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)

Phase $\phi$ of the magnetization:

$$M_\perp(t) = M_\perp(0)e^{\phi(t)}$$

$$\phi(t) = \int_0^t \gamma G_x x(t') dt'$$

$$x(t) = x_0 + vt$$

$$\phi(2T) = \gamma G v T^2$$

Blood moving with velocity $v$

For transverse magnetization at point $(x,y)$:

$$m_\perp(x,y) \propto e^{i \int G_x(t')dt} = e^{ik_x(t)x}$$

$$m_\perp(x,y) \propto e^{i \phi} = e^{i \frac{G_x(TE)}{T^2}}$$
13-2. How does self-Diffusion influence the MR signal?

Einstein random walk:

$$<r> = \sqrt{6D\Delta}$$

- $$<r> = 20 \mu m$$
  - $$\Delta = 0.1 \text{ s}$$
- $$<r> = 45 \mu m$$
  - $$\Delta = 0.5 \text{ s}$$
- $$<r> = 63 \mu m$$
  - $$\Delta = 1 \text{ s}$$

D: self diffusion coefficient
$$<r>$$: 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
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

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

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

$S(b) = S_0 e^{-bD}$

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)

Myelin  Cell membrane  Microtubules + neurofilaments

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

⇒ Anisotropic mean displacement
⇒ Anisotropic diffusion coefficient

Diffusion coefficient depends on gradient orientation

→ Diffusion tensor $D_i$

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

Diffusion tensor symmetric: $D_{ij} = D_{ji}$

3 orthogonal Eigenvectors

→ Eigenvalues $\lambda_i$

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

Pseudocolor directionality

**Diffusion tensor imaging (DTI)**

imaging anisotropic diffusion
**13-4. Bio-imaging modalities comparison**

I. contrast and limitations

### Contrast mechanisms

- **CT**  
  - e\(^{-}\) density, Z
- **SPECT**  
  - Tracer distribution in tissue
- **PET**  
  - (Spin concentration)
  - Relaxation of magnetization
  - Fat/Water (chemical shift)
  - Diffusion
  - (etc …)
- **MR**  
  - Boundaries of tissues with different mechanical properties

### Major limitations

- strong e\(^{-}\) density differences (bone)
- Ionizing radiation
- \(\gamma\) emitters available
- non-uniform spatial resolution & sensitivity
- sensitivity
- time-consuming & motion-sensitive
- complex methodology
- does not penetrate hard objects (e.g. bone)

### Comparison II

SNR, reconstruction, contrast agents

#### Maximize SNR

- **CT**  
  - Increase radiation dose
- **SPECT**  
  - Increase tracer dose
- **PET**  
  - Increase magnetic field

#### Image reconstruction

- **CT**  
  - Directionality of photon
  - → Radon transform
- **SPECT**  
  - Projection reconstruction
  - precession of \(M\)
  - (gradient G)
  - → Frequency analysis
- **PET**  
  - Fourier transform

#### Contrast agents

- **CT, x-ray**  
  - Compounds with high Z
- **MR**  
  - Compounds shortening relaxation times (\(T_{1}, T_{2},\) or \(T_{2}^*\))
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Notes:
- US: Bone Air
- MRI: Immobile spins
- NMR: Metallic implants & devices