Diffusion MRI

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Advanced MRI in the Clinic

Learning Objectives

- To understand commonly-used diffusion MRI pulse sequences in the clinic;
- To understand the common diffusion models in diffusion MRI analysis;
- To be able to implement diffusion imaging protocols and conduct quality assurance.

Outline

- Diffusion MRI signals
- Diffusion models and protocols
- Examples of clinical applications
- Quality assurance

Diffusion-Weighted Imaging

\[ S = S_0 \exp(-bD) \]

\( b \): b-factor
\( D \): diffusion coefficient

Diffusion Gradient in a Spin Echo Sequence

- Stejskal and Tanner gradient

\[ b \approx \gamma^2 G^2 \delta^2 \left( \Delta - \delta/3 \right) \]

The sequence is extremely sensitive to motion.

Acquired using a single-shot EPI pulse sequence at 3T

**DWI Using Single-Shot EPI in the Abdomen**


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**Single-Shot EPI for Diffusion Imaging**

- **Pros**
  - Motion resilient
  - Low SAR
  - Time efficient

- **Cons**
  - Image distortion (sensitivity to off-resonance)
  - Low spatial resolution
  - Sensitivity to eddy currents

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**Multi-shot EPI diffusion**

- Higher resolution (e.g., 256^2)
- Less distortion
- Reduced sensitivity to eddy currents
- Less ghosting
- Slower
- Motion correction is needed (MUSE, RESOLVE, etc.)
- Residual motion artifacts

**PROPELLER/BLADE/Multi-VANE Diffusion**

- Very robust against motion
- Distortion free
- Relatively slow

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**ADC vs. Cellularity**

Clinical Demonstration on Patients

- Jiang; BJR 2016 (Breast cancer)
- Chen; PlosONE 2014 (Lung cancer)
- Kishimoto; Acta Radiol 2016 (Endometrial cancer)

Average \( r = -0.61 \)

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**Logarithm of Relative Signal Intensity**

\[
\text{Log} \left( \frac{S}{S_0} \right) = S_0 \exp(-bD)
\]

\( D \): apparent diffusion coefficient (ADC)

Gaussian Diffusion (monoexponential model) → Cellularity

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**b-value (s/mm^2)**

- 0 ~ 200
- 200 ~ 1,500
- 1,500 ~ 4,000
- 4,000 ~ 8,000

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**ADC maps**

Pipe et al., MRM 47: 42-52, 2002

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**b = 1000 s/mm^2**

128x128

~1 min/image
**IVIM Diffusion Imaging**

\[
\frac{S}{S_0} = f \exp(-bD^*) + (1-f)\exp(-bD)
\]

Perfusion fraction (f); pseudo-diffusion coefficient (D*); diffusion coefficient (D).

- Note that D << D*
- D* mimics perfusion, but is not perfusion.
- 3-8 b-values are typically used.

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**IVIM: Differentiation between Malignant and Benign Mediastinal Lymph Nodes (MLN)**

<table>
<thead>
<tr>
<th>8 b-values (0-1000 s/mm²)</th>
<th>Benign</th>
<th>Malignant</th>
</tr>
</thead>
<tbody>
<tr>
<td>IVIM D</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IVIM D*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IVIM f</td>
<td></td>
<td></td>
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<tr>
<td>ADC (mm²/sec)</td>
<td></td>
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</tbody>
</table>

**Diffusion “b-Spectrum”**

- Gaussian parameters can complement ADC.

**Diffusion Models**

- **Gaussian**
  - Mono-exponential
  - ADC
  - FA, MD, RD, AD, eigen-vectors, etc.

- **Non-Gaussian**
  - Compartmentalized models
    - IVIM, NODDI, AxCaliber, Charmed, RSI, VERDICT, etc.
  - Non-compartmentalized models
    - DSI, q-Ball, DTI, DKG, stretch exponential, fractal, CTRW, PRCO, FM, etc.
Fractional Order Calculus (FROC) Model

\[ M_T = M_0 \exp\left(-D r^{2\beta-1/2}\left(\mu - \frac{2\beta - 1}{2\beta + 1}\right)\right) \]

- \( D \): Diffusion coefficient, similar to ADC
- \( \beta \): Degree of intravoxel tissue heterogeneity
- \( \mu \): Spatial quantity, related to the diffusion mean free length

Example of Grading Pediatric Brain Tumors

Diffusion Tensor Imaging

- Applying the diffusion gradient in \( \geq 6 \) directions
- Analyzing the signals using a diffusion tensor
- Fractional anisotropy (FA)
- Mean diffusivity (MD)
- Principal eigen-vector \( \rightarrow \) tractography

DTI for Pre-Surgical Planning

Tissue Heterogeneity

0 1 (Gaussian)

Low-grade High-grade

D \( \beta \) \( \mu \) T2

Ependymoma PA PA Medulloblastoma

AT/RT


Quality Assurance for DWI

- Image distortion
  - Use a spherical phantom
  - Check the distortion wrt the image with \( b=0 \)
  - Eddy currents (time constants \( \approx 50 -100 \) ms)
- EPI-related image quality
  - Ghosting level (< 3%)
  - SNR
- ADC accuracy
  - Use a standard water phantom at a fixed temperature
  - Check ADC value of the water phantom quarterly

Conclusions

- DWI is typically acquired using a single-shot EPI pulse sequence.
- \( b \)-Value determines the degree of diffusion weighting, and probes the different tissue structural information.
- ADC is the most prevalent parameter used clinically.