Introduction to Diffusion-weighted Imaging

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Motivation

• Magnetic resonance imaging provides information about the spatial distribution of water.
• Diffusion-weighted MRI (DWI) provides information about the motion of water.
• DWIs are sensitive to cellular architecture and tissue integrity.
• DWI can provide quantitative measures that are directly comparable.
• Diffusion imaging can be used to identify specific white matter tracts
Outline

- What is diffusion?
- How do we measure diffusion in MRI?
- How do we extract directional information?
- What are the practical problems and limitations?
- Beyond the diffusion tensor
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Diffusion refers to the random translational (Brownian) motion of molecules that results from the thermal energy of these molecules.

\[ D = \frac{kT}{6\pi\eta R_H} \]  

(Stokes-Einstein)
Gaussian Distribution

• A large number of particles that are free to diffuse have a squared displacement of a Gaussian form

\[
\sqrt{2DT_{\text{diff}}}
\]

Einstein, A. Ann Physik (1905) 4: 549-590
Diffusion

For $\text{H}_2\text{O}$ at $37^\circ \text{C}$

\[
D \approx 3.0 \times 10^{-3} \text{ mm}^2/\text{s}
\]

\[
T_{\text{dif}} \approx 30 \text{ ms}
\]

\[
r \approx 25 \text{ \mu m}
\]

\[
\langle r^2 \rangle \approx 6 DT_{\text{dif}}
\]

- If the motion of water is hindered by cell membranes, macromolecules, etc. the displacement will be less and $D$ will appear lower.
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Image Intensity in MRI

- Physical property of tissue water
  - \( \rho \) proton density
  - \( T_1 \) relaxation time
  - \( T_2 \) relaxation time
  - \( T_2^* \) relaxation time
  - \( D \) diffusion coefficient

- Experimentally controlled parameters
  - Sequence Spin-echo/gradient echo
  - TR Time of Repetition
  - TE Time to echo
  - \( b \)-value diffusion-weighting factor

Concentration of water
Rotational motion,
Magnetic field strength
Translational motion
Gradients make the resonance frequency a function of spatial position

\[ \omega = \gamma B = \gamma B_0 + \gamma z G_z \]
Basic Diffusion-weighting

$90^\circ$ +x

$S_{total}$
Phase Twist
Basic Diffusion-weighting
Guess the intensity
Spin-echo Diffusion Preparation

\[ b = (\gamma G \delta)^2 \left( \Delta - \frac{\delta}{3} \right) \]

$S = S_0 e^{-bD}$

- **Non-diffusion-weighted signal intensity**
- **B-value** (sec/mm$^2$)
- **Diffusion Coefficient** (mm$^2$/sec)
**Typical DWI**

- **Single-shot “spin-echo” Echo Planar Imaging**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>TE</td>
<td>50-100ms</td>
<td>Limited by b-value</td>
</tr>
<tr>
<td>TR</td>
<td>&gt;5s</td>
<td>Fully relaxed</td>
</tr>
<tr>
<td>Matrix</td>
<td>96 x 96</td>
<td>2.5 x 2.5 mm</td>
</tr>
<tr>
<td>Slice Thickness</td>
<td>2.5 mm</td>
<td>Equal dimensions</td>
</tr>
<tr>
<td>B-value</td>
<td>~1000 s/mm²</td>
<td>For brain*</td>
</tr>
</tbody>
</table>

Calculate Diffusion Parameters

\[ S = S_0 e^{-bD} \]
\[ I_z = I_0 e^{-bD_z} \]

\[ D_z = \frac{1}{-b} \ln \left( \frac{I_z}{I_0} \right) \]
Water Diffusion in Tissue

EM of mouse corpus callosum

Not Free

Cell membranes
Myelin
Organelles
Extracellular matrix

Anisotropy

$D_{\text{perpendicular}}$
$D_{\text{parallel}}$
$D_{\text{perpendicular}} \ll D_{\text{parallel}}$

8 μm
ADC = \frac{1}{-b} \ln \left( \frac{I_{ave}}{I_0} \right)

b = 0 \text{ s/mm}^2

ADC

Gx

Gy

Gz
Acute Stroke

b = 0 \text{s/mm}^2 \quad 720 \text{s/mm}^2

0.75 \times 10^{-3} \text{ mm}^2/\text{s} \quad 0.43 \times 10^{-3} \text{ mm}^2/\text{s}

Diffusion Map

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- Cell membranes
- Myelin
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Anisotropy
- $D_{\text{perpendicular}}$
- $D_{\text{parallel}}$
- $D_{\text{perp}} \ll D_{\text{par}}$

EM of mouse corpus callosum

8 μm
Anisotropic Diffusion
The Diffusion Tensor

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

Calculate Diffusion Tensor
Diagonalize DT

$$D = \begin{bmatrix} \lambda_1 & 0 & 0 \\ 0 & \lambda_2 & 0 \\ 0 & 0 & \lambda_3 \end{bmatrix}$$

Eigenvalues

Eigenvectors
Quantitative Parameters

\[ D = \begin{bmatrix} \lambda_1 & 0 & 0 \\ 0 & \lambda_2 & 0 \\ 0 & 0 & \lambda_3 \end{bmatrix} \]

Average Diffusivity

\[ <D> = \frac{\lambda_1 + \lambda_2 + \lambda_3}{3} \]

Fractional Anisotropy

\[ FA = \frac{\sqrt{3(\lambda_1 - <\lambda>)^2 + (\lambda_2 - <\lambda>)^2 + (\lambda_3 - <\lambda>)^2}}{\sqrt{2(\lambda_1^2 + \lambda_2^2 + \lambda_3^2)}} \]

\[ 0 \leq FA \leq 1 \]
Directional Encoding for DTI

\[ D = \begin{bmatrix}
\lambda_1 & 0 & 0 \\
0 & \lambda_2 & 0 \\
0 & 0 & \lambda_3 
\end{bmatrix} \]

Applications of DTI

- Cerebral Ischemia (Stroke)
- Brain Cancer and Effects of Radiotherapy
- Multiple Sclerosis
- Epilepsy
- Metabolic Disorders
- Normal Brain Maturation and Aging
- Traumatic Brain Injury
- Alzheimer’s Disease
- Amyotrophic Lateral Sclerosis
- Niemann-Pick type C Disease
- Dementias
- Connectivity
Pediatric DIPG

T2-weighted

MD

FA

DEC
Guess the ellipsoid
Guess the ellipsoid
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Typical DW SSEPI

**PRO**
- Time Efficient
- Insensitive to Bulk motion

**CON**
- Low Resolution
- Distortions - Field inhomogeneities
- Distortions - Diffusion weighting
CON: Distortions from field inhomogeneities

- T2-weighted FSE
- Non-diffusion-weighted SSEPI
- SSEPI corrected
CON: Distortions from DW

DW SSEPI volumes

FA maps
Other Common Problems in DTI

- Low SNR
- Incomplete Fat Suppression
- Bulk movement
- Cardiac pulsation
Low SNR

2.5 mm iso
1.7mm iso
1.3mm iso
Low SNR

2.5 mm iso
15.625 mm³

1.7 mm iso
4.913 mm³

1.3 mm iso
2.197 mm³
Low SNR

2.5 mm iso
15.625 mm³

1.7mm iso
4.913 mm³

1.3mm iso
2.197 mm³
Incomplete Fat Suppression

$b=1100 \text{ s/mm}^2$

MD

FA
Cardiac Pulsation

Diffusion weighting in Z
Bulk Movement
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What is Tractography?

The use of orientation information from diffusion imaging to reconstruct estimates of white matter pathways in the brain.
Limitation to DTI comes from partial volume effects

Typical resolution for SSEPI DTI
2.5 x 2.5 x 2.5 mm

Cortical projection systems of left cerebral hemisphere
Partial Volume Effect

distribution  DT ellipsoid

distribution  DT ellipsoid
Sub-millimeter DTI
Beyond Standard DTI

• High Angular Resolution Diffusion Imaging (HARDI)
  – Multi-tensor models
  – Non-parametric algorithms
    • DSI, Qball, SD, PAS
Non-parametric Algorithms

distribution  fODF  distribution  fODF
$b = 0 \text{ s/mm}^2$
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