Diffusion MRI

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Advanced MR in Clinic

Outline

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

Learning Objectives

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

Diffusion-Weighted Imaging

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

- \( S_0 \): T2-weighted
- \( S \): Diffusion-weighted (DW) image
- \( b \): b-factor
- \( D \): diffusion coefficient

Diffusion Gradient in a Spin Echo Sequence

- Stejskal and Tanner gradient
- b-value

\[ b \approx \gamma^2 G_d^2 \delta^2 (\Delta - \delta / 3) \]

\[ S = S_0 e^{-bD} \]

The sequence is extremely sensitive to motion.

Diffusion-Weighted Imaging of the Human Brain

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

- Zou XJ, et al., MRM 2010; 63:562-569
**DWI Using Single-Shot EPI in the Abdomen**


**Single-Shot EPI for Diffusion Imaging**

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

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

**Multi-shot EPI diffusion**

- Higher resolution (e.g., 256²)
- 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

**ADC vs. Cellularity**

Clinical Demonstration on Patients

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

Average $r = -0.61$
IVIM Diffusion Imaging

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

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

- \( D^* \) mimics perfusion, but is not perfusion.
- 3-8 \( b \)-values are typically used.

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

Diffusion “b-Spectrum”

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

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

\[ M_D = M_0 \exp \left[ -D_D^{(2\beta - 1)} (\gamma G_0 \delta)^{2\beta} \left( \Delta - \frac{2\beta - 1}{2\beta + 1} \right)^{\frac{2}{\beta + 1}} \right] \]

- \( D \): 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

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

Quality Assurance for DWI
- Image distortion
  - Use a spherical phantom
  - Check the distortion with the image with \( b=0 \)
  - Eddy currents (time constants ~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