13: Advanced MRI Contrast Mechanisms

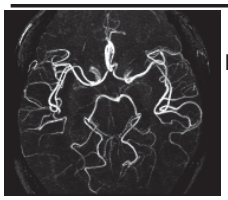
1. How does moving blood affect the image phase ?
2. What is the effect of self-diffusion on the MR signal ?
3. Why is diffusion in vivo not isotropic ?
   - Fiber tracking
4. How do the different imaging modalities compare ?
   - Capabilities
   - Limitations
   - Choice
5. Comparison by examples

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)

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

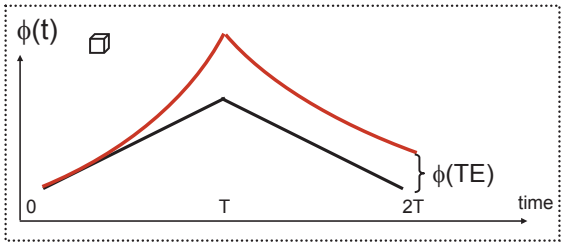
$x(t)=x_0+vt$

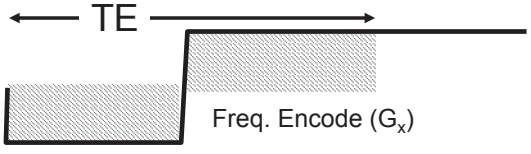
$$\phi(2T) = \underbrace{\int_0^T \gamma G_x(x+vt)dt}_{\gamma G_x(xt+v\frac{t^2}{2})\Big|_0^T} \underbrace{-\int_T^{2T} \gamma G_x(x+vt)dt}_{-\gamma G_x(xt+v\frac{t^2}{2})\Big|_T^{2T}}$$

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

ϕ does not depend on x
⇒ Entire echo has phase ϕ at TE

Blood moving with velocity *v*



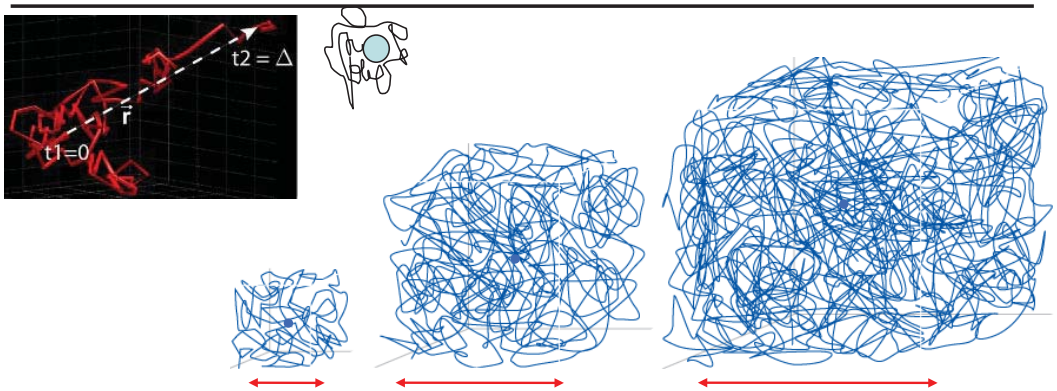


For transverse magnetization at point (x,y):

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

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

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:

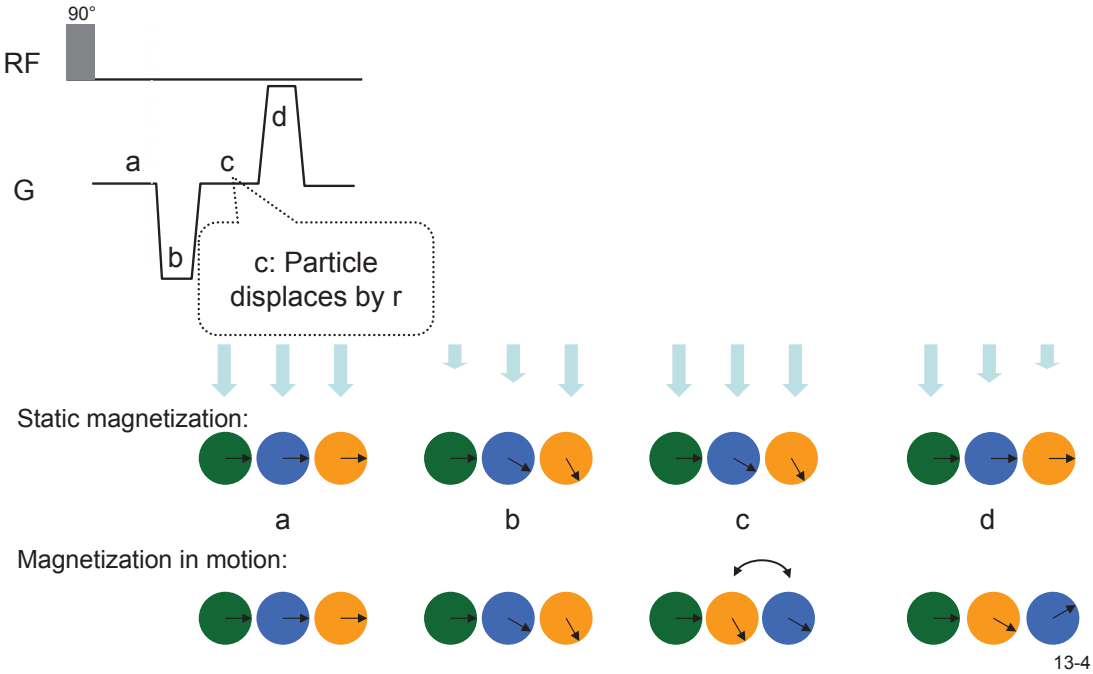
$$\langle r \rangle = \sqrt{6D\Delta}$$

D: self diffusion coefficient

<r>: root mean square displacement after Δ seconds

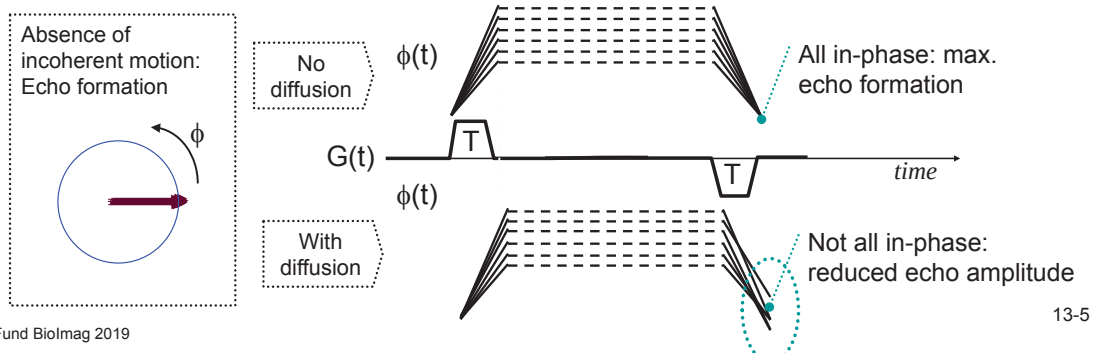
What is the effect of random motion on magnetization phase ?

when applying pulsed gradient



Ex. Effect of Diffusion on Magnetization

Phase ϕ of M_{xy}

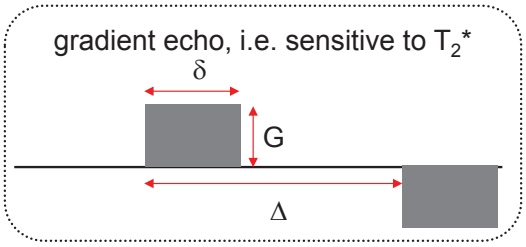


How is the effect of diffusion on the MR signal described ?

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)

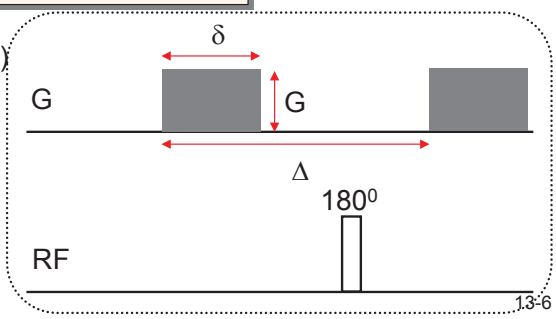


Attenuation of the signal (echo amplitude) due to diffusion in the direction of G

$$S(b) = S_0 e^{-bD} \qquad b = (\gamma G \delta)^2 (\Delta - \delta/3)$$

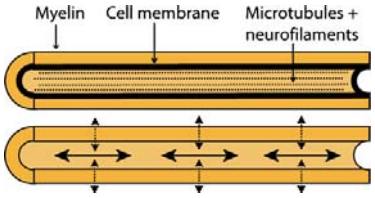
D: **apparent diffusion coefficient** (ADC)

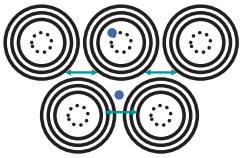
Equivalent sequence (spin echo, i.e. sensitive to T_2)

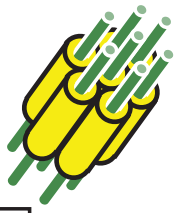


13-3. How is Anisotropic Water Diffusion described ?

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}

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

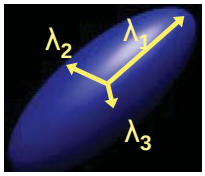
Diffusion tensor imaging (DTI)

imaging anisotropic diffusion

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

3 orthogonal **Eigenvectors**

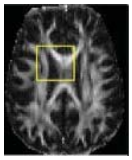
→ **Eigenvalues** λ_i

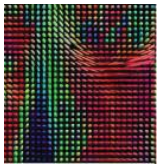


$$DT = \begin{pmatrix} \lambda_1 & 0 & 0 \\ 0 & \lambda_2 & 0 \\ 0 & 0 & \lambda_3 \end{pmatrix}$$

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 ?