Faculty of Engineering
Cairo University

Magnetic Resonance Imaging

submitted to:
IEEE-CUFE

submitted by:
Mohamed Ahmed Abdelaziz
(+20)01552516133
Mohamed.ahmed997@eng-st.cu.edu.eg

Contents

1 MRI history

- 1946 felix bloch recieved nobel prize for discovering new properties of the atomic neocleous. nucleos behave like magnet(proton is a charged particle spilling around its axis and has a magnetic field)
- 1950s theories are verified experemently
- 1960 nuclear magnetic resonance spectrometers
- $1960s - 1970s$ NMR widely used in academic and industrial research
- Raymond Damdians 1974 first NMR image for rat tumour
- 1977 first super conducting NMR scanner (indomitable). first image of human body took 5 hours to scan

NMR turned to MRI beacouse of fear of word nuclear to find wide acceptance.

2 Why MRI

X-Ray contrast is poor and require larger dose of radiation or parameter manipulation (Kvp - mAs)to increase the image contrast and quality which add an extra dose for the patient. CT has more contrast which help in detecting lesions in soft tissue, but CT construct other planes from axially data set. X-ray and CT has better spatial rosultion for bone structures. MRI has excellent contrast. MRI could be optimized for certain pathologies by changing parameters and pulse sequences. MRI image could be taken in any imaginable plane.

3 Hardware

You are spoiled for choice.

- Permenant, Resistive, Superconductive(Depend on your money).
- Open, Bore Type Magnet.
- With or without helium.
- Low or high field strength(better image, higher contrast, wider field of application)

3.1 magnet types

ADVANTAGES	DISADVANTAGES
Low power consumption	Limited field strength (<0.3T)
Low operating cost	Very heavy
Small fringe field	No quench possibility
No cryogen	

Figure 1: Permenant magnet

ADVANTAGES	DISADVANTAGES
Low capital cost	High power consumption
Light weight	Limited field strength (<0.2T)
Can be shut off	Water cooling required
	Large fringe field

Figure 2: Resistive magnet

ADVANTAGES	DISADVANTAGES
High field strength	High capital costs
High field homogeneity	High cryogen costs
Low power consumption	Acoustic noise
High SNR	Motion artifacts
Fast scanning	Technical complexity

Figure 3: Bore type superconductive magnet. Liquid helium at -269°C to make the wire losses its electrical resistance

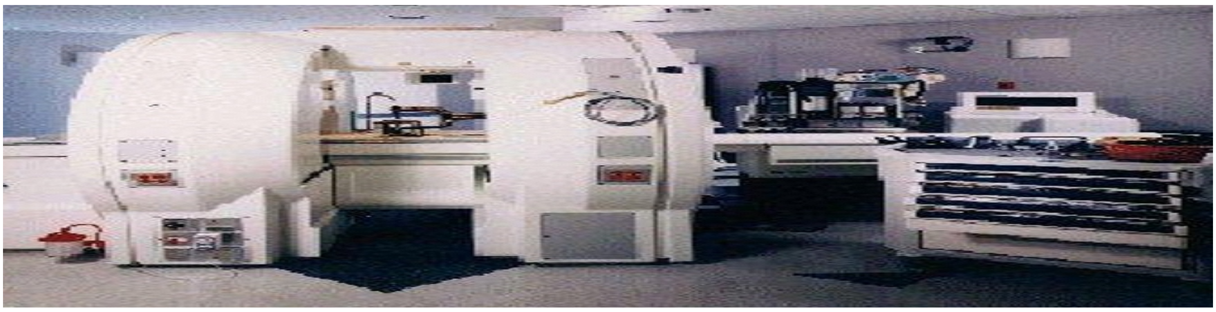

Figure 4: GE superconducting double dount MRI

3.2 RF coils

it is needed to transmit and recieve the radio frequency waves used in MRI. affect image quality

there are multiple RF coils for specific body parts

- volume coil : usually saddle ,qurantee uniform RF field used to transmit and receive and sometimes for receive only

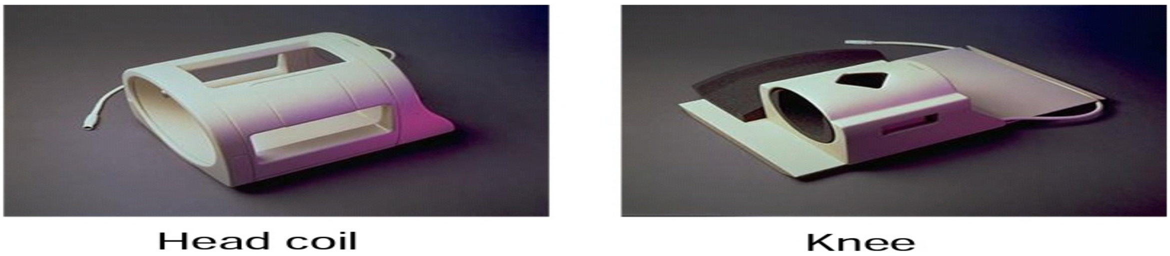

Figure 5: Volume coils

- surface coil : close to the area under examination , high SNR
  disadventage : loses signal uniformity when you move away from the coil

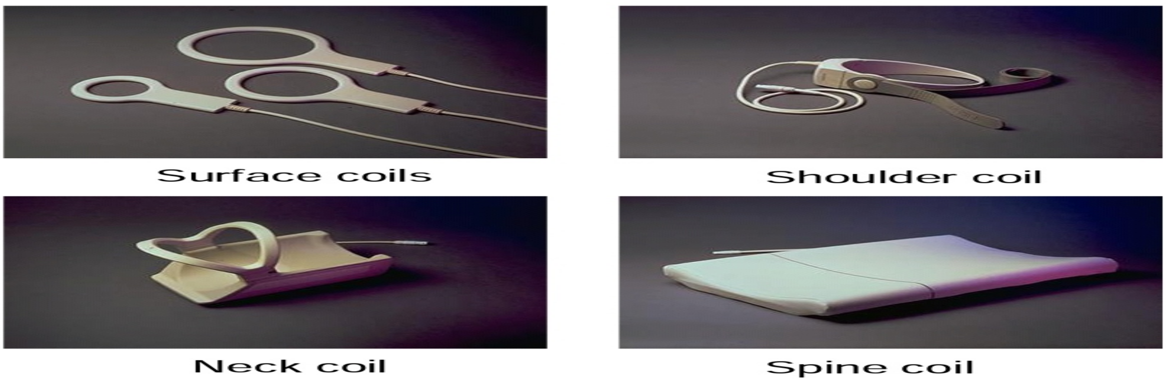

Figure 6: Surface coil

- quadrature coils : two loops of wire placed at right angles to one another produce $\sqrt{2}$ signal more than signal coil (most volume coils are quadrature)

- phased array coils : multiple service coil (4 or 6) to create large sensetive are$\sqrt{2}$ more than quadrature

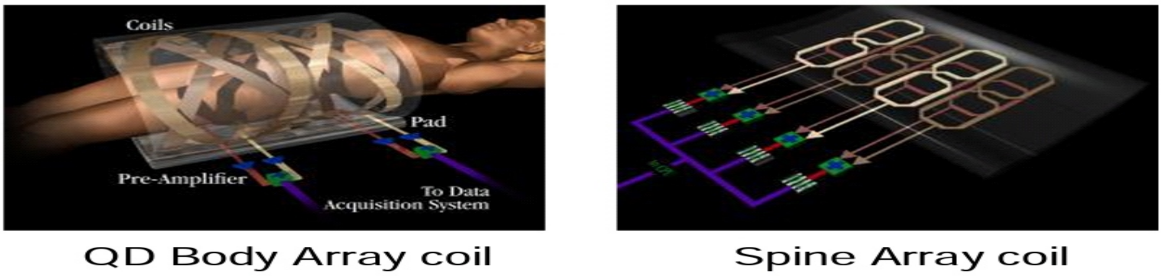

Figure 7: Phased Array coils

3.3 other hardware

- patient table
- magnet
- cryogon storage
- cryogenerator
- magnetic power supply
- computer capinet
- RF electronics
- gradient coils , shim coils

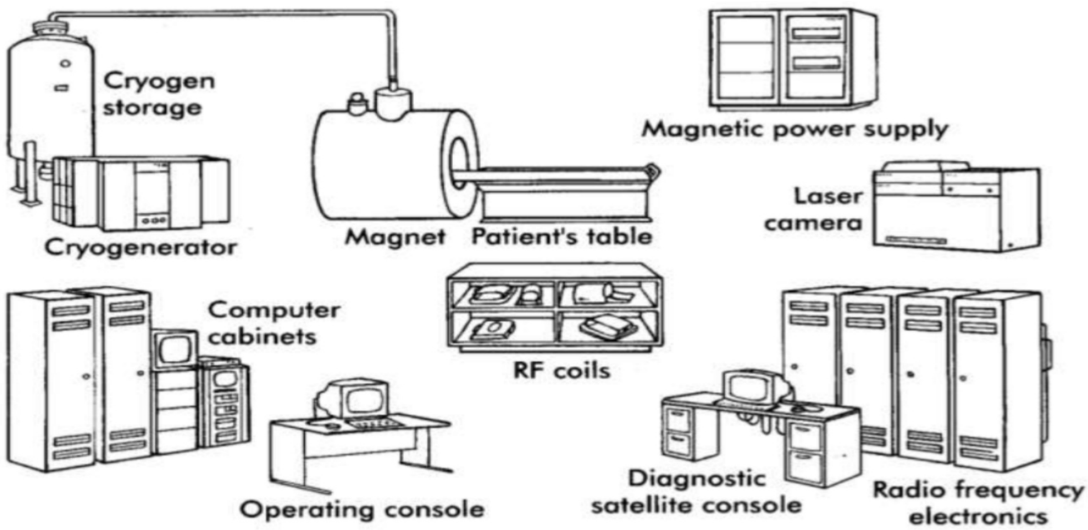

Figure 8: MRI Hardware

3.4 effect of MRI on environment

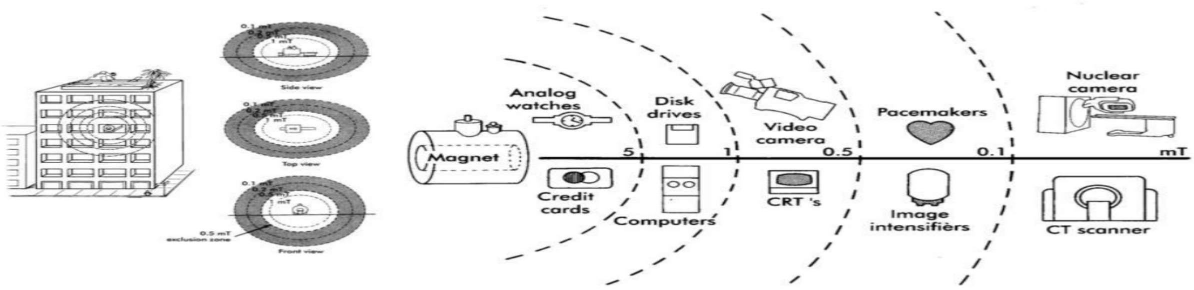

Figure 9: effect of mri on the environment

3.5 effect of environment on MRI

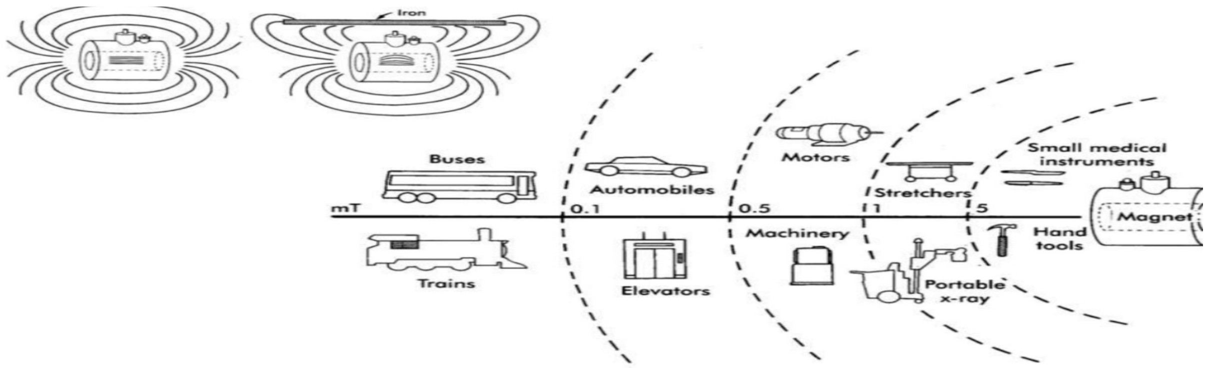

Figure 10: effect of environment on MRI

3.6 shielding and medical planning

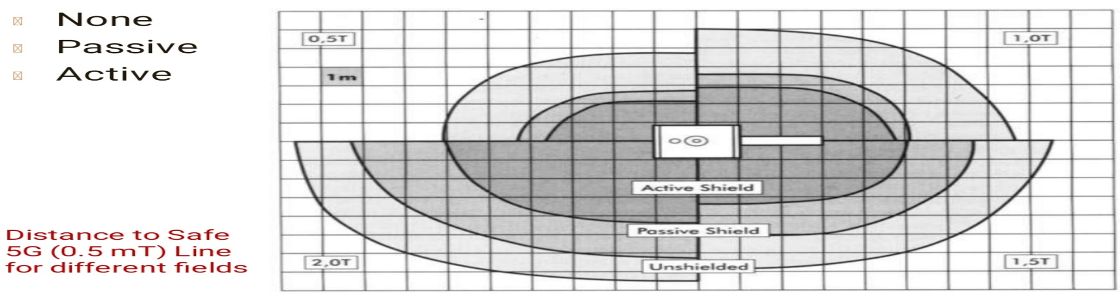

Figure 11: MRI Shielding

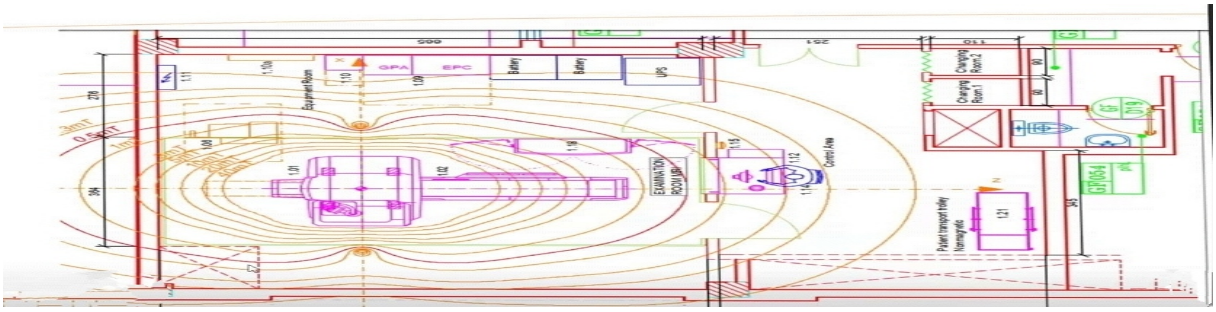

Figure 12: MRI Shielding

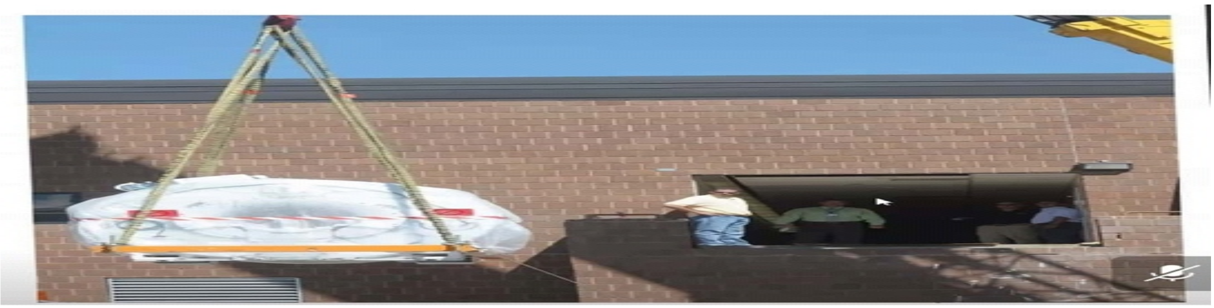

Figure 13: MRI Installation

4 MRI physics

4.1 magnetization

remember : rotating electrical charge create magnetic field
our body consist of 80% water (110 element)
hydrogen atom has one proton and one electron . the proton is electrically charged and rotate its axis so we can treat it as magnet with north and south poles

why H atom

- we have a lot of hydrogen in our bodies most abundant element
- gyromagnetic ratio for hydrogen is the largest (42.57 MHZ/T)

any element with odd number of proton could be used

Isotope	Symbol	Spin Quantum number	Gyro Magnetic Ratio (MHz/T)
Hydrogen	^{1}H	1/2	42.6
Carbon	^{13}C	1/2	10.7
Oxygen	^{17}O	5/2	5.8
Fluorine	^{19}F	1/2	40.0
Sodium	^{23}Na	3/2	11.3
Magnesium	^{25}Mg	5/2	2.6
Phosphorus	^{31}P	1/2	17.2
Sulphur	^{33}S	3/2	3.3
Iron	^{57}Fe	1/2	1.4

Figure 14: MRI friendly elements

protons repel and attract in such way that the magentic forces equalize.
1.5 T is 30000 times more stringer than the earth gravitational field (dangerous equipment)

When person enters MRI machine into magnet:

- The H atoms align parallel(low energy state) and anti-parallel(high energy state) where B_o is the magnetic field of the MRI.

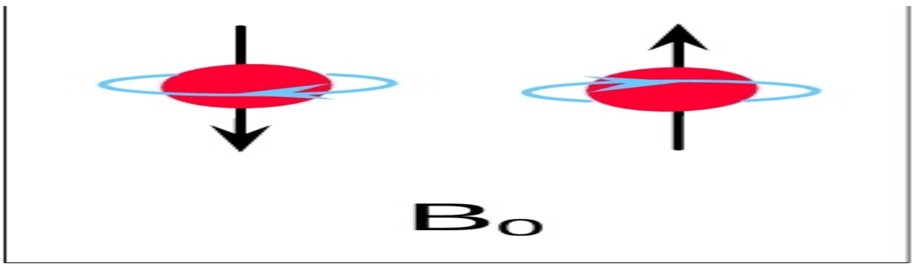

Figure 15: parallel and anti-parallel protons

- H precess duo to magnetization momentum with lamor frequency ($\omega_0 = \gamma B_0$)
  - ω_0 Lamor frequency (MHz).
  - γ gyromagnetic ratio (MHz/T).
  - B_0 magnetic field strength.

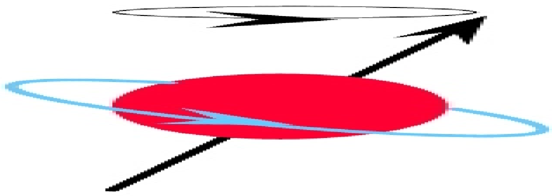

Figure 16: Precessing

The protons are lazy (most in low state, parallel).Not that big diffrence 3 part per milion for 0.5 T , 6 ppm for 1 T and so on. In real life that number add to be large enough for imaging.

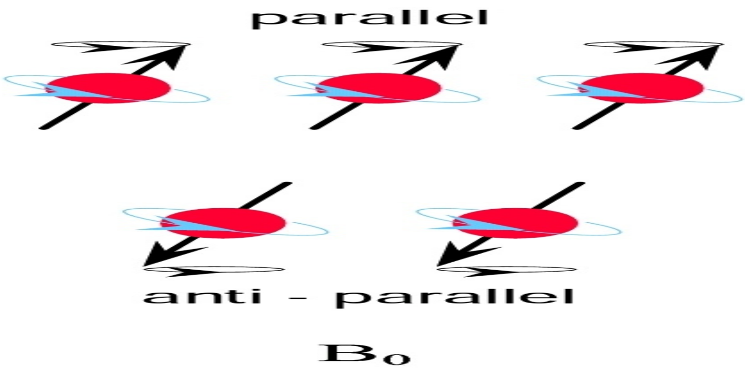

Figure 17: low and high energy states

4.2 excitation

before the system start we run quick measurement(pre-scan) to determine some parameter one is the lamor freq .(with no fancy pulse sequence we will start the acquisition)
we send the RF pulse with the same freq of the center freq we measured this is will excite the protons and the net magnetization will flip to be in the x-y plane (high energy state

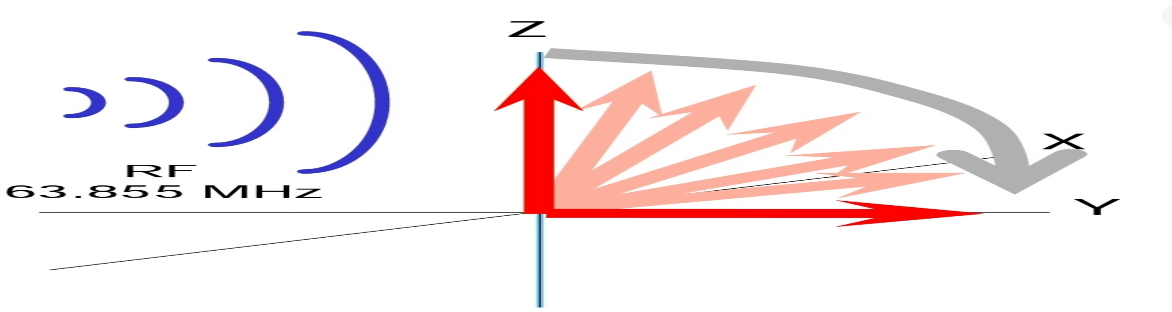

Figure 18: Excitation

FA (flip angle) could range from 1 to 180 degree and this will affect the image contrast as we will see in further session

4.3 relaxation

the relaxation process could be divided into T1 , T2 relaxation

4.3.1 T1 relaxation (spin lattice relaxation)

after the RF pulse stop , the net magnetization will regrow along the z axis , while emitting RF waves

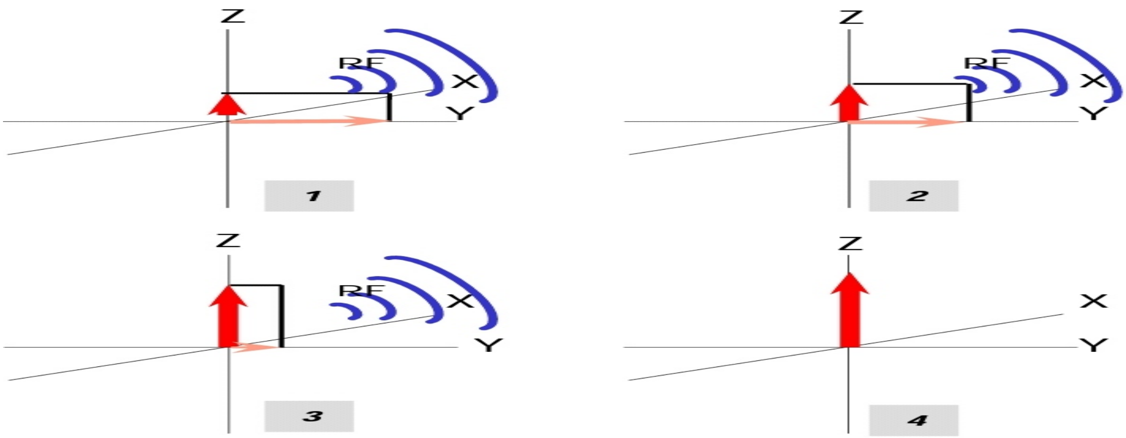

Figure 19: T1 relaxation

T1 relaxation curve

not all the protons are bound in their modules in the same way
H atom bound tightly in fat tissue , looser bound in water (CSF) tightly bound atoms will release their energy much faster to return to their relaxed state
T1: the time it takes for longitudinal magnetization (MHZ) to reach 63% of its original magnetization

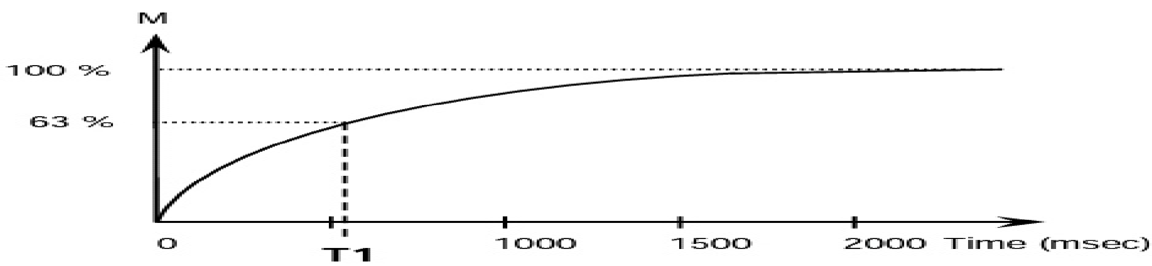

Figure 20: T1 relaxation curve

4.3.2 T2 relaxation(dephasing)(spin- spin relaxation)

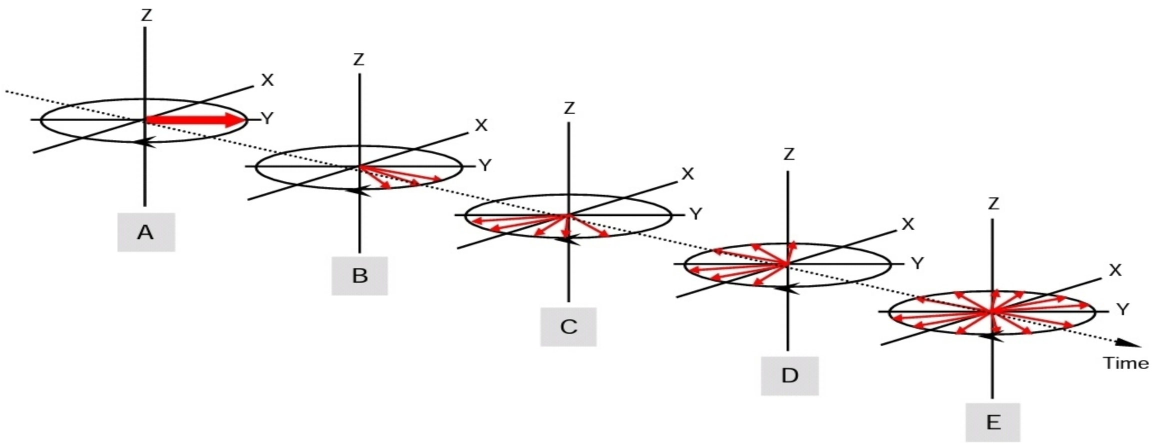

Figure 21: T2 relaxation

T1 , T2 are two independent process , they only happen simultaneously . T2 describe what happens in X-y plane

- with applying magnetic field the net magnetization happen because protons are aligned along the z-axis (spin with same speed but out of phase)
- RF excitation pulse flip the net magnetization (Spin with the same speed and in phase)
- RF excitation stop so the protons start dephasing and began to repel so some are slowed down and some are speed up

T2 relaxation curve

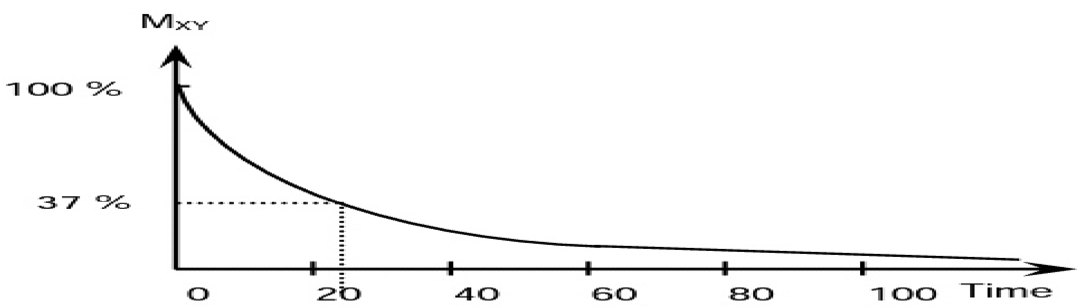

Figure 22: T2 relaxation curve

T2: is the time for the spin to dephase to 37% of its original value.

Note: The rate of dephasing is different for each tissue(fat dephase quickly, water dephase slowly)

T2 relaxation is much faster than T1 relaxation

4.4 Acquisition

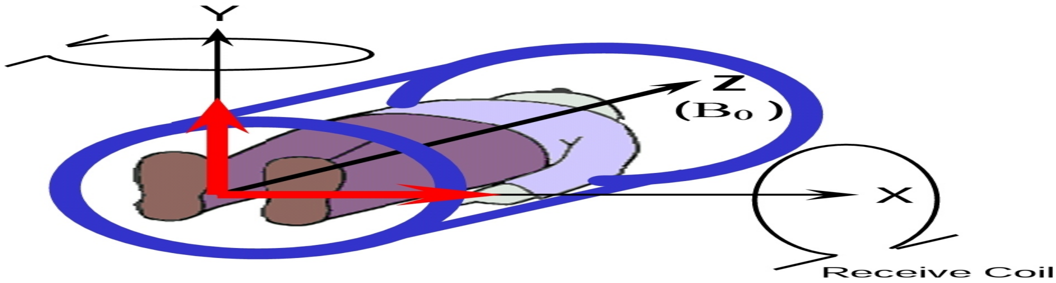

Figure 23: Acquisition coils at right angle to B_0

We need to pick up the signal to produce an image so we use a receive coil which must be positioned at right angle to the main magnetic field B_0 in order not to have an overwhelmed signal.

According to Faraday RF consist of magnetic and electrical components which are right angle from one another and 90 degree phase difference moving with the speed of light. **magnetic component induce current in the coils**

We can only receive signal from processes that hapen at right angle to B_0 **Free Induction Decay Signal FID**(T2 relaxation).

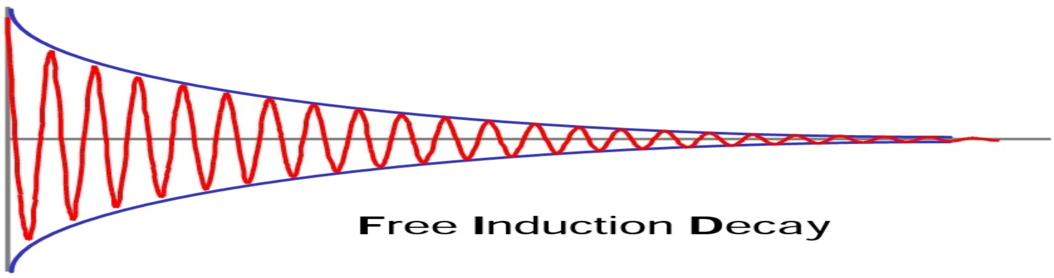

Figure 24: Free Induction Decay FID

FID signal would be recieved in absence of any magnetic field or T2 decay will go much faster due to **magnetic field inhomogenity** and **chemical shift** known as **T2***

4.5 Gradient Coils

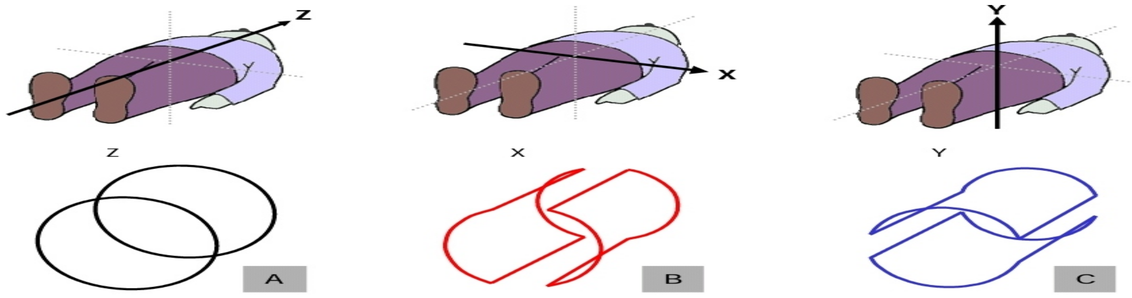

Figure 25: $G_z, G_y, G_x Gradientcoils$

Assume the field has 100% homogenity this means all protons in the body spin with lamor frequency and return signal so how get a specific section or slice?
gradient coils are set of wire enabel us to create additional magnetic field in a way that is superimposed on the main magnetic field.

source of noise in MRI is that the gradient coils vibrate because of the strong magnetic field even thought it is tightly fixed in a kind of resin.

4.6 Signal coding

4.6.1 slice encoding gradient G_{ss}

The Z gradient is switched on which super impose magnetic field on B_0 which create higher lamor frequency in the head , lower lamor frequency in the feet. The protons spin at slightly diffrent frequencies. So with a certain frequency we only excite a specific slice.

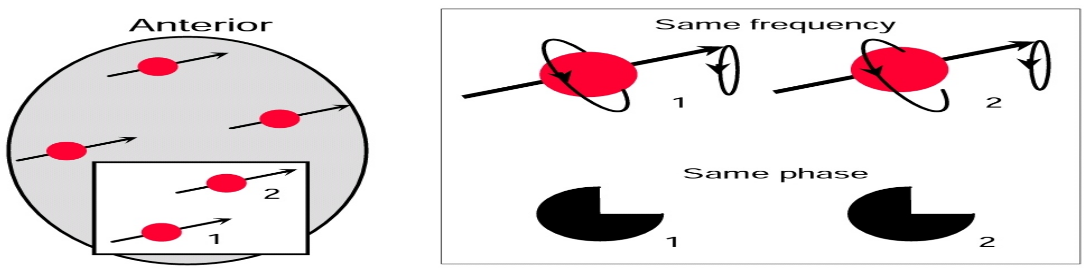

Figure 26: Slice Coding

Z gradient make protons-in the section- spin with same frequency and same phase

4.6.2 Slice Thickness

The slice thickness is determined by two factors

- Steppness of the slope of gradient field
- the bandwidth of the 90° RF pulse.

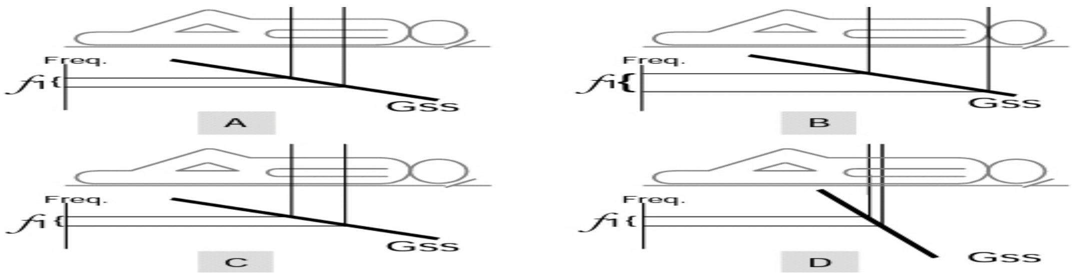

Figure 27: Slice Thickness

4.6.3 Phase Encoding Gradient

Only one row at a time. Gy gradient is turned on to code the anterior and posterior directions.
Anterior protons will spin faster than posterior protons so they are not in phase.
Gy gradient off so protons spin with same frequency but different phase.

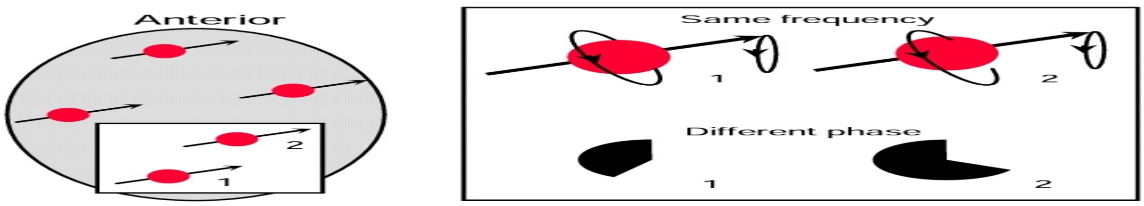

Figure 28: Phase Encoding Gradient

4.6.4 Frequency encoding gradient

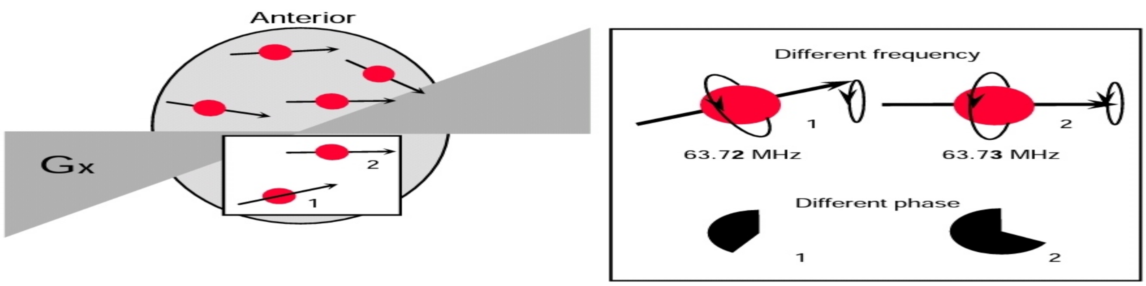

Figure 29: Frequency Encoding Gradient

Gx gradient is turned so protons on left spin with lower frequency than protons in the right which make phase difference **different frequency and different phase**

- **Gz** axial slice
- **Gy** rows with different phase
- **Gx** columns with different frequency

gradient specification

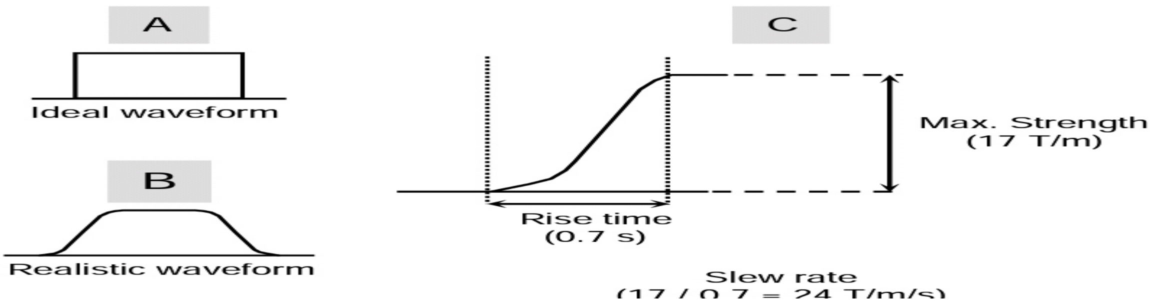

Figure 30: Slew Rate of RF Signal

Ideal waveform does not exist. realistic waveform have $slewrate = \frac{maxStrength}{riseTime}$

- max strength as high as possible (minimum FOV, max matrix)
- rise time as short as possible
- slew rate as big as possible (min TR, TE, TSE)

4.7 TASK 1

4.7.1 K space

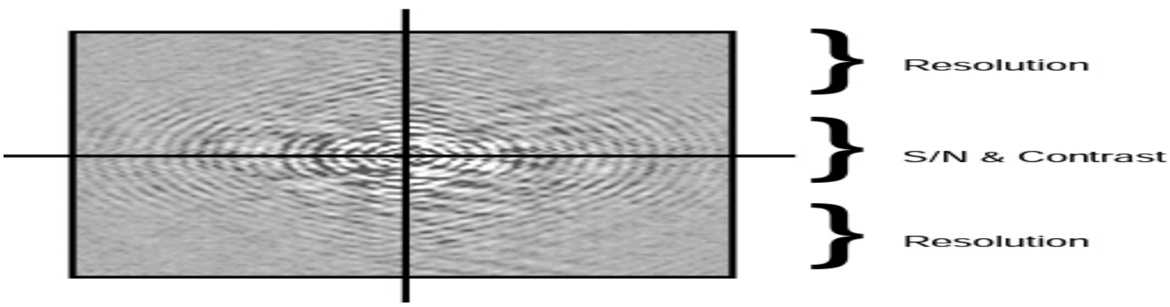

Figure 31: K-Space

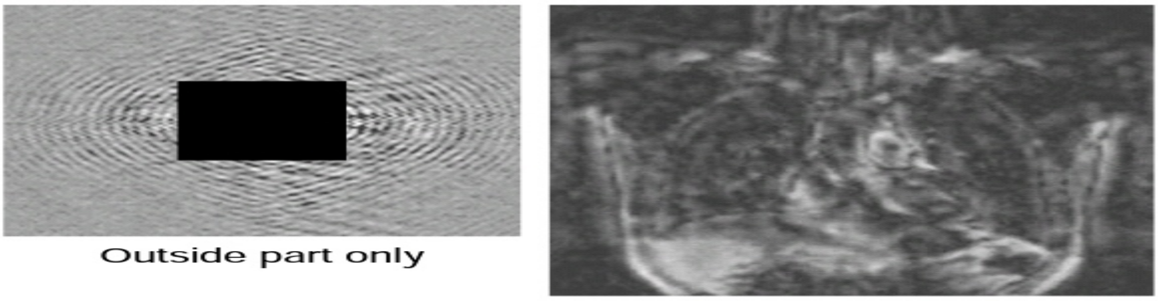

Figure 32: K-Space

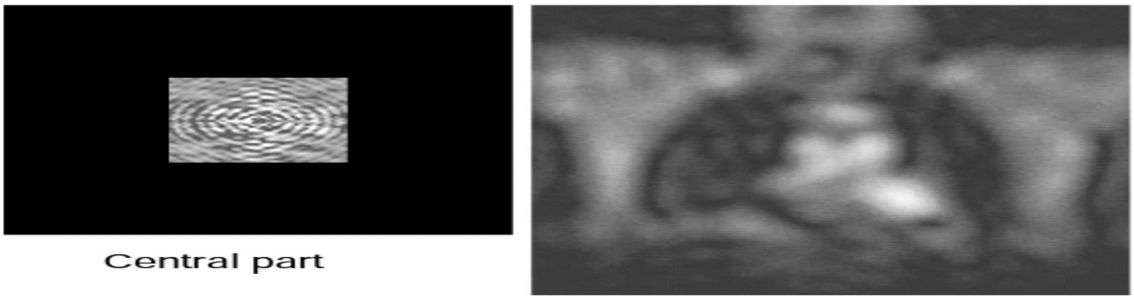

Figure 33: K-Space

Recommended reading your FIRST TASK

5 Pulse Sequences

Without pulse sequence we can not do MRI. It determine what contrast we want to see, which kind of pathology we want to detect.

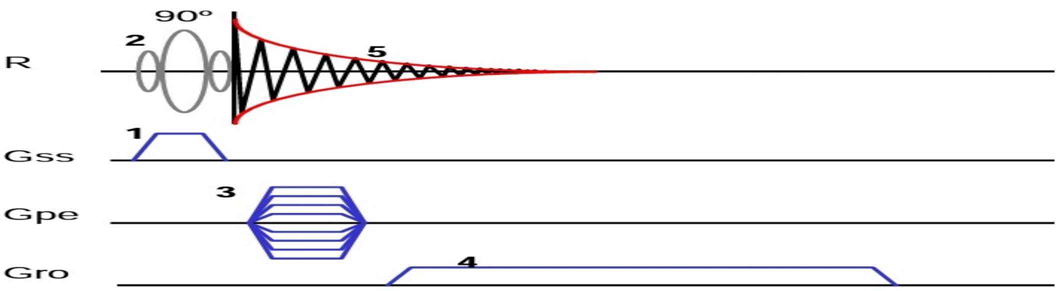

Figure 34: Basic Pulse Sequence

The hardware could not be switched fast enough to sample the signal only last part of the signal -already undergo decay **FID-** is sampled.

5.1 Spin Echo

After 90° excitation pulse the net magnetization in X-Y plane starts to dephase (T2 relaxation) so the signal drob quickly **FID**.
A short time after 90° pulse we give 180° pulse which cause the net magnetization to rephase(signal grows) then drop again.NOw we have enough time to sample the signal.
note: 180° pulse is in middel between 90° pulse and echo.

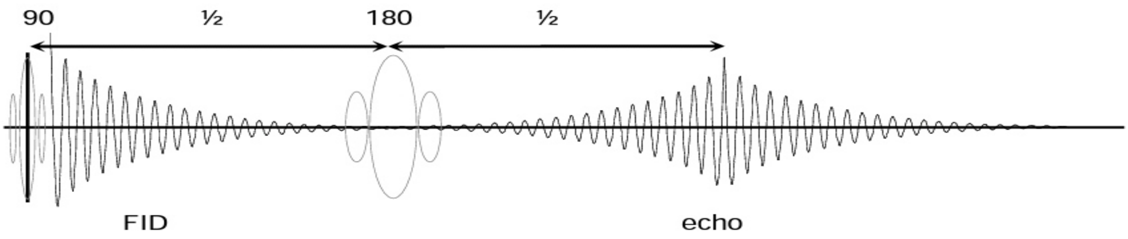

Figure 35: Spin Echo

Pros

- strong signal.
- less artifact as it compensate for local field inhomogenities.

cons

- takes time to rephase
- increase the amount of RF one has to put in the body.

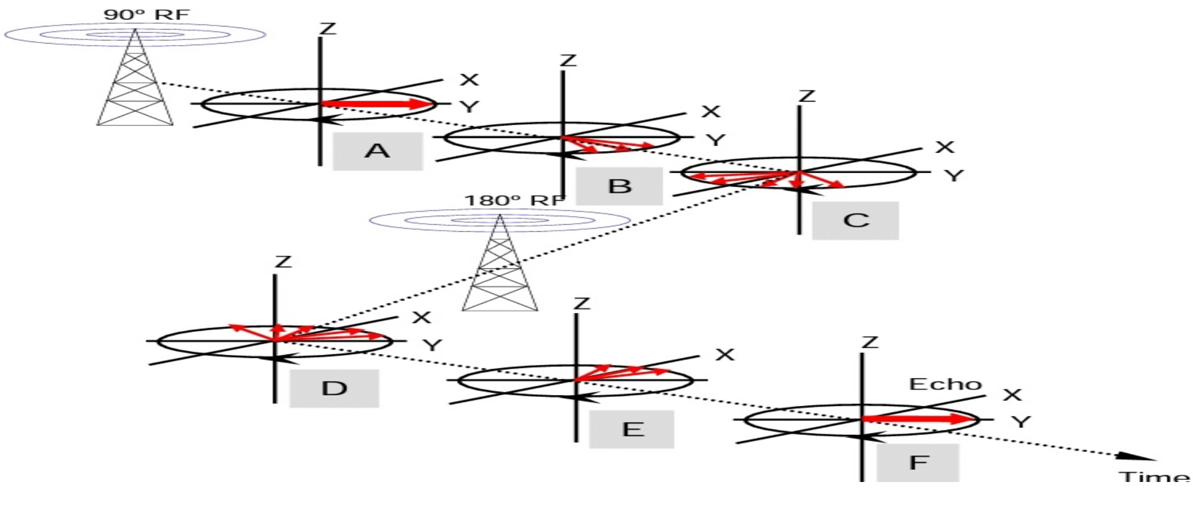

Figure 36: Spin Echo Visualization

5.2 TASK 2

5.2.1 Multi Slicing Sequence

Your SECOND TASK ON SEQUENCES from multi slicing sequence to FAST ADVANCED SPIN ECHO

5.2.2 Multi Echo Sequence

5.2.3 Turbo Spin Echo Sequence

5.2.4 Fast Advanced Spin Echo

5.3 Image Contrast

The contrast depend on how much of each relaxation processes(T1,T2) we allow to happen.

5.3.1 T1 Contrast (Short TE, Long TR)

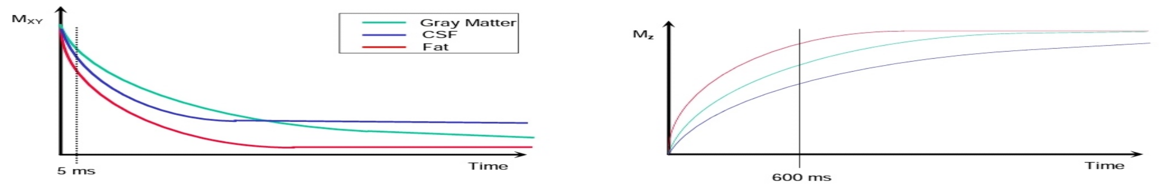

Figure 37: T1 Weighted Image

- Short TE : no dephasing yet. We recieve alot of signal from all tissues (littel influence by T2 relaxation)
- Long TR :not all tissue undergo complete T1 relaxation for example fat relax faster than CSF so when we excite again we will not have alot of signal influenced by CSF and we are able to diffrentiate the tissues from one another. "**T1 Weighted Image**" note: CSF will be dark, fat is bright, grey matter in between

5.3.2 T2 contrast (Long TE, Long TR)

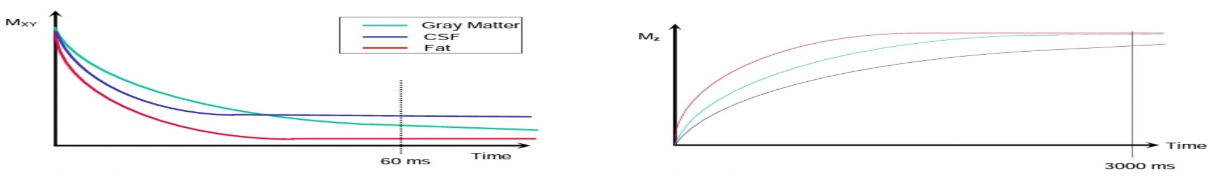

Figure 38: T2 Weighted Image

- Long TE: most of the tissue have dephased and will not prodce much signal, but CSF have some phase coherence "**T1 Weighted Image**".
- Long TR: allow all tissue to relax completely for next excitation does not affect the contrast.

5.3.3 Proton Density contrast (Short TE, Long TR)

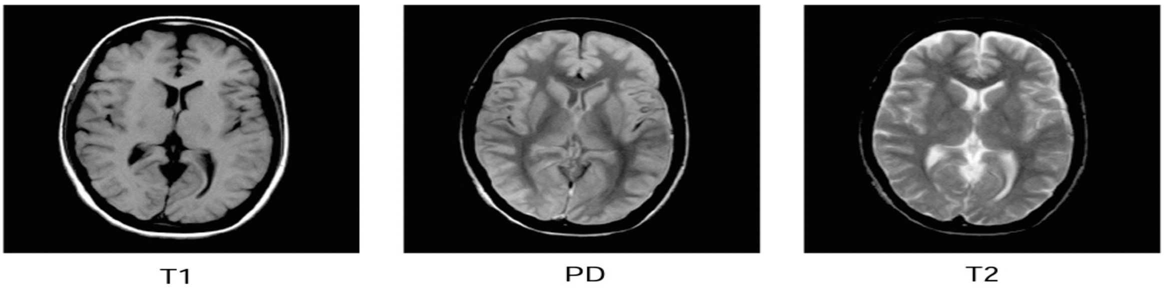

Figure 39: T1, T2, PD

- Short TE: reduce T2 relaxation effect as discussed previously.
- Long TR:reduce T1 relaxation effct as discussed previously.
  The signal is completely dependant on the amount of protons in the tissue (few protons, low signal, dark image)(many protons, high signal, bright image)

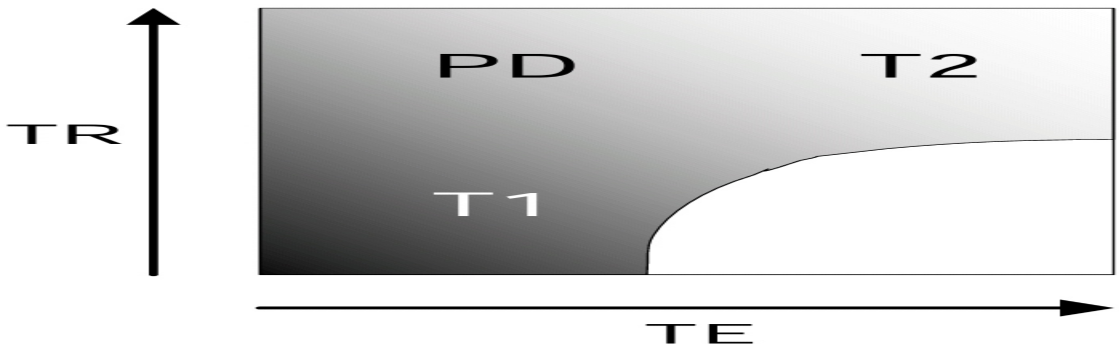

Figure 40: TE, TR effect on spin echo contrast

5.4 When to use each contrast?

T1, IR: for anatomical structures. T2, PD: for pathology because they produce edema **bright in the image**.

MR senstive contrast medium could be used in T1 weighted image because it shorten the T1 relaxation time for the tissue.

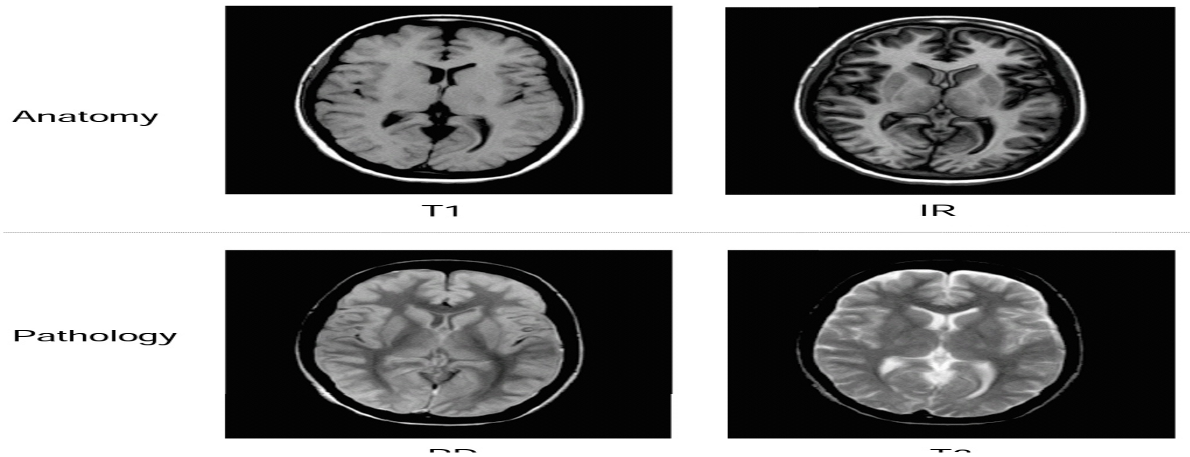

Figure 41: Contrast Choice

5.5 Gradient Echo Pulse Sequence (GE)

Differ from the spin echo in the way tissue is formed in GE sequence we use a gradient reversal polarity(remember spin echo uses 180° rephasing pulse)

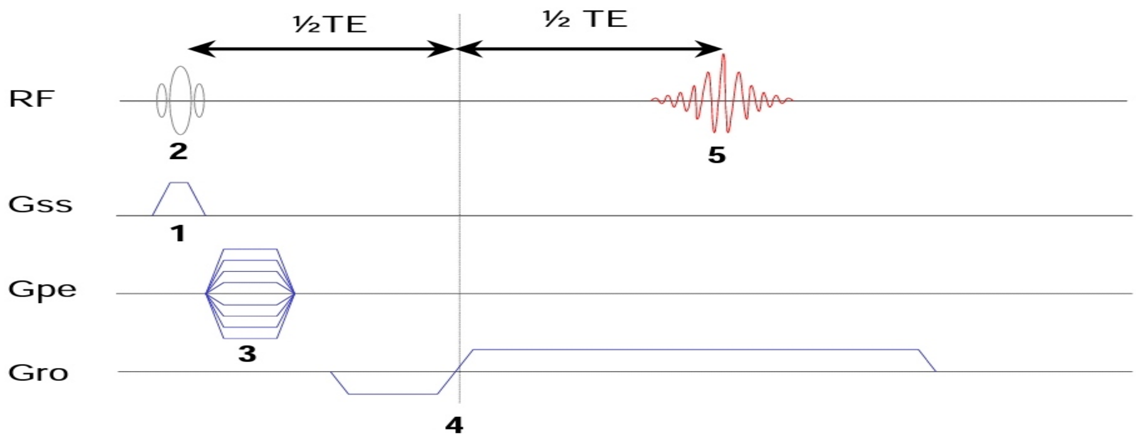

Figure 42: GE Sequence

note:Gradient echo is much faster than spin echo, but it does not compensate for magnetic field inhomogenities **FA of excitation pulse (α) can range from 1° to 180°**.

The gradient polarity reversal reverse the dephasing sped of the spins, at certain moment all spins are in phase again then dephase creating echo

The contrast depend on FA, TE. The apperance of GE images differ from SE image.

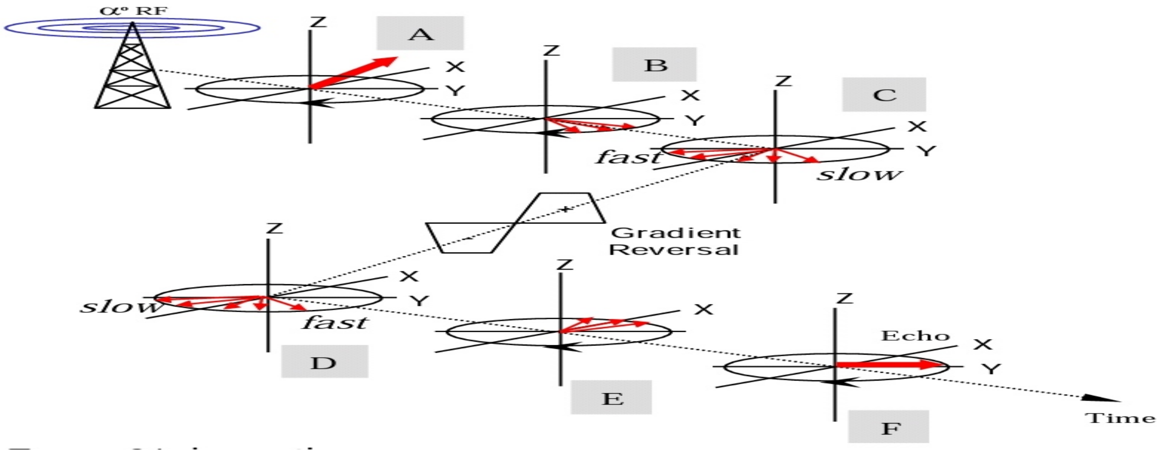

Figure 43: GE Visualisation

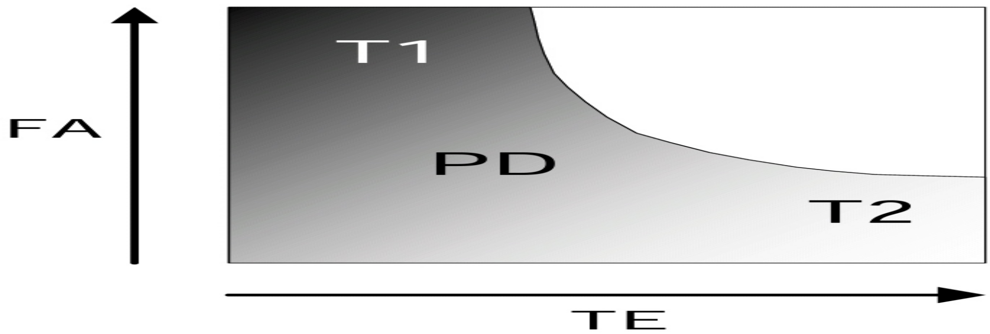

Figure 44: TE, FA effect on GE contrast

5.6 Inversion recovery Pulse Sequence

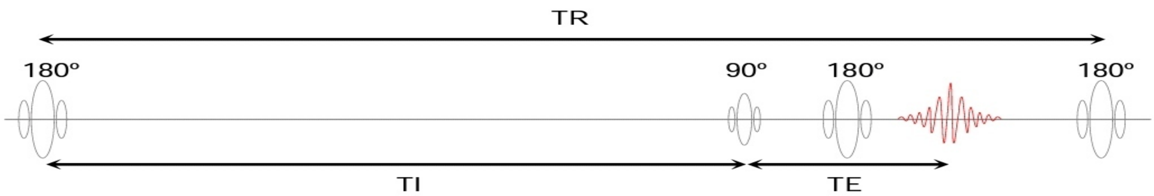

Figure 45: IR Sequence

It is a spin Echo sequence preceded by another 180° excitation pulse which flip the magnitization (Mz=> -Mz)
There is no magnetization in x-Y Plane (no T2 relaxation). T1 relaxation will take twice as long allowing curves to pull away from each other which create higher T1 contrast.

T1 is allowed to happen for a certain time **Inversion time TI** determined by 90° pulse. IR usually have long TR, short TE the image is most dependant on TI.
EXAMPLE: basel gangluia of the brain with SE is poor. IN IR Sequence the structure are more detailed.
disadvantage: long scan time, but it could be combinned with TSE to reduce the scan time.

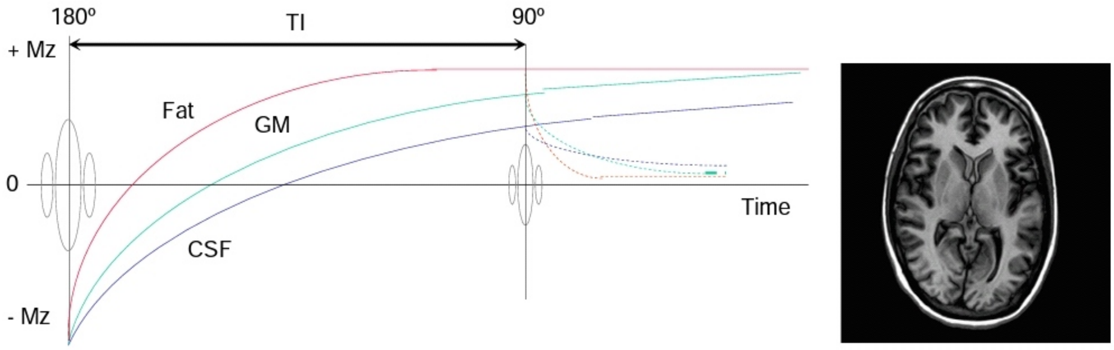

Figure 46: IR curve

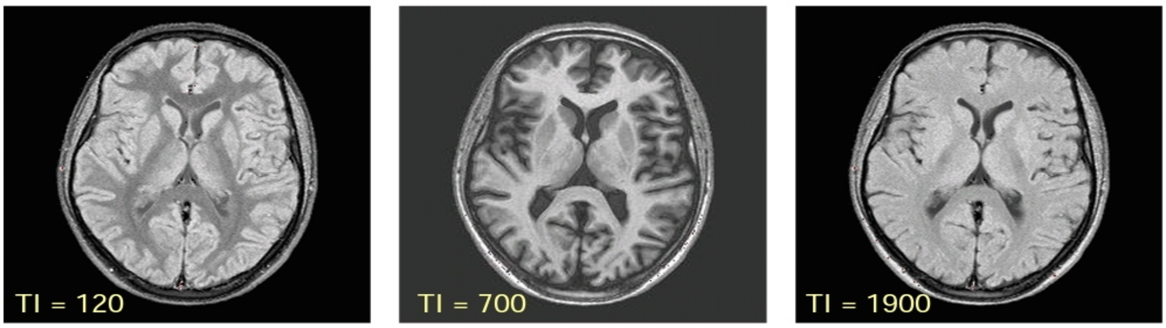

Figure 47: IR Image with different TI

5.7 Task 3

5.7.1 STIR

5.7.2 FLAIR

5.8 Choosing the right sequence

SEQUENCE	TR	TE	TI	FA
SPIN ECHO				
T1	600	10~30		90
Proton Density	1000	10~30		90
T2	2000	80~250		90
Gradient Echo				
T1		2~14		60~90
Proton Density		2~14		30~60
T2		20~34		5~30
Inversion Recovery				
T1	2000	10~30	400~700	90
STIR	2000	10~30	80~120	90
FastFLAIR	5000	10~30	1800~2200	90

Remarks: 1. The TR in a GE sequence has little influence on image contrast.
2. The TI varies per field strength B_0. (1800 for 0.35T; 2200 for 1.5T)

Figure 48: Recommended parameters for each contrast

SEQUENCE	ADVANTAGE	DISADVANTAGE
(Turbo) Spin Echo	High signal Compensates for T2* effects "Real" T1 and T2 images	High RF deposit Long scan times Motion artifacts
Gradient Echo	Low RF deposits Short scan times Dynamic scan possibility	Low signal T2* related artifacts Motion artifacts
Inversion Recovery	High signal Real T1 images High T1 contrast Fat suppression	High RF deposit Very long scan times Limited number of slices Motion artifacts

Figure 49: Image Contrasts Comparison

6 Sequence Parameters

6.1 Repetition time TR

The time between two excitation pulses.

- SE: between two 90° excitation pulses.
- GE: between two $\alpha°$ pulses.

- IR: between two 180° pulses.

Increase TR will lead to :

- less image contrast
- more PD contrast
- more magnitization available for next excitation
- increase of scan time

Figure 50: TE effect

6.2 Echo Time TE

The time between the excitation pulse and the echo.
Increase TE will lead to:

- more T2 contrast
- more dephasing, less signal
- possible contrast swap

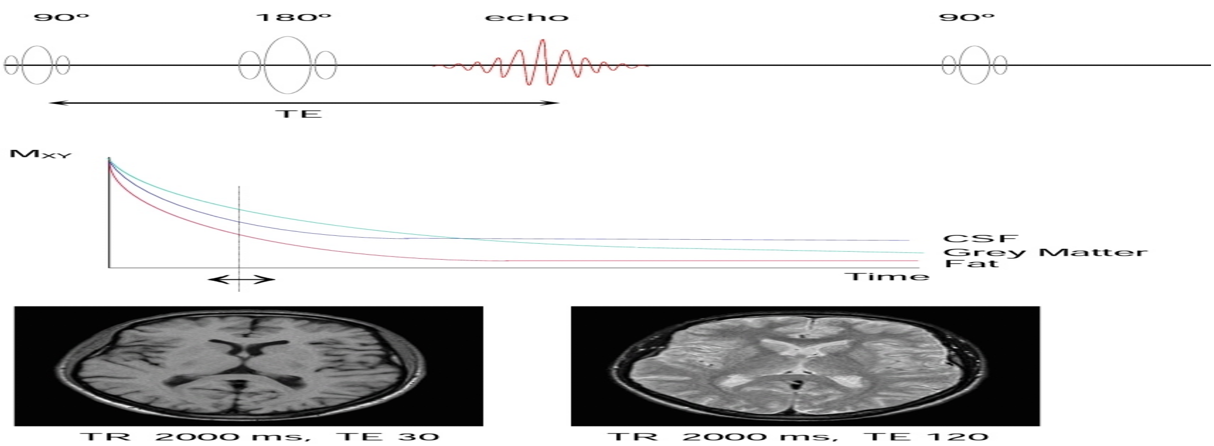

Figure 51: TE effect

6.3 Flip angle FA

FA determine how much net magnitization is flibbed into x-y plane.
SE, IR: FA usually 90°
GE: FA ranges from 1° to 180°
Increase FA will lead to :

- more T1 contrast
- more signal
- possible contrast swap

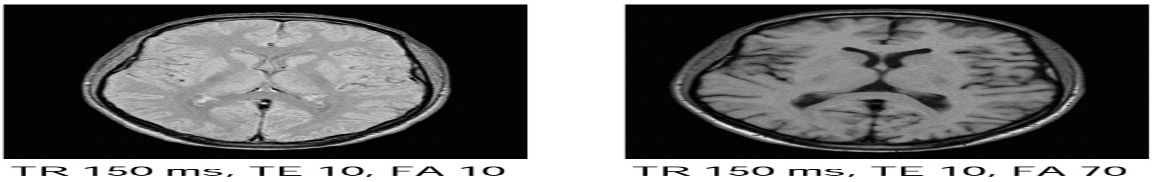

Figure 52: FA effect

6.4 Inversion Time TI

Time between 180° pulse and 90° pulse. T1 is only used in IR sequence and special kind of GE (TGE). T1 has the most impact o image contrast.In certain sequences we can make fat and fluid suppression.
Increased TI will lead to:

- T1 contrast change
- more signal

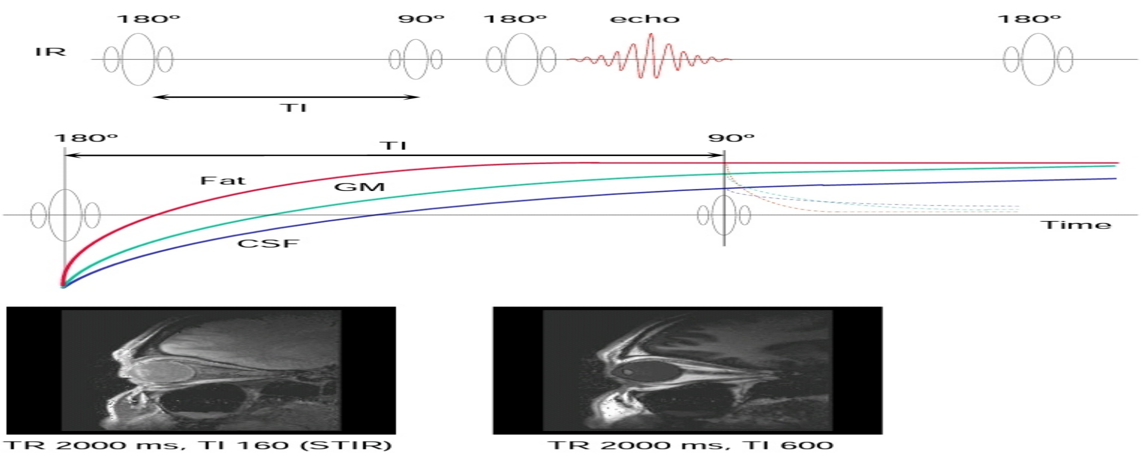

Figure 53: Inversion time effect

6.5 Number Of Acquisitions NEX

SNR is poor in most cases so we repeat the entire scan once ore multiple times then average the acquisition to have a better SNR and better image.
NA = 2 double the scan time but only increase SNR by $\sqrt[1]{2}$ some devices allow to choose fractional number of acquisitions. **to increase the SNR we only need to fill the lines around the center of K space**.
Increase NA will lead to:

- more signal $\sqrt[1]{NA}$
- less noise, fewer artifacts
- longer scan time

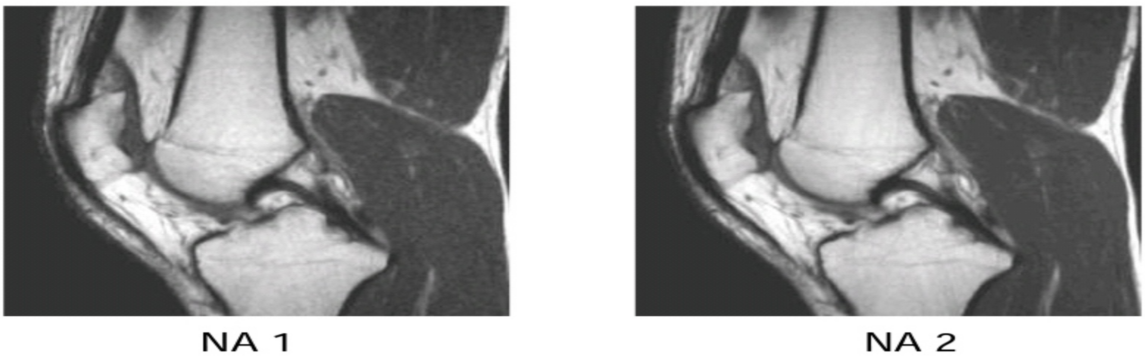

Figure 54: NA effect

6.6 Matrix MX

The acquisition matrix determine the spatial resolution by decreasing the voxel size and will lead to :

- lower signal (small voxel contain fewer protons)
- higher spatial resolution
- increase scan time (MX_{PE} only , MX_{RO} has no effect on scan time)

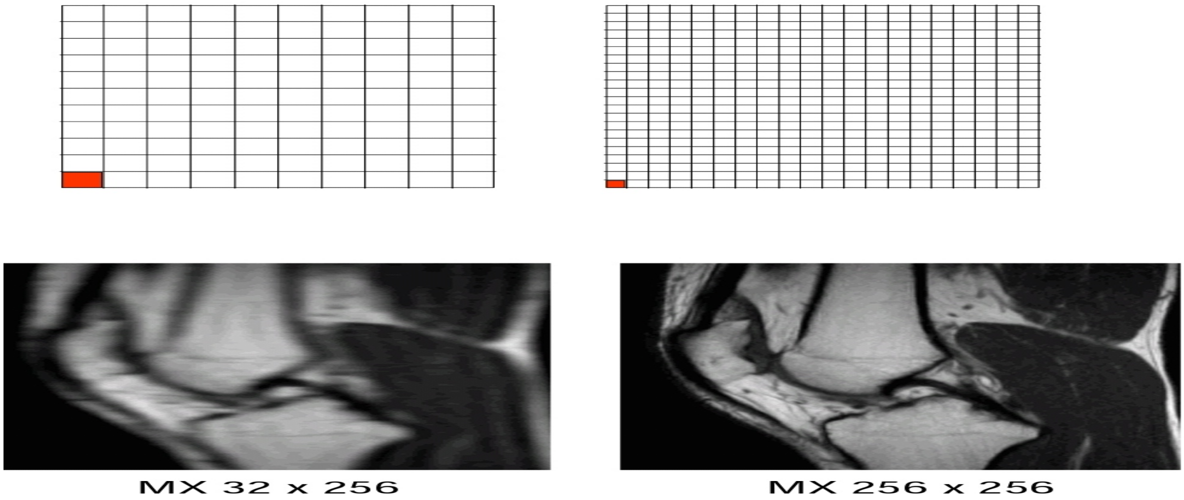

Figure 55: Matrix effect

6.7 Field Of View FOV

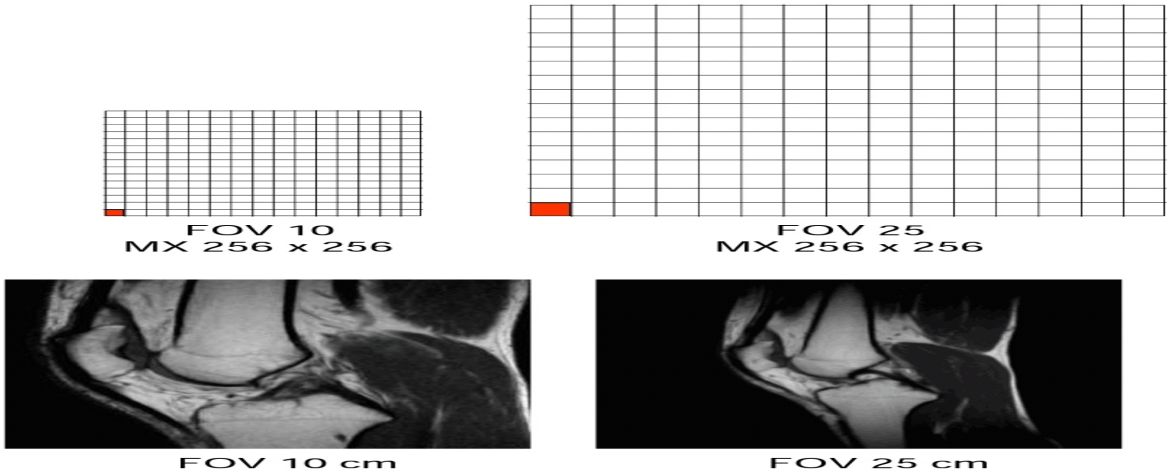

Figure 56: FOV effect

Determine how much we are going to see.
Increase FOV will lead to:

- increase voxel size , hence signal
- lower spatial resolusion
- increase viewing area

6.8 Slice Thikness ST

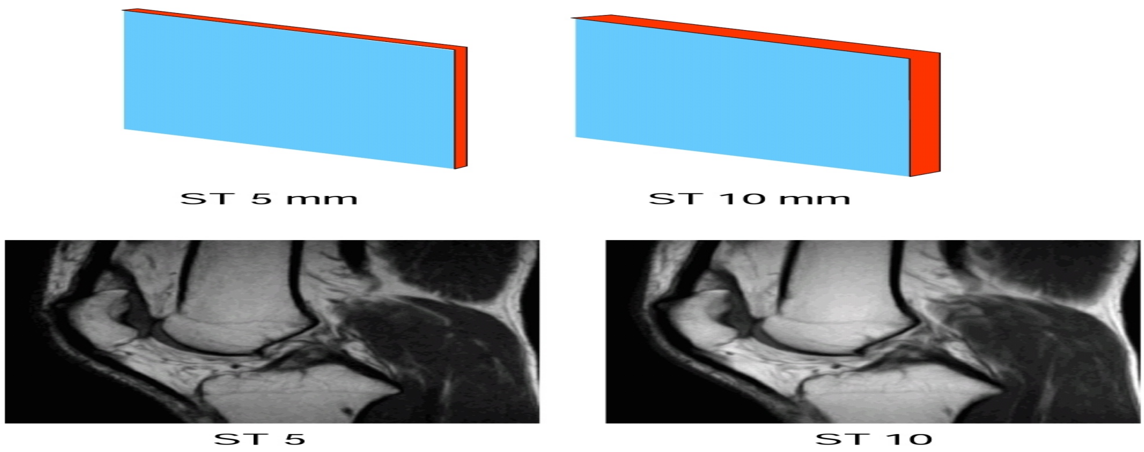

Figure 57: Slice thickness effect

ST affect the amount of signal and sharpness.
Increase ST will lead to

- increase voxel size
- lower resolution
- increase partial volume effect
- larger object coverage

MX, FOV, ST all determine voxel size hence spatial resolution. We should choose value for each parameter to have enough SNR with a reasonable time

6.9 Slice Gab SG

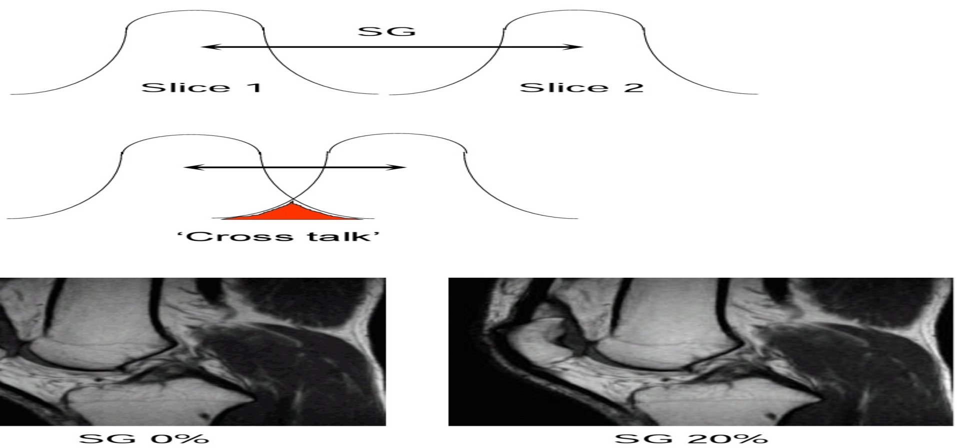

Figure 58: SG effect

The amount of space between slides(Non Ideal RF pulse).
Increase SG will lead to : less cross talk and increase coverage.
"**Interleaving mode**" eliminate cross talk but has some issues like signal intensity difference(1,3,5,7,.... then 2,4,6,....)

6.10 TASK 3

6.10.1 Phase Echo Direction PE

6.10.2 Bandwidth BW

7 Image Artifacts

7.1 Motion Artifact

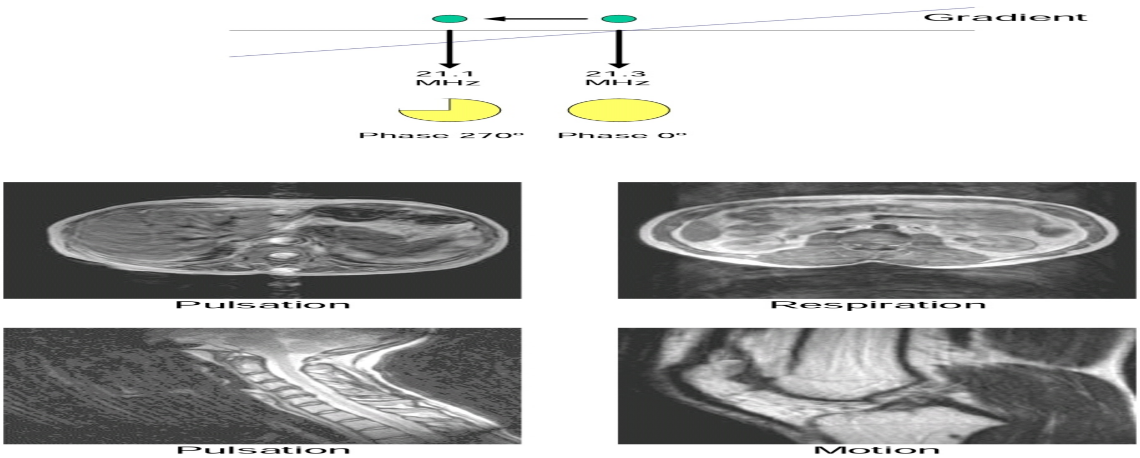

Figure 59:

Caused by phase mismapping of protons because of the time lapse between excitation and sampling signal.
Motion could be due to respiration or pulsation or the patient movement.
Techniques such as "**Flow Compensation**" "**cardiac triggering**" are used to eliminate motion related artifacts.
Motion artifacts are displayed in PE direction.

7.2 Para-magnetic Artifacts

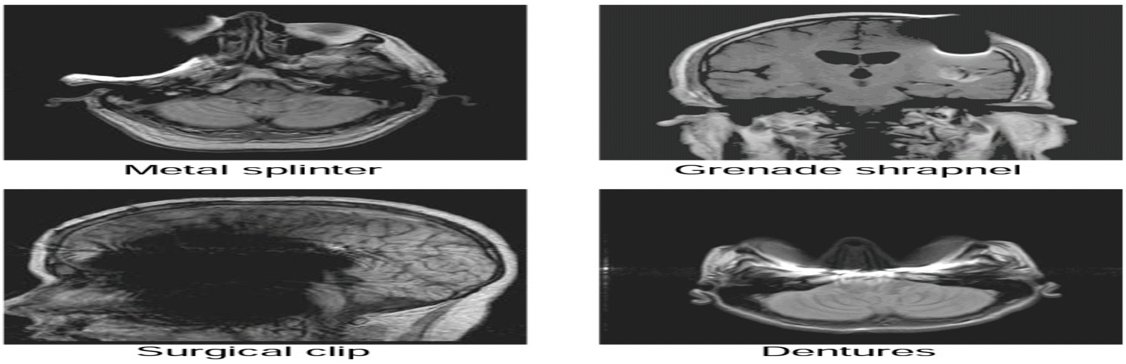

Figure 60:

Caused by metal because metal deflect the magnetic field. This will change the resonance frequency and protons will not react with RF excitation pulses.
We should make sure that implants are MRI compatable.
AL - Ti produce lessartifacts. artifitial hip patients can go into MRI machine.

7.3 Phase Wrap Artifacts

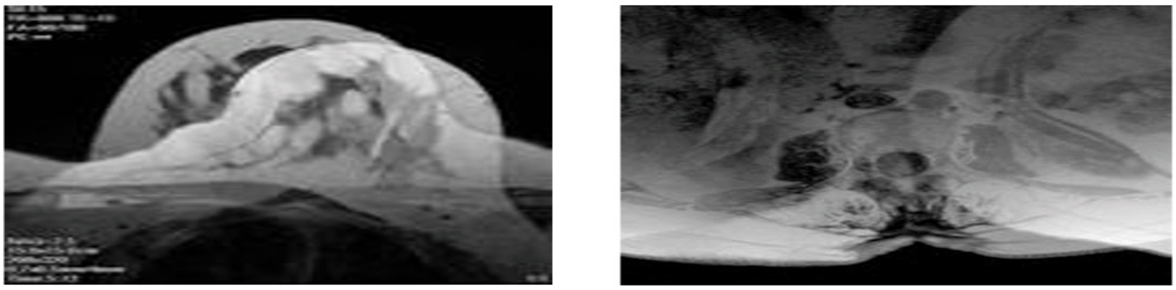

Figure 61:

When FOV is smaller than the object. We should use "No Wrap or Double matrix " feature to eliminate this artifact, but this double the scan time.
Most of the time the operator forget to turn of this feature.

7.4 Frequency Artifacts

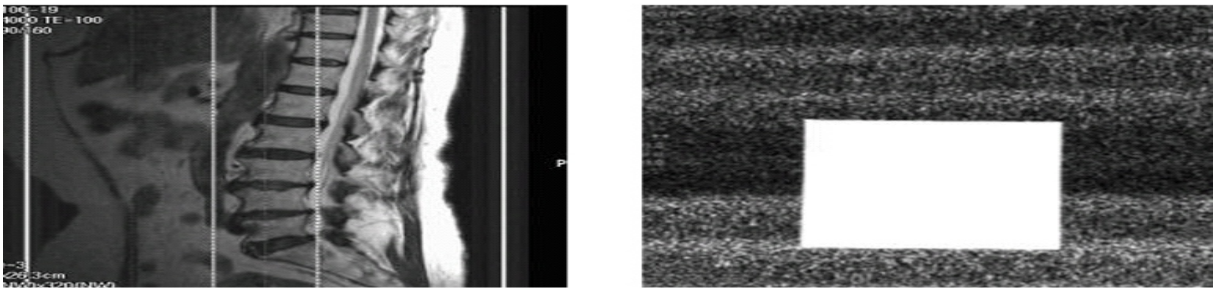

Figure 62:

caused by dirty frequencies (Faulty electronics, Rf cage leak, external transmitter, non shielding equipment,metal in the patient, Open door) .
this type require an engineer.

7.5 Susceptibility Artifacts

susceptibility is the ability of the material to be magnatized.
EX. Iron in the blood and diffrent bonding properities of the tissues cause local magnetic field inhomoginities. Resonance frequency at boundaries change and therefor will not be displayed (black line around tissue)

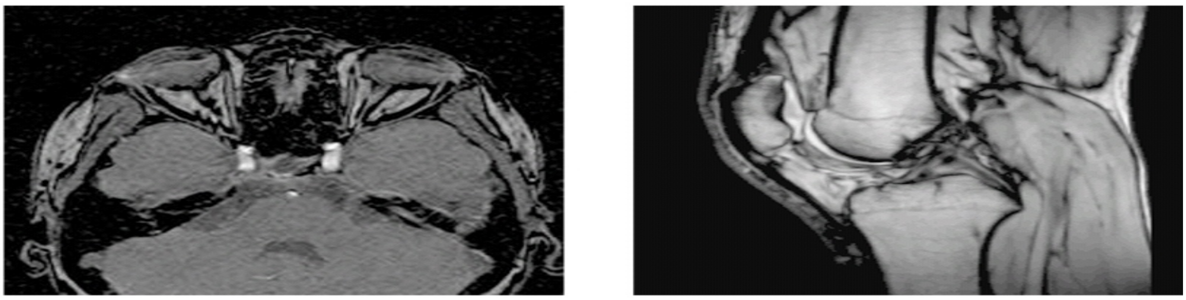

Figure 63:

7.6 Clipping Artifacts

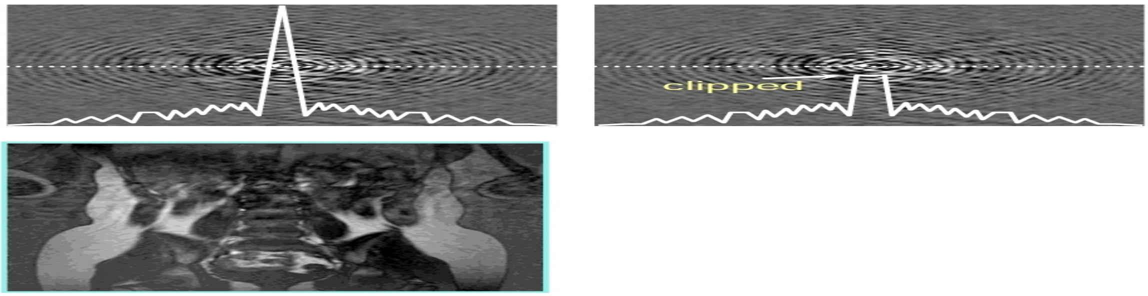

Figure 64:

The maximum received signal is higher than the value set in the receiver gain therefore the excess signal is clipped

7.7 Spike Artifacts

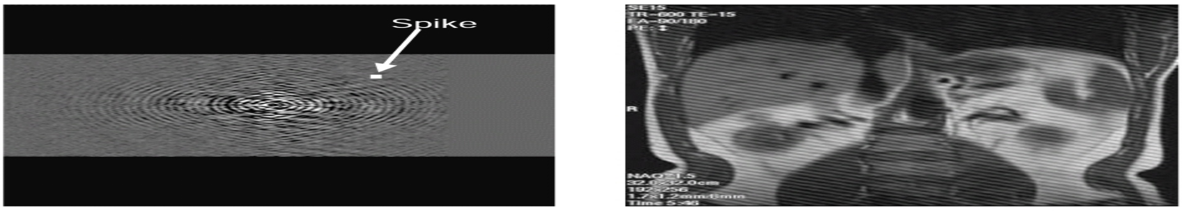

Figure 65:

Caused by one bad data point in k space (lines through the image) . The scan Shall be repeated

7.8 Zebra Artifacts

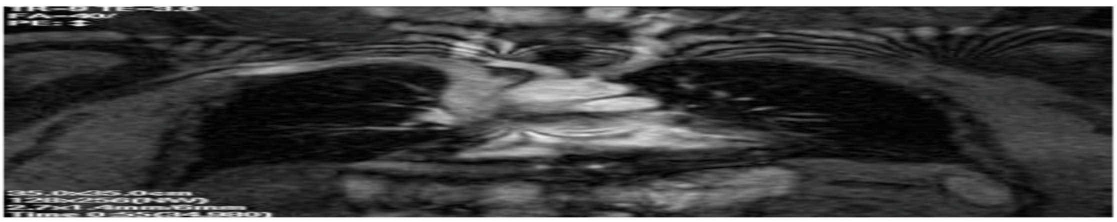

Figure 66:

May occur when the patient touches the coil or as a result of phase wrap

7.9 Task 4

7.9.1 Chemical Shift Artifacts

8 What IS Next?