Magnetic Resonance Imaging in a small nutshell

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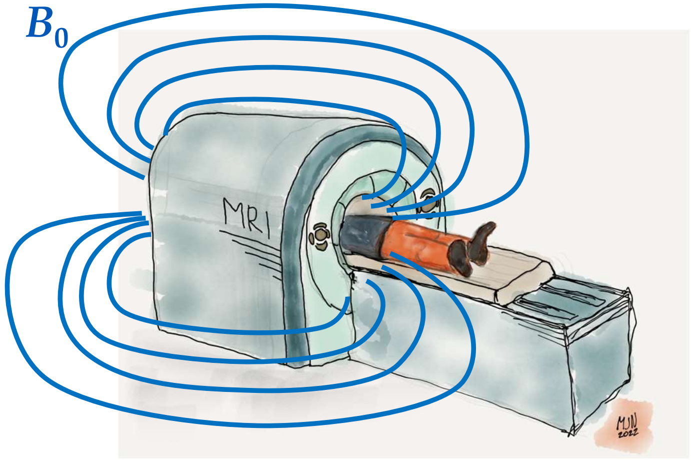
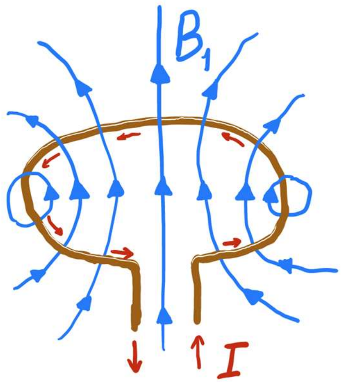
Principles of MRI



Spins in the imaging target interact with magnetic field

→ Formation of equilibrium and **net magnetization**



RF energy can be used to disturb equilibrium

→ Formation of **detectable** magnetization

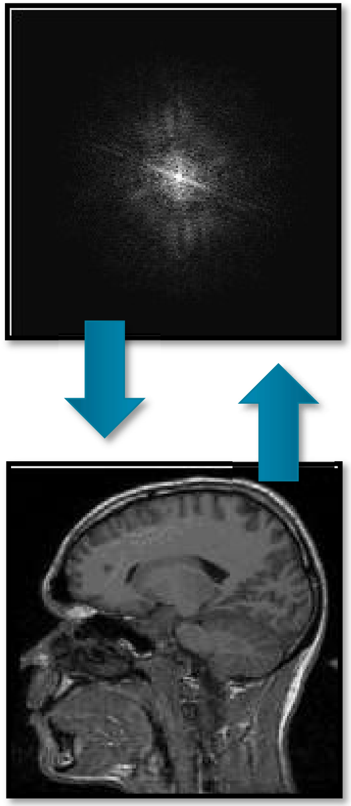
Back to equilibrium

Spins interact:
- Relaxation processes

→ **Contrast**

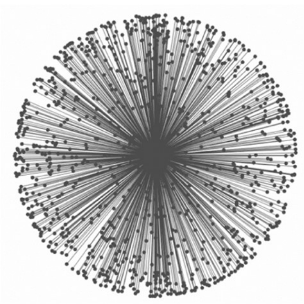
Spatial encoding:
- Magnetization is localized

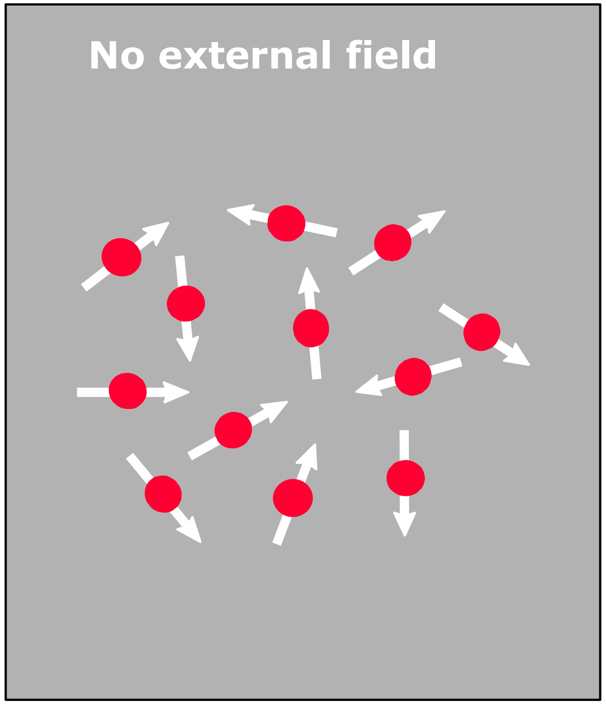
→ **Images**

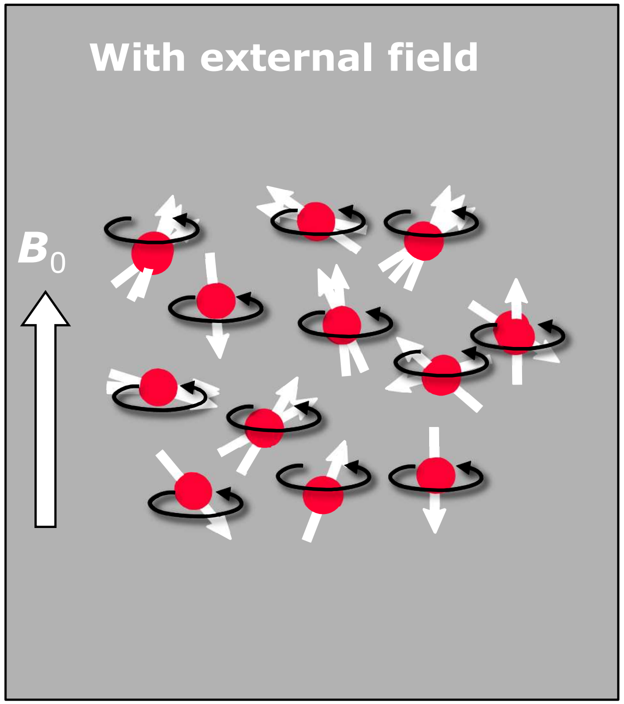


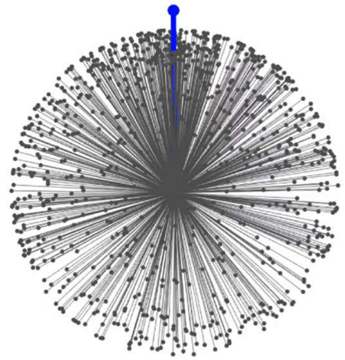
Basics of MRI: 1. Thermal equilibrium

- The hydrogen nuclei (protons, spins) interact with the external magnetic field of the scanner. Over time, **thermal equilibrium** is reached and **net magnetization** is created. Torque exerted by the external field causes spins to start **precessing**.



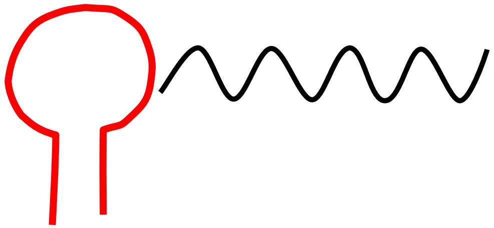




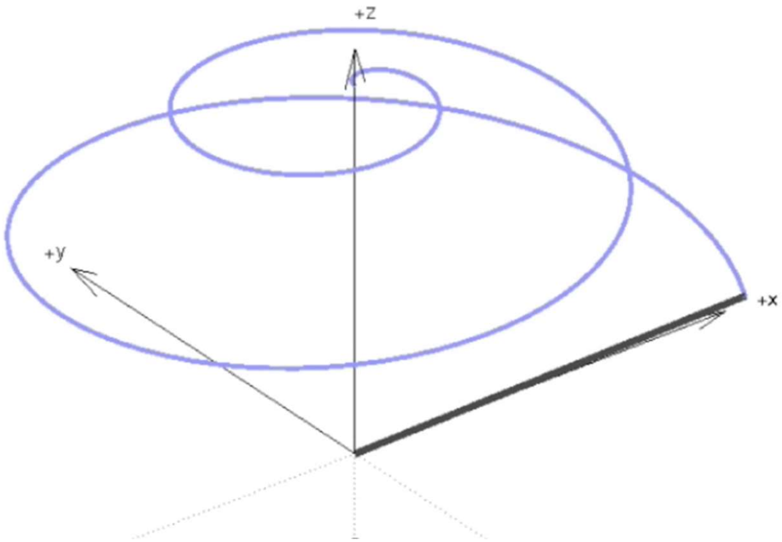


2. Equilibrium can be disturbed

- Using radio frequency (RF) energy at *resonance* frequency

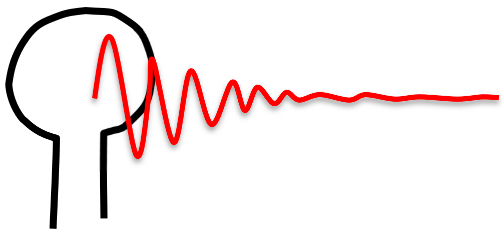


Absorption of energy

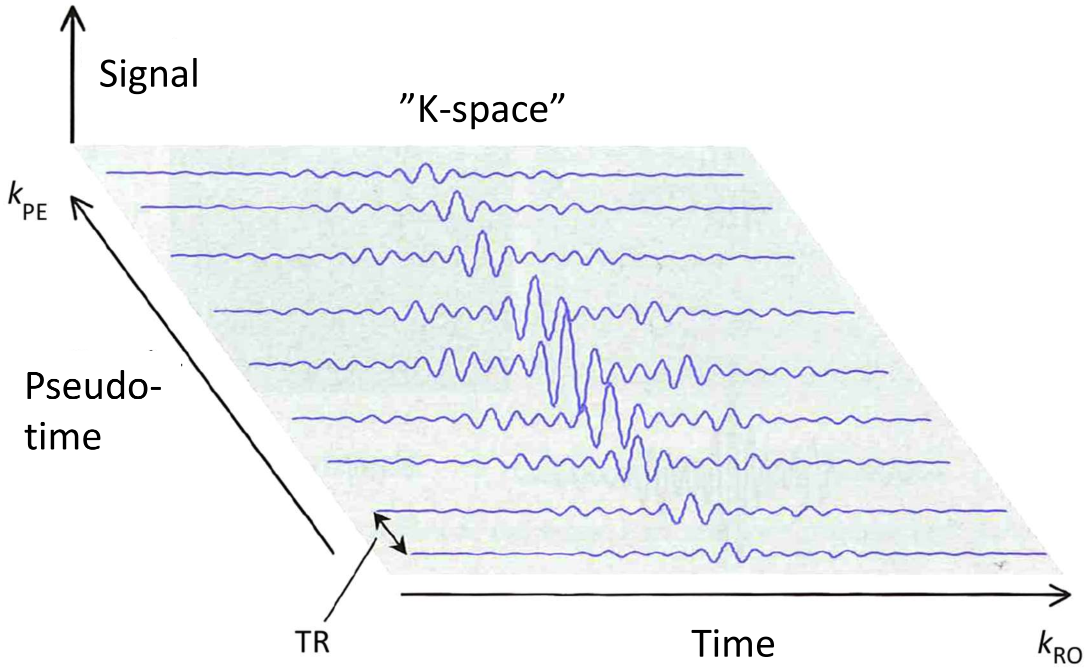


3. The equilibrium returns

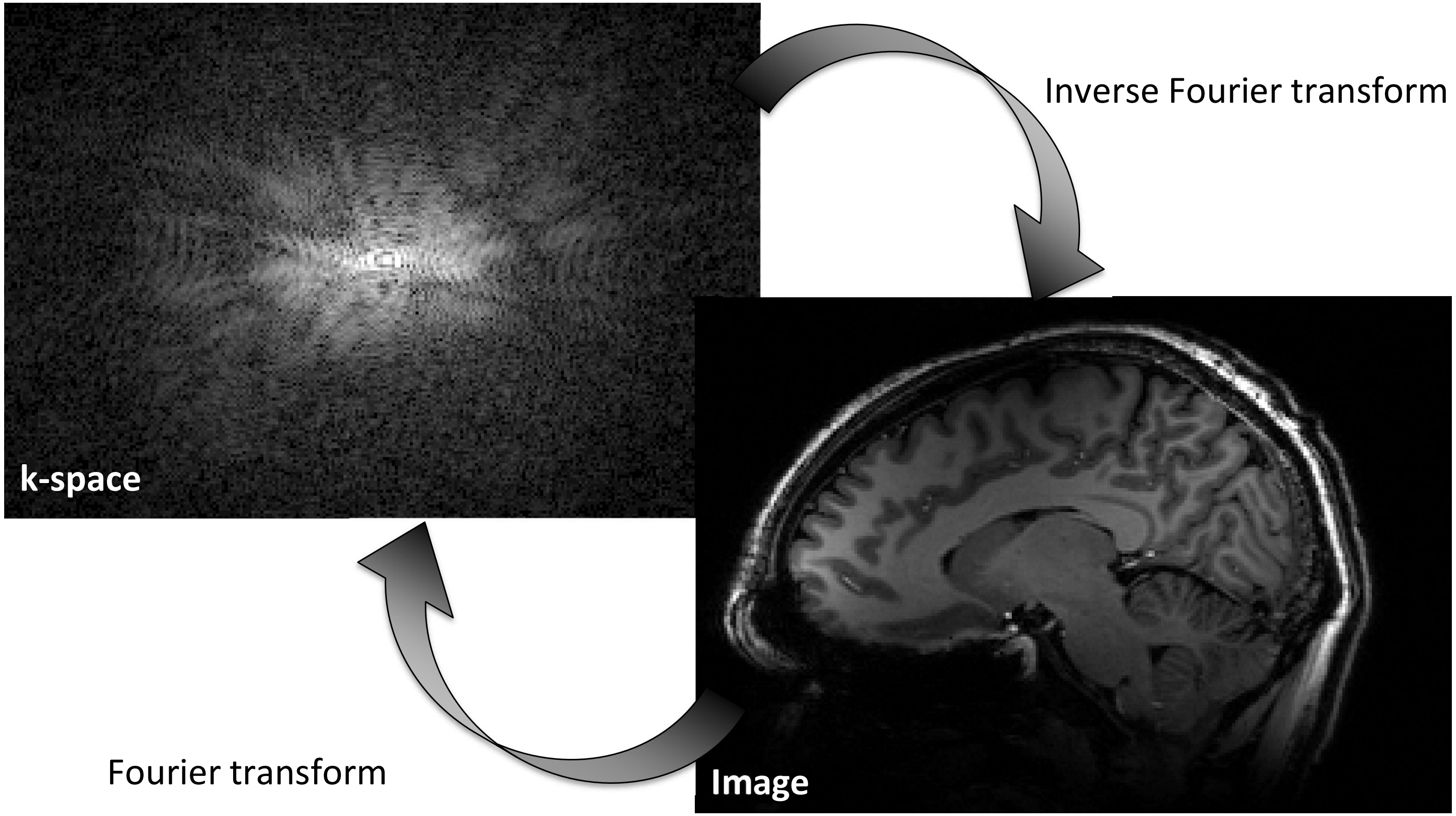
- After excitation, the system “emits” RF energy that can be measured. Received signal depends on the sample and measurement details



Electromagnetic induction
NOT emission as in gamma radiation etc



4. Collected signal can be turned into an image



Principles of MRI

Some additional concepts

NMR, MRI and resonance

- Everything in MRI and NMR is based on frequencies
  - Frequency of the precession motion is called **Larmor frequency** (resonance frequency)

$$\omega_0 = -\gamma B_0 \qquad \text{(rad/s)}$$
$$\upsilon_0 = -\gamma B_0 / 2\pi \qquad \text{(Hz)}$$

ω_0 = resonance frequency [rad/s]
γ = gyromagnetic ratio $\left[\frac{\text{rad}}{\text{s}*\text{T}}\right]$
B_0 = field strength [T]
υ_0 = resonance frequency [Hz/s]

- Besides the main field strength B_0, nucleus-specific constant "gyromagnetic ratio" γ defines the resonance frequency

Gyromagnetic ratios

Isotope	Ground-state spin	Natural abundance/%	Gyromagnetic ratio $\gamma/10^6$ rad s^{-1} T^{-1}	NMR frequency at 11.74 T $(\omega^0/2\pi)$/ MHz
^{1}H	1/2	~100	267.522	−500.000
^{2}H	1	0.015	41.066	−76.753
^{3}H	1/2	0	285.349	−533.320
^{10}B	3	19.9	28.747	−53.718
^{11}B	3/2	80.1	85.847	−160.420
^{13}C	1/2	1.1	67.283	−125.725
^{14}N	1	99.6	19.338	−36.132
^{15}N	1/2	0.37	−27.126	+50.684
^{17}O	5/2	0.04	−36.281	+67.782
^{19}F	1/2	~100	251.815	−470.470
^{23}Na	3/2	~100	70.808	−132.259
^{27}Al	5/2	~100	69.763	−130.285
^{29}Si	1/2	4.7	−53.190	+99.336
^{31}P	1/2	~100	108.394	−202.606

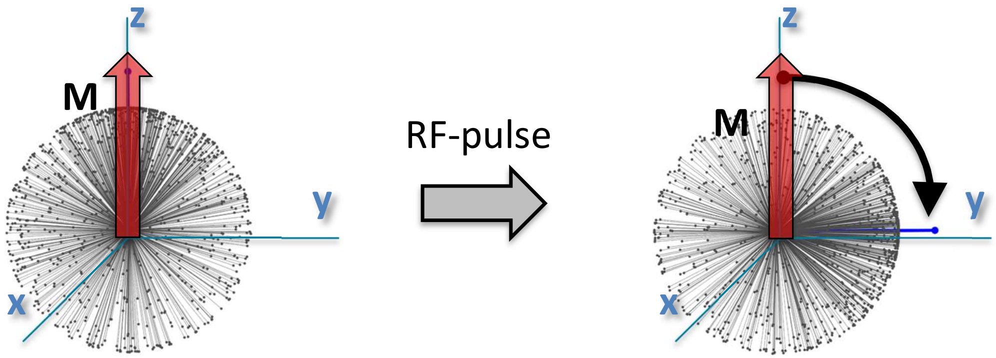
$$sensitivity \propto \gamma^3 I(I+1)$$

$$SNR \propto B_0, \rho$$

- I – the spin number
- γ – gyromagnetic ratio
- B_0 – magnetic field strength
- ρ – concentration of the nucleus

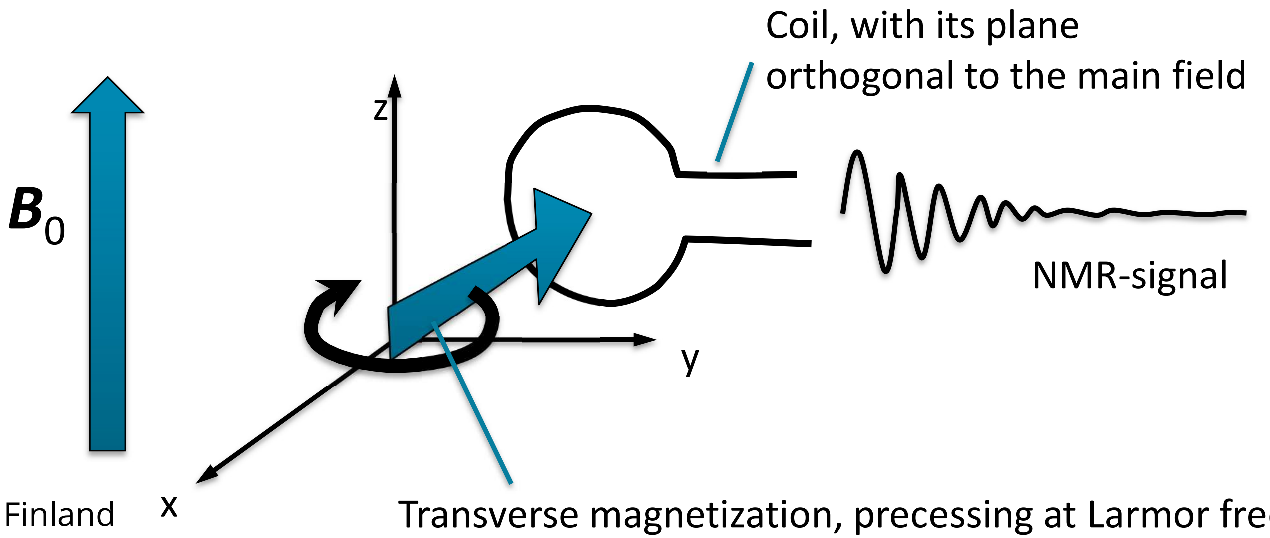
Excitation (disturbing the equilibrium)

- Key concept is ***resonance*!**
- Excitation of the spins can be done using ***radio frequency* (RF) *energy*.** An external (electro)magnetic field oscillating at the resonance frequency
- The correct frequency is the Larmor frequency: $$\omega_0 = -\gamma B_0$$



Detection of NMR signal

- The precession of net magnetization M induces a small but detectable signal
- The oscillating EM field is detected as current in conducting material (in a coil)



Relaxation times

- Relaxation times arise from tissue microstructure and chemical composition

- Different tissue types have unique relaxation times

  ⇨ Tissue contrasts

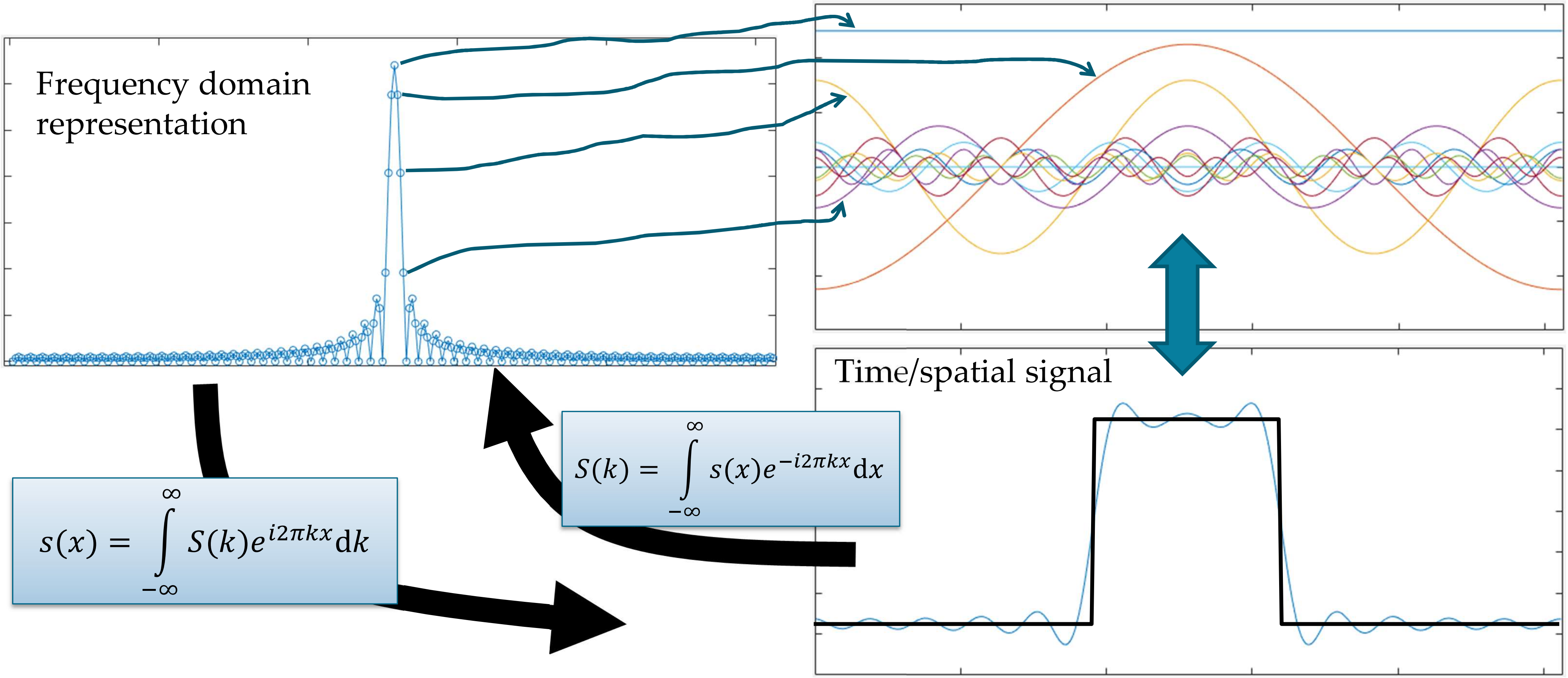
- Molecular structure(s) change in disease

  ⇨ Disease contrast

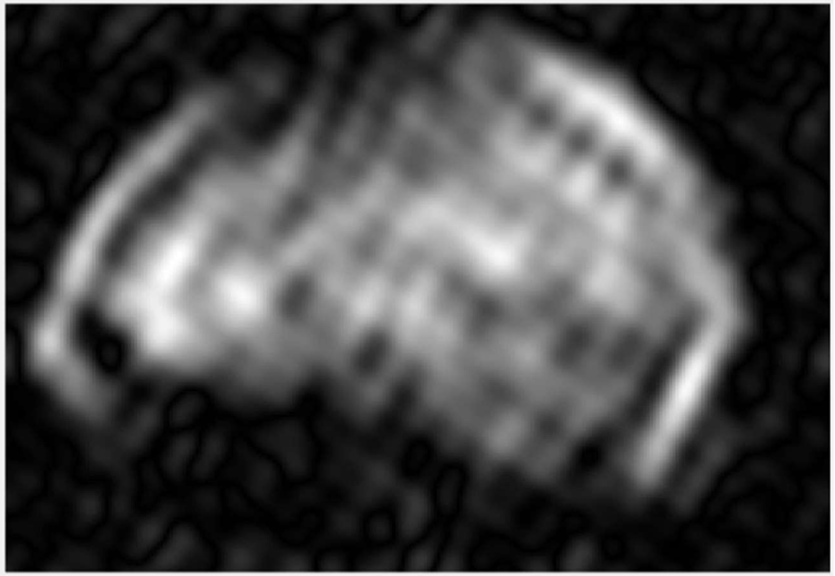
Relaxation times of some tissues

Tissue	T_1 (ms)	T_2 (ms)
Fat	240	60
Muscle	400	50
Gray matter	1300	80
White matter	830	110
Synovial fluid	2000	250
Cartilage	900	40
Meniscus	1500	4-8
Cortical bone	350, 1000	~0.5
Tooth enamel	?	~0.07

Fourier transform

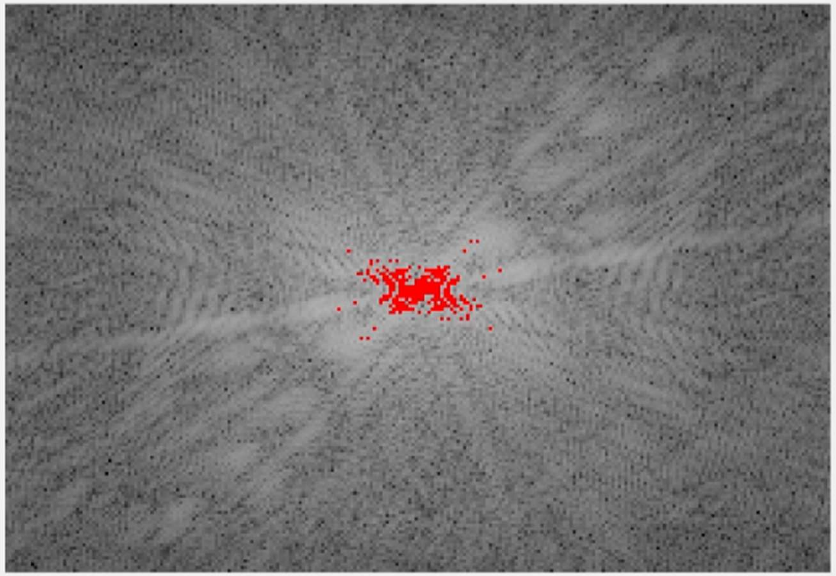


Individual spatial waveform



Sum of n waveforms, i.e. k-space components

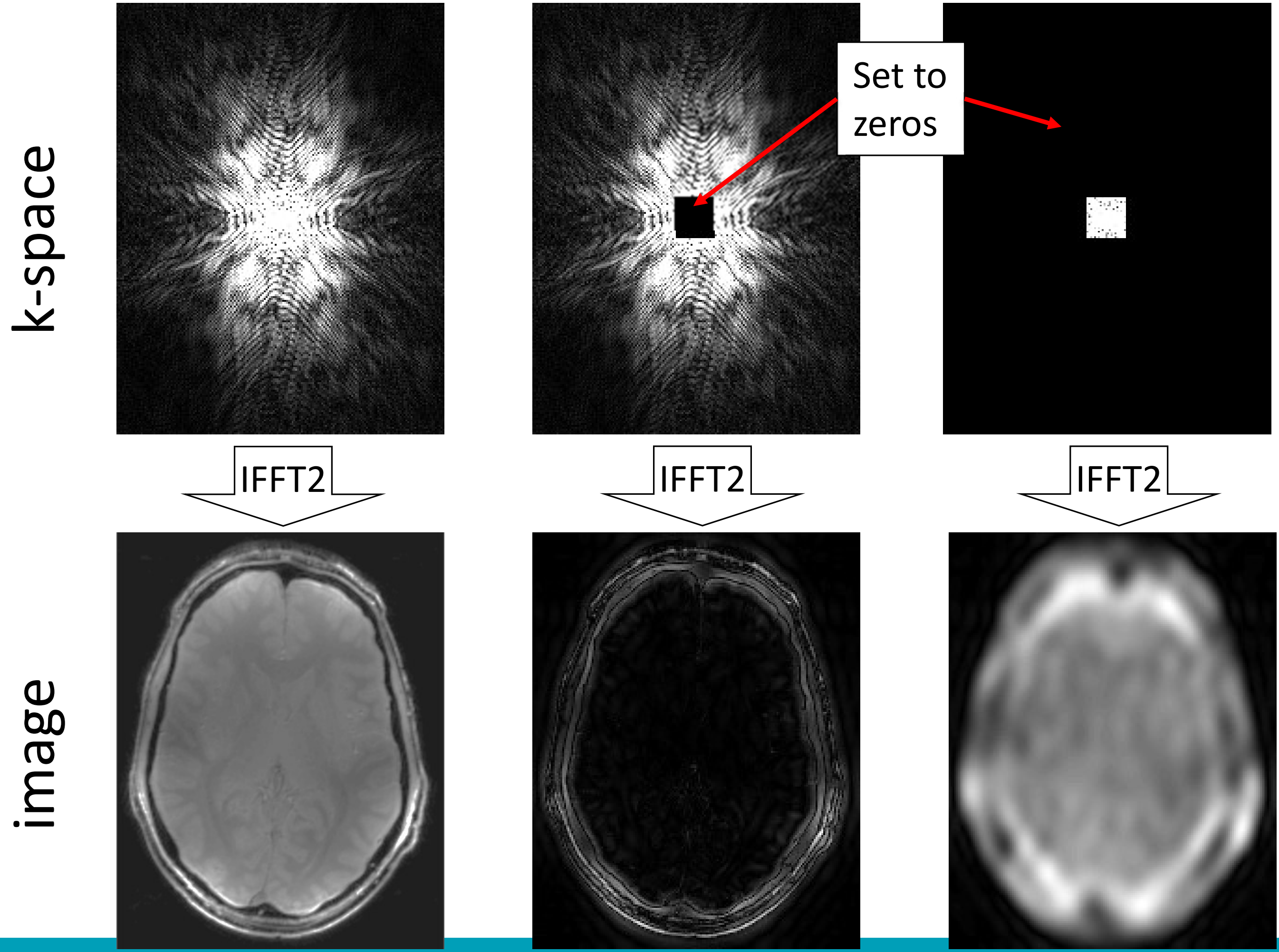
k-space



Number of k-space points:

250

The effect of different regions of K-space



Principles of MRI

In more detail

Image localization / acquisition

- Based on direct sampling of k-space

- Controlled by “pulse sequences”, which
  - Define how the k-space is sampled
  - Define the contrast of the image(s)

- Localization is based on spatially varying resonance frequency

Gradients

- In MRI, gradient implies changing the magnetic field to induce spatially dependent resonance frequency

$$\vec{G} = \frac{\partial B_z}{\partial x}\hat{x} + \frac{\partial B_z}{\partial y}\hat{y} + \frac{\partial B_z}{\partial z}\hat{z} = G_x\hat{x} + G_y\hat{y} + G_z\hat{z}$$

- Then main magnetic field becomes

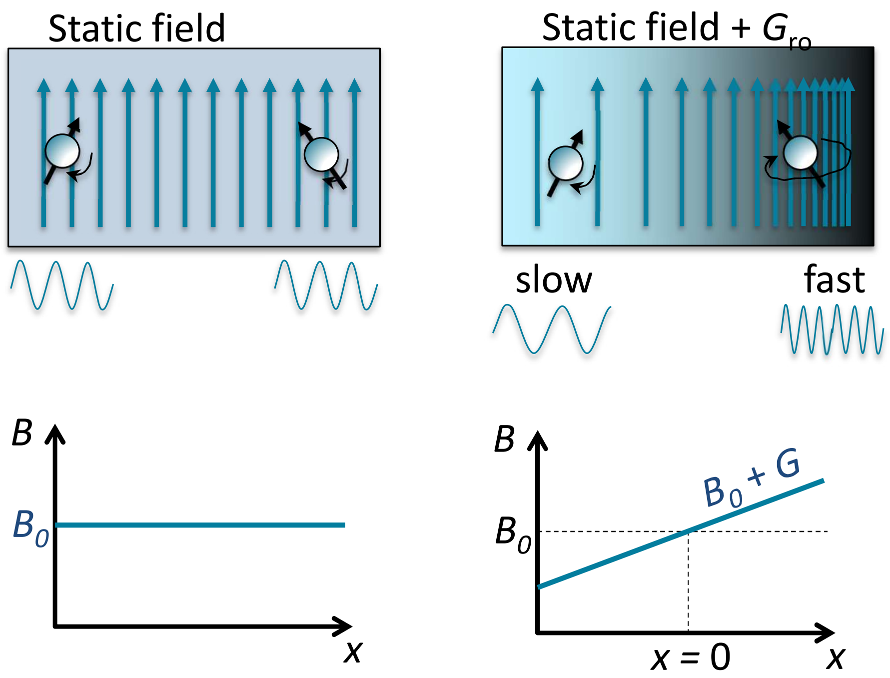
$$\vec{B} = (B_0 + G_x\hat{x} + G_y\hat{y} + G_z\hat{z})\hat{z}$$

Note:
Gradients add to the **z-component** of B0!

Spatial location can be encoded with gradients

$$\boxed{\omega_0 = -\gamma B_0 = -\gamma(B_0 + G)}$$

- With the gradient on, resonance frequency varies spatially
- Gradients modify the phase distribution (spatial phase accumulation) of excited magnetization
- Phase distribution depends on the duration and amplitude of the gradient



General signal equation and k-space

- MRI signal has the form

$$S(t) = \int M_\perp(\vec{r}) B_\perp(\vec{r}) e^{-i\phi(\vec{r},t)} d^3r \qquad (d^3r = dxdydz)$$

- where $M(\boldsymbol{r})$ is transversal magnetization and $B(\boldsymbol{r})$ is the receive coil sensitivity
- Phase accumulated in the sample depends on gradients:

$$\phi(\vec{r},t) = \gamma \int_0^t \vec{r} \cdot \vec{G}(t') dt'$$

- K-space vector can be defined with gradients:

$$\vec{k}(t) = \gamma \int_0^t \vec{G}(t') dt'$$

- Now, the signal can be written

$$\boxed{S(t) = \int M_\perp(\vec{r}) B_\perp(\vec{r}) e^{-i\vec{k}(t)\cdot\vec{r}} d^3r = \int S(\vec{r})\, e^{-i\vec{k}(t)\cdot\vec{r}} d^3r}$$

- Here $\boldsymbol{k}(t)$ and $\boldsymbol{r}$ are Fourier-conjugates
- $\boldsymbol{S}(t)$ is a k-space path $\boldsymbol{k}(t)$ as a function of time

Cartesian 2-D case:

$$s(t, G_{\mathrm{pe}}) = \int\int m(x,y) e^{-i\gamma G_{\mathrm{pe}} \tau_{\mathrm{pe}} y} e^{-i\gamma G_{\mathrm{ro}} t x} dydx$$

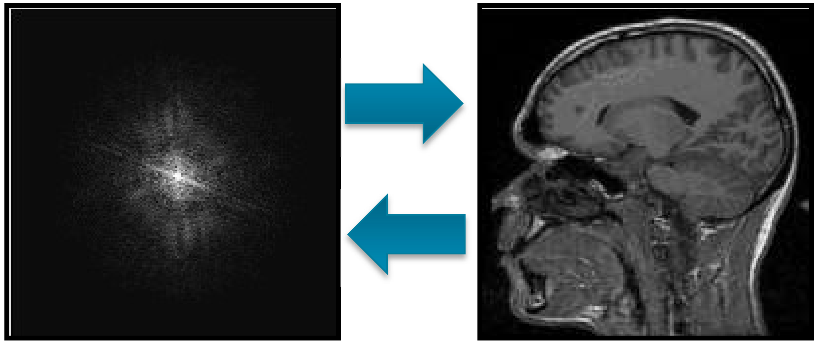
<u>Fourier transform</u>

$$S(k) = \int_{-\infty}^{\infty} s(x) e^{-i2\pi kx} \mathrm{d}x$$

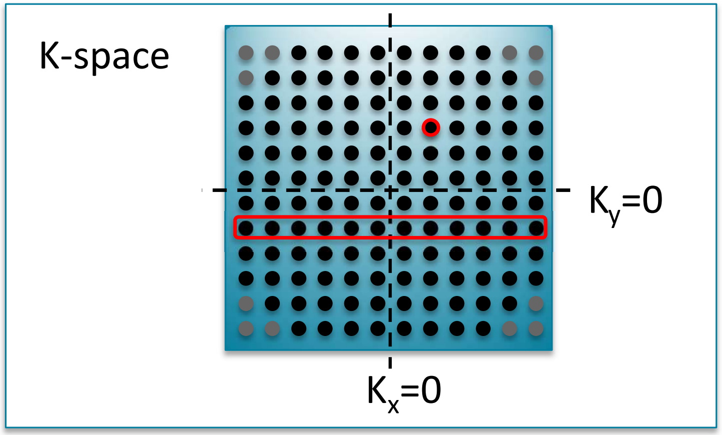
$$s(x) = \int_{-\infty}^{\infty} S(k) e^{i2\pi kx} \mathrm{d}k$$

Spatial encoding

- K-space is directly sampled in MRI
- Every point in k-space
  - Contains information of the *entire image*
  - corresponds to certain ***phase encoding*** in MRI



- Collection in various ways
  - Point-by-point
  - Line-by-line
  - Large chunks along various paths

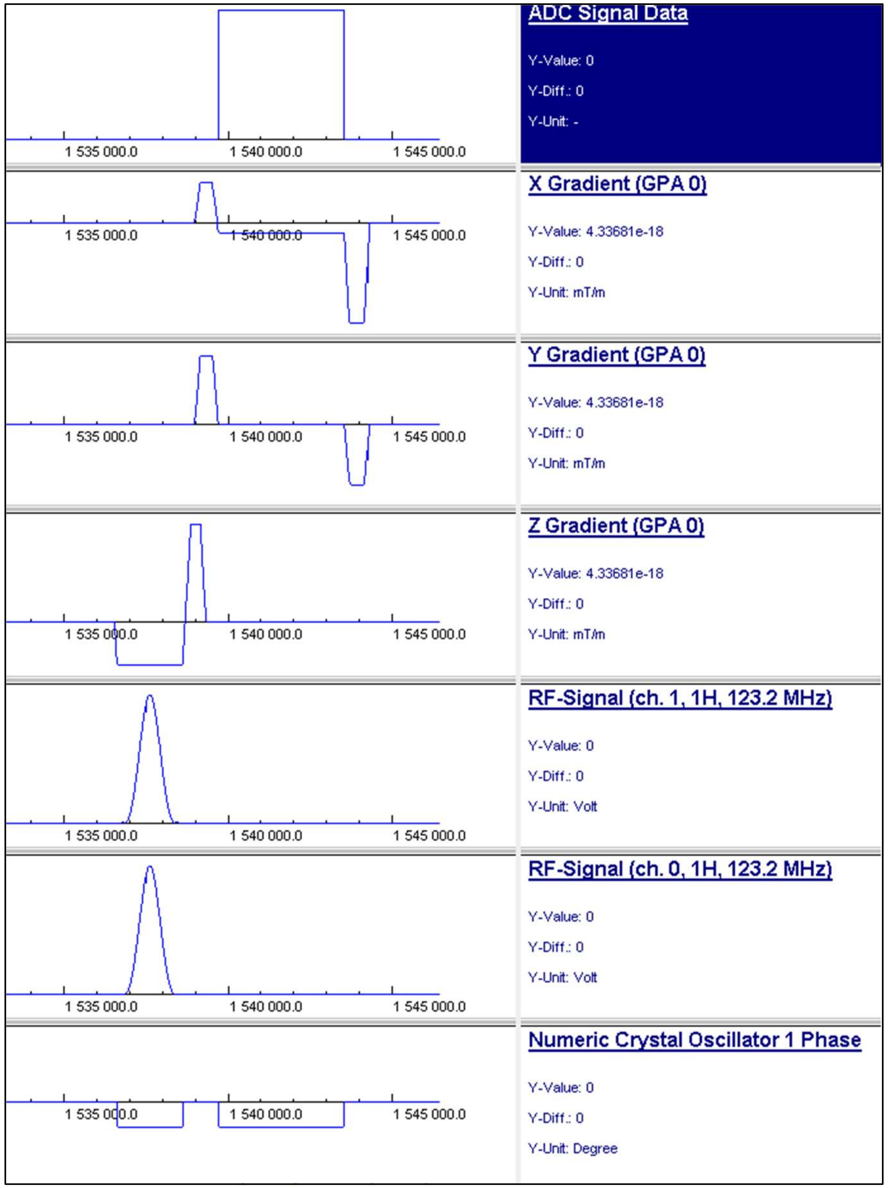


Principles of MRI

Pulse sequences

On pulse sequences

- A sequence describes what happens on different channels during the experiment, “the staves”
  - Respective timing of events
  - Duration of pulses
  - Amplitude of pulses
  - Loop structures
- Typical channels:
  - RF transmission (all nuclei)
  - RF reception
  - Field gradients
  - Acquisition
  - Other parameters (physiological gating/triggering…)
  - Output signals



Imaging sequence flow

Slice selection and excitation

↓

Phase encoding

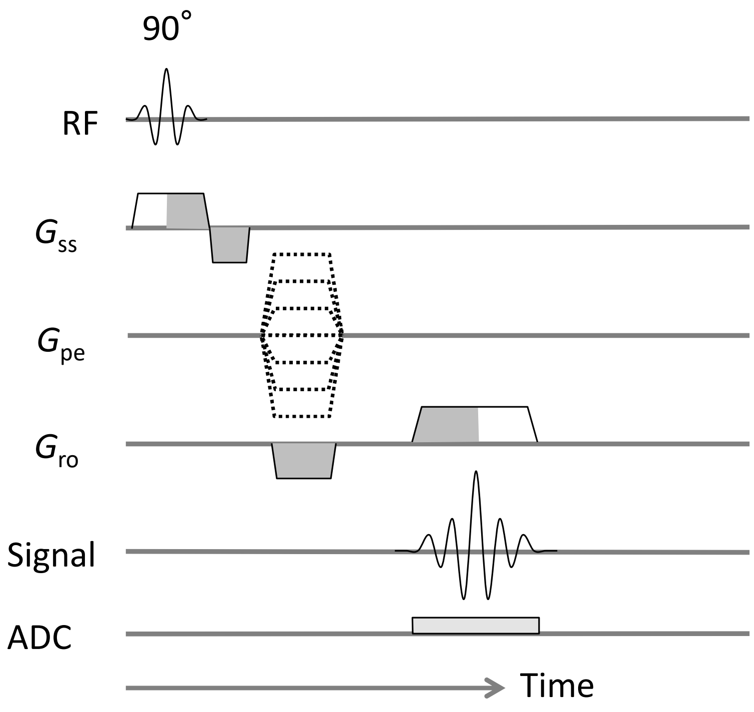
↓

Frequency encoding

↓

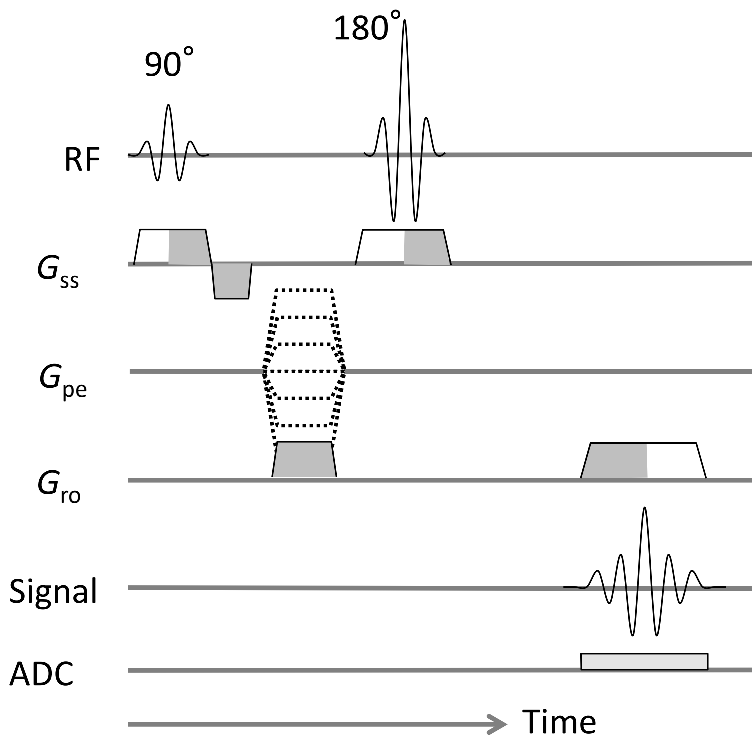
Data acquisition

Pulse sequence diagram



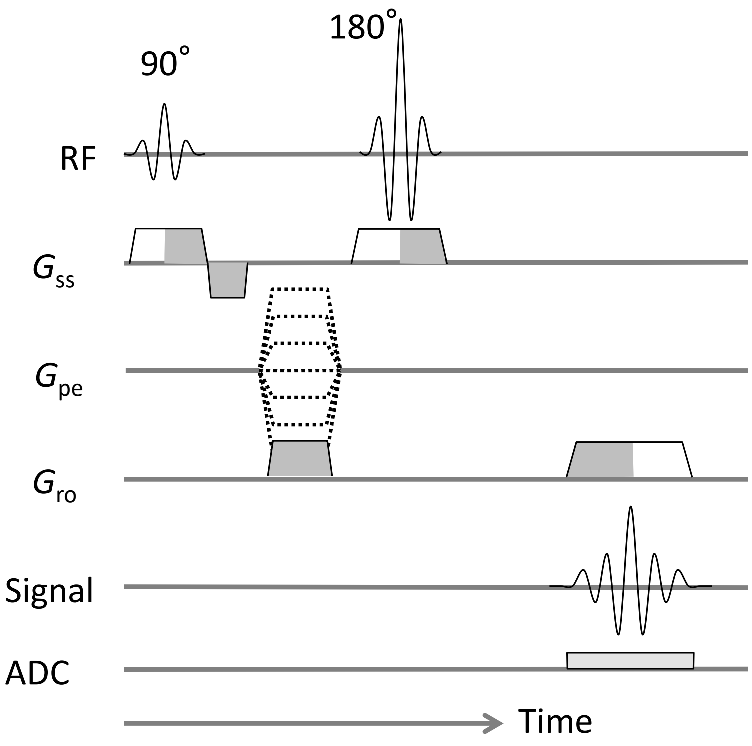
Gradient echo sequence

Pulse sequence diagram

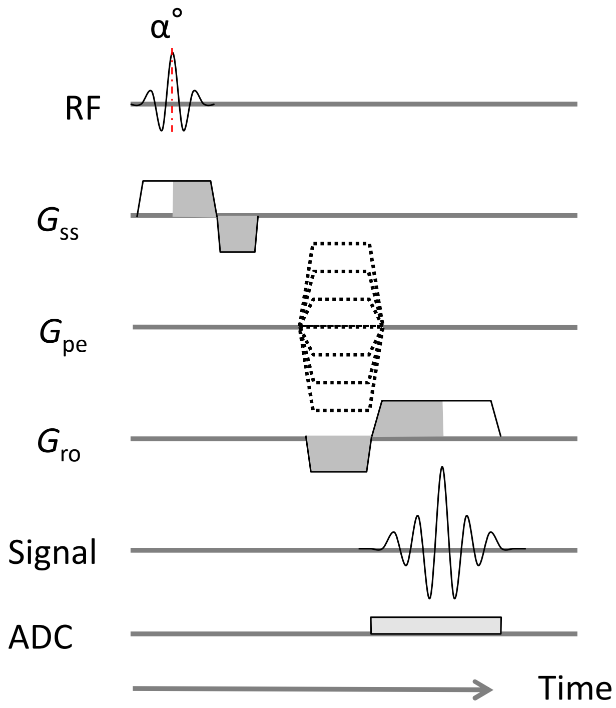


Spin-echo sequence

Pulse sequence: two main families

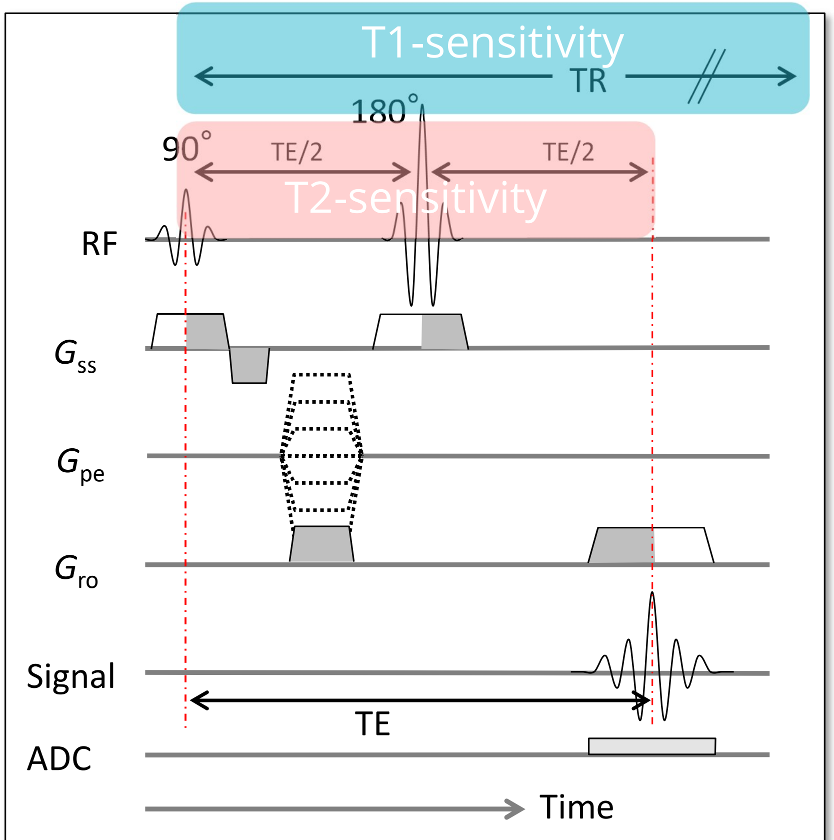


Spin-echo sequence

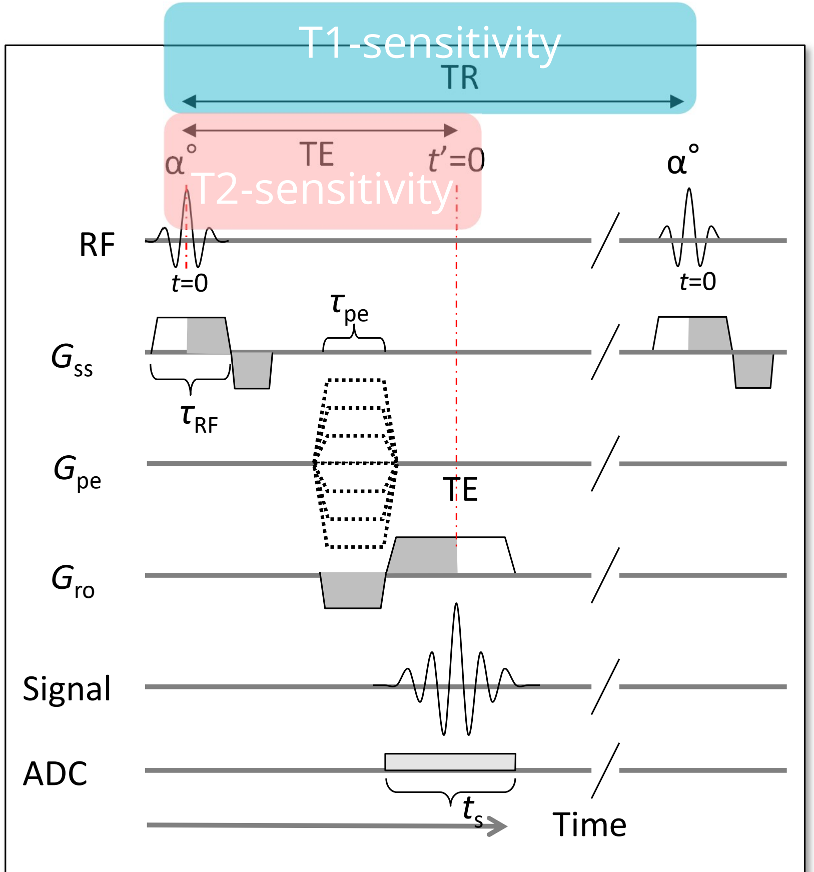


Gradient-recalled echo sequence

Pulse sequence



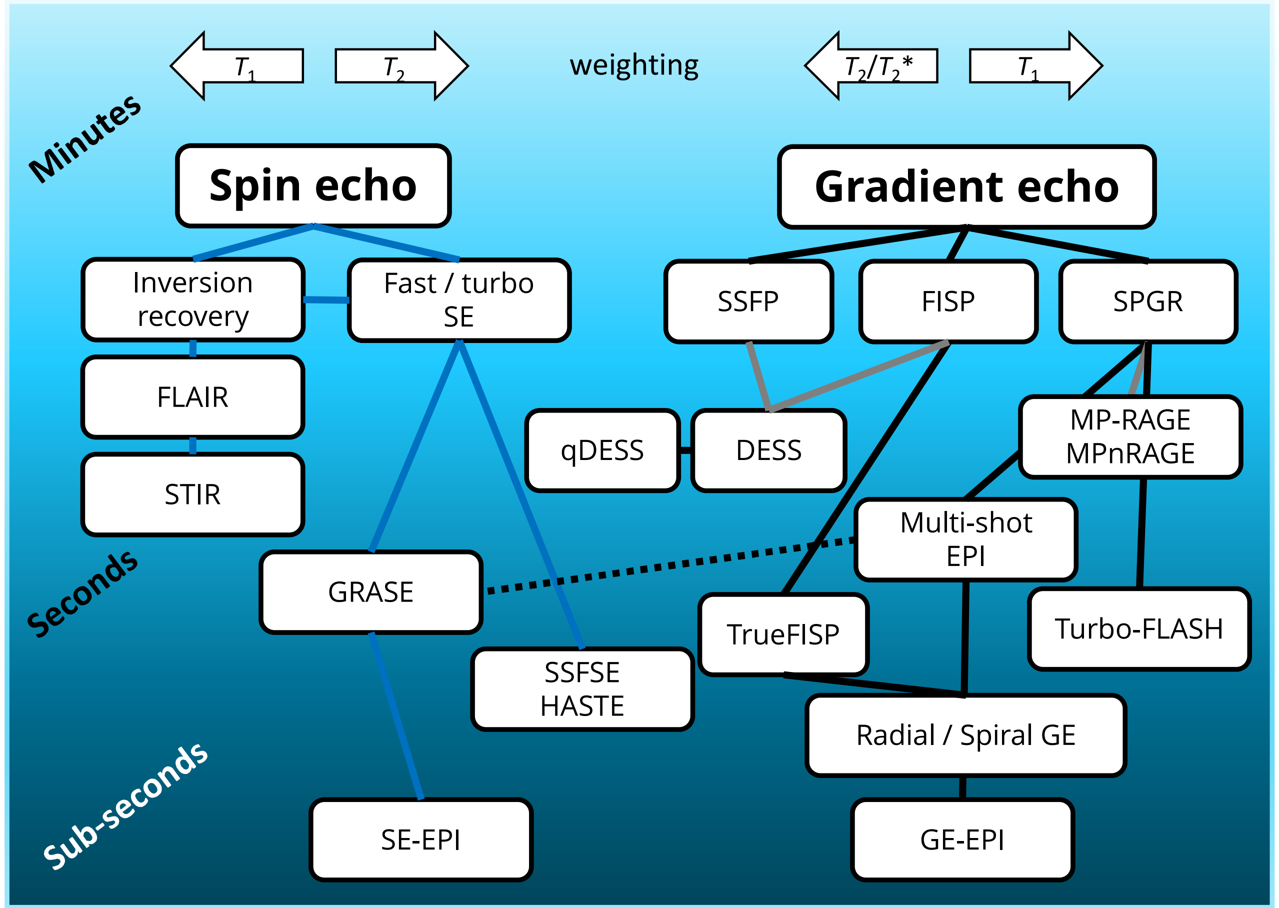
Spin-echo sequence



Gradient-recalled echo sequence

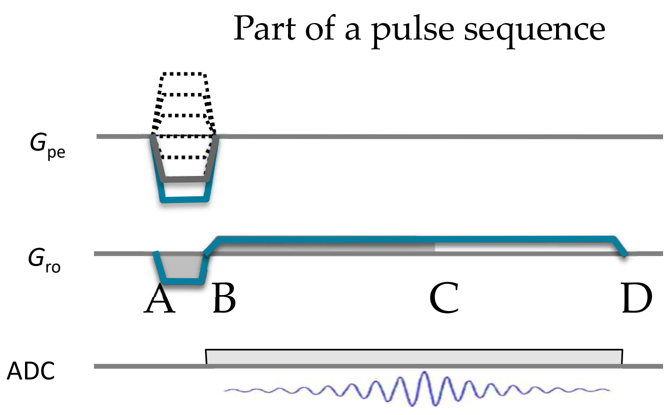
On pulse sequences

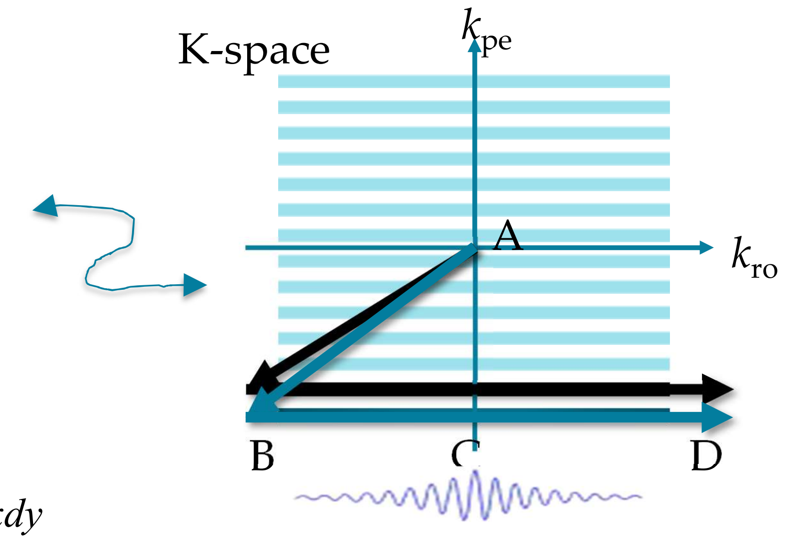
- Roughly two main families
  - Spin-echo sequences
  - Gradient-echo sequences
- And their variations/extensions
  - Speed
  - Specificity on processes
  - Prepared the magnetization
  - Different sampling strategies (k-space)
  - Weighting
- Naming: acronyms that don't say much of the purpose of the technique



Encodings and k-space

- Gradients provide a way to navigate in ***k-space***
- Immediately after excitation, position is in the center of the k-space
- Every k-space line contains information from the whole slice
  - As well as every single point in k-space

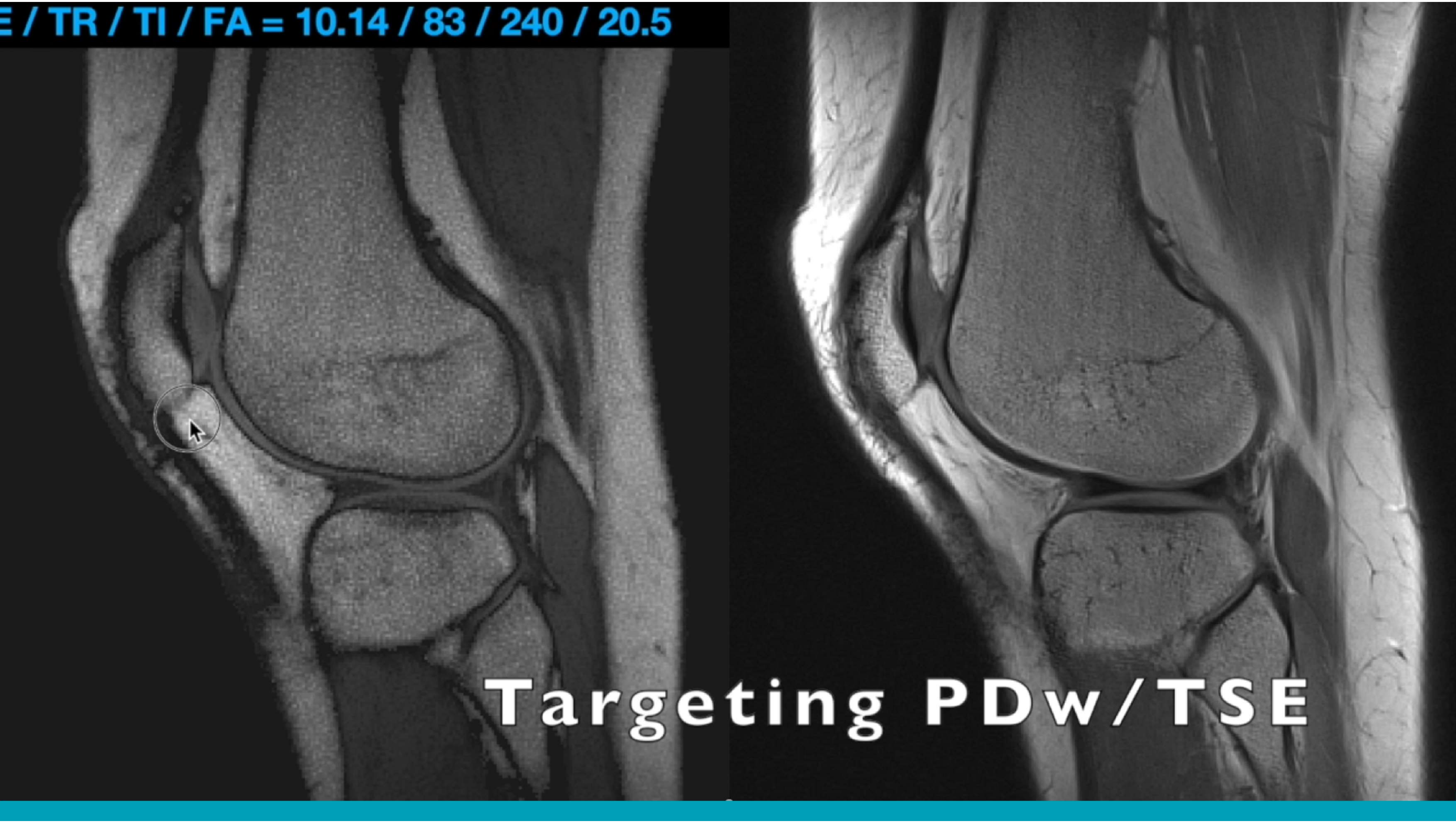


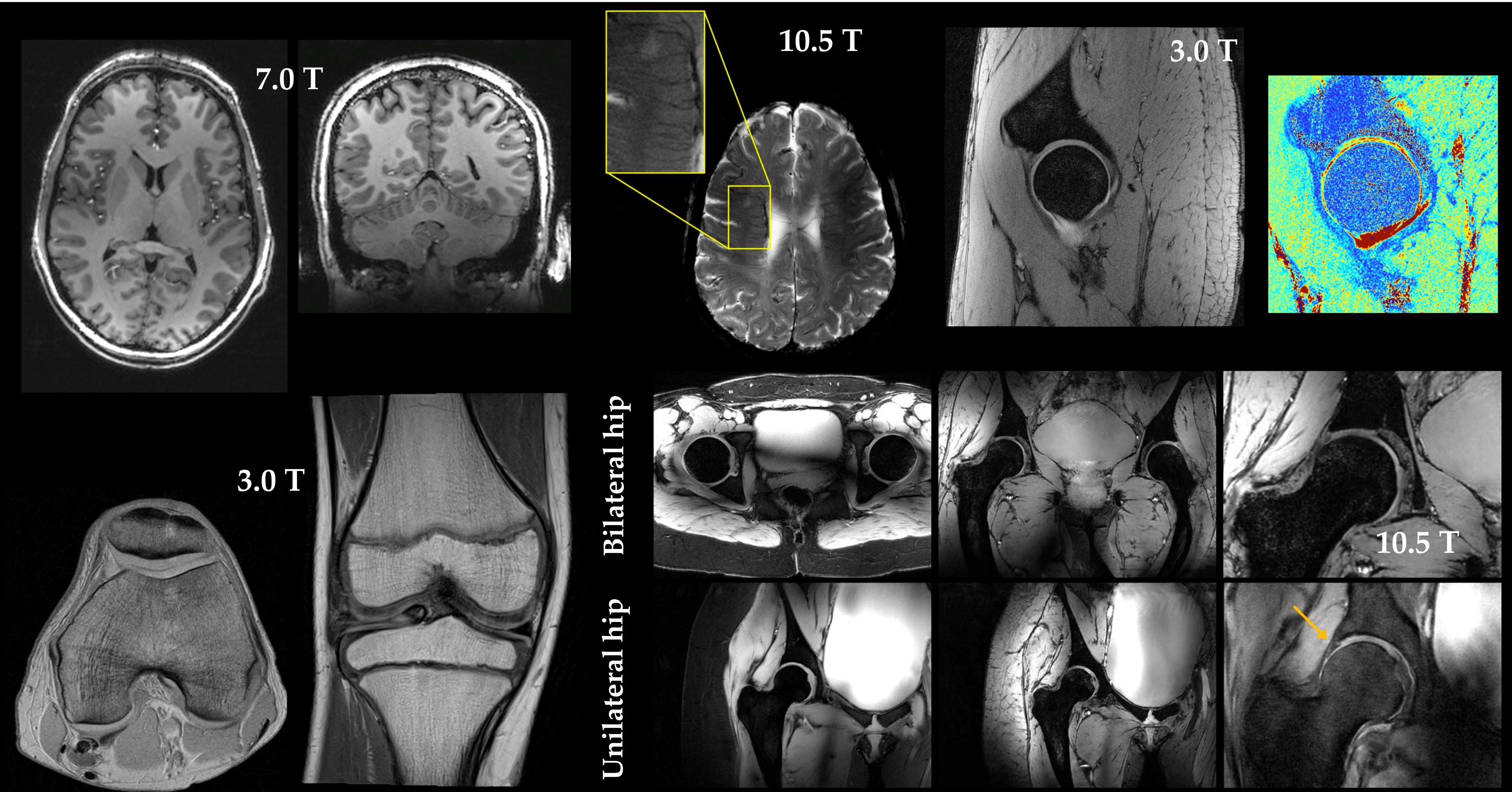


$$s(k_{ro},k_{pe}) = \int\int m(x,y)e^{-i2\pi(k_{ro}(t)x+k_{pe}(G_{pe})y)}dxdy$$

Principles of MRI

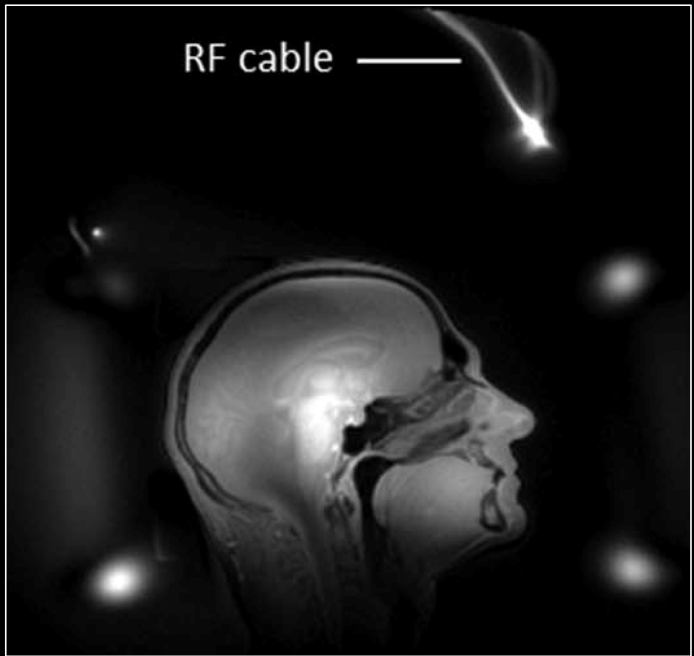
Random examples

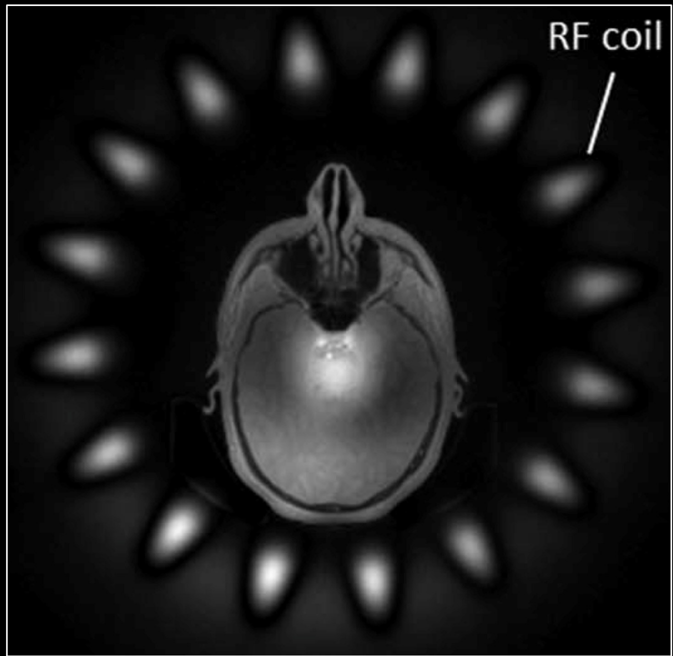

E / TR / TI / FA = 10.14 / 83 / 240 / 20.5
Targeting PDw/TSE



10.5T studies: He et al, 2019 MRM; Sadeghi-Tarakameh et al, MRM 2019

Ultra-short / Zero echo time imaging





ZTE Imaging in Humans
Markus Weiger,* David O. Brunner, Benjamin E. Dietrich, Colin F. Müller, and Klaas P. Pruessmann

Magnetic Resonance in Medicine 70:328–332 (2013)

Department of applied physics organizes a full MRI course! Next run in 2024, but course is fully available online, please contact me for further details!

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Thank you!

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