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

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 $\rightarrow$ low signal
  - Low (restricted) diffusion along gradients $\rightarrow$ 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**

- Abscess, tumor at high cell density

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

- $S_0$ 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
- $\gamma$ is the gyromagnetic ratio
- $G$ is the gradient strength
- $\delta$ is the gradient duration
- $\Delta$ is the time interval between dephasing and rephasing gradients
Diffusion weighted imaging, DWI

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

\[ \text{ADC} = \frac{D_x + D_y + D_z}{3} \]

ADC is an isotropic (directional independent) map.

ADC↓ for acute stroke infarction

ADC↑ (hyper-intensity), due to high T2 signal caused by vasogenic edema (disrupted BBB)

Irreversible tissue necrosis

DWI/ADC of stroke

- Acute (0~7 days)
  - ADC↓ (hypo-intensity), maximal signal reduction at 1~4 days
  - DWI↑ (hyper-intensity)
  - Ischemia→ cytotoxia edema (intact BBB)→ restricted extracellular 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)

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

http://radiopaedia.org/articles/diffusion-weighted-mri-in-acute-stroke-1

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

- Axon bundles (perpendicular to axons)
- Axon bundles (parallel with axons)

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 $D_{xx}$, $D_{yy}$, $D_{zz}$, $D_{xy}$, $D_{xz}$, $D_{yz}$.
1.5 Tesla GE Echo speed scanner system
- multi-slice gradient-echo EPI pulse sequence
- FOV: 240 x 240 mm
- matrix: 128 x 128; slice = 50
- 3 mm slice thickness; no inter-slice distance
- TE: 69.70 ms; TR: 15000 ms
- b-value: 1000 s/mm²
- thirteen directional DWI images

Diffusion tensor matrix

The diffusional signal loss by the gradient application:

$$ S = e^{-10 \cdot g} $$

The matrix of diffusion tensor

<table>
<thead>
<tr>
<th>$S$</th>
<th>$b_{xx}$</th>
<th>$b_{yy}$</th>
<th>$b_{zz}$</th>
<th>$b_{xy}$</th>
<th>$b_{xz}$</th>
<th>$b_{yz}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_1$</td>
<td>$b_{xx}$</td>
<td>$b_{yy}$</td>
<td>$b_{zz}$</td>
<td>$b_{xy}$</td>
<td>$b_{xz}$</td>
<td>$b_{yz}$</td>
</tr>
<tr>
<td>$S_2$</td>
<td>$b_{xx}$</td>
<td>$b_{yy}$</td>
<td>$b_{zz}$</td>
<td>$b_{xy}$</td>
<td>$b_{xz}$</td>
<td>$b_{yz}$</td>
</tr>
<tr>
<td>$S_{13}$</td>
<td>$b_{33}$</td>
<td>$b_{33}$</td>
<td>$b_{33}$</td>
<td>$b_{33}$</td>
<td>$b_{33}$</td>
<td>$b_{33}$</td>
</tr>
</tbody>
</table>

Three principal axes of ellipsoid model

Isotropic maps from DTI
- TRACE image
  - $D_{xx} + D_{yy} + D_{zz}$
- Exponential ADC (eADC)
  - $e^{-b(D_{xx} + D_{yy} + D_{zz})}$
- Isotropically DWI (isoDWI)
  - $I_0 \cdot e^{-b(D_{xx} + D_{yy} + D_{zz})}$

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)
  \[ FA = \sqrt[2]{ \frac{(1-\lambda_3^2) + (1-\lambda_2^2) + (1-\lambda_1^2)}{\lambda_1 + \lambda_2 + \lambda_3} } \]

- Relative anisotropy (RA)
  \[ RA = \frac{\sqrt{(1-\lambda_3^2) + (1-\lambda_2^2) + (1-\lambda_1^2)}}{\lambda_1 + \lambda_2 + \lambda_3} \]

- Volume ratio (VR)
  \[ VR = \frac{\lambda_1 \lambda_2 \lambda_3}{(\lambda_1^2 + \lambda_2^2 + \lambda_3^2)^{\frac{3}{2}}} \]

Fractional Anisotropy (FA) map

Higher intensity → larger anisotropic property of water molecular motion.

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).

White matter structure

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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

\[
\begin{bmatrix}
D_{xx} & D_{xy} & D_{xz} \\
D_{yx} & D_{yy} & D_{yz} \\
D_{zx} & D_{zy} & D_{zz}
\end{bmatrix}
\]

eigenvectors

Three principal axes of ellipsoid model

Fiber Assignment by Continuous Tracking (FACT) algorithm

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

Axonal fiber bundles

- Tract
- Fasciculus
- Radiation

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)

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)

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.

Middle cerebellar peduncle

- Mcp contains efferent fibers from the pons to the cerebellum (pontocerebellar tracts).
**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. It penetrates the cerebral peduncles.

**Projection fibers**

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

**Corona radiata**

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

**Internal capsule**

- Corona radiata
- Corticopontine tract
- Corticospinal tract
Association fibers

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


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.


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)
