Human neuroanatomy and its clinical application

MRI essentials

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May 16, 2022
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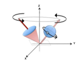
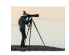
MRI essentials - Spinning



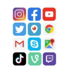
Basic physics

- Spins
- Magnetization
- Signal formation
- Type of fields
- Equipment



Imaging

- Position encoding
- Image Contrast
- Pulse sequences
- Field strength

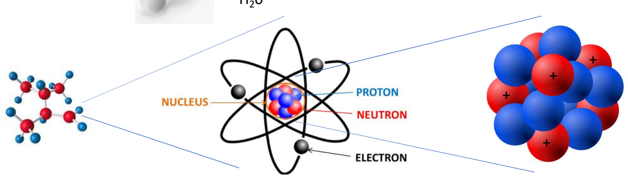


Applications

- Neuroimaging

MRI essentials – The very basics

H_2O



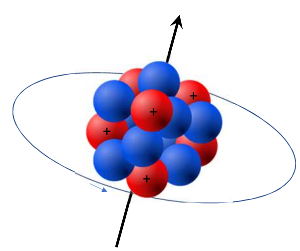
Nuclear Magnetic Resonance = NMR

- Nuclear - atomic nucleus
- Magnetic – magnetic field of nucleus
- Resonance – matching of magnetic fields

MRI = Magnetic Resonance Imaging

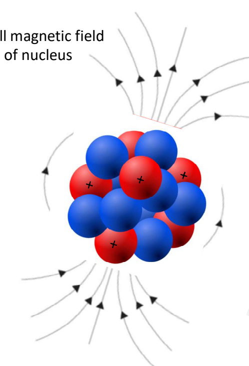
- Magnetic - many magnetic fields
- Resonance – ability to absorb and re-emit RF energy
- Imaging – making (internal) pictures

MRI essentials – Spinning



Nucleus rotates → magnetic moment μ (spin)
angular momentum

small magnetic field
of nucleus



External magnetic field
e.g. $B_0 = 3.0$ T

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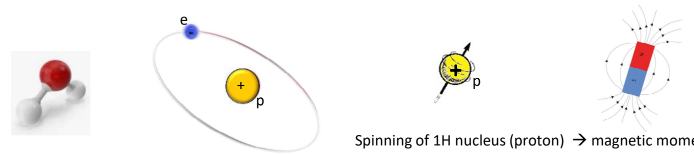
MRI essentials – Nuclei

Nucleus	Gyromagnetic ratio (γ) in MHz/Tesla	Relative Sensitivity
1-H	42.58	1
13-C (not 12-C)	10.71	-
19-F	40.05	$3\cdot10^{-8}$
23-Na	11.26	$1\cdot10^{-4}$
31-P	17.24	$6\cdot10^{-4}$

H_2O

Not all nuclei have nuclear spin!

H_2O -molecule — 1-H atom — 1-H nucleus — small magnet



Spinning of 1H nucleus (proton) → magnetic moment

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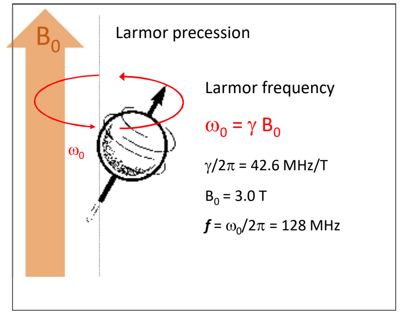
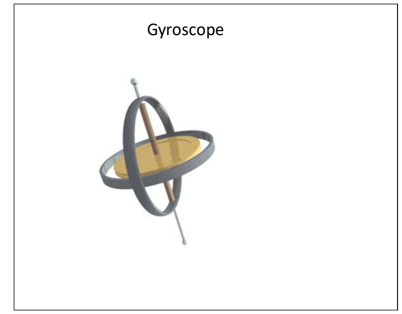
MRI essentials – Larmor frequency

Magnetic spin in magnetic field B0



Frequency of Larmor precession is proportional to magnetic field



Precession: combined rotation,
or change in orientation of rotation axis of a rotating body

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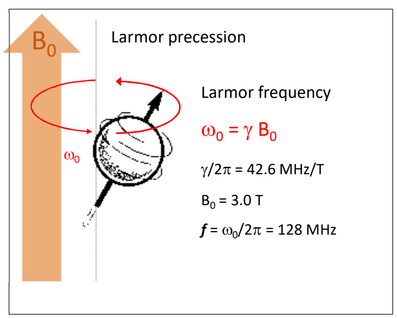
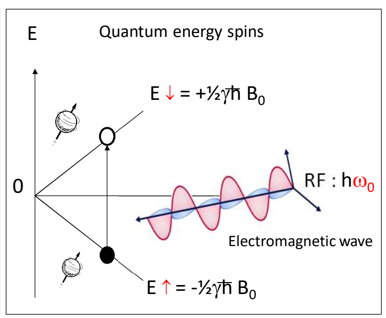
MRI essentials – Larmor frequency

Two spin states





RF = radiofrequent waves (energy) with matching frequency → Resonance (MRI)
RF energy tips the spins, absorption of energy

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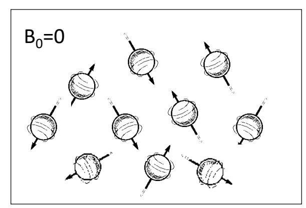
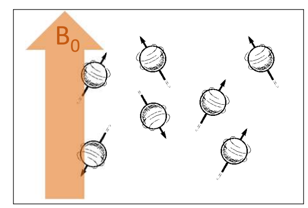
MRI essentials – Many spins



Random orientation of spins



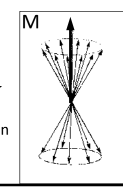
2 spin states: ↑,↓ either aligned up or down

$n\uparrow - n\downarrow = N\hbar\,\omega_0/2kT$
$= 9.10^{-6}$ N for T=310 K, B_0=3 T

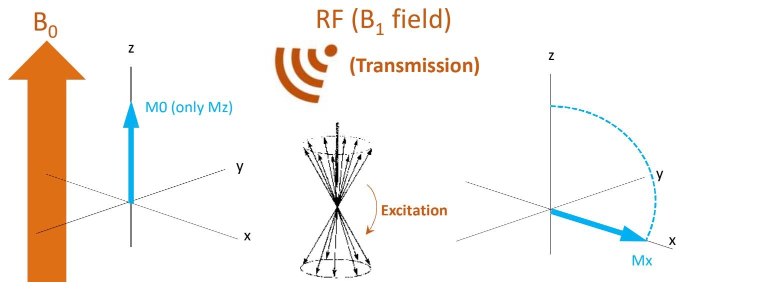
Many spins in homgeneous magnetic field →
net magnetization along magnetic field

$M = (1/V)\,\Sigma\,\vec{\mu_i}$

net magnetization
(**M**RI)



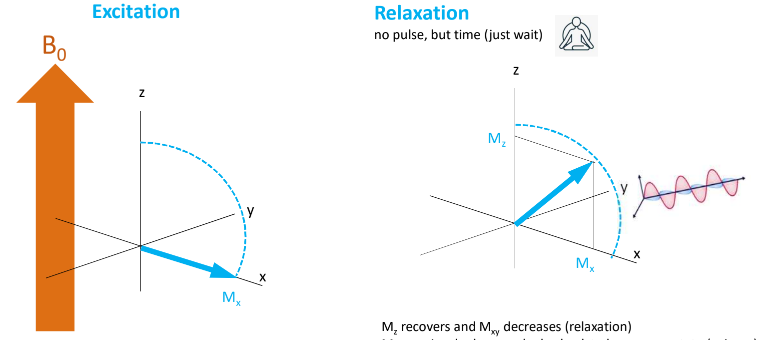
MRI essentials – Excitation



Mz cannot be measured (directly)

Net magetization M_z is flipped to xy-plane by RF wave
(flip angle here is 90°)
Spins become in phase
M_{xy} can be measured in the xy-plane

MRI essentials – Relaxation and Signal



M_z recovers and M_{xy} decreases (relaxation)
Many spins dephase and relax back to low energy state (spin up)
Excess of energy is emitted as RF and detected → measurable signal

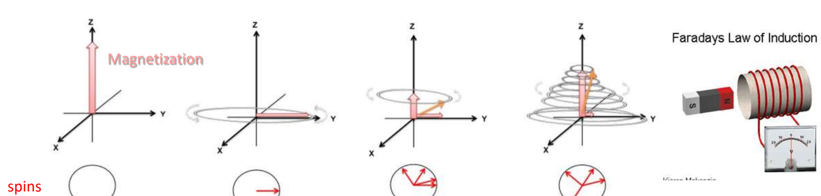
MRI essentials – Relaxation and Signal

90° excitation

.. just wait - relaxation

measurement

Faradays Law of Induction



Longitudinal magnetization

Transverse Magnetization
Spins are all in phase

Spins dephase
Mz recovers
Mxy shrinks due dephasing

Magnetization spirals

Emission of RF wave = signal

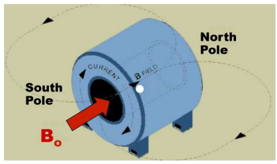
Measurement analogy

MRI essentials – Recapitulation

- Origin of the MRI signal is the nuclear spin
- For MR imaging it is mostly the hydrogen nucleus of water molecules (or lipids)
- Spins precess (gyroscope) with Larmor frequency, which is proportional to magnetic field
- Spins align in magnetic field and form the magnetization (net vector)
- Two energic spin states: spin up & spin down
- RF (i.e. B1 field) waves tips the spins (resonance) and turns longitudinal magnetization into transverse magnetization
- In ground state the net magnetization is along external magnetic field (B_0)
- Longitudinal magnetization direction can be changed to transverse magnetization by resonant RF pulse,
  i.e. excitation of spin states
- Thereafter relaxation of magnetization (to B_0 direction), i.e. spins return to ground state and re-emit RF energy
- Transverse magnetization provides signal that can be measured

MRI essentials – many fields

External field B_0
(homogeneous, static)

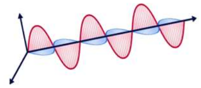


Typical field strength in Tesla
1.0, 1.5, 3.0, 7.0, 9.4 T, …

Homogeneity: in the order of ppm

Safety: Pulling force/torque force

RF field or B_1 field
(wave, time dependent)

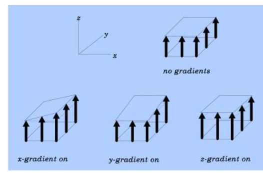


Magnitude: ~10 μT

(Larmor) Frequency : 128 MHz @3.0T

Safety: Tissue heating

Gradients
(switch on/off, vary linearly over space)



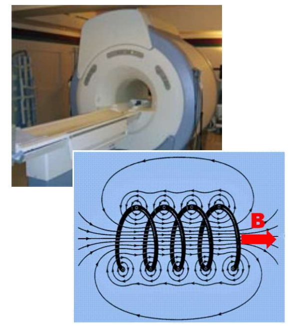
Magnitude: ~10 mT

Grad strength: 40-80 mT/m (=ΔB/Δx)

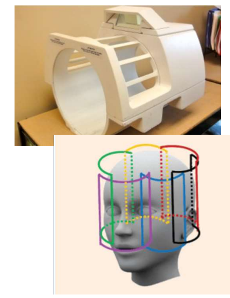
Safety: switching
– peripheral nerve stim

MRI essentials – Equipment

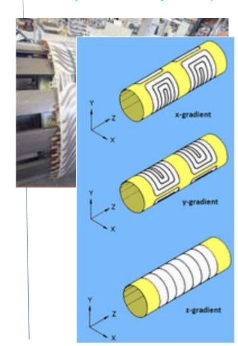
External field B_0
(homogeneous)



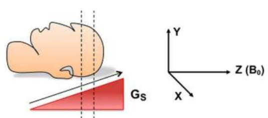
RF field or B1 field (transmission and signal reception)



Gradients
(ΔB/Δx, ΔB/ Δy, ΔB/Δz)



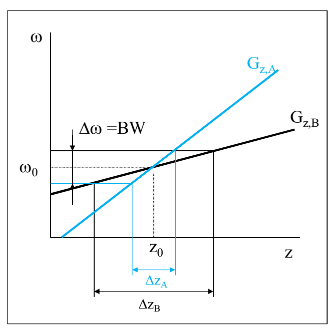
MRI essentials – Spatial encoding / slice selection



With gradients the magnetic field and the Larmor frequency increases linearly <u>with position</u> :

$$\omega = \gamma B = \gamma (B_0 + G_s \cdot z)$$

Signal receivers are sensitive to certain frequency band width (BW) around Larmor frequency

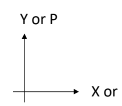


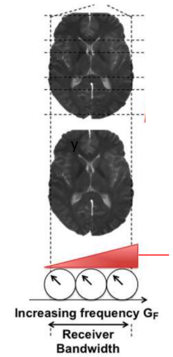
Stronger slice selection gradient → thinner slices
(Band width BW remains the same)

$G_S = G_z$

MRI essentials – spatial encoding - frequency & phase

Inplane (x,y) encoding

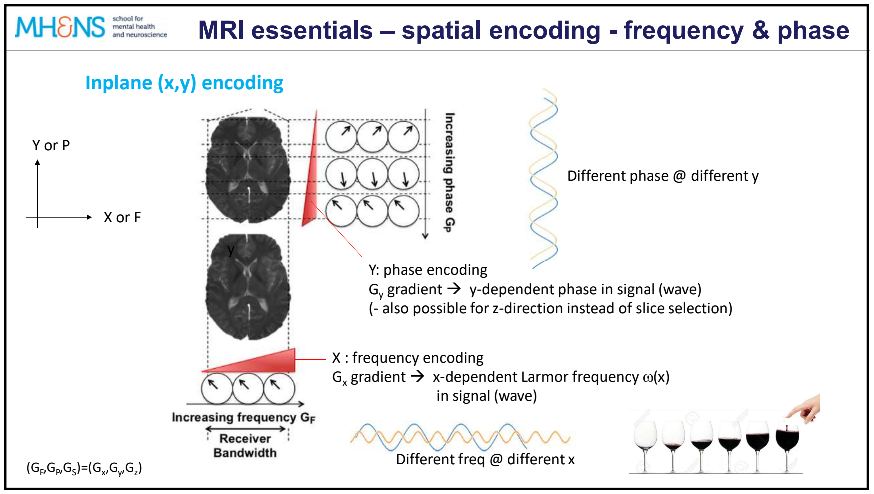




X : frequency encoding
G_x gradient → x-dependent Larmor frequency ω(x)
in signal (wave)

Different freq @ different x

$(G_F,G_P,G_S)=(G_x,G_y,G_z)$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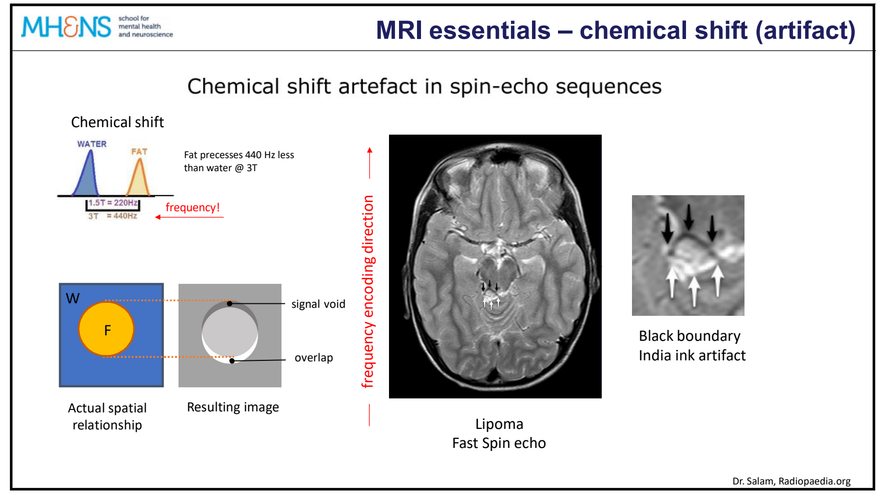
MRI essentials – spatial encoding - frequency & phase
Inplane (x,y) encoding
Y or P
X or F
Increasing phase Gp
Different phase @ different y
Y: phase encoding
Gy gradient → y-dependent phase in signal (wave)
(- also possible for z-direction instead of slice selection)
X : frequency encoding
Gx gradient → x-dependent Larmor frequency ω(x) in signal (wave)
Increasing frequency GF
Receiver Bandwidth
Different freq @ different x
(GF,GP,GS)=(Gx,Gy,Gz)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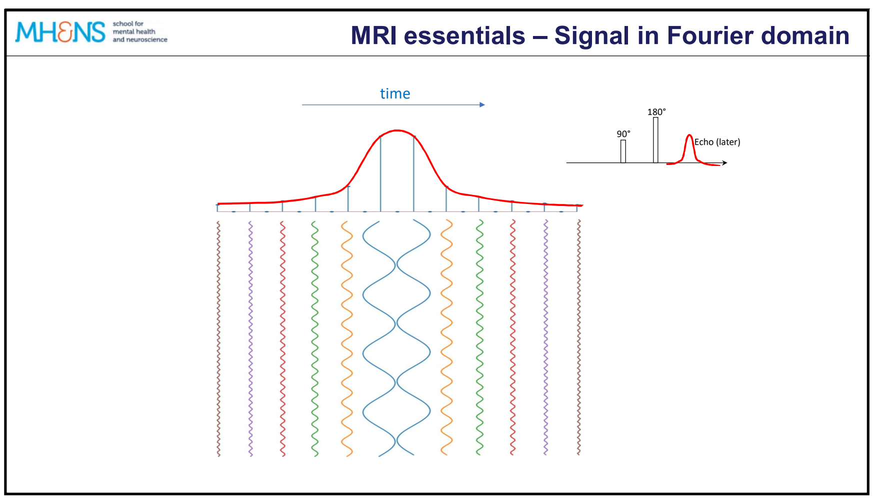
MRI essentials – chemical shift (artifact)
Chemical shift artefact in spin-echo sequences
Chemical shift
WATER
FAT
Fat precesses 440 Hz less than water @ 3T
1.5T = 220Hz
3T = 440Hz
frequency!
W
F
signal void
overlap
Actual spatial relationship
Resulting image
frequency encoding direction
Lipoma
Fast Spin echo
Black boundary
India ink artifact
Dr. Salam, Radiopaedia.org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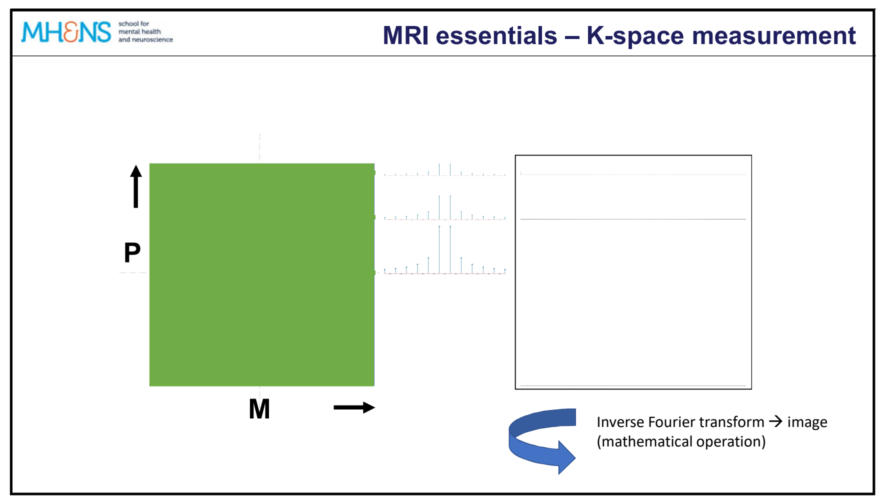
MRI essentials – Signal in Fourier domain
time
90°
180°
Echo (later)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MRI essentials – K-space measurement
P
M
Inverse Fourier transform → image
(mathematical operation)

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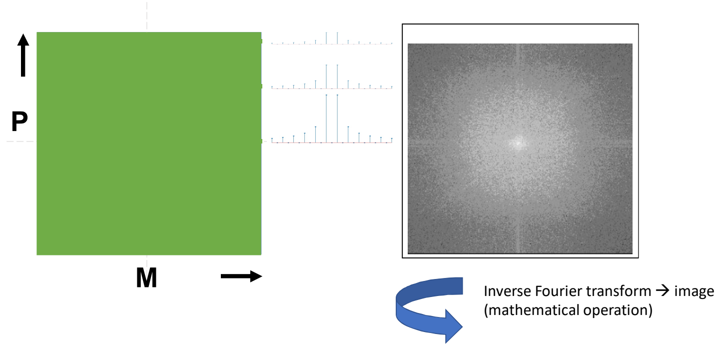
MRI essentials – K-space measurement



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MRI essentials – Relation k-space and image

Every k-point signal contributes to all image pixels!
Visa versa : each image pixel is build up by all k-space points

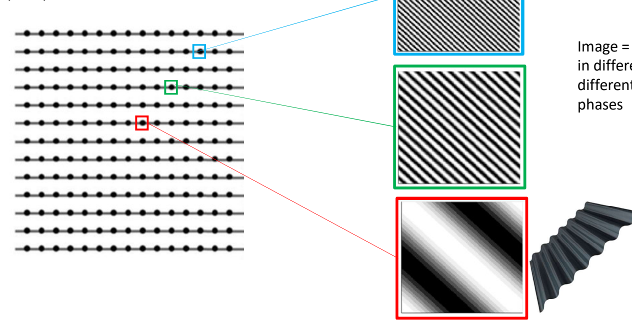

Image = summation of waves in different directions with different frequencies and phases

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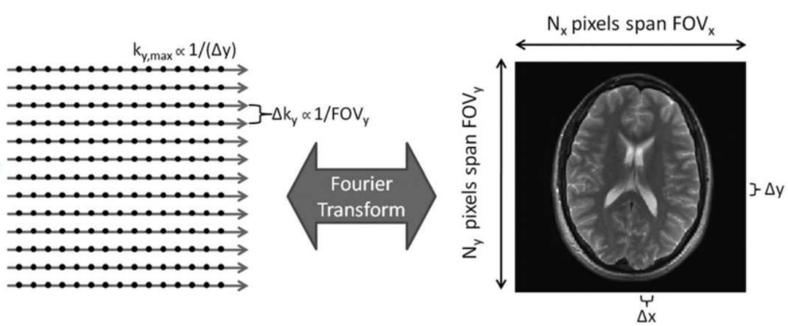
MRI essentials – Relation k-space and image



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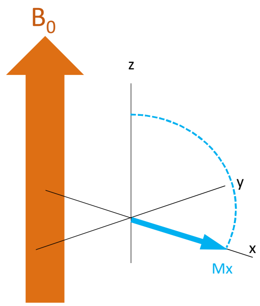
MRI essentials – Recapitulation

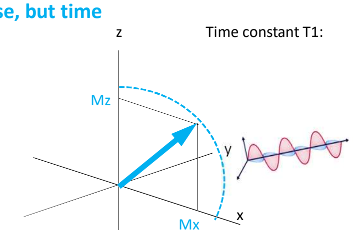
- (Magnetic) gradients in XYZ serve to localize the signal (position encoding)
- Z-gradient → slice selection/encoding
- X-gradient → frequency encoding
- Y- gradient→ phase encoding
- Signal acquisition in Fourier or k-space
- Image is a summation of numerous waves in different directions with different frequencies and phases

MRI essentials – T1 relaxation



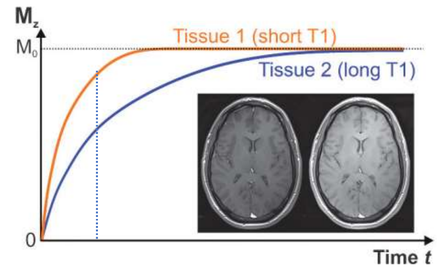
Relaxation
no pulse, but time

Time constant T1:



Characteristic time of longitudinal recovery: T1
(T1 in the order of 1 second)

MRI essentials – T1 Contrast



$$M_z(t) = M_0\{1-\exp(-t/T_1)\}$$

A solution of 1st Bloch equation

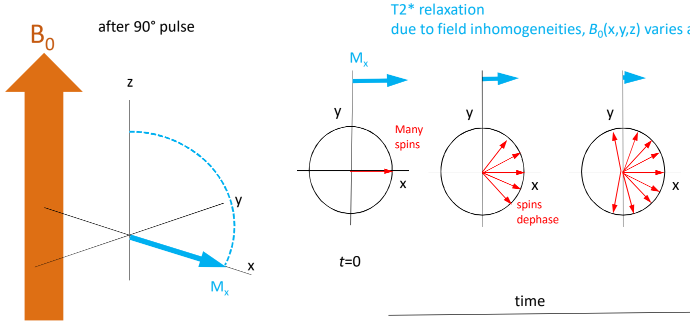
- T1 = longitudinal relaxation time
  (regrow of magnetization)
- T1 is time at 63% regrowth of magnetization (0.63 = 1-1/e)
- T1 is tissue dependent
- T1 depends on field strength
  (increases with B_0)

Tissue	T1 (ms) @ 1.5 Tesla	T1 (ms) @ 3.0 Tesla
Grey matter	920	1200
White matter	780	1010
CSF	>3000	>3000
Blood	1200	1550
Fat	252	292

MRI essentials – Spin dephasing

after 90° pulse

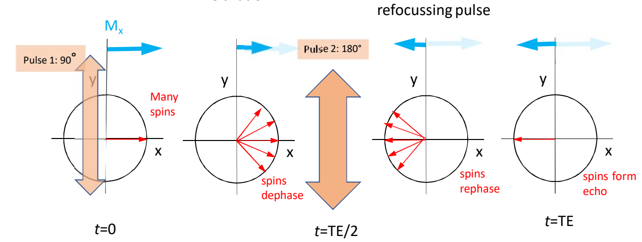
T2* relaxation
due to field inhomogeneities, $B_0(x,y,z)$ varies a bit



$M_x = M_0$

M_x has decreased according to T2 time!

MRI essentials – Spin echo

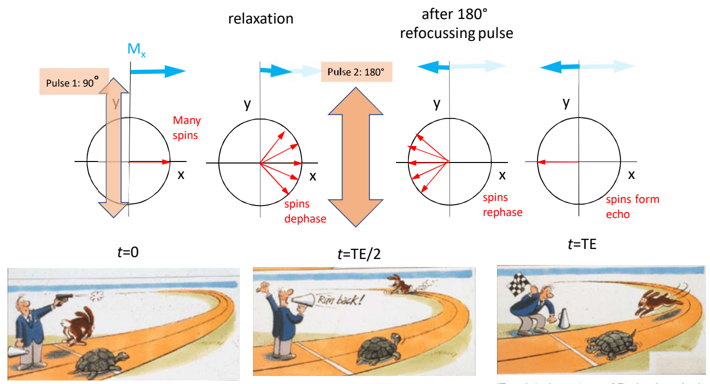


$M_x = M_0$

M_x has decreased according to T2* time!

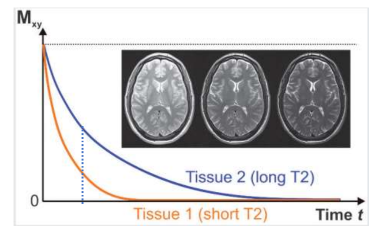
M_x has decreased according to T2 time!

MRI essentials – Spin echo



(Reprinted courtesy of Berlex Imaging)

MRI essentials – T2 Contrast



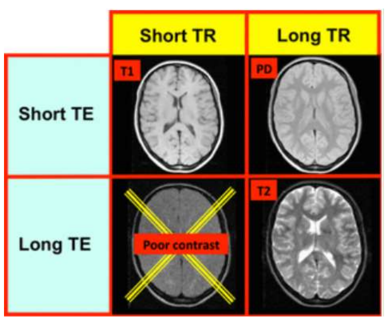
$$M_{xy}(t) = M_0 \exp(-t/T_2)$$

Solution of 2nd Bloch equation

- T2 = transverse relaxation time
- At T2 time only 37% of initial magnetization is left (0.37 = 1/e)
- T2 is tissue dependent
- T2 slightly depends on field strength

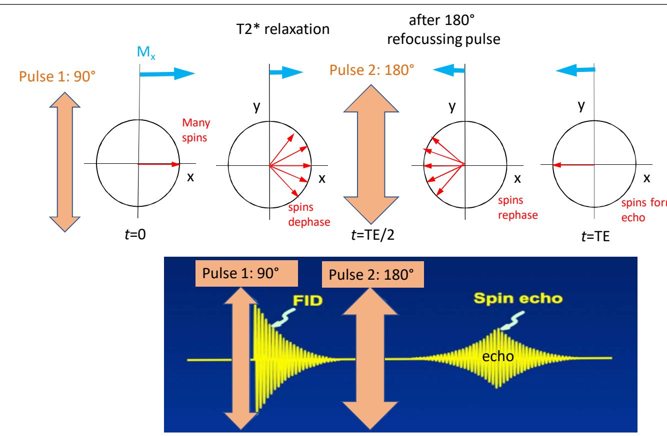
Tissue	T2 (ms) @ 3.0 Tesla	T1 (ms) @ 3.0 Tesla
Grey matter	100	1200
White matter	90	1010
CSF	>2500	>3000
Blood	100	1550
Fat	80	292

MRI essentials – Image contrast



- PD = proton density
- Contrast may also depend on flip angle

MRI essentials – Spin echo



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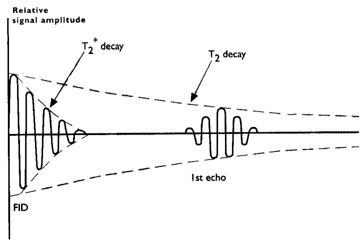
MRI essentials – T2* and T2 decay



T2 is longer than T2*

Loss of phase coherence:

- T2 decay: protons of free water molecules move randomly (diffusion) in field (dynamic field fluctuations) of other macro-molecules (40-200 ms)
- T2* decay : due susceptibility variations (giving rise to field inhom.) in tissue (T2*<T2)

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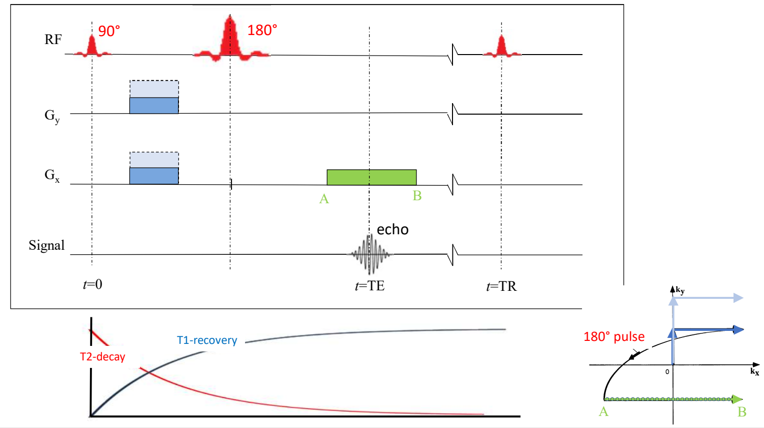
MRI essentials – Spin echo



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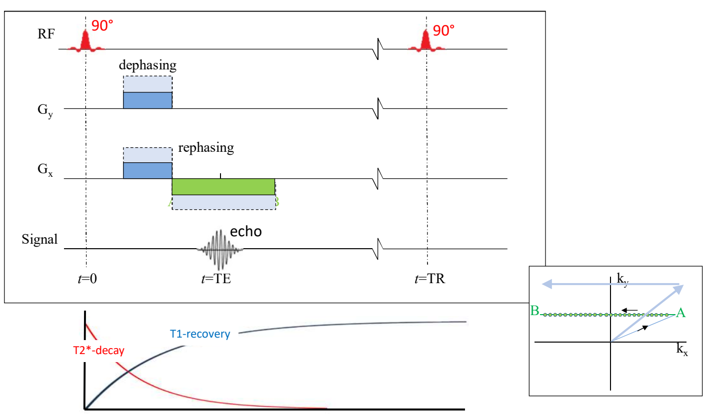
MRI essentials – Gradient echo



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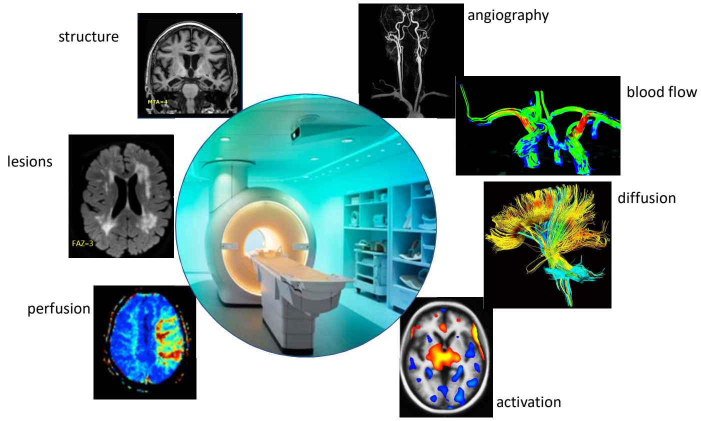
MRI essentials – Recapitulation

- T1, T2 and T2* are tissue relaxation times that determine MR image contrast
- T1 is the characteristic recovery time of the longitudinal relaxation
- T2 is the characteristic dephasing time of the transverse magnetization after a refocussing puls
- T2* is the dephasing time of the transverse magnetization due local field inhomogeneities (without refocussing pulse)
- T2*<T2<T1
- Tissue relaxation times generally depend on field strength
- Gradient switching and refocussing pulse determine k-space trajectory
- Spin echo sequence has 180° refocussing pulse for refoccusing of spins and (may have) T2-weighing
- Gradient echo sequence uses gradient switching for spin rephasing of spins and (may have) T2*-weighing

MRI essentials – Neuroimaging application

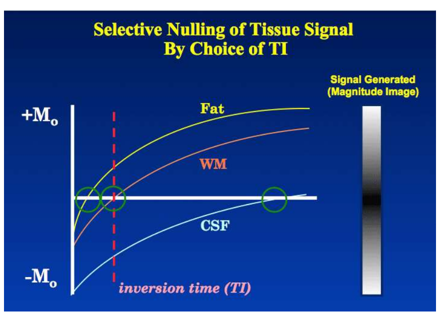


MRI essentials – Neuroimaging applications

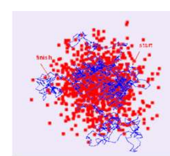
- Neuroradiology
  - involves almost allways T1w (structure) and T2w (pathology based on water content)
  - 180°(inversion) prepulse→ Inversion Recovery for nulling tissue parts (e.g. CSF, FLAIR) and/or enhancing tissue contrast
- Iron deposition or local field inhomogeneities → T2*-weighting (gradient echo)
- Contrast-enhancement with administration of gadolinium-chelate
  - shortens T1 (almost not T2) - angiography of macrovessels or hyperpermeability of microvessels
  - shortens T2* - blood volume and perfusion (dynamic susceptibility contrast)
- Diffusion – water spins follow Brownian motion, free or restricted → spin dephasing → signal decay (microstructure)
- Arterial Spin Labeling – blood water spins excited → T1 recovery and inflowing in saturated tissue → inflow enhancement
- Blood Oxygen Level Dependent (BOLD) effect – blood (de)oxygenation (magnetic effect) influences T2*

MRI essentials – FLAIR

FLAIR : FLuid Attenuated Inversion Recovery
- Inversion (pre)pulse to null CSF
- longer echo time → T2w contrast

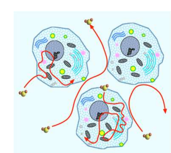


MRI essentials – Diffusion



Random walk

$$D = \frac{kT}{6\pi r\eta}$$



Hindered diffusion in tissue

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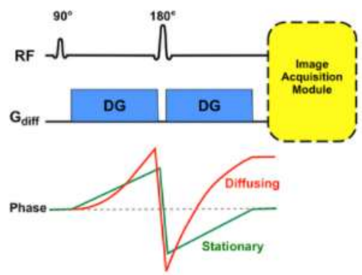
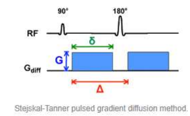
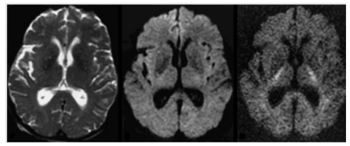
MRI essentials – Diffusion imaging

Stejskal-Tanner pulsed gradient spin echo technique





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



b = 0 s/mm² b=1000 b=3000

Stationary spins are not affected by the paired gradients, but diffusing spins are dephased → signal attenuation

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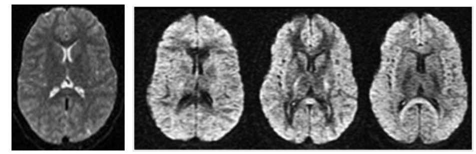
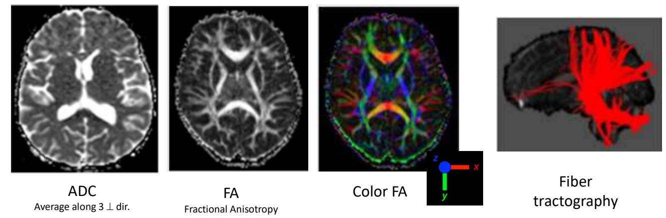
MRI essentials – Diffusion tensor imaging



b = 0 s/mm² Grad. along: x, y z

Attenuation along gradient direction

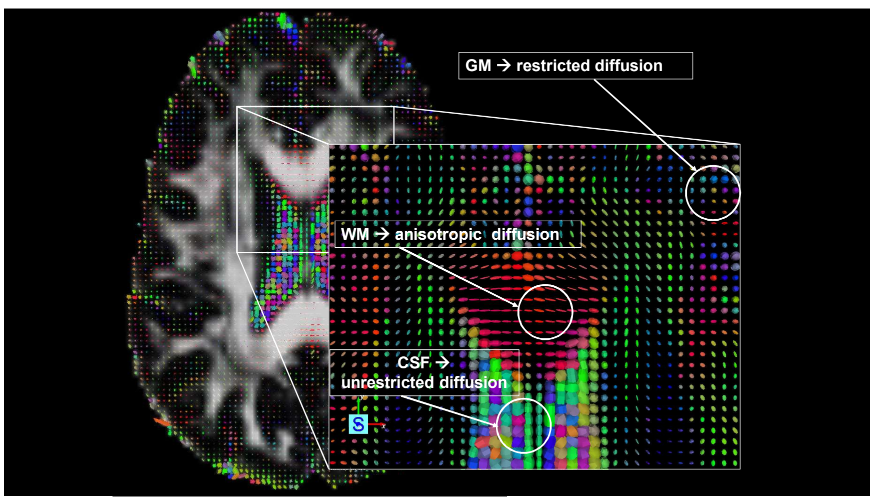


ADC
Average along 3 ⊥ dir.

FA
Fractional Anisotropy

Color FA

Fiber tractography



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DTI - Tractography