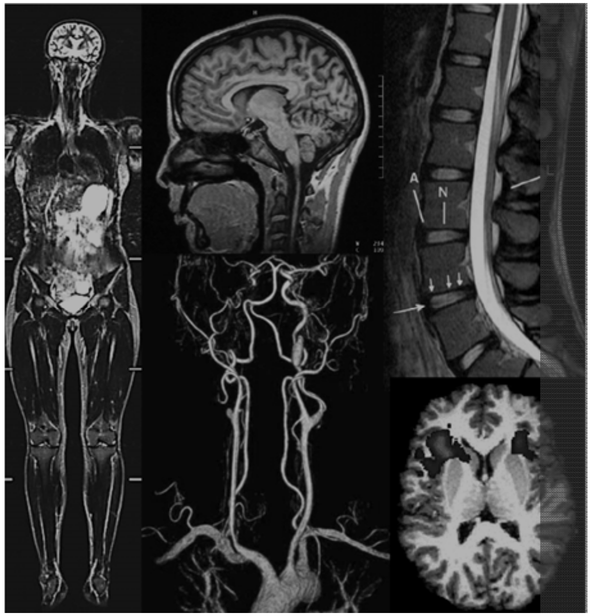
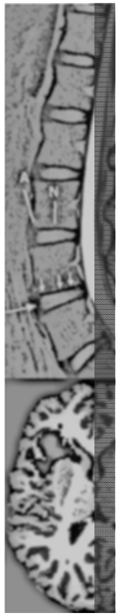


磁振擴散影像
A Course of MRI

盧家鋒 助理教授
國立陽明大學 物理治療暨輔助科技學系
alvin4016@ym.edu.tw



本週課程內容

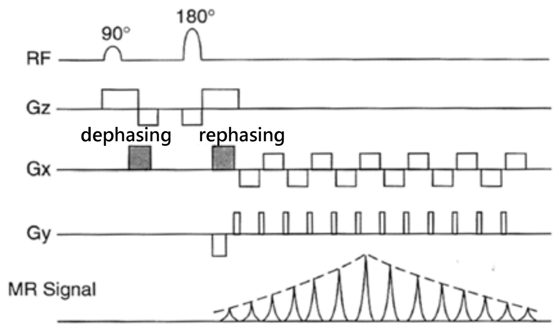
- 磁振擴散權重影像(diffusion weighted images)
- 磁振擴散張量影像(diffusion tensor images)
- 白質結構與神經纖維連結

磁振擴散權重影像

Diffusion Weighted Images

Diffusion Gradients

- Apply a pair of diffusion gradients before and after the 180° RF pulse (SE-EPI)

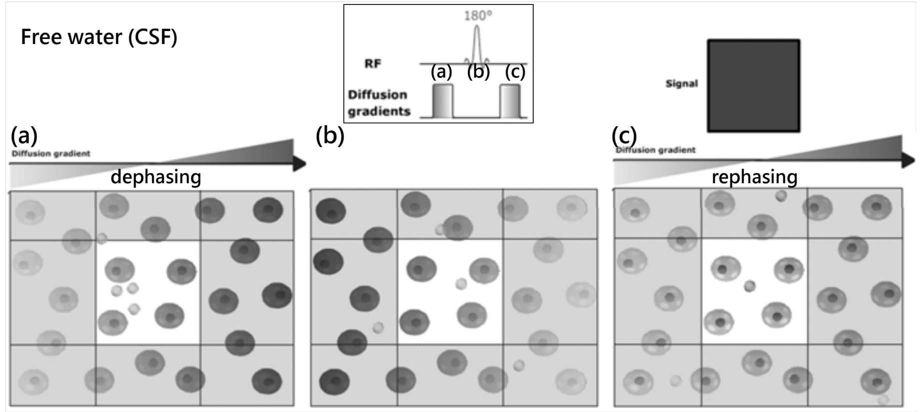


For a "fixed-position" proton, this pair of gradients won't cause dephasing.

Diffusion weighted imaging, DWI

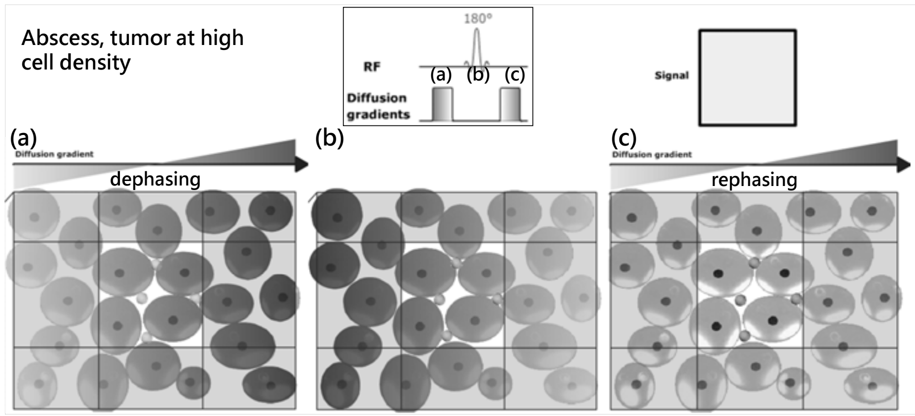
- Diffusion is defined as the process of random molecular thermal motion (Brownian motion)
  - High (free) diffusion along gradients → low signal
  - Low (restricted) diffusion along gradients → high signal
- DWI aims at highlighting the differences in water molecule mobility, irrespective of their direction of displacement.
  - Applying diffusion gradients in at least 3 spatial directions
  - Diffusion magnitude (trace image)
  - T2-weighted image

Diffusion gradient and motion



IMAIO 2014, http://www.imaios.com/en/e-Courses/e-MRI/Diffusion-Tensor-Imaging/diffusion-principles

Diffusion gradient and motion



IMAIO 2014, http://www.imaios.com/en/e-Courses/e-MRI/Diffusion-Tensor-Imaging/diffusion-principles

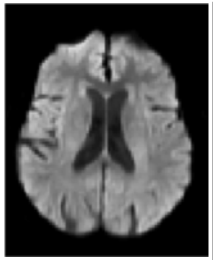
Diffusion weighted imaging, DWI

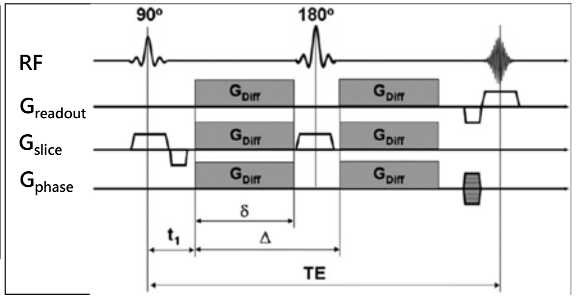
- Diffusional signal loss by the gradient application
  - $\frac{S}{S_0} = e^{-\gamma^2 G^2 \delta^2 \left(\Delta - \frac{\delta}{3}\right) D} = e^{-bD}$
  - S_0 is the signal intensity with out the diffusion weighting (no gradient application)
  - S is the signal with the gradient application
  - D is a diffusion constant
  - γ is the gyromagnetic ratio
  - G is the gradient strength
  - δ is the gradient duration
  - Δ is the time interval between dephasing and rephasing gradients

Diffusion weighted imaging, DWI

- Apply diffusion gradients along each orthogonal axis simultaneously.
- Isotropically diffusion-wieghted images

SE DWI

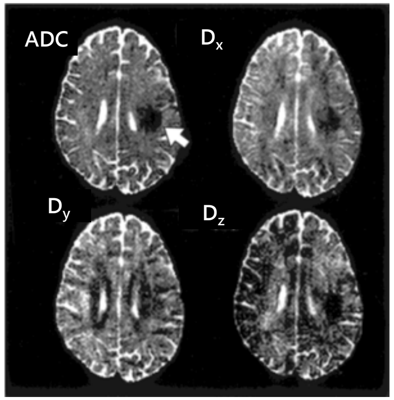




R. Bammer, EJR 45:169-184, 2003

Apparent Diffusion Coefficient, ADC

- Apply diffusion gradients along each orthogonal axis to obtain D_x, D_y, and D_z, respectively.
- $ADC = \frac{D_x+Dy+Dz}{3}$
- ADC is an isotropic (directional independent) map.
- ADC↓ for acute stroke infarction

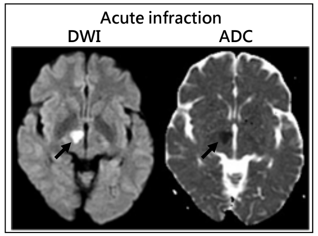


Mori et al. Anat Record 257:102-109, 1999.

DWI/ADC of stroke

Acute stroke
Sensitivity: 88~100%
Specificity: 86-100%

- Acute (0~7 days)
  - ADC↓(hypo-intensity), maximal signal reduction at 1~4 days
  - DWI↑(hyper-intensity)
  - Ischemia→ cytotoxia edema(intact BBB)→ restricted extracelluar space
- Subacute (1~3 weeks)
  - ADC return to near baseline (~2 weeks)
  - DWI↑(hyper-intensity), due to high T2 signal caused by vasogenic edema (disrupted BBB)
  - Irreversible tissue necrosis
- Chronic (>3 weeks)
  - ADC↑(hyper-intensity), DWI↓(hypo-intensity)



- http://radiopaedia.org/articles/diffusion-weighted-mri-in-acute-stroke-1
- http://www2.cmu.edu.tw/~cmcmd/ctanatomy/clinical/ischemicinfarction.html

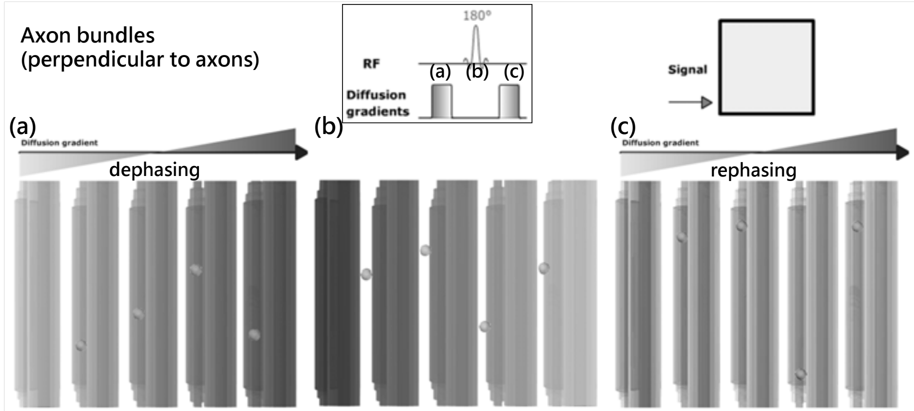
磁振擴散張量影像

Diffusion Tensor images

Diffusion MRI

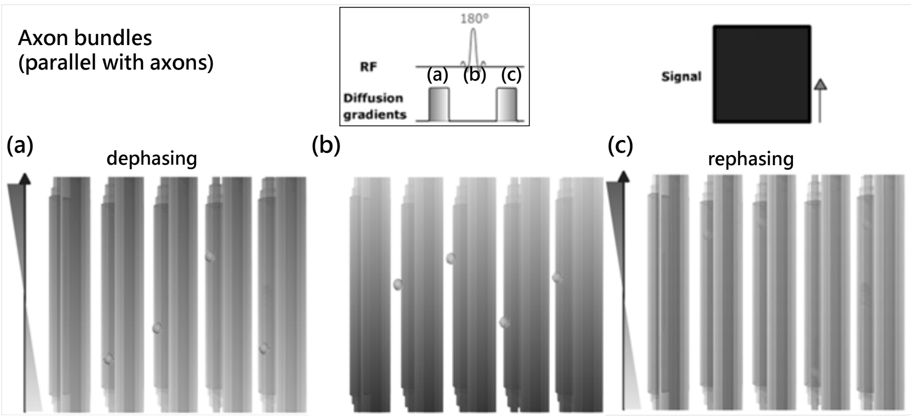
- Two types of diffusion acquisition
  - Isotropic (directional independent) maps
    - DWI, ADC, and TRACE
  - Anisotropic (directional dependent) maps
    - FA, RA, VR
- The anisotropic maps (related to diffusion tensors) can provide information about the micro-structural properties of tissue.

Diffusion gradient and motion



IMAIO 2014, http://www.imaios.com/en/e-Courses/e-MRI/Diffusion-Tensor-Imaging/diffusion-principles

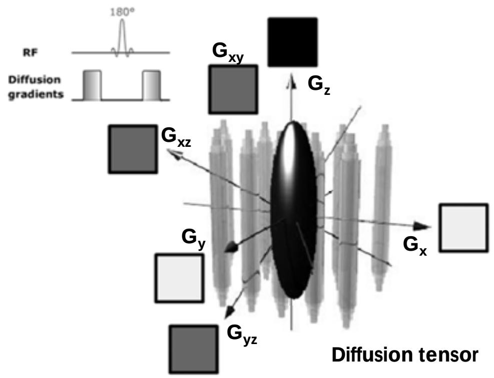
Diffusion gradient and motion



IMAIO 2014, http://www.imaios.com/en/e-Courses/e-MRI/Diffusion-Tensor-Imaging/diffusion-principles

Diffusion tensor imaging, DTI

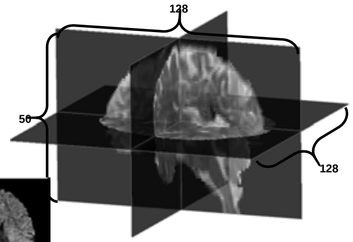
- Perform diffusion-weighted acquisitions in at least 6 non-collinear directions with 1 b0 (no diffusion gradient)
- We can reconstruct the diffusion tensor of D_{xx}, D_{yy}, D_{zz}, D_{xy}, D_{xz}, D_{yz}.

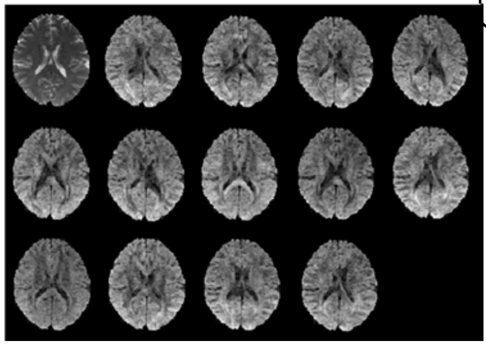


IMAIO 2014, http://www.imaios.com/en/e-Courses/e-MRI/Diffusion-Tensor-Imaging/diffusion-tensor-anisotropy

1.5 Tesla GE Echo speed scanner system

- multi-slice gradient-echo EPI pulse sequence
- FOV: 240x240 mm
- matrix = 128x128; slice = 50
- 3 mm slice thickness; no inter-slice distance
- TE: 69.70 ms; TR: 15000 ms
- b-value: 1000 s/mm^2
- thirteen directional DWI images





13-direction encoding table

	x	y	z
1	-0.754267365796	0.173499508397	-0.633228759202
2	0.330321246216	-0.372227441281	0.867372242037
3	-0.533035489131	-0.458931921778	0.710812674690
4	-0.686807855664	-0.708384153523	-0.162747843106
5	-0.321357401597	0.941504078299	-0.101486407881
6	0.617869468935	0.786068318474	-0.018273424674
7	0.019352413289	0.576222568464	0.817063666854
8	0.311368579326	-0.948900371701	0.051358469549
9	-0.882505894394	0.313694805173	0.350398224264
10	-0.038448968078	-0.536051111410	-0.843309482225
11	0.184148321180	0.468947287620	-0.863815858410
12	0.936881686583	0.003852303897	0.349625321023
13	0.813567705110	-0.236010693892	-0.531419365069

Diffusion tensor matrix

The diffusional signal loss by the gradient application: $\frac{S}{So} = e^{-bD}$

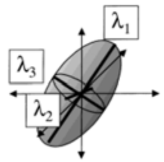
13 x 1 ***13 x 6*** ***6 x 1***

$$\begin{bmatrix} S1 \\ S2 \\ \dots \\ S13 \end{bmatrix} = -b \begin{bmatrix} b1xx & b1yy & b1zz & b1xy & b1xz & b1yz \\ b2xx & b2yy & b2zz & b2xy & b2xz & b2yz \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ b13xx & b13yy & b13zz & b13xy & b13xz & b13yz \end{bmatrix} \begin{bmatrix} Dxx \\ Dyy \\ Dzz \\ Dxy \\ Dxz \\ Dyz \end{bmatrix}$$

The matrix of diffusion tensor

$$\begin{bmatrix} Dxx & Dxy & Dxz \\ Dyx & Dyy & Dyz \\ Dzx & Dzy & Dzz \end{bmatrix} \xrightarrow{\text{eigenvectors}}$$

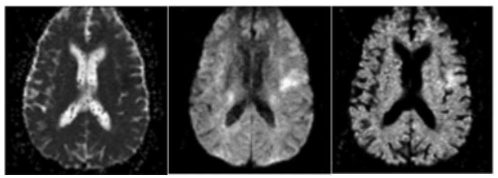
Three principal axes of ellipsoid model



Isotropic maps from DTI

- TRACE image
  - $D_{xx} + Dyy + Dzz$
- Exponential ADC (eADC)
  - $e^{-b(Dxx+Dyy+Dzz)}$
- Isotropically DWI (isoDWI)
  - $I_0 \cdot e^{-b(Dxx+Dyy+Dzz)}$

$$\begin{bmatrix} Dxx & Dxy & Dxz \\ Dyx & Dyy & Dyz \\ Dzx & Dzy & Dzz \end{bmatrix}$$



Harris et al. JMRI 20:193-200, 2004.

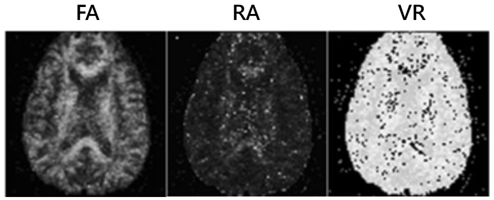
Anisotropic maps from DTI

- Fractional Anisotropy (FA)
  - Ratio of the anisotropic component of the diffusion tensor
- Relative anisotropy (RA)
  - Ratio of the magnitude of the anisotropic and isotropic parts of diffusion tensor matrix
- Volume ratio (VR)
  - Ratio of the volume of the diffusion ellipsoid with the volume of an equivalent isotropic diffusion sphere

Anisotropic maps from DTI

- Fractional Anisotropy (FA)
  - $FA = \sqrt{\frac{1}{2}} \cdot \frac{\sqrt{(\lambda_1-\lambda_2)^2+(\lambda_2-\lambda_3)^2+(\lambda_3-\lambda_1)^2}}{\sqrt{\lambda_1^2+\lambda_2^2+\lambda_3^2}}$
- Relative anisotropy (RA)
  - $RA = \frac{\sqrt{(\lambda_1-\lambda_2)^2+(\lambda_2-\lambda_3)^2+(\lambda_3-\lambda_1)^2}}{\lambda_1+\lambda_2+\lambda_3}$
- Volume ratio (VR)
  - $VR = \frac{\lambda_1\lambda_2\lambda_3}{\left(\frac{\lambda_1+\lambda_2+\lambda_3}{3}\right)^3}$

$$\begin{bmatrix} Dxx & Dxy & Dxz \\ Dyx & Dyy & Dyz \\ Dzx & Dzy & Dzz \end{bmatrix} \rightarrow \begin{bmatrix} \lambda_1 & 0 & 0 \\ 0 & \lambda_2 & 0 \\ 0 & 0 & \lambda_3 \end{bmatrix}$$



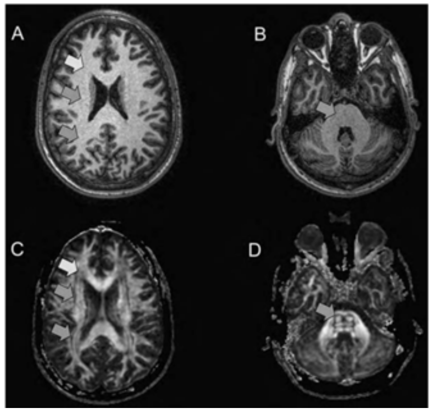
Harris et al. JMRI 20:193-200, 2004.
R. Bammer, EJR 45:169-184, 2003.

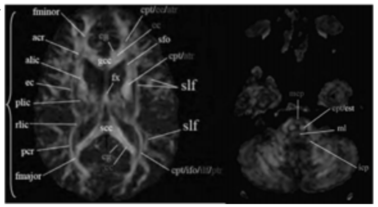
白質結構與神經纖維連結

Mori et al. MRI Atlas of Human White Matter, Elsevier, 2005.

White matter structure

- The DTI (C and D)can provide the internal structure of WM, which can only be presented as a homogeneous field in T1W images (A and B).

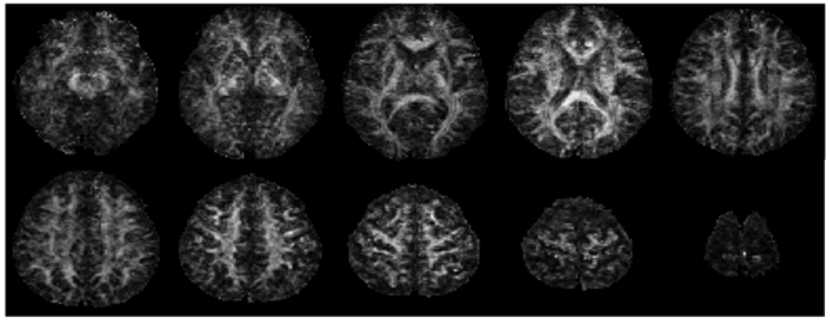




Mori et al. MRI Atlas of Human White Matter, Elsevier, 2005.

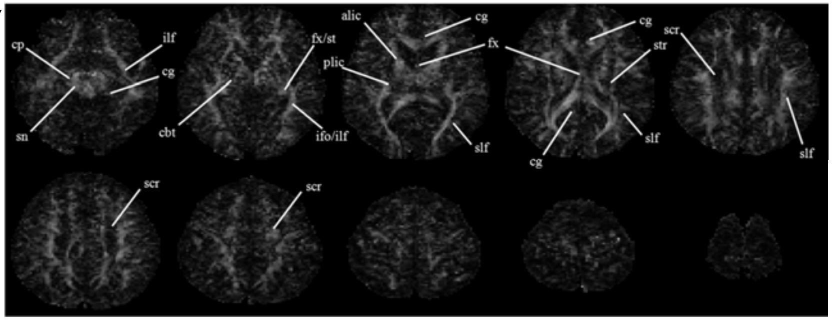
Fractional Anisotropy (FA) map

- Higher intensity → larger anisotropic property of water molecular motion.



Color-coded orientation map

- Color coding of the principal axes (the 1st eigenvector)



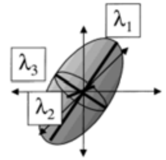
DTI tractography

The matrix of diffusion tensor

$$\begin{bmatrix} Dxx & Dxy & Dxz \\ Dyx & Dyy & Dyz \\ Dzx & Dzy & Dzz \end{bmatrix}$$

eigenvectors

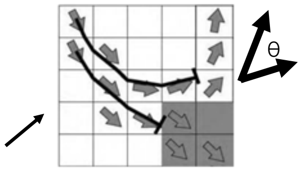
Three principal axes of ellipsoid model



Map of 1st principal axes

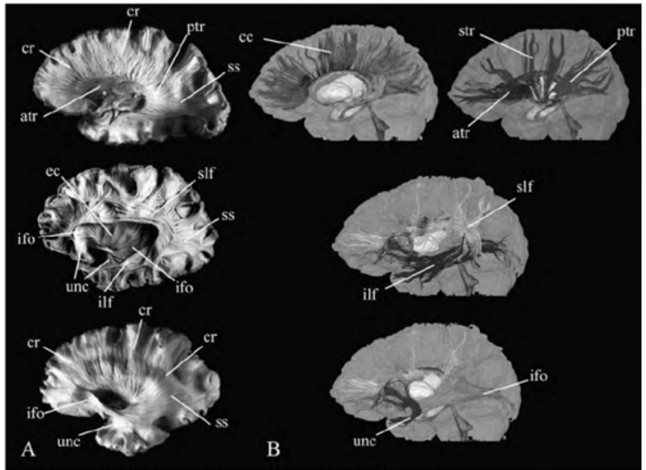
Fiber Assignment by Continuous Tracking (FACT) algorithm

- Stopping criteria
  - FA lower than 0.2
  - Turning angle larger than 60°



(every voxel is seed)

Axonal fiber bundles

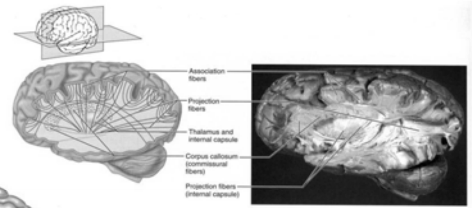


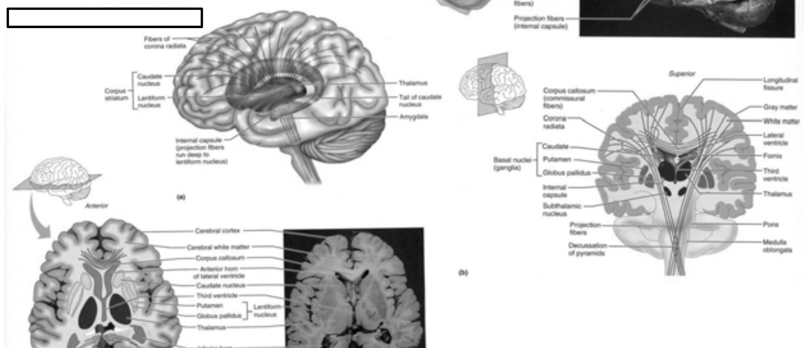
- Tract
- Fasciculus
- radiation

Mori et al. MRI Atlas of Human White Matter, Elsevier, 2005.

Neuronal Fiber types

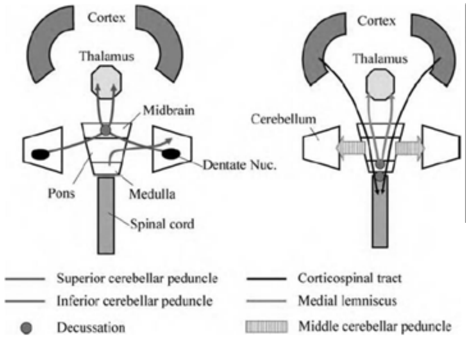
- Commissures
- Association fibers
- Projection fibers

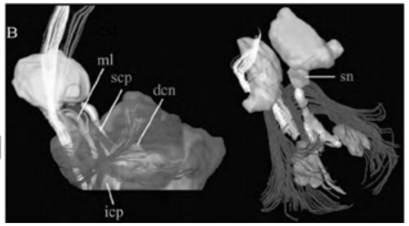




E.N. Marieb. Human anatomy, 3rd (2001)

Tracts in the brainstem

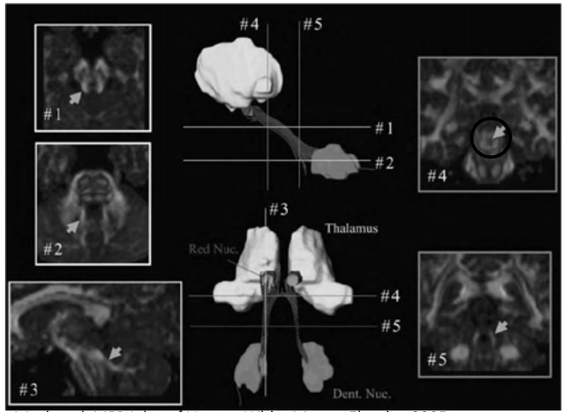




- Superior cerebellar peduncle (scp)
- Middle cerebellar peduncle (mcp)
- Inferior cerebellar peduncle (icp)
- Corticospinal tract (cst)
- Medial lemniscus (ml)

Mori et al. MRI Atlas of Human White Matter, Elsevier, 2005.

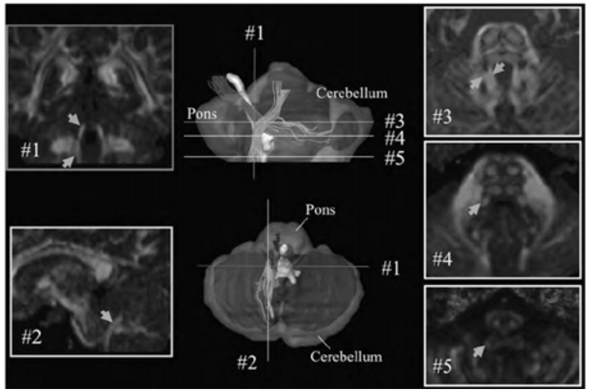
Superior cerebellar peduncle



- Scp is the main efferent pathway from the dentate nucleus of the cerebellum toward the thalamus.
- Limitation at the decussation (crossing fiber)

Mori et al. MRI Atlas of Human White Matter, Elsevier, 2005.

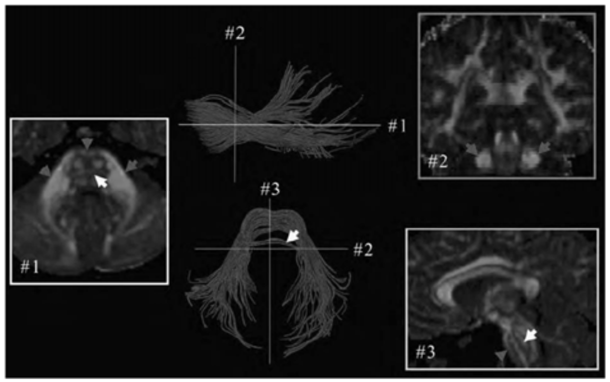
Inferior cerebellar peduncle



- Icp contains afferent and efferent connections to the cerebellum.
- It originates in the caudal medulla, transverses the pons, and branches into the cerebellar cortex.

Mori et al. MRI Atlas of Human White Matter, Elsevier, 2005.

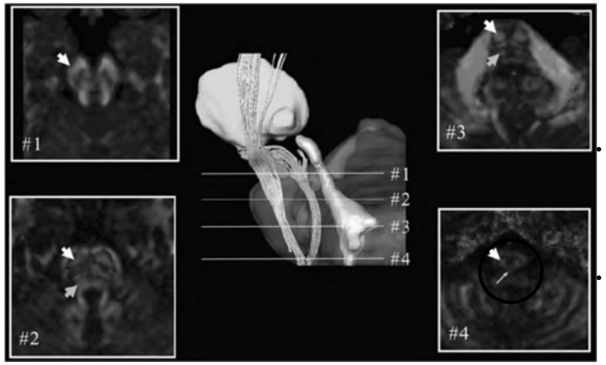
Middle cerebellar peduncle



- Mcp contains efferent fibers from the pons to the cerebellum (pontocerebellar tracts).

Mori et al. MRI Atlas of Human White Matter, Elsevier, 2005.

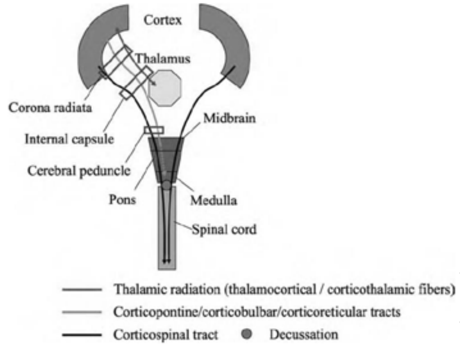
Medial lemniscus & corticospinal tract



- Ml is a major pathway for ascending sensory fibers, decussated at the level of ventral medulla (#4).
- Cst is a descending pathway from the cortex. Its penetrates the cerebral peduncles.

Mori et al. MRI Atlas of Human White Matter, Elsevier, 2005.

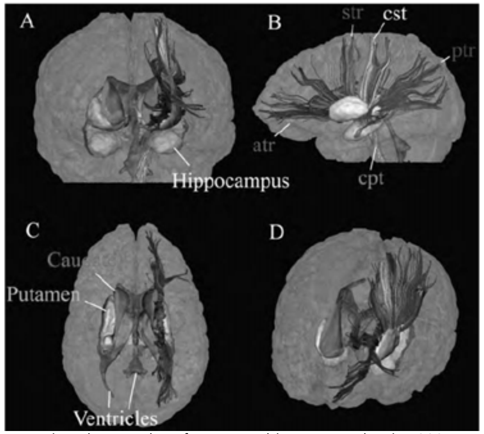
Projection fibers



- Corticothalamic/thalamocortical fibers (thalamic radiations)
- Corticopontine tracts (cpt)

Mori et al. MRI Atlas of Human White Matter, Elsevier, 2005.

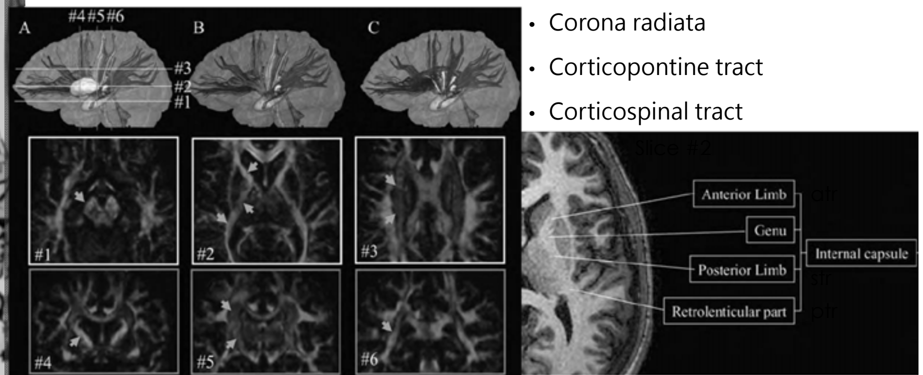
Corona radiata



- Corona radiata (reciprocal connections)
  - Anterior thalamic radiation (atr)
  - Superior thalamic radiation (str)
  - Posterior thalamic radiation (ptr)

Mori et al. MRI Atlas of Human White Matter, Elsevier, 2005.

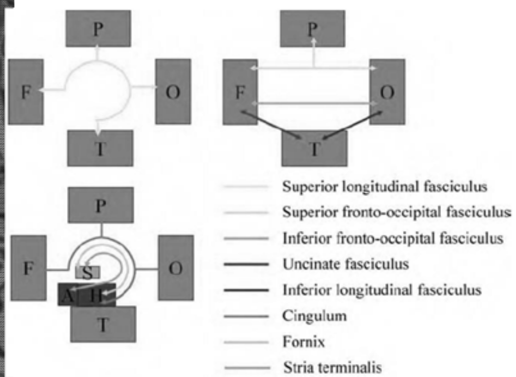
Internal capsule



- Corona radiata
- Corticopontine tract
- Corticospinal tract

Mori et al. MRI Atlas of Human White Matter, Elsevier, 2005.

Association fibers

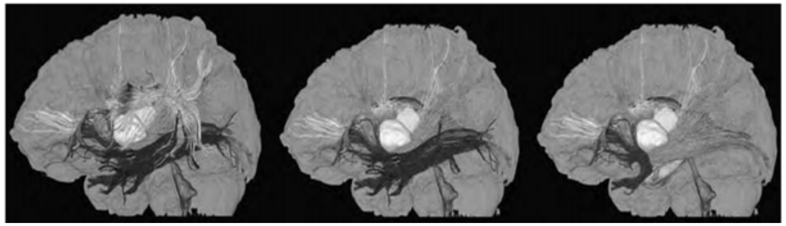


- Short association fibers
  - Within lobe, adjacent gyri, U-fibers
- Long association fibers
  - Between lobes, prominent fiber bundles

Mori et al. MRI Atlas of Human White Matter, Elsevier, 2005.

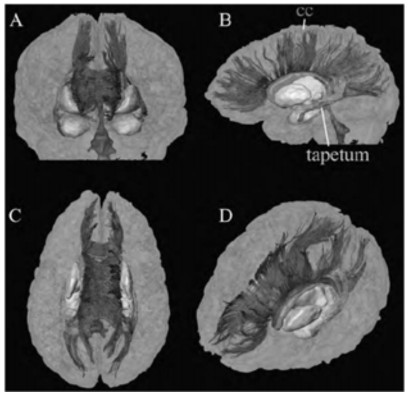
Association fibers

- Superior longitudinal fasciculus (yellow)
- Inferior longitudinal fasciculus (brown)
- Uncinate fasciculus (red)
- Superior fronto-occipital fasiculus (light yellow)
- Inferior fronto-occipital fasiculus (orange)



Mori et al. MRI Atlas of Human White Matter, Elsevier, 2005.

Commissural fibers

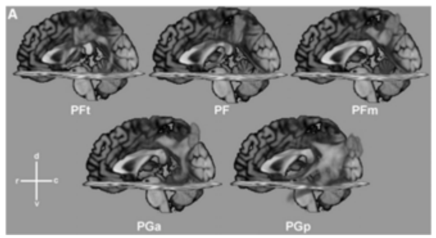


- Corpus callosum (cc)
  - Contains more than 300 million axons
  - The largest fiber bundle in the human brain
  - Interconnect homologous cortical area between hemispheres
- DTI-based tractography often fails to reveal commissural connections to the lateral areas of the hemispheres.

Mori et al. MRI Atlas of Human White Matter, Elsevier, 2005.

Other options of tractography

- Probabilistic fiber tracking
  - In contrast to the deterministic fiber tracking technique (e.g. FACT)
  - Provide the probability maps of fiber connections from a given seed ROI.
  - Huge computation consumption
- Solutions of crossing fiber problem
  - Increase the directions of gradient table
  - Diffusion spectrum imaging (DSI)
  - Q-ball imaging (QBI)



Caspers et al. NeuroImage, 58(2):362-380, 2011.

THE END

alvin4016@ym.edu.tw