MRI Theory

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Introduction

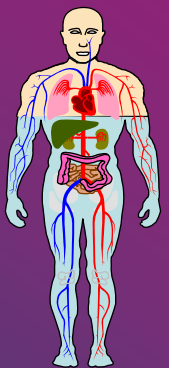
- Background and introduction
  - Magnetic Resonance Imaging
  - Relaxation mechanisms
- Imaging
  - gradients
  - FFT
- Basic sequences
  - parameters
  - SE
  - GE
  - IR
- Artifacts

Background and introduction

Magnetic Resonance Imaging

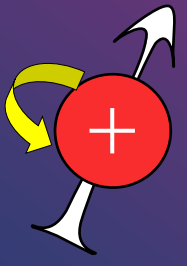
- Several advantages when compared to other imaging techniques:
  - Safe and non-invasive
  - Can be optimized to image specific tissues
  - Can be used quantitatively
- Rapid development of devices will allow:
  - higher and higher resolutions in future
  - more rapid aqcuisitions

- Nuclear Magnetic Resonance (NMR):
  - Based on the interaction between external magnetic field ($\boldsymbol{B}_0$) and the nucleus of an atom
  - Only nucleons possessing *spin*-property react to the external magnetic field
    - depends on its amount of protons and neutrons:
      - Nuclei with an identical number of protons and neutrons = no spin
      - Nuclei with an odd number of protons or an odd number of neutrons or both have an overall spin
- The nucleus studied in MRI is usually ^{1}H, water proton
  - tissues consist mostly of water (60-80%) and fat
  - ^{1}H is the most common isotope of hydrogen (about 99.985%)



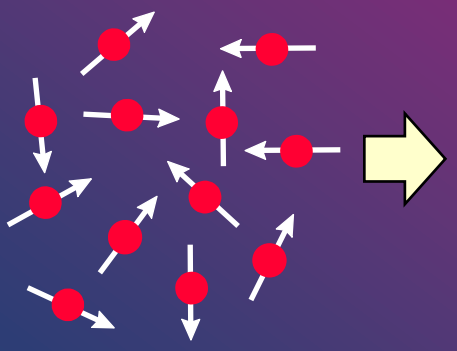
Nucleus and magnetic field

- Rotating charge induces a magnetic field
- ^{1}H, hydrogen nucleus (proton) can be viewed as ”small bar magnet”



Outside the magnetic field

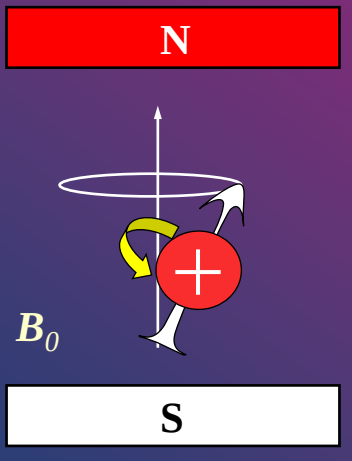
- Protons without magnetic field are randomly orientated
- No orientational preference



no net magnetization

Inside an external magnetic field B_0

- A proton starts to precess inside the magnetic field

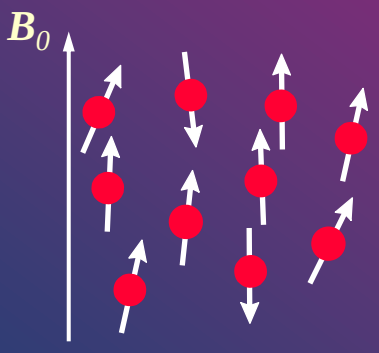


•The rate of precession is the Larmor-frequency:

$$\omega = \gamma B_0$$

•γ = 42.57 MHz / T for ^{1}H, so-called gyromagnetic ratio

- Inside the magnetic field, net magnetization will occur



or:

•The magnetic dipolemoment = μ

•μ has the direction of the B_0 field

•The nucleus can have 2s + 1 energy stages:

$E = -m_s\gamma\hbar B_0 = -m_s\gamma\hbar\omega_0$,

where ms=−s, −s + 1, . . . , s − 1, s and

$\hbar$ is Dirac's constant

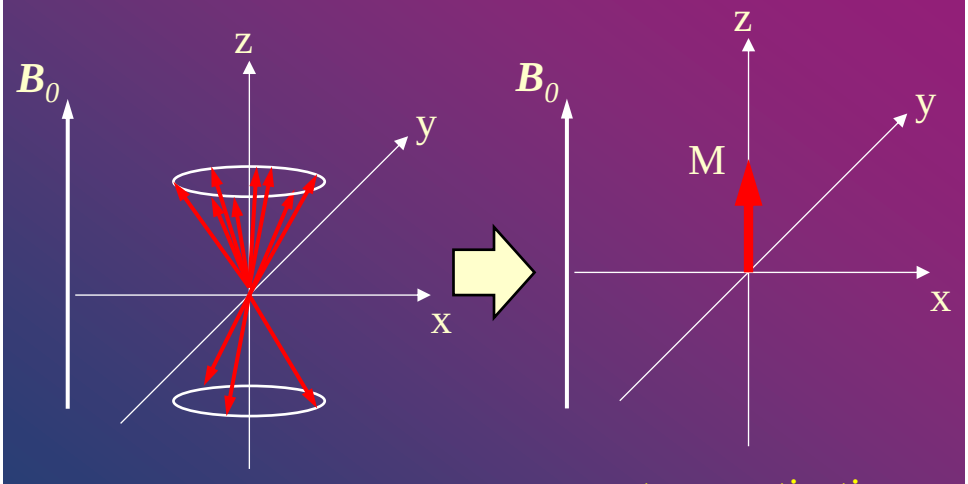
•^{1}H has two possible energy levels:

•parallel (+1/2) or anti-parallel (−1/2) state with respect to the static field

•The uneven distribution of the proton populations is given by the Bolzmann equation

$N_{-1/2}/N_{+1/2} = e^{-\Delta E/kT} = e^{-\hbar\omega_0/kT}$

- Inside the magnetic field, net magnetization will occur

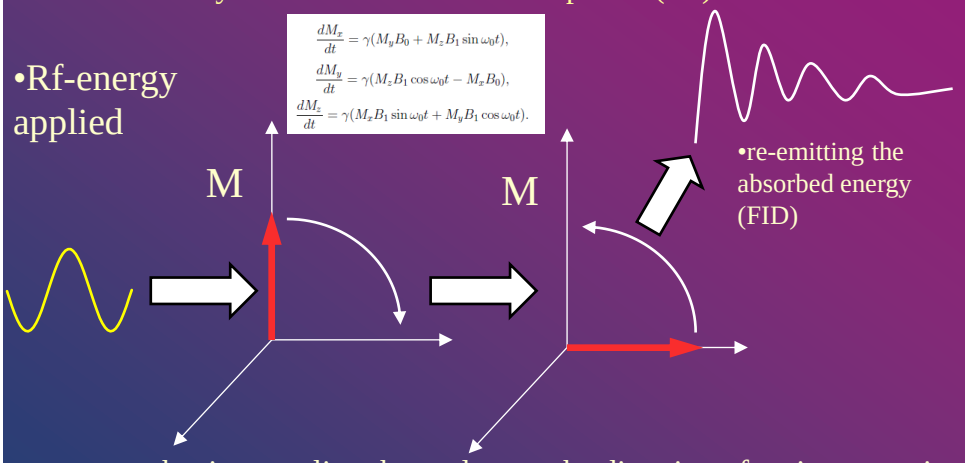


net magnetization

Magnetic resonance

- Energy is applied as radiofrequency (RF) energy
  - usually in so-called 90º and 180º pulses (SE)

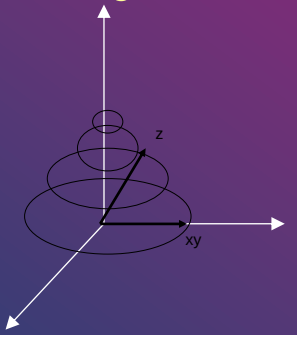
$$\frac{dM_x}{dt} = \gamma(M_y B_0 + M_z B_1 \sin\omega_0 t),$$
$$\frac{dM_y}{dt} = \gamma(M_z B_1 \cos\omega_0 t - M_x B_0),$$
$$\frac{dM_z}{dt} = \gamma(M_x B_1 \sin\omega_0 t + M_y B_1 \cos\omega_0 t).$$



• protons begin to realign themselves to the direction of main magnetic field

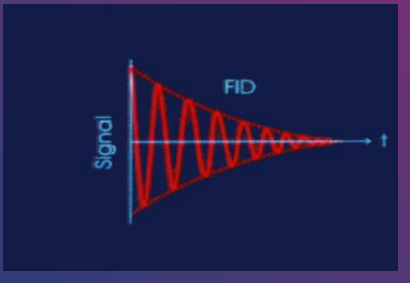
Relaxation

- Relaxation times characterize the behavior of magnetization after rf-pulses
- T_1 relaxation, *spin-lattice* or longitudinal relaxation (towards z axis)
  - protons return to equilibrium by releasing their energy to surroundings ”lattice”



Relaxation

- T_2 relaxation, *spin-spin* or transverse relaxation (xy-plane)
  - decrease of transverse coherence of protons
  - energy is exchanged between spins
  - sensitive to water mobility
- combination of magnetic field inhomogeneities and spin spin transverse relaxation, with the result of
- rapid loss in transverse magnetization and MRI signal=Free Induction Decay (FID)



$$\frac{1}{T_2^*} = \frac{1}{T_2} + \frac{1}{T_2'}$$

T_2* = total relaxation time

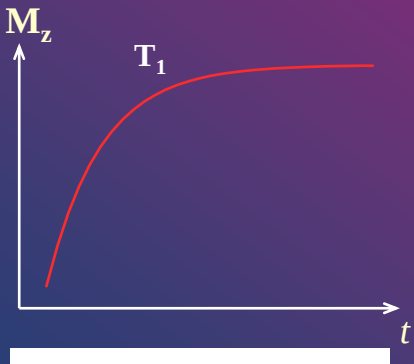
T_2= spin-spin relaxation

T_2`= component of T_2

Relaxation time induced by field inhomogeneities

T_1 relaxation

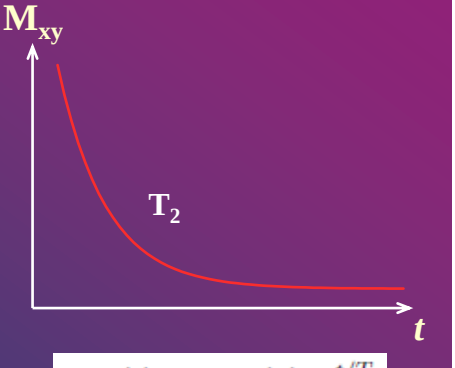
increase of longitudinal magnetization



$$M_z(t) = M_z(0)e^{-t/T_1} + M_0(1 - e^{-t/T_1}).$$

T_2 relaxation

decrease of transverse magnetization



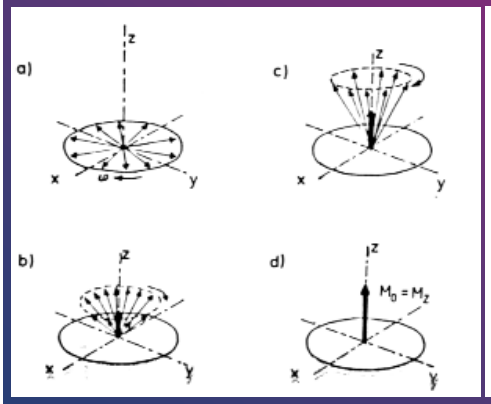
$$M_{xy}(t) = M_{xy}(0)e^{-t/T_2}$$

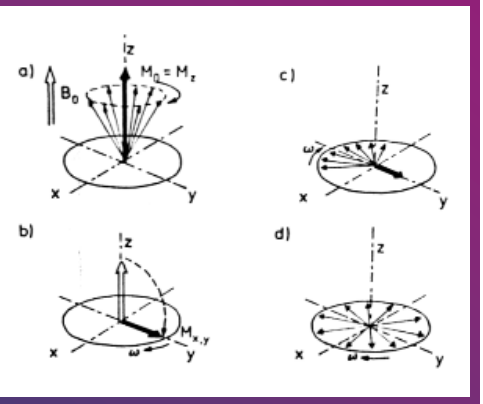
T_1 relaxation

increase of longitudinal magnetization

T_2 relaxation

decrease of transverse magnetization





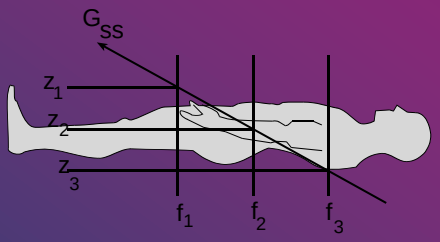
Imaging

Gradients

- Three physical gradients: x, y and z gradients
  - embedded inside magnet
  - used to modify static magnetic field
- Gradients used in imaging
  - Slice selection gradient (G_{SS})
  - Read-out or frequency encoding gradient (G_{RO})
  - Phase encoding gradient (G_{PE})

•Slice selection gradient together with appropriate Rf-pulse is used to select one slice

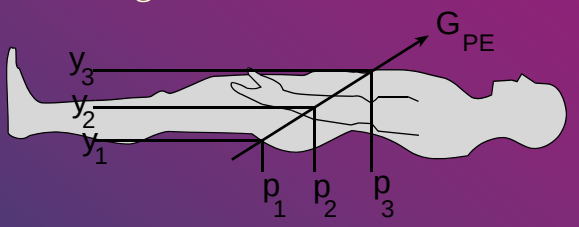
—The slice selection gradient G_{SS} determinates both the slice thickness and the slice position.



•Slice selection in MRI is the selection of spins in a plane through the object.

•Tissue located at position z_i will absorb rf energy broadcasted with a central frequency f_i. Each position will have a unique resonant frequency.

- Once the slice is selected, (frequency) read out gradient G_{RO} and phase encoding gradients G_{PE} are used for spatial encoding

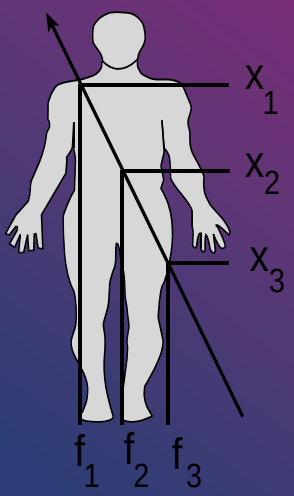


•Prior to application of G_{PE}, all protons will precess at the same frequency

•The precessing frequency of the protons is dependent of the y_i position

•Once G_{PE} is turned off, the proton will precess at it's originally frequency. Phase shift is marked with p_i.

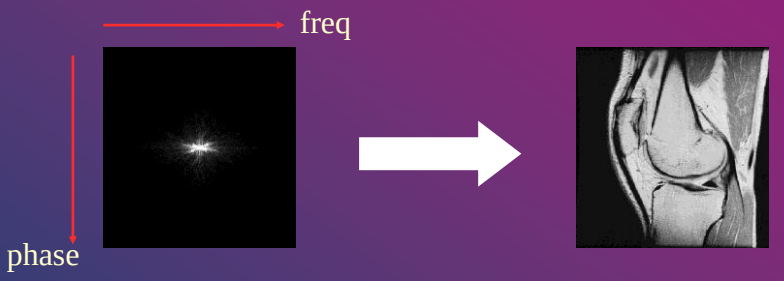
•The read out gradient G_{RO} is perpendicular to the slice & pulse direction:



•In G_{RO} encoding, each proton within the excited volume precesses at the same frequency f_i.

•Frequency of the precession depends on its position x_i.

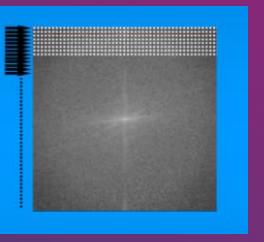
- From this frequency and phase map, regular image can be calculated using *Fourier Transform*



- Each pixel in the image is related to the amount of spins and the magnetic environment at the corresponding location in the sample

K-space

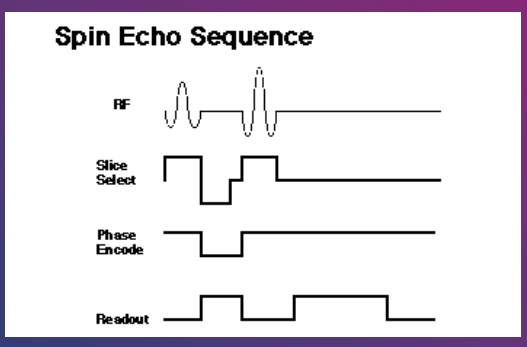
- is an extension of the concept of Fourier space
- is a temporal memory of the spatial frequency information in two or three dimensions of an object
- is defined by the space covered by the phase and frequency encoding data
- In 2-D FT imaging, a line of data corresponds to the digitized MRI signal at a particular phase encoding level
- The position in **k-space** is directly related to the gradient across the object being imaged
- By changing the gradient over time, the **k-space** data are sampled in a trajectory through Fourier space at each point until it is filled.
- In SE every TR is one line on a k-space



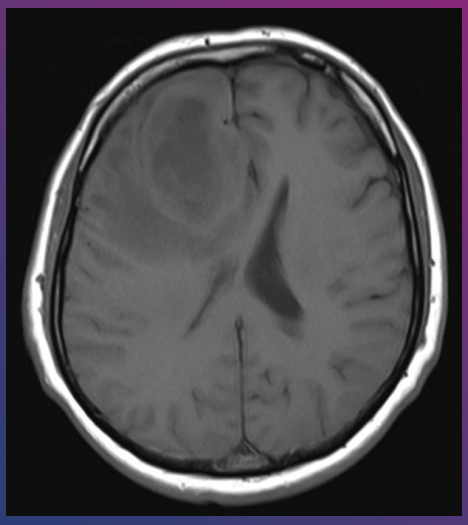
Sequences

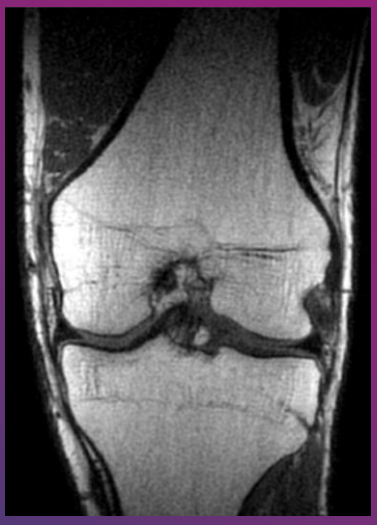
Spin Echo (SE)

- spin echo refers to the refocusing of precessing nuclear spin magnetisation by a *180°* pulse of resonant radiofrequency.
  - 90° RF pulse -> excitation pulse: rotates the magnetization M_z into the xy-plane -> dephasing of the transverse magnetization (M_{xy}) starts
  - 180° pulse -> refocuses the spins to generate signal echoes



SE sequences

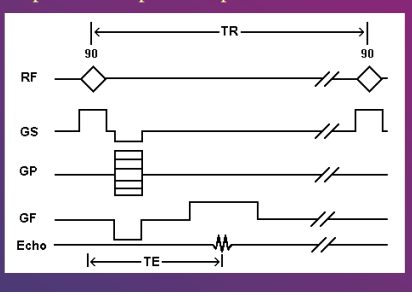




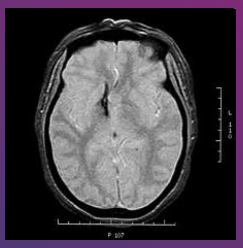
Gradient Echo (GE)

- generated by using a pair of bipolar gradient pulses
- There is no refocusing 180° pulse
- data are sampled during a gradient echo:
  - negatively pulsed gradient dephases the spins -> they are rephased by an opposite gradient with opposite polarity to generate the echo
- The echo is produced by
  - reversing the direction of a magnetic field gradient or
  - by applying balanced pulses of magnetic field gradient before and after a refocusing RF pulse so as to cancel out the position dependent phase shifts that have accumulated due to the gradient.

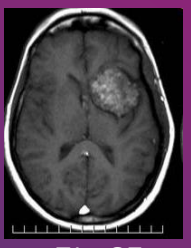
1. exitation pulse
2. negative gradient is applied (rapid dephasing of transversal M)
3. Positive gradient is applied (reverses the magnetic field)
4. Spins begin to rephase forming a gradient echo



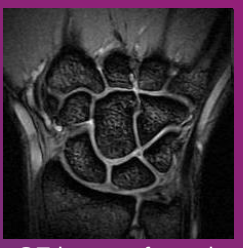
GE sequences



GE



T1w GE



GE image of a wrist

- short TR

-> shorter acquisition time

- artifacts in regions with varying susceptibility e.g.
  - between the air-containing sinuses and brain
  - especially between haemogghages and normal tissue

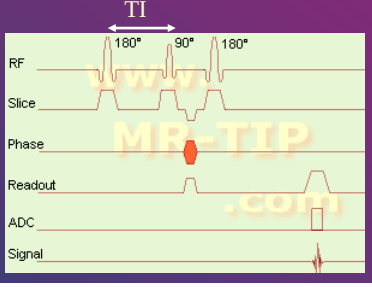
Inversion recovery (IR)

- T_1 in a given region can be calculated from the change in the MR signal from the region due to an inversion pulse with a different inversion time (TI)
- 180° RF pulse -> tilts the magnetization to z-direction -> rotates the magnetization M_z into the negative plane
- After TI -> 90° RF pulse tilts some or all of the z-magnetization into the xy-plane -> signal is rephased with a 180° pulse as in the SE sequence
- During the initial time period, various tissues relax with their intrinsic T_1 relaxation time
- provides very strong contrast between tissues having different T_1 relaxation times or to suppress tissues like fluid or fat

- additional inversion RF pulse increases aqcuisition time

$$M_z(TI) = 0$$

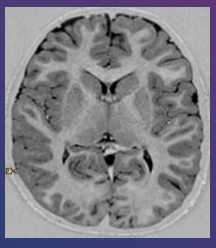
$$M_{xy}(TI) = M_0(1 - 2e^{-TI/T_1})$$



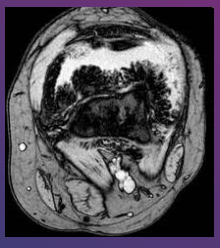
IR sequences

- better T1-contrast
- „Selective suppression" (FLAIR)

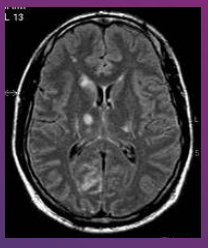
- longer measurement time
- allows to choose less slices (acquisition time should be in clinical routines as short as possible)



IR T1

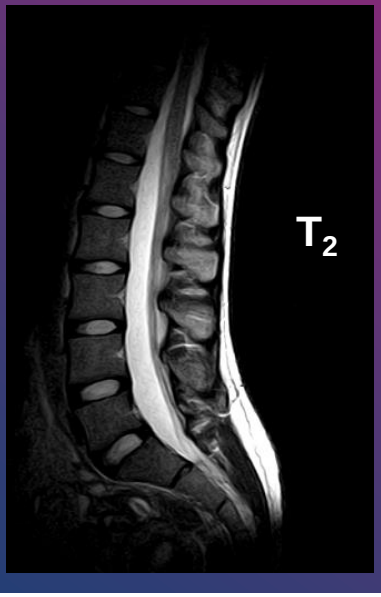


STIR



FLAIR

SE sequences

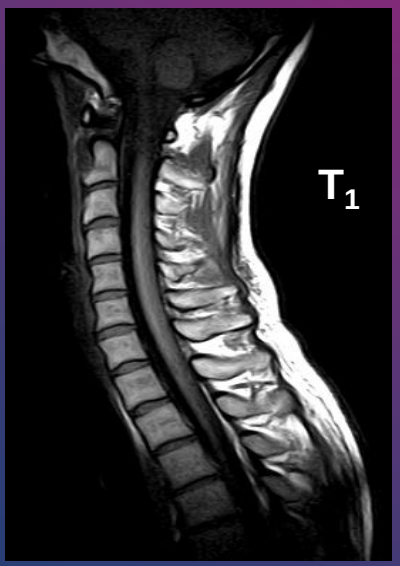


T2:

- long TR
- long TE
- fat bright
- Liquid bright

- Could be used for:
  - detection for abnormal fluids
  - meniscal tear in knee (synovial fluid will be seen brighter than the cartilage) etc.

SE sequences



T1:
- short TR
- short TE
- fat bright
- liquid dark

- used for:
  - predicting pathology with oedema or a lot of capillaries
  - fatty lesions
  - clear boundaries between different tissues etc.

Timing parameters

Spin echo-sequences
- TR = repetition time, desides the T_1 weighting
- TE = echo time, desides the T_2 weighting

Contrast values for IR:
PD-w: TE: 10-20 ms, TR: 2000 ms, TI: 1800 ms
T_1-w: TE: 10-20 ms, TR: 2000 ms, TI: 400-800 ms
T_2-w: TE: 70 ms, TR: 2000 ms, TI: 400-800 ms

weighting	TR	TE
T_1	short	short
T_2	long	long
PD	long	short

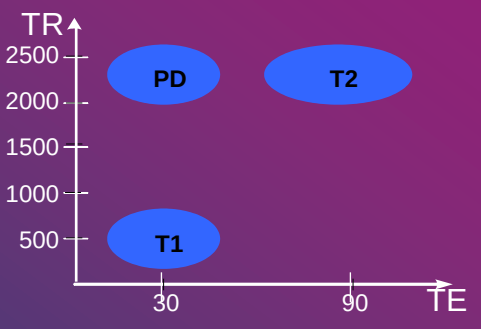
Gradient echo-sequences
- TR, TE
- α = flip angle, defines the angle of exitation

Longer TR requires bigger α

Flip angle α	TE	
	Short (<15ms)	Long (>30ms)
Small (<40°)	PD-w	T_2-w
Large (>50°)	T_1-w	-

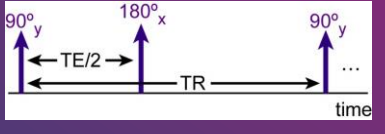
Contrast on SE images

Parameters	SI
Short T_1	increases
Long T_1	decreases
Short T_2	decreases
Long T_2	increases
short PD	decreases
long PD	increases
Short TE	increases
Long TE	decreases
Short TR	decreases
Long TR	increases

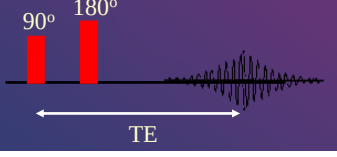


Timing parameters

- Repetition time TR
  - The amount of time that exists between successive pulse sequences applied to the same slice
  - It is delineated by initiating the first RF pulse of the sequence then repeating the same RF pulse at a time t.
  - Variations in the value of TR have an important effect on the control of image contrast
  - TR is also a major factor in total scan time



- Echo time TE
  - represents the time in milliseconds between the application of the 90° pulse and the peak of the echo signal in SE and IR pulse sequences

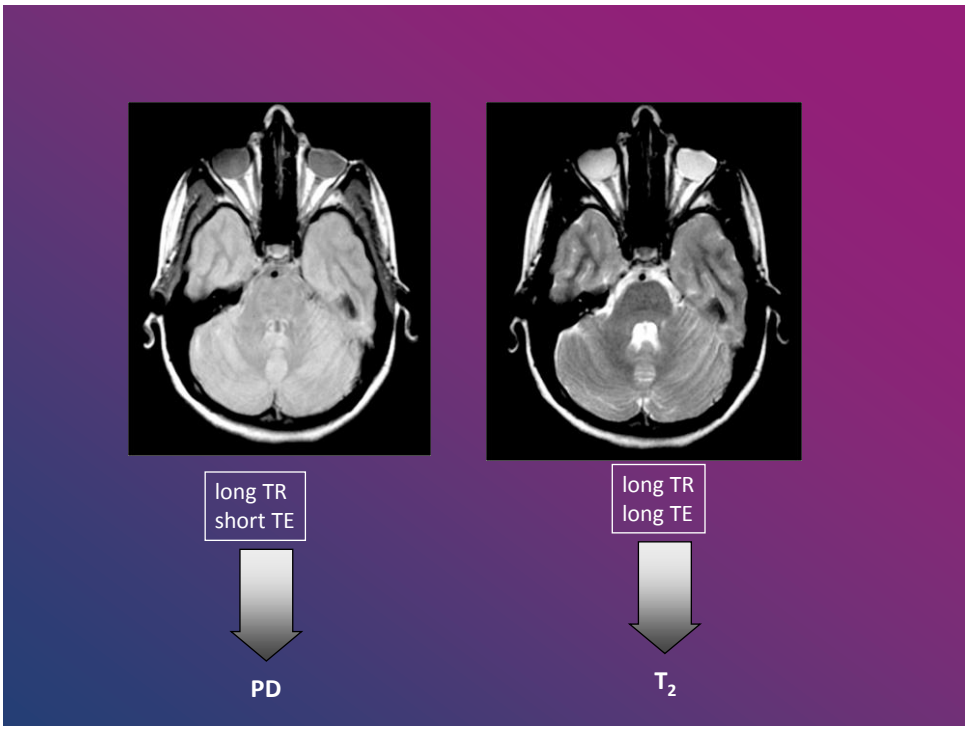


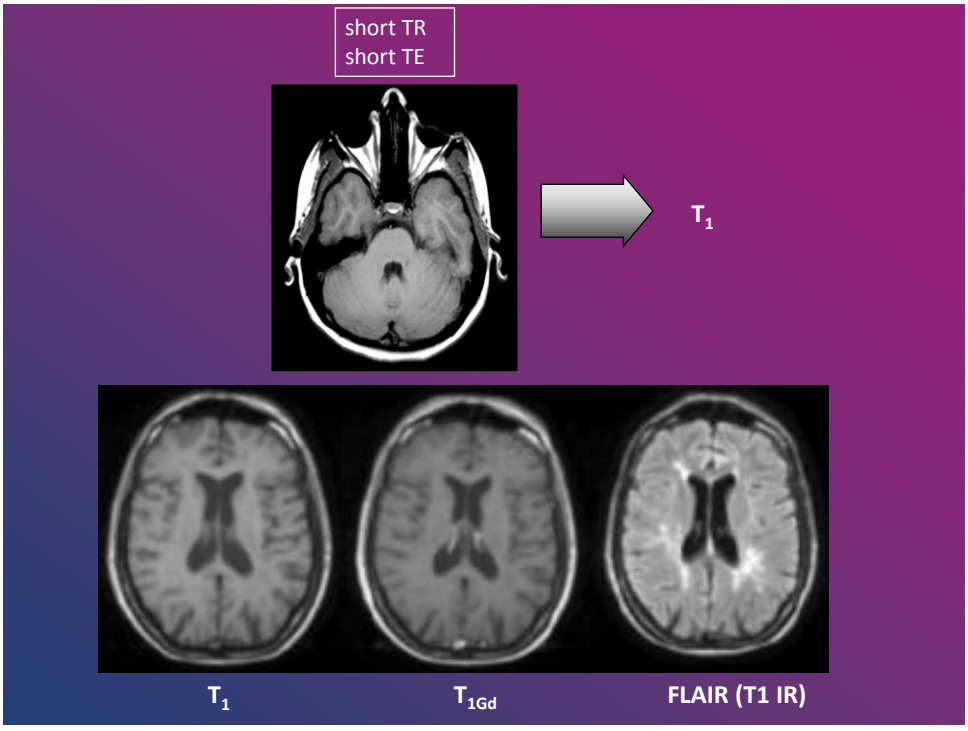
Timing parameters

- Flip angle α
  - is the angle to which the net magnetization is rotated or tipped relative to the main magnetic field direction via the application of a RF excitation pulse at the Larmor frequency
  - The radio frequency power (which is proportional to the square of the amplitude) of the pulse is proportional to α through which the spins are tilted under its influence
  - α=0°- 90° are used in GE sequences
  - α = 90° and a series of 180° pulses: SE sequence
  - initial 180° pulse followed by a 90° and a 180° pulse: IR sequence
- Inversion time TI
  - The time period between the 180° inversion pulse and the 90° excitation pulse in an IR pulse sequence
  - The inversion time controls the signal of different tissues and with the change of this parameter also fat and water suppression is attainable.

Relaxation times in different tissues @ 1.5T

Tissue	T_1 (ms)	T_2 (ms)
Gray matter	1100	95
White matter	800	80
Spinal fluid	4500	2200
fat	250	60
cartilage	900	40
muscle	1000	40
blood	1400	300


long TR
short TE
PD
long TR
long TE
T2

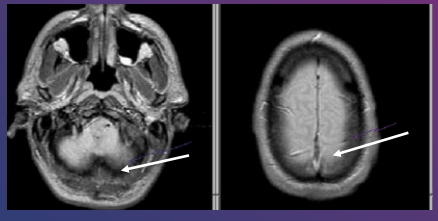

short TR
short TE
T1
T1
T1Gd
FLAIR (T1 IR)

Artifacts

Artifacts

Partial volume

- Image voxel is containing a mixture of tissue types
- Loss of contrast between two adjacent tissues
- Reason: insufficient resolution
- Help: thinner slices

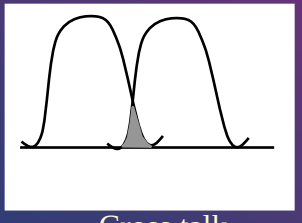


Partial volume: dim brain tissue in the first MRI slice and blurs the edge of the brain in the last slice.

Artifacts

Cross-talk

- Appears as a reduced intensity on all but the first slice of a multi-slice set
- Reason: if the slice gap is too small the edges of the slice may overlap with ist neighbours
- Help: slice gap minimum 10%

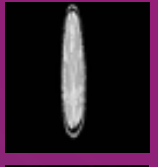


Cross talk

Artifacts

Gradients

- False gradient strenght leads to geometrical distortion
- Help: calibrate gradients

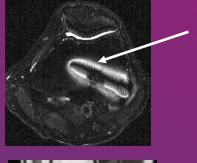


Unhomogeneity from RF-field

- Field is not uniform over the whole image

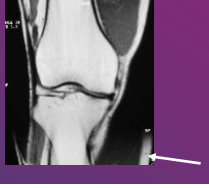
Susceptibility/metal artefact

- Signal dropout, bright spots, spatial distortion
- Reason: Field inhomogeneity
- Help: reduce TE or increase resolution



Phase wrap-around artefact

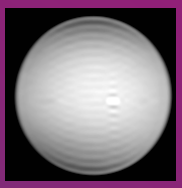
- Produces the image of the tissue at the opposite edge of the scan
- in the phase-encoding direction (undersampling)
- Reason: anatomy continues outside the field of view (FOV)
- Help: use spatial saturation bands just outside the FOV to saturate
- the signal or larger FOV



Artifacts

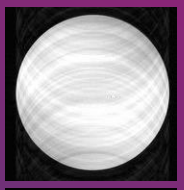
Gibb's artefact/truncation

- Undersampling in the phase-encode direction
- Occures at high-contrast boundaries where intensity changes
- from dark to bright
- Reason: pixel size is too large to represent accurately the
- high-contrast boundary
- Help: phase-encoding matrix should not be less than half the
- frequency-encode matrix



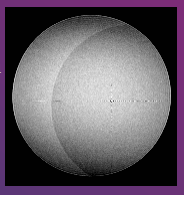
Motion

- Field is not uniform over the whole image
- Reason: Movement of the imaged object



Ghost

- Displaced reduplications of image in phase-encoding direction
- Reason: motion, heart beat, respiration
- Help: triggering or change the band width

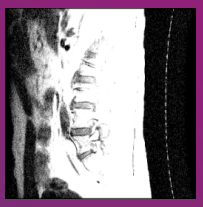


Artifacts

Zipper

- Bands through image center
- Reason: hardware or software problem
- Help: larger FOV, oversampling, integrety of the

RF-shielding in the scan room



- Magic angle
- Increase of T_2 time, bright signal in tendons
- Reason: angle about 55° to the main magnetic field
- Help: Angle not ~55°