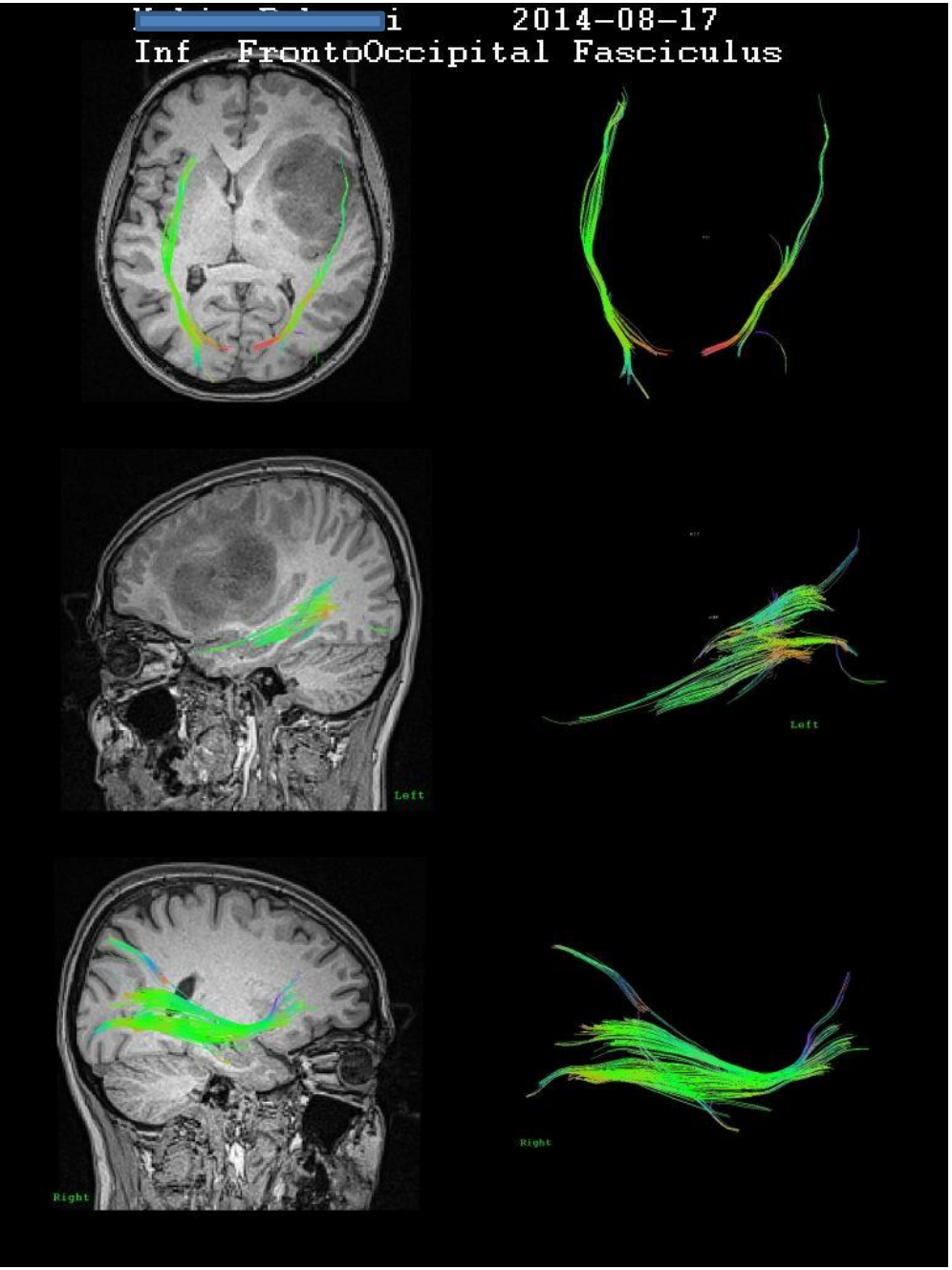
Visual Pathway Tractography







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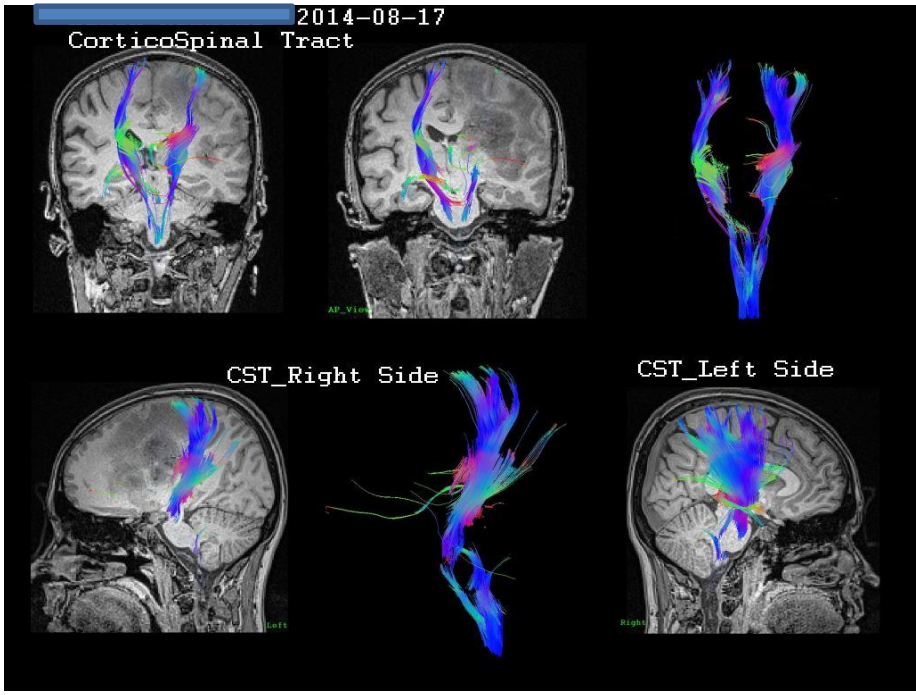
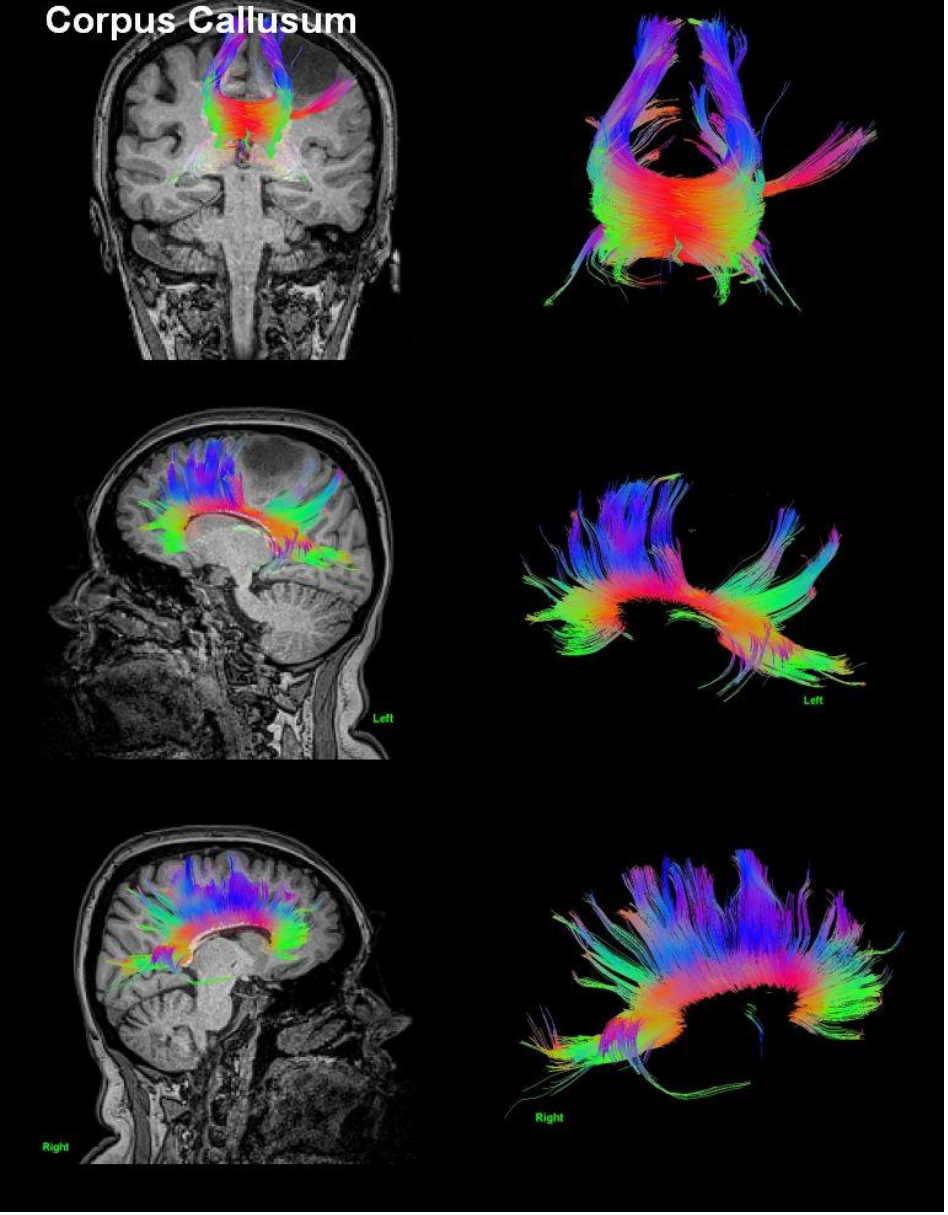
Inf. FrontoOccipital Fasciculus
Left
Left
Right
Right


[redacted] 2014-08-17
CorticoSpinal Tract
CST_Right Side
CST_Left Side

[redacted] 2014-10-12

Corpus Callusum



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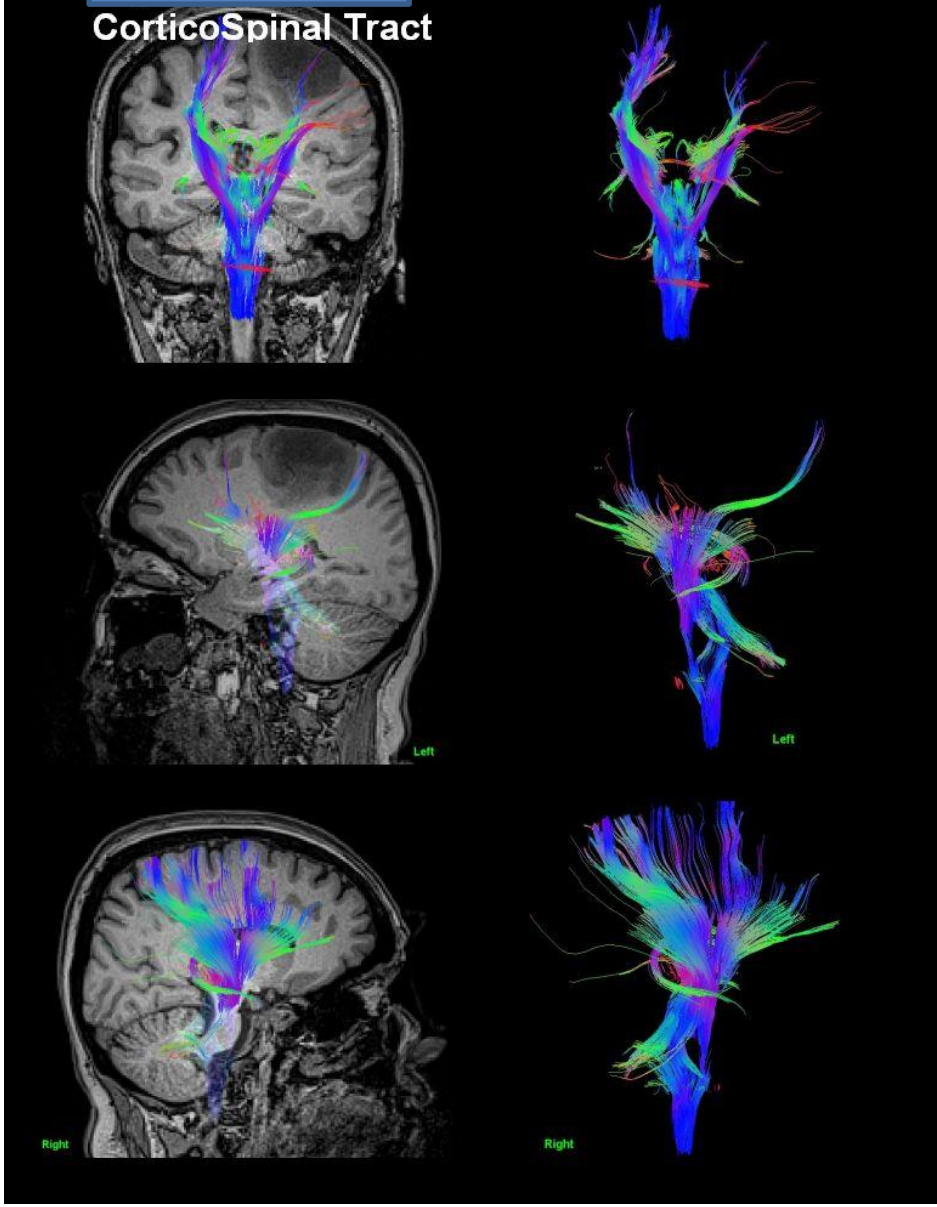
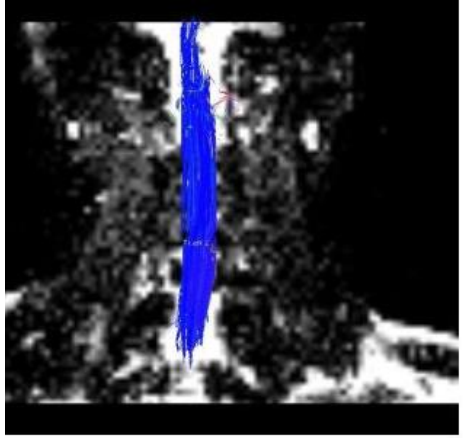
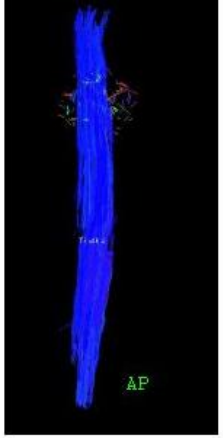
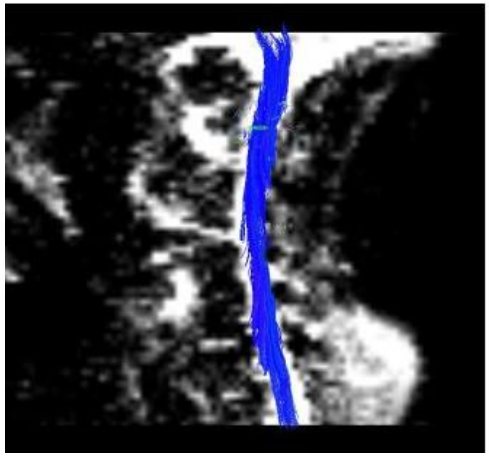
CorticoSpinal Tract

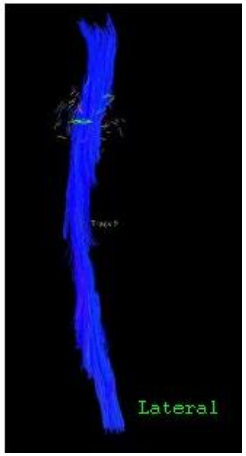


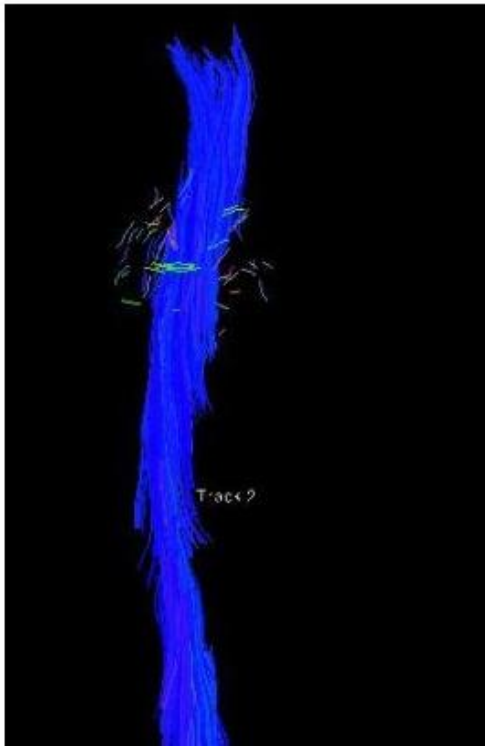
Spine Tractography
93-02-31

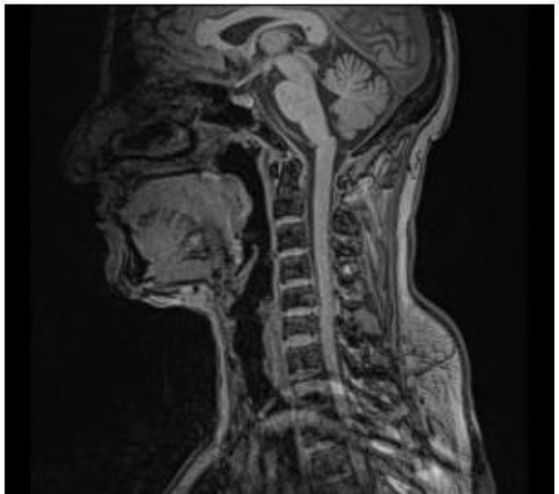


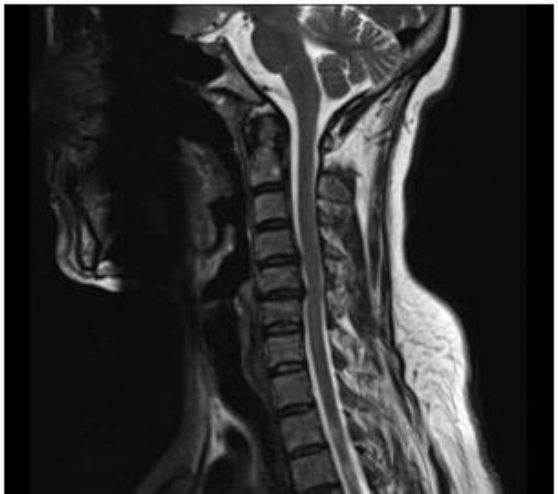












Pre-surgical Tractography Reporting

MIC

NeuroImaging and Analysis Group
Research Center for Molecular and Cellular Imaging
Imam Khomeini Imaging Center, Imam Khomeini Hospital, Tehran/Iran

NIAG

Brain DTI with Fiber tracking

Patient Name: ---------- **Age: ----------** **Date of Study: ----------**

Infarct/Lesion location (based on MRI report): ----------

Other complementary MRI studies exist for this Patient: □ Post Gd, □ fMRI, □ MRS, □ DWI, □ DCE/Perfusion

MRI Sequence: 2D EPI, 20 Axial slices: 3 mm, In plane Res: 3×3 mm, 30 Direction

DTI Analysis: All the fiber tracts were reconstructed using a diffusion model obtain from DWI images in 30 directions, and streamline deterministic tractography algorithm with optimized parameters in NIAG lab. Tractography propagation masks (see below) were used on both patient's functional and T1 data in order to enhance the visibility of superficial and deep anatomical connectivity. This also improves the accuracy of the connectivity and reduces false positives tracks.

Pre-surgical Tractography Reporting (Cont..)

Masks used as seeds for this patient:

- ■ Corpus Callosum
- ☐ Internal Capsule
- ☐ Fornix and AC/PC
- ■ Inferior Longitudinal Fasciculus
- ☐ Superior/middle Longitudinal Fasciculus
- ☐ Fronto-occipital fasciculus
- ☐ Uncinate fasciculus
- ☐ Optical track/Optic Radiation
- ■ Standard Language Mask
- ■ Standard Motor Mask
- ■ Patient's Language map
- ☐ Patient's Hand area
- ☐ Patient's Visual area
- ☐ Patient auditory area
- ☐ Tumor volume

***Finding*:**

Please check and describe location of lesion as compared to main WM anatomical tracks, lesion dimension, mass effect, etc. Check if tumor/lesion invaded the WM fibers (eg. cortico-spinal track). Please refer to tracktography printed images for each ROI mask and check for any normal/abnormal continuity, Left&Right Symmetricity, and possible damage to track shape and length, especially in lesion areas. You may also be interested to check for any possible track termination, redirection, or relocation around lesion areas.

In the case that tracks are delineated from motor and languages fMRI masks, describe location of the fibers as compared with lesion and proximity (close or far), and report any affect implied by tumor/lesion.

Medical Physicist: **Radiologist:**

Thanks

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