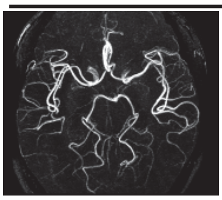
13: Advanced MRI Contrast Mechanisms

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)



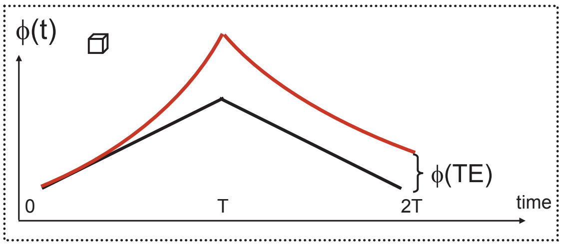
Phase ϕ of the magnetization:

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

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

(Gradient along x)

Blood moving with velocity *v*

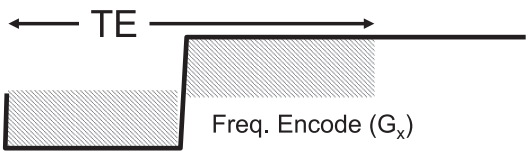


$$\phi(t) = \int_0^T \gamma G_x x(t)dt - \int_T^{2T} \gamma G_x x(t)dt$$

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

$$\phi(2T) = \underbrace{\int_0^T \gamma G_x(x+vt)dt}_{\gamma G_x\left(xt + v\frac{t^2}{2}\right)\Big|_0^T} - \underbrace{\int_T^{2T} \gamma G_x(x+vt)dt}_{-\gamma G_x\left(xt + v\frac{t^2}{2}\right)\Big|_T^{2T}}$$

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



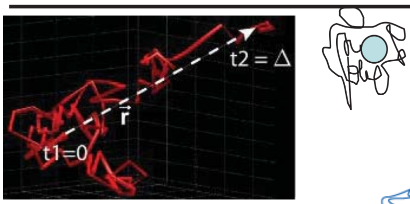
For transverse magnetization at point (x,y):

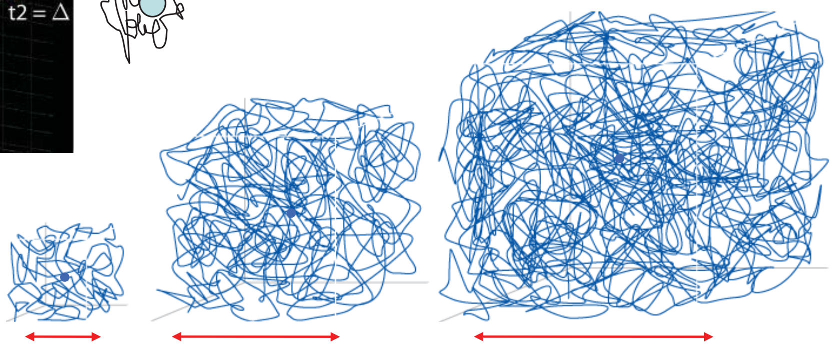
$$m_\perp(x,y) \propto e^{i\int \gamma G_x(t)x dt} = e^{ik_x(t)x}$$

ϕ does not depend on x
$\Rightarrow$ Entire echo has phase ϕ at TE

$$m_\perp(x,y) \propto e^{i\phi} = e^{i\gamma G v\left(\frac{TE}{2}\right)^2}$$

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





<r> = 20 μm
Δ = 0.1 s

<r> = 45 μm
Δ = 0.5 s

<r> = 63 μm
Δ = 1 s

Einstein random walk:

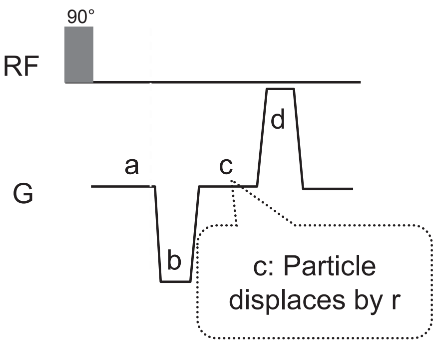
$$\langle r \rangle = \sqrt{6D\Delta}$$

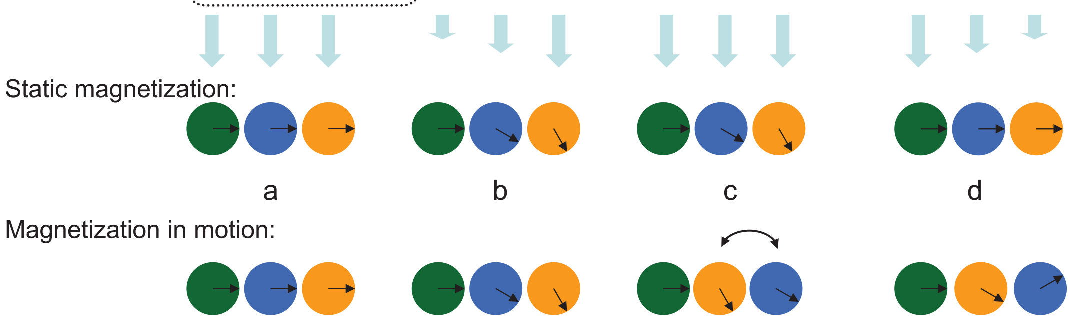
D: self diffusion coefficient

<r>: root mean square displacement after Δ seconds

What is the effect of random motion on magnetization phase ?

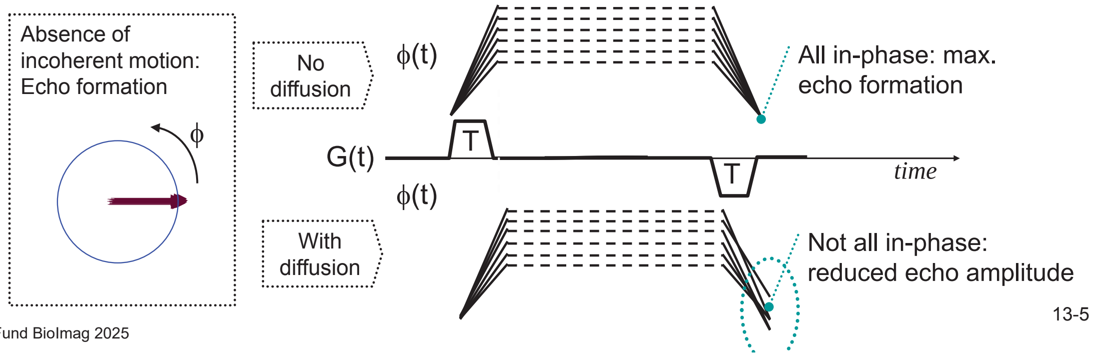
when applying pulsed gradient





Ex. Effect of Diffusion on Magnetization

Phase ϕ of M_{xy}

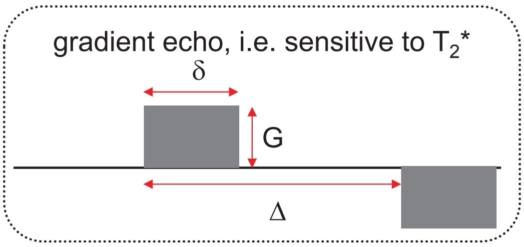


How is the effect of diffusion on the MR signal described ?

Mathematical description

Degree of echo signal reduction

1. Strength of the diffusion process (D)
2. Delay between dephasing and rephasing gradient (Δ)
3. Area of the dephasing gradient (strength G, duration δ)



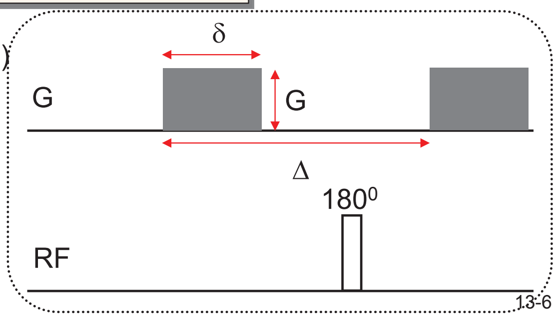
Attenuation of the signal (echo amplitude) due to diffusion in the direction of G

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

$$b = (\gamma G \delta)^2 (\Delta - \delta / 3)$$

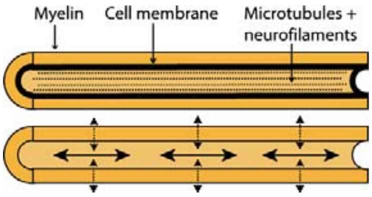
D: **apparent diffusion coefficient** (ADC)

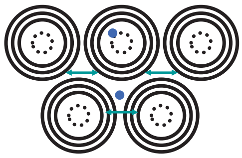
Equivalent sequence (spin echo, i.e. sensitive to T_2)

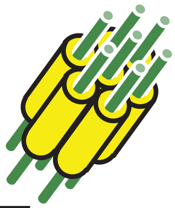


13-3. How is Anisotropic Water Diffusion described ?

Consider structure along (myelinated) axon (or myofibril)







Motion (diffusion) of water molecules:

Restricted by cell membranes

⇒ Anisotropic mean displacement
⇒Anisotropic diffusion coefficient

Diffusion coefficient depends on gradient orientation

→ Diffusion tensor D_{ij}

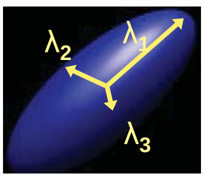
$$D = \begin{pmatrix} D_{xx} & D_{xy} & D_{xz} \\ D_{yx} & D_{yy} & D_{yz} \\ D_{zx} & D_{zy} & D_{zz} \end{pmatrix}$$

Diffusion tensor imaging (DTI)
imaging anisotropic diffusion

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

3 orthogonal **Eigenvectors**

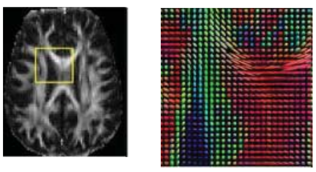
→ **Eigenvalues** λ_i



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

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

Pseudocolor directionality



13-4. Bio-imaging modalities comparison

I. contrast and limitations

Contrast mechanisms

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

Major limitations

- strong e^- density differences (bone)
- Ionizing radiation

- γ 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, PET → Increase tracer dose
- MR → Increase magnetic field

Limited by:

- Effective radiation dose
- Scatter noise; Radiation dose
- Equilibrium magnetization (Boltzmann distribution)

Image reconstruction

- CT, SPECT, PET → Directionality of photon →Radon transform; **Projection reconstruction**
- MR → precession of $M_\perp$ (gradient G) → Frequency analysis; **Fourier transform**

Contrast agents

(contrast modifiers)

- CT, x-ray → Compounds with high Z
- MR → Compounds shortening relaxation times (T_1, T_2, or T_2*)

Which bioimaging modality is right for you ?

- Rapid and least invasive assessment of tissue close to surface → **US** (Bone Air)
- Contrast between air-tissue or bone-tissue; Rapid scan with high spatial resolution → **X-ray, CT** (multiple exposures (ionizing radiation))
- Image receptors, glucose metabolism, transport, perfusion → **SPECT, PET**
- Biochemical information of tissue → **NMR spectroscopy** (Immobile spins)
- Exquisite soft tissue contrast with mm spatial resolution (rodent 100µm) → **MRI** (Metallic implants & devices)
- Functional information → **MRI** (Air-Tissue interface)
- Moving blood (angiography) → **MRI (multiple means)**, **CT (contrast agents)**, **Doppler US**