13: Advanced MRI Contrast Mechanisms

1. How does moving blood affect the image phase?
2. What is the effect of self-diffusion on the MR signal?
3. Why is diffusion in vivo not isotropic?
   * Fiber tracking
4. How do the different imaging modalities compare?
   * Capabilities
   * Limitations
   * Choice
5. Comparison by examples

After this week you
1. Understand the influence of motion on the phase of magnetization
2. Understand how random motion leads to echo amplitude reduction
3. Are able to calculate the attenuation of the MR signal due to diffusion
4. Understand how diffusion-weighted MRI signal reflects cellular structure and how this can be exploited to track nerve fibers, among others
5. Have a firm grasp on the premises and limitations of the imaging modalities covered in this course

13-1. How does Bulk Motion affect the Rephased Signal?
(Blood Flow)

For transverse magnetization at point (x,y):

\[ m(x, y) \propto e^{i\int G_s(x) dt} = e^{i\phi} \]

\[ \phi = \frac{\gamma \mu_0 T^2}{2} \]

Phase \( \phi \) of the magnetization:

\[ M_{\perp}(t) = M_{\perp}(0) e^{i\phi(t)} \]

\[ \phi(t) = \int_0^T \gamma G_s(x(t)) dt \]

\[ x(t) = x_0 + vt \]

\[ \phi(2T) = \frac{\gamma \mu_0 T^2}{2} \]

Blood moving with velocity \( v \)

\[ \phi \text{ does not depend on } x \]

\( \Rightarrow \) Entire echo has phase \( \phi \) at TE

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13-2. How does self-Diffusion influence the MR signal?

Einstein random walk:

\[
\langle r \rangle = \sqrt{6D\Delta}
\]

- \( \langle r \rangle = 20 \ \mu m \)  
  \( \Delta = 0.1 \ s \)
- \( \langle r \rangle = 45 \ \mu m \)  
  \( \Delta = 0.5 \ s \)
- \( \langle r \rangle = 63 \ \mu m \)  
  \( \Delta = 1 \ s \)

D: self diffusion coefficient
\( \langle r \rangle \): root mean square displacement after \( \Delta \) seconds

What is the effect of random motion on magnetization phase?
when applying pulsed gradient

Static magnetization:
- a
- b
- c
- d

Magnetization in motion:
- a
- b
- c
- d

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Ex. Effect of Diffusion on Magnetization

Phase $\phi$ of $M_{xy}$

Absence of incoherent motion: Echo formation

- No diffusion
- All in-phase: max. echo formation

With diffusion
- Not all in-phase: reduced echo amplitude

How is the effect of diffusion on the MR signal described?

Mathematical description

1. Strength of the diffusion process ($D$)
2. Delay between dephasing and rephasing gradient ($\Lambda$)
3. Area of the dephasing gradient (strength $G$, duration $\delta$)

Attenuation of the signal (echo amplitude) due to diffusion in the direction of $G$

D: apparent diffusion coefficient (ADC)

Equivalent sequence (spin echo, i.e. sensitive to $T_2$)
13-3. How is Anisotropic Water Diffusion described?

Consider structure along (myelinated) axon (or myofibril)

- Anisotropic mean displacement
- Anisotropic diffusion coefficient

Diffusion coefficient depends on gradient orientation

\[ D_{ij} \]

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

Motion (diffusion) of water molecules: Restricted by cell membranes

\[ \Rightarrow \text{Anisotropic mean displacement} \]
\[ \Rightarrow \text{Anisotropic diffusion coefficient} \]

Diffusion tensor imaging (DTI)

Imaging anisotropic diffusion

Diffusion tensor symmetric: \( D_{ij} = D_{ji} \)

3 orthogonal **Eigenvalues** \( \lambda_i \)

**Eigenvectors**

\[ DT = \begin{pmatrix} \lambda_1 & 0 & 0 \\ 0 & \lambda_2 & 0 \\ 0 & 0 & \lambda_3 \end{pmatrix} \]

For each voxel determine direction of principal eigenvector (largest \( \lambda \)):

Pseudocolor directionality
### 13-4. Bio-imaging modalities comparison

#### I. Contrast and limitations

<table>
<thead>
<tr>
<th>Contrast mechanisms</th>
<th>Major limitations</th>
</tr>
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<tbody>
<tr>
<td>CT</td>
<td>e(^{-}) density, Z</td>
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<tr>
<td>SPECT</td>
<td>Tracer distribution in tissue</td>
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<tr>
<td>PET</td>
<td>(Spin concentration)</td>
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<tr>
<td>MR</td>
<td>Relaxation of magnetization</td>
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<td></td>
<td>Fat/Water (chemical shift)</td>
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<tr>
<td></td>
<td>Diffusion (etc...)</td>
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<tr>
<td>US</td>
<td>Boundaries of tissues with different mechanical properties</td>
</tr>
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<td></td>
<td>strong e(^{-}) density differences (bone)</td>
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<td></td>
<td>Ionizing radiation</td>
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<td>(\gamma) emitters available</td>
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<td>non-uniform spatial resolution &amp; sensitivity</td>
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<tr>
<td></td>
<td>sensitivity</td>
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<td></td>
<td>time-consuming &amp; motion-sensitive</td>
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<td>complex methodology</td>
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<td>does not penetrate hard objects (e.g. bone)</td>
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#### Comparison II

SNR, reconstruction, contrast agents

Maximize SNR

<table>
<thead>
<tr>
<th>Modality</th>
<th>Increase radiation dose</th>
<th>Increase tracer dose</th>
<th>Increase magnetic field</th>
</tr>
</thead>
<tbody>
<tr>
<td>CT</td>
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<td></td>
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<td>SPECT</td>
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<td>PET</td>
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<td>MR</td>
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Effective radiation dose

Limited by

- Scatter noise
- Radiation dose

Equilibrium magnetization (Boltzmann distribution)

Image reconstruction

- CT, x-ray: Directionality of photon
  - Radon transform
- Projection reconstruction: precession of \(M\) \(\rightarrow\) Gradient G
  - Frequency analysis
  - Fourier transform

Contrast agents (contrast modifiers)

- CT, MR: Compounds with high Z
- PET: Compounds shortening relaxation times (\(T_1\), \(T_2\), or \(T_2^*\))
<table>
<thead>
<tr>
<th>Trait</th>
<th>Modality</th>
</tr>
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<tbody>
<tr>
<td>Rapid and least invasive assessment of tissue close to surface</td>
<td>US</td>
</tr>
<tr>
<td>Contrast between air-tissue or bone-tissue</td>
<td>X-ray, CT</td>
</tr>
<tr>
<td>Rapid scan with high spatial resolution</td>
<td>SPECT, PET</td>
</tr>
<tr>
<td>Image receptors, glucose metabolism, transport, perfusion</td>
<td>NMR spectroscopy</td>
</tr>
<tr>
<td>Biochemical information of tissue</td>
<td>MRI</td>
</tr>
<tr>
<td>Exquisite soft tissue contrast with mm spatial resolution (rodent 100μm)</td>
<td>MRI</td>
</tr>
<tr>
<td>Functional information</td>
<td>MRI (multiple means)</td>
</tr>
<tr>
<td>Moving blood (angiography)</td>
<td>CT (contrast agents) Doppler US</td>
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</tbody>
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