Advanced MR in Clinic

Diffusion MRI

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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.

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Outline

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

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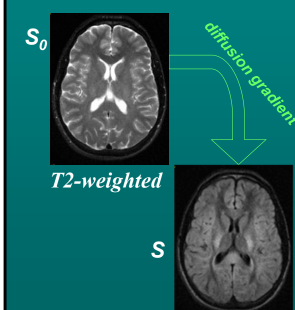
Diffusion-Weighted Imaging



$S = S_0 \exp(-bD)$

***b**: b-factor*

***D**: diffusion coefficient*

Diffusion-weighted (DW) image

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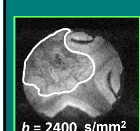
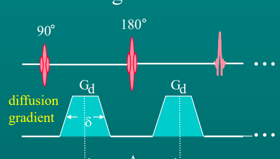
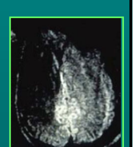
Diffusion Gradient in a Spin Echo Sequence

- 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.

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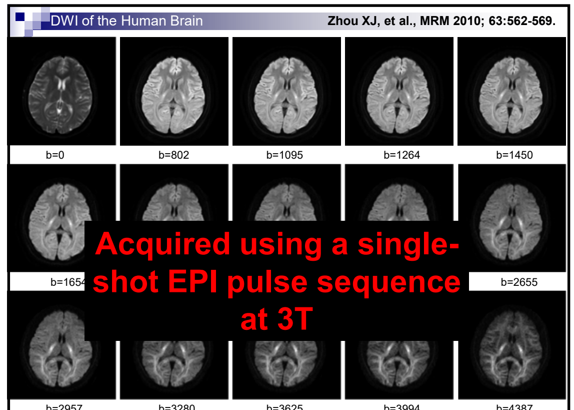
DWI of the Human Brain **Zhou XJ, et al., MRM 2010; 63:562-569.**



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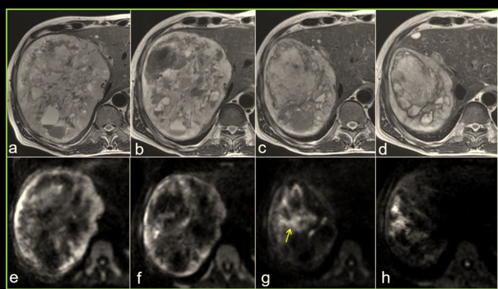
DWI Using Single-Shot EPI in the Abdomen



Tang L and Zhou XJ, JMRI 2019.

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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

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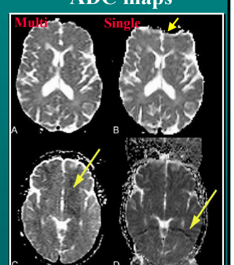
Multi-shot EPI diffusion

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

ADC maps



b = 0, 800 s/mm²; ~5 min

van Pul et al., MRI 22: 1169-1180, 2004

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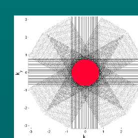
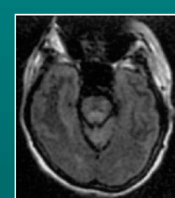
PROPELLER/BLADE/Multi-VANE Diffusion

- *Very robust against motion*
- *Distortion free*
- *Relatively slow*





b = 1000 s/mm²
128x128
~1 min/image

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

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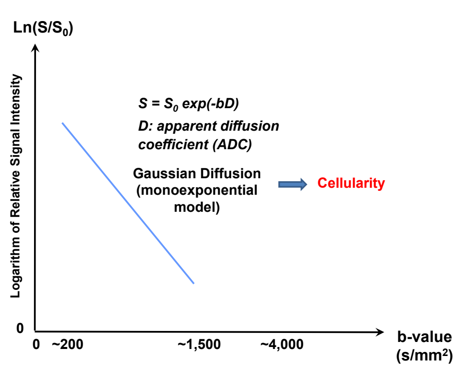

Tang L and Zhou XJ, JMRI 2019.

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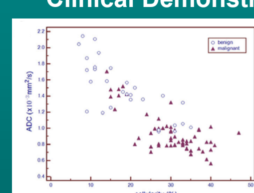
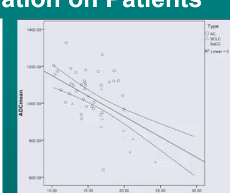
ADC vs. Cellularity
Clinical Demonstration on Patients

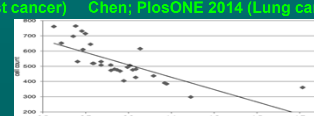




Jiang; BJR 2016 (Breast cancer)

Chen; PlosONE 2014 (Lung caner)

Kishimoto; Acta Radiol 2016 (Endometrial cancer)



Average r = -0.61

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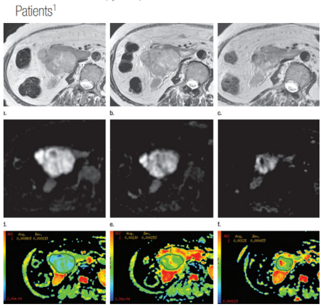
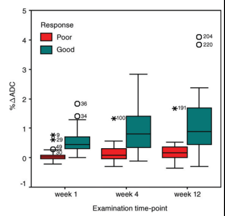
Gastrointestinal Stromal Tumors Treated with Imatinib Mesylate: Apparent Diffusion Coefficient in the Evaluation of Therapy Response in Patients[1]

Radiology





Tang L, et al., Radiology 2010.

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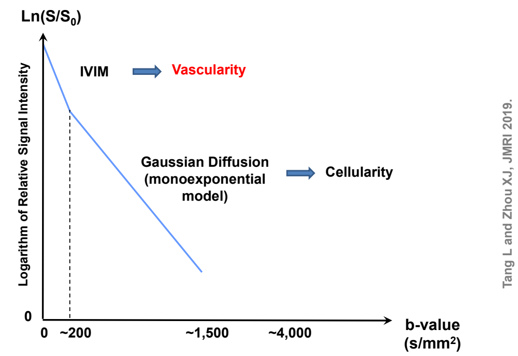

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IVIM Diffusion Imaging

$$S/S_0 = f\exp(-bD^*) + (1-f)\exp(-bD)$$

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.

Iima and Le Bihan, Radiology 2016.

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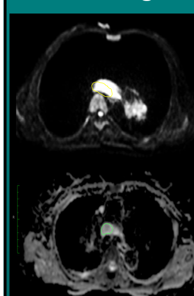
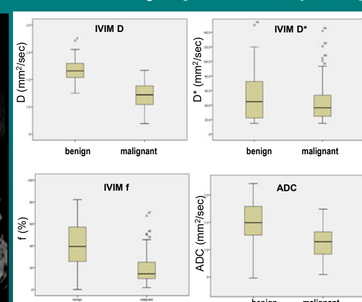
IVIM: Differentiation between Malignant and Benign Mediastinal Lymph Nodes(MLN)



8 b-values (0-1000 s/mm²)



- IVIM parameters can complement ADC.

Benign or Malignant?

Qi L, et al. Euro Radiol 2018; 28: 1301-1309

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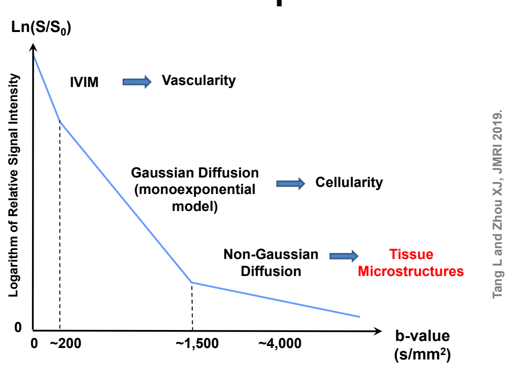
Diffusion “b-Spectrum”



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Diffusion Models

Gaussian

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

Non-Gaussian

- Compartmentalized models
  - IVIM, NODDI, AxCaliber, Charmed, RSI, VERDICT, etc.
- Non-compartmentalized models
  - DSI, q-Ball, QTI, DKI, stretch exponential, fractal, CTRW, FROC, FM, etc.

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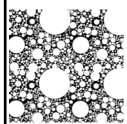
Fractional Order Calculus (FROC) Model

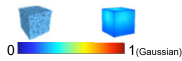


Tissue Heterogeneity

$$M_{xy} = M_0 \exp\left[-D\mu^{2(\beta-1)}(\gamma G_z \delta)^{2\beta}\left(\Delta - \frac{2\beta-1}{2\beta+1}\delta\right)\right]$$

D: Diffusion coefficient, similar to ADC

β: Degree of intravoxel tissue heterogeneity



μ: Spatial quantity, related to the diffusion mean free length

Magin, et al., JMR, 2008; Zhou, et.al., MRM, 2010; Sui, et al., Radiology, 2015.

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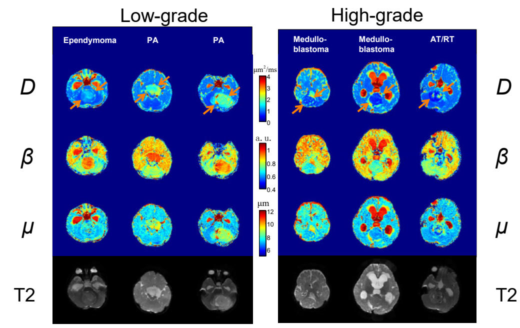
Example of Grading Pediatric Brian Tumors



Y. Sui, et al., Radiology, 2015.

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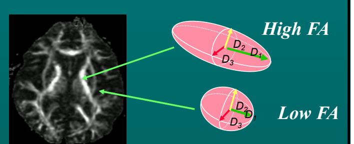
Diffusion Tensor Imaging

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

$$\begin{bmatrix} D_{xx} & D_{xy} & D_{xz} \\ D_{xy} & D_{yy} & D_{yz} \\ D_{xz} & D_{yz} & D_{zz} \end{bmatrix}$$



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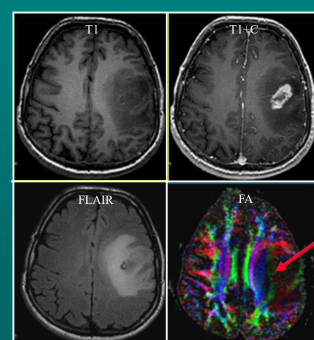
DTI for Pre-Surgical Planning



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Quality Assurance for DWI

- **Image distortion**
  - Use a spherical phantom
  - Check the distortion wrt 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

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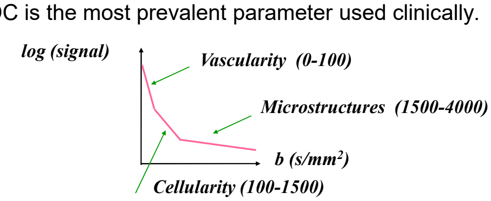
Conclusions

- 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.



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