Basic Principles on NMR and its Applications on MRI & Spectroscopy

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Part I

Nuclear Magnetic Resonance (NMR)

The principle of NMR

The following analysis is focused to

hydrogen nucleus, the proton.

What are the basic properties of proton for NMR?

- A proton turns around itself, so it has its intrinsic angular momentum. We call it **spin**

From Quantum Mechanics spin is given by:

$$\text{spin } \vec{\boldsymbol{I}} = \sqrt{I(I+1)} * \left({}^{h}\!/_{2\pi}\right)$$

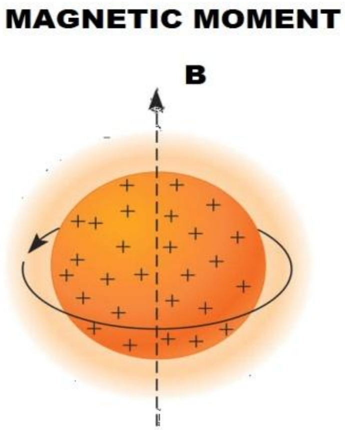
- $\boldsymbol{h} = 6.63 * 10^{-34}$ Joules s molecule^{-1} , Planck's constant
- ***I*** is the spin quantum number (integral or half integral – depends on element nuclei)
- For hydrogen nuclear *I=1/2, so*

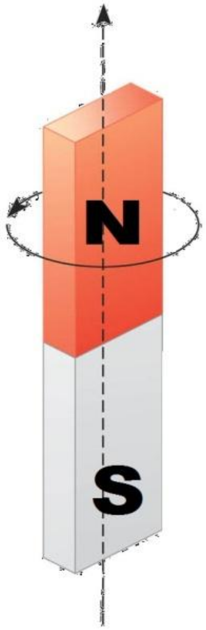
$$\text{spin } \vec{\boldsymbol{I}} = \frac{(\sqrt{3})}{2} * \left({}^{h}\!/_{2\pi}\right)$$

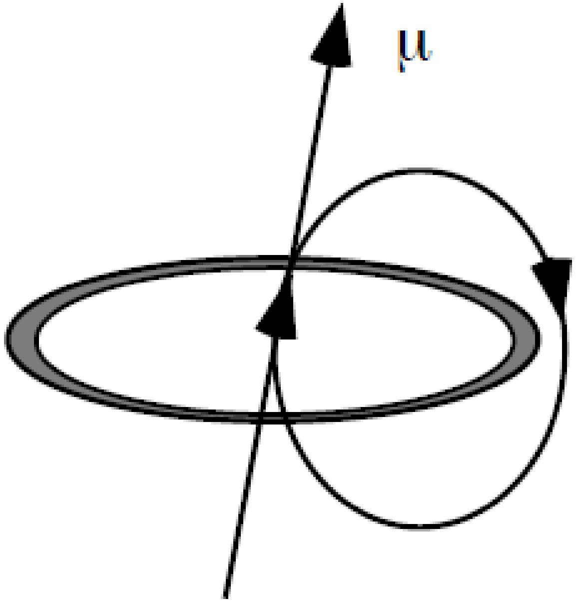
Why proton looks like a magnetic dipole?

- The positively electric charged proton, after its spin, is equivalent to a very small *current loop*.
- That *current loop* creates a small ***magnetic dipole*** and has a ***magnetic moment μ***.

Approximations of Proton spin and its magnetic moment





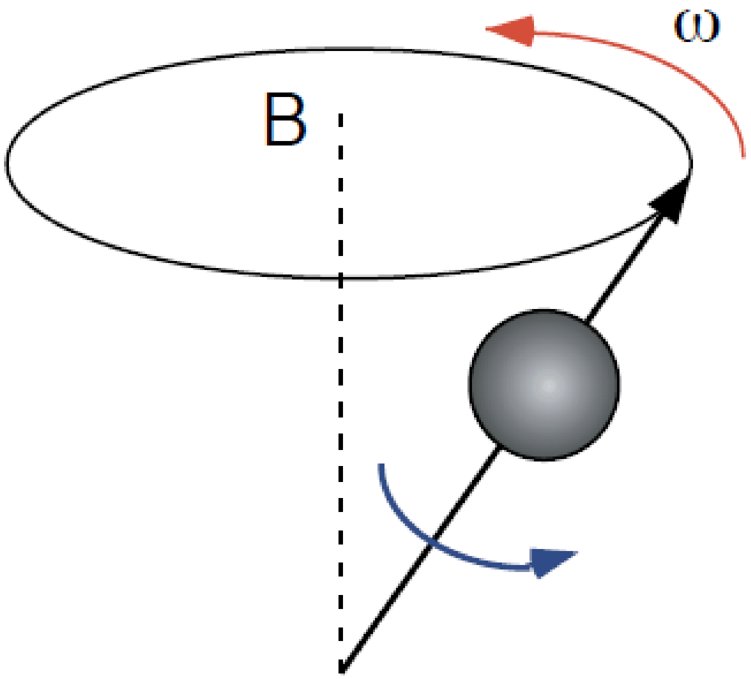


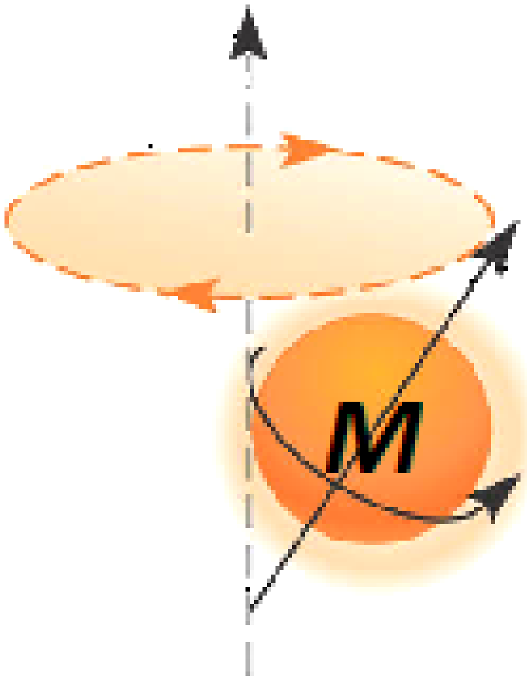
In quantum mechanics we take for μ:

- Magnetic moment $\vec{\mu} = \frac{Gqh}{4\pi m} * \sqrt{I(I+1)}$ JT^{-1}

- *G* = Lande splitting factor
- *q=charge and m=mass of proton*

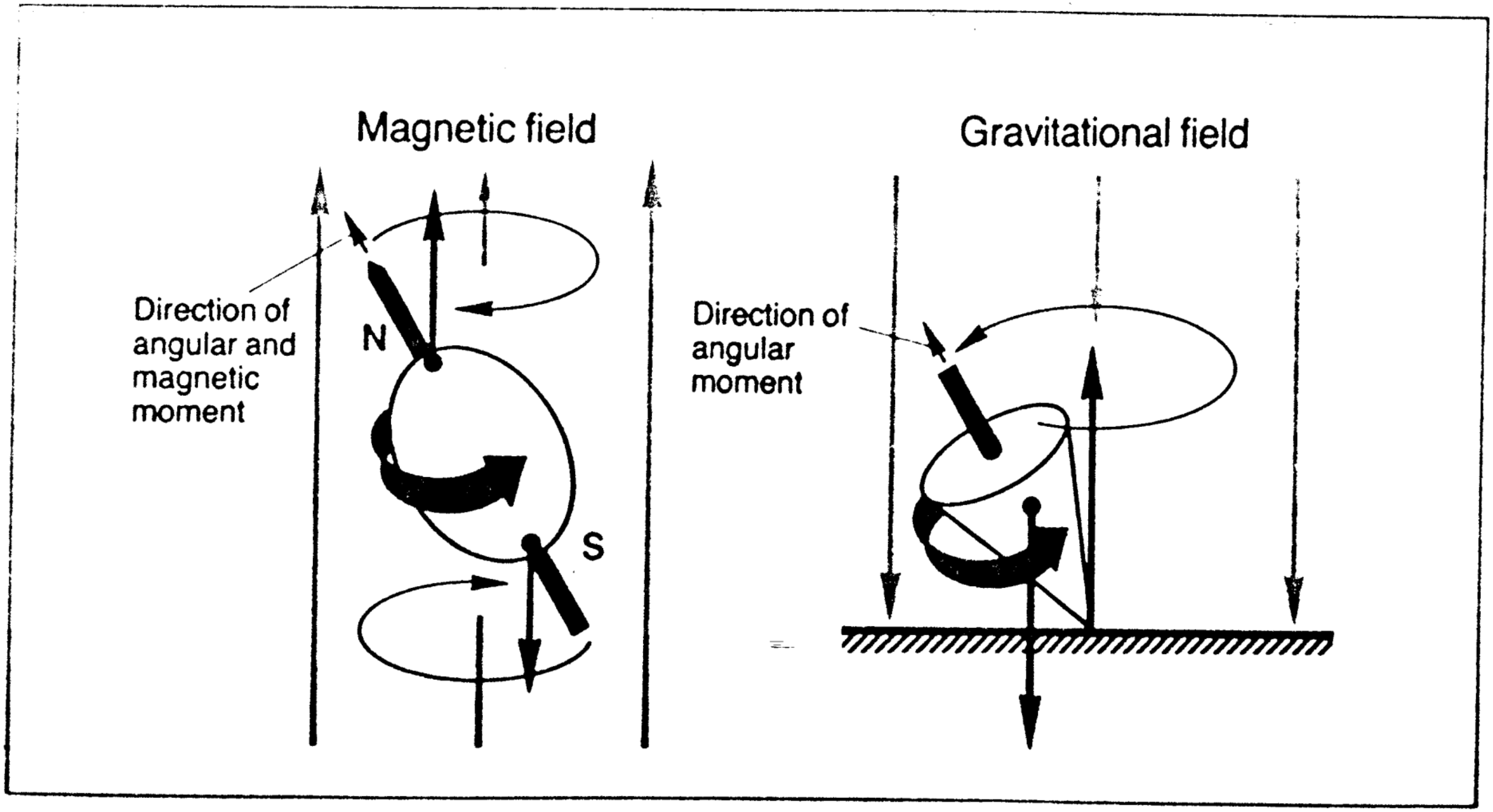
What happens when a proton is placed in a static magnetic field B?





3. *Spinning Nucleus and Spinning Top*

Illustration of the similarity between a spinning and precessing top in a gravitational field and a spinning and precessing nucleus in a magnetic field.



- When a proton is placed in a static magnetic field B, spins (rotates) about its own axis and **precesses** about the direction of B. The precessing frequency f_0 is proportional to the magnetic field B:

$$f_0 = \gamma^* B$$

- f_0 is called "the Larmor frequency",
- γ^* is called "the gyromagnetic ratio".

For H_2 protons γ^* = 42,58 MHz / T

NOTICE

spin never aligns to B.

Spin only **precesses** about the direction of B.

For H_2 protons, magnetic moment has one of two components (states) on direction z of magnetic field B.

- A parallel to it (μ_z) or
- an antiparallel ($-\mu_z$) (opposite direction).

- *More spins tend to precess about the magnetic field B, with their z component (μ_z) to be parallel (same direction) with the field B.*
- Spins parallel to B have lower energy than spins antiparallel to B.

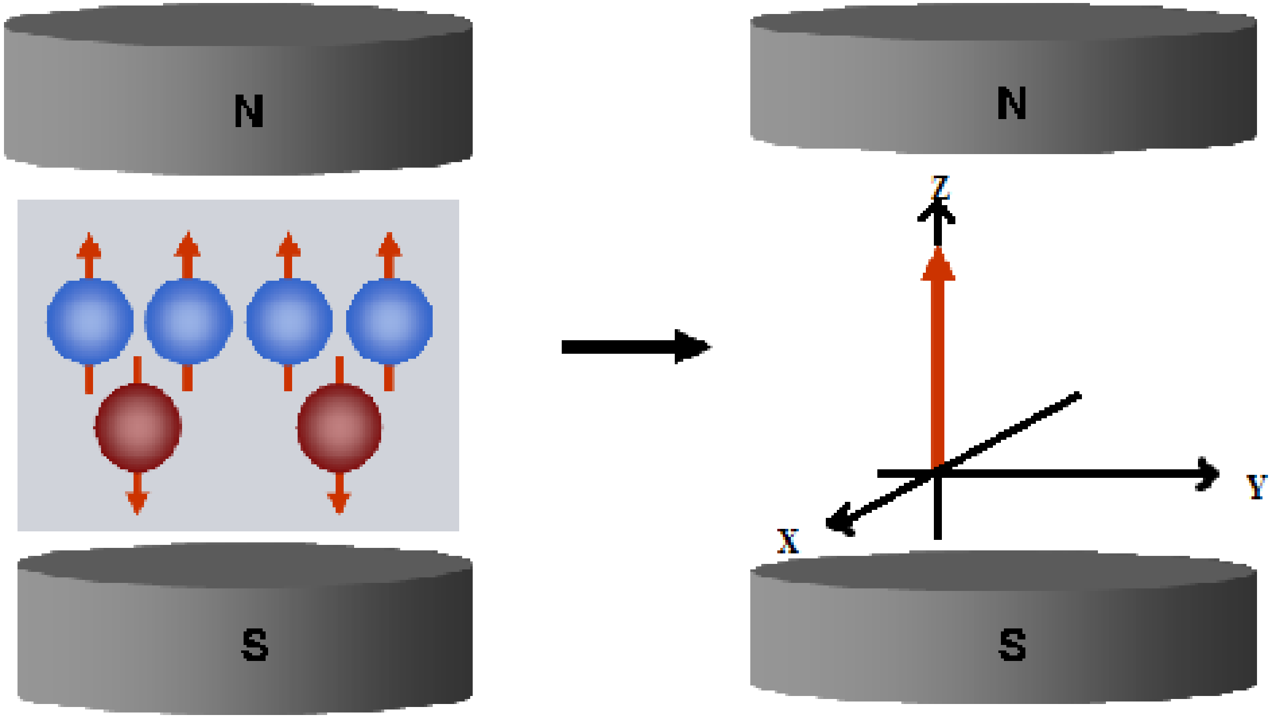
Macroscopic view of magnetization. Net Magnetization M_z

- When hydrogen atoms are placed in a static magnetic field B, a slightly larger fraction of spins aligns parallel to this field B.
- Summation of individual magnetic moment vectors represent the ***Longitudinal magnetization Mz*** in the z-direction.

Macroscopic view of magnetization. Net Magnetization M_z

- Energy difference between spin orientations (parallel and antiparallel) depends on the strength of the external magnetic field.
- Spins parallel to B are directly proportional to it.
- Longitudinal Magnetization Mz increases with the field strength.

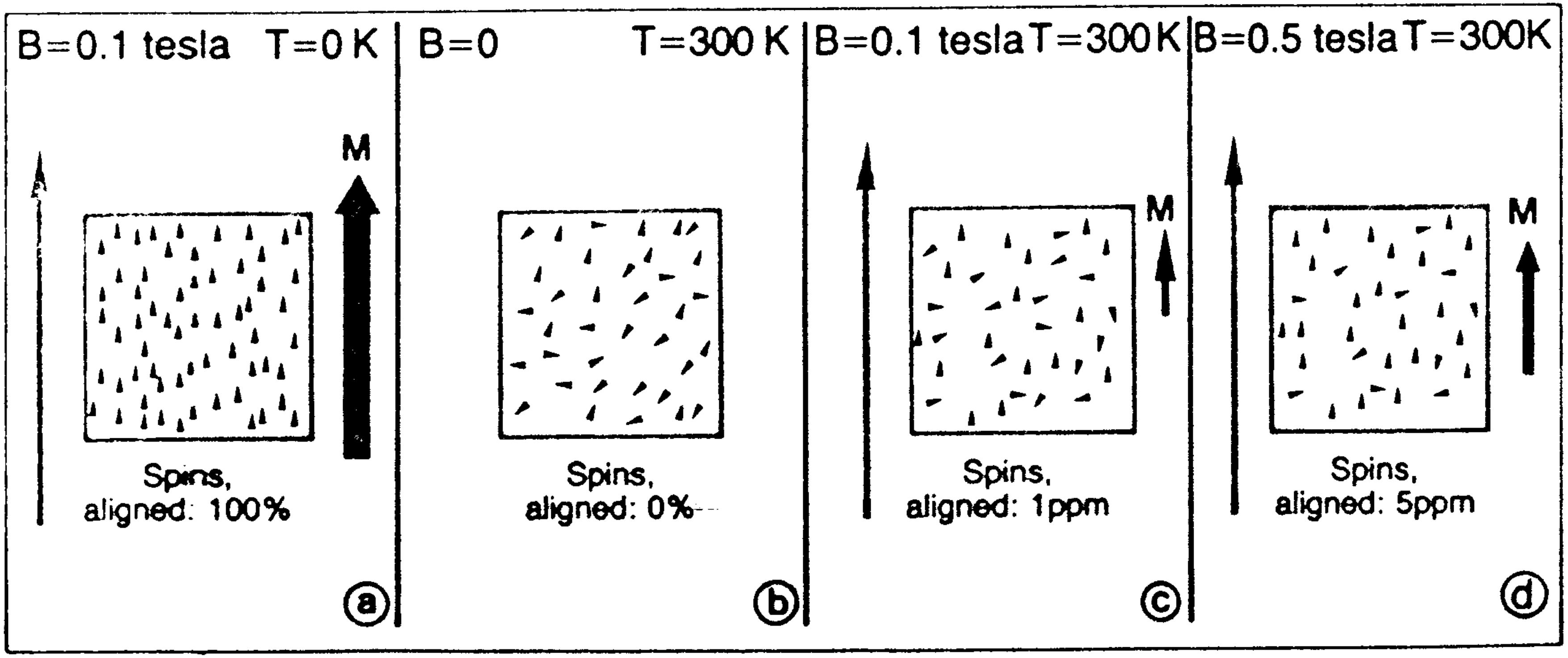
Building up of net magnetization, the Longitudinal Magnetization M_z.



Net Magnetization depends on B as well as on temperature T

4. Net Magnetization and Temperature

Representation of the influence of temperature and the strength of the applied magnetic field on the net magnetization.

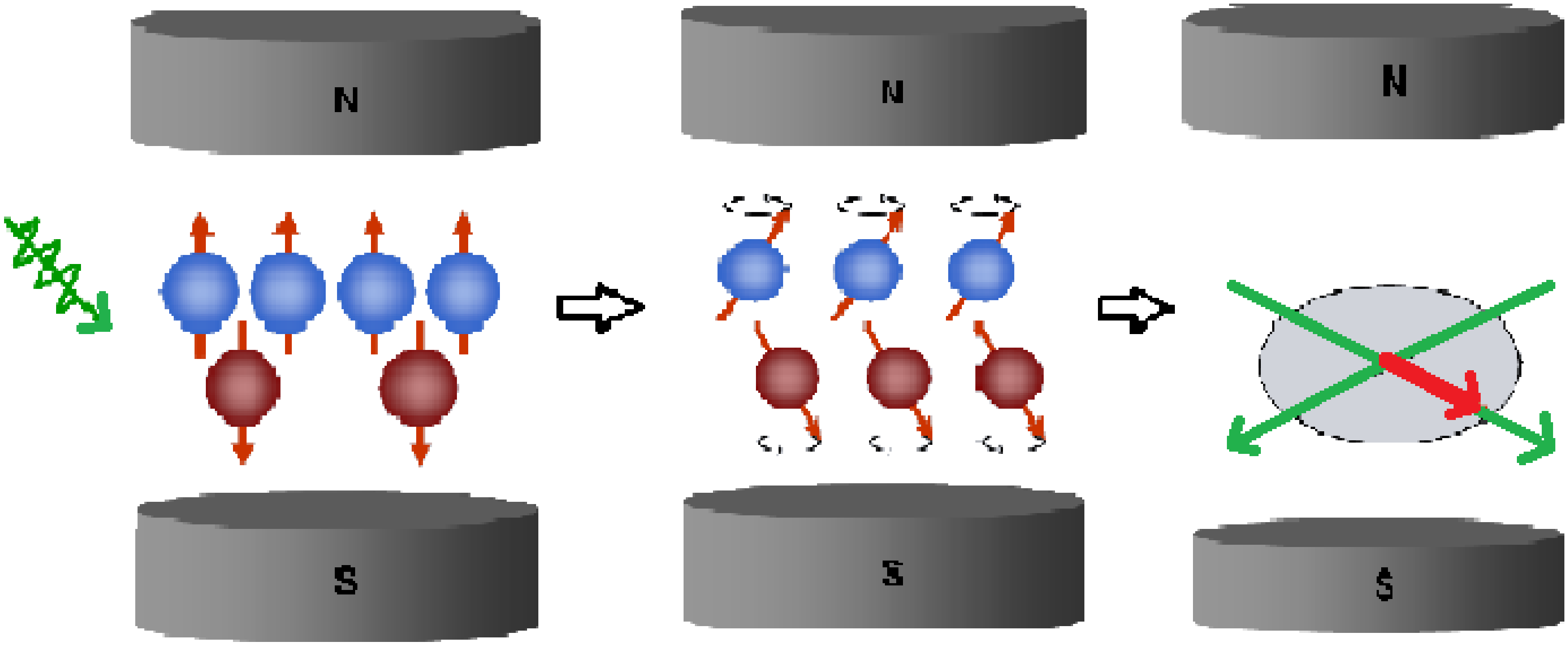


The interaction of Mz and RF pulse

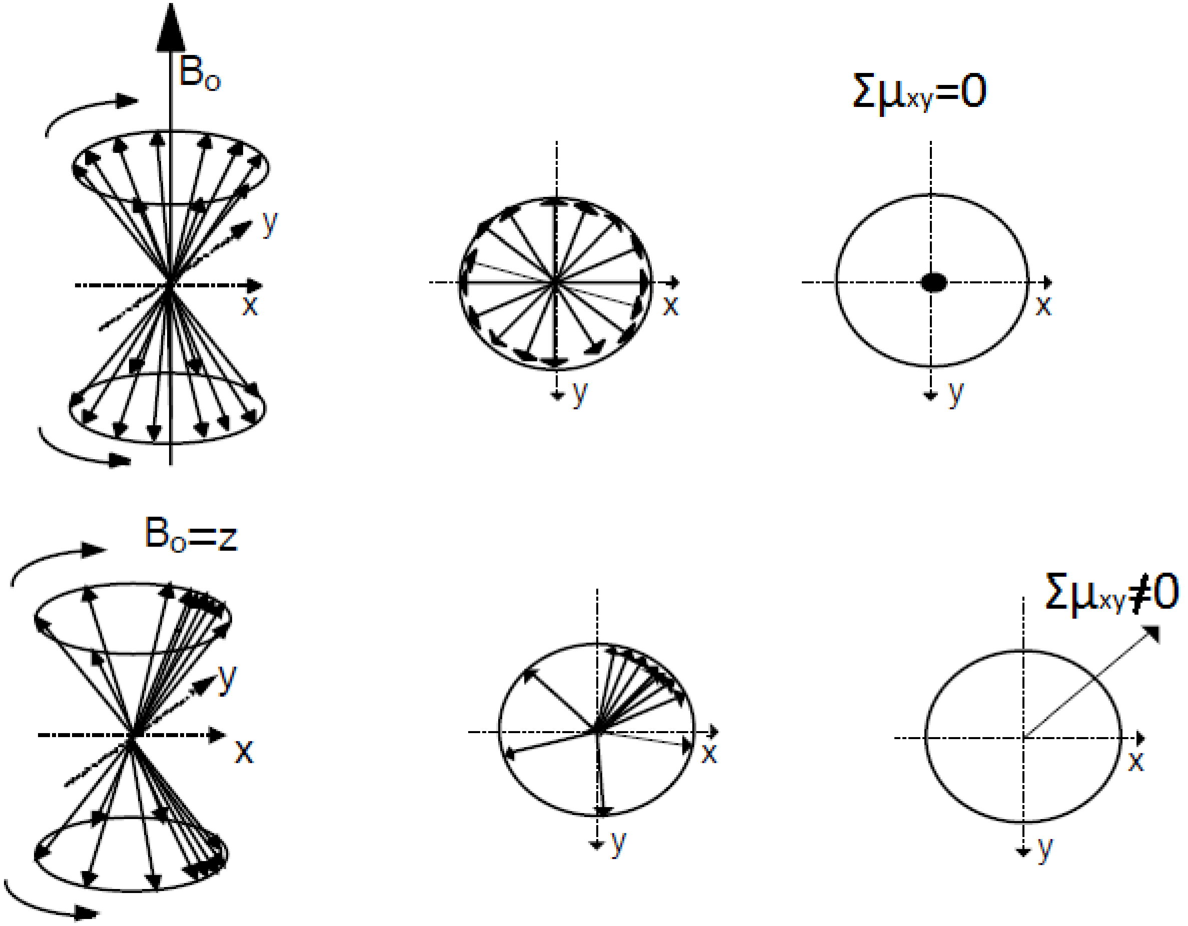
When protons are excited by an RF pulse of magnetic field B_1, perpendicular to B and having the Larmor frequency f_0 then NMR happens and:

- Longitudinal magnetization Mz precesses with f_0 and **flips** gradually to the transverse xy plane building the ***transverse magnetization Mxy***.
- Actually, a phase **coherent** movement of spins is imposed during RF pulse, so Mxy magnetization is developed gradually.

RF pulse excitation and Mz rotation to Mxy plane



1)Uncoherent spins give Mxy=0 (upper) 2)Coherent spins after 90^o RF pulse give Mxy>0

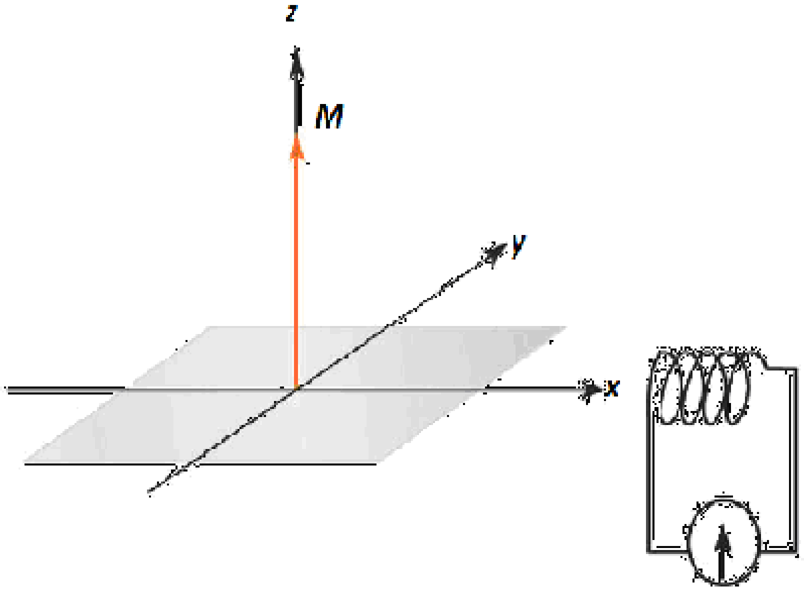


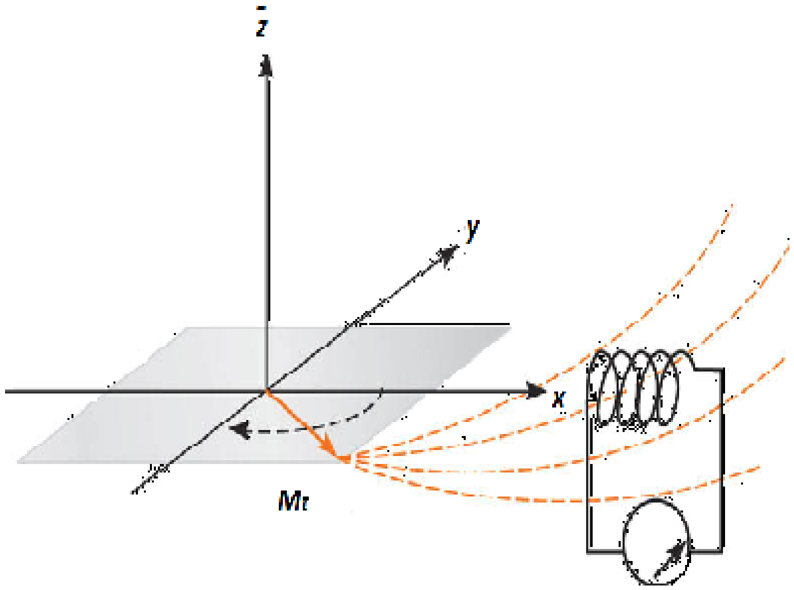
The interaction of Mz and RF pulse

After Mxy is built, RF excitation pulse - called 90^0 pulse - stops. Then:

- Transverse Magnetization Mxy continuous precessing with f_0 and slowly flips out to its original direction, Mz.
- With a coil placed axially to x or y axis a voltage (signal) is induced in f_0 which is exponentially reduced with time constant T_2.
- This is called ***FID (Free Induction Decay)*** signal.

Excitation of Mz with 90^0 RF pulse (left) and FID signal with pick up coil (right)

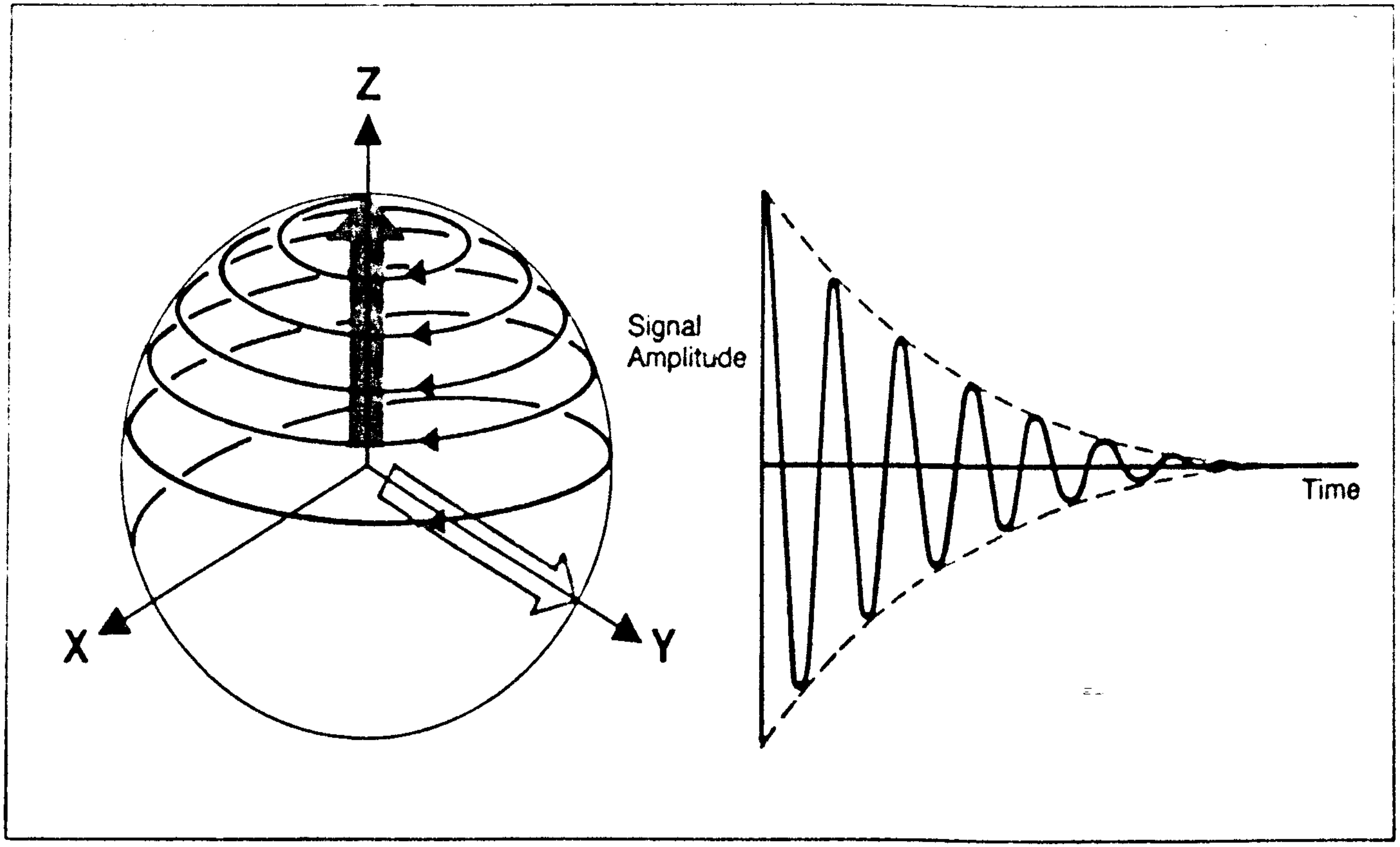




The interaction of Mz and RF pulse

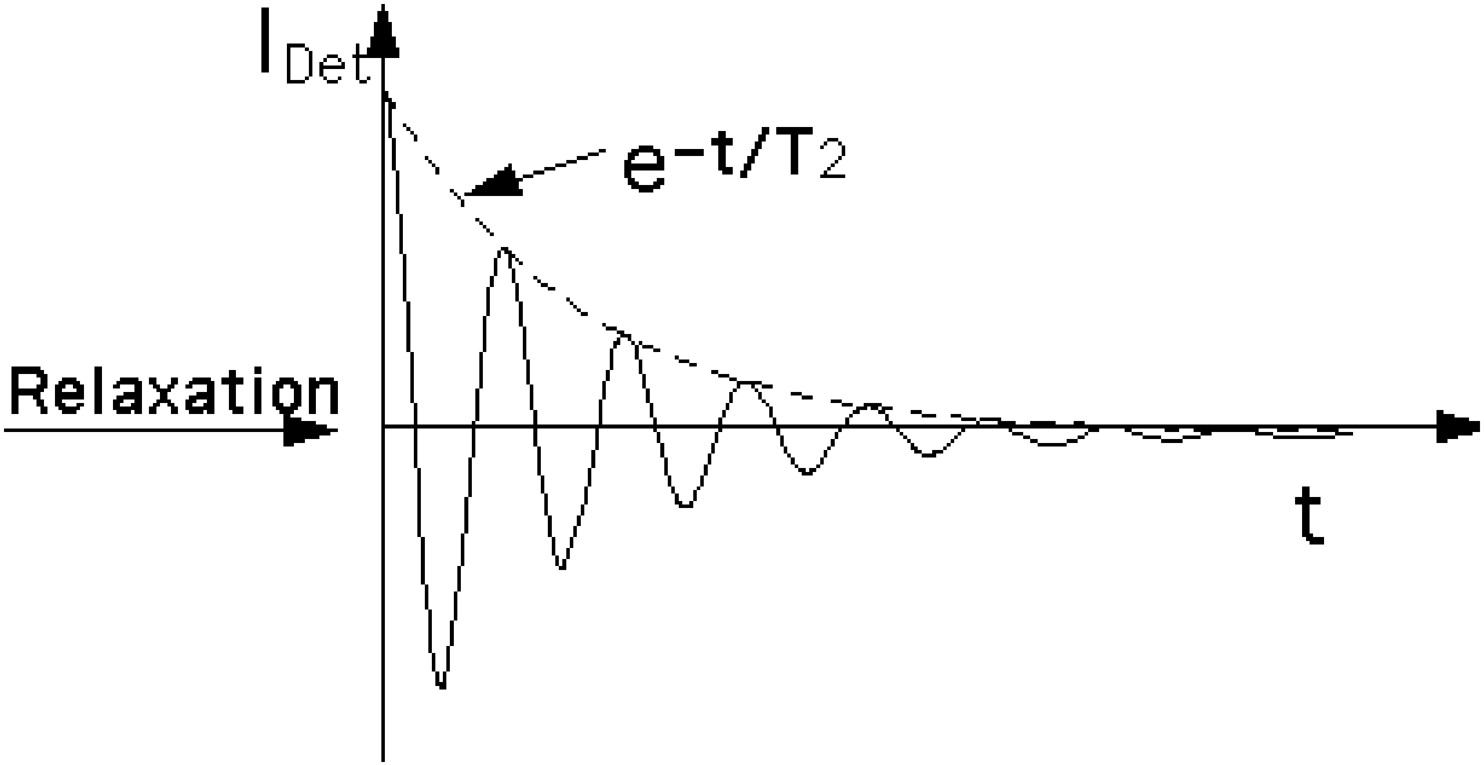
16. Free Induction Decay Signal

The net magnetization is shown pictorially to spiral into the transverse plane on excitation, the graph depicting the decay of the MR response signal detected during relaxation.



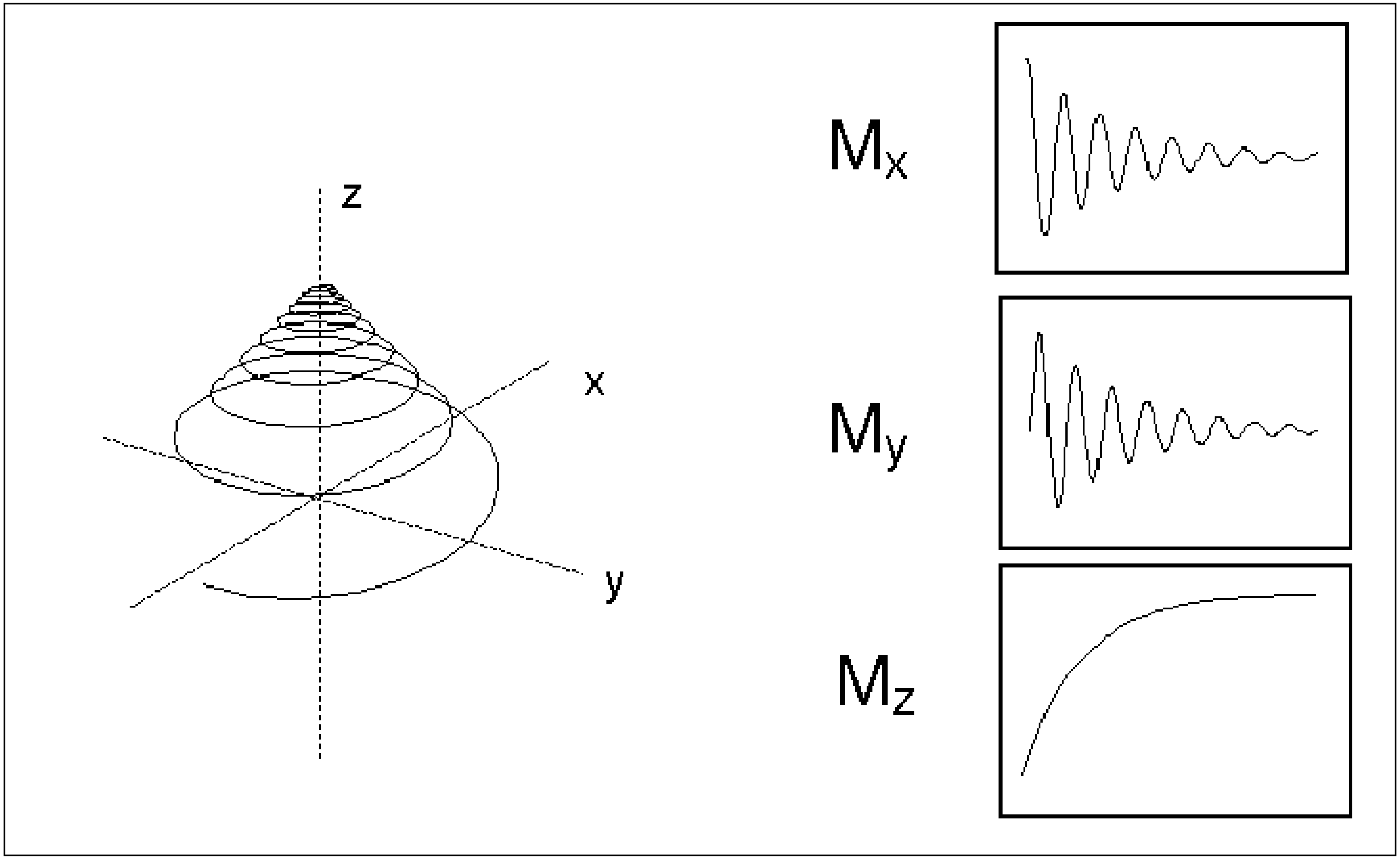
FID signal

T_2 is the transverse or spin-spin relaxation time



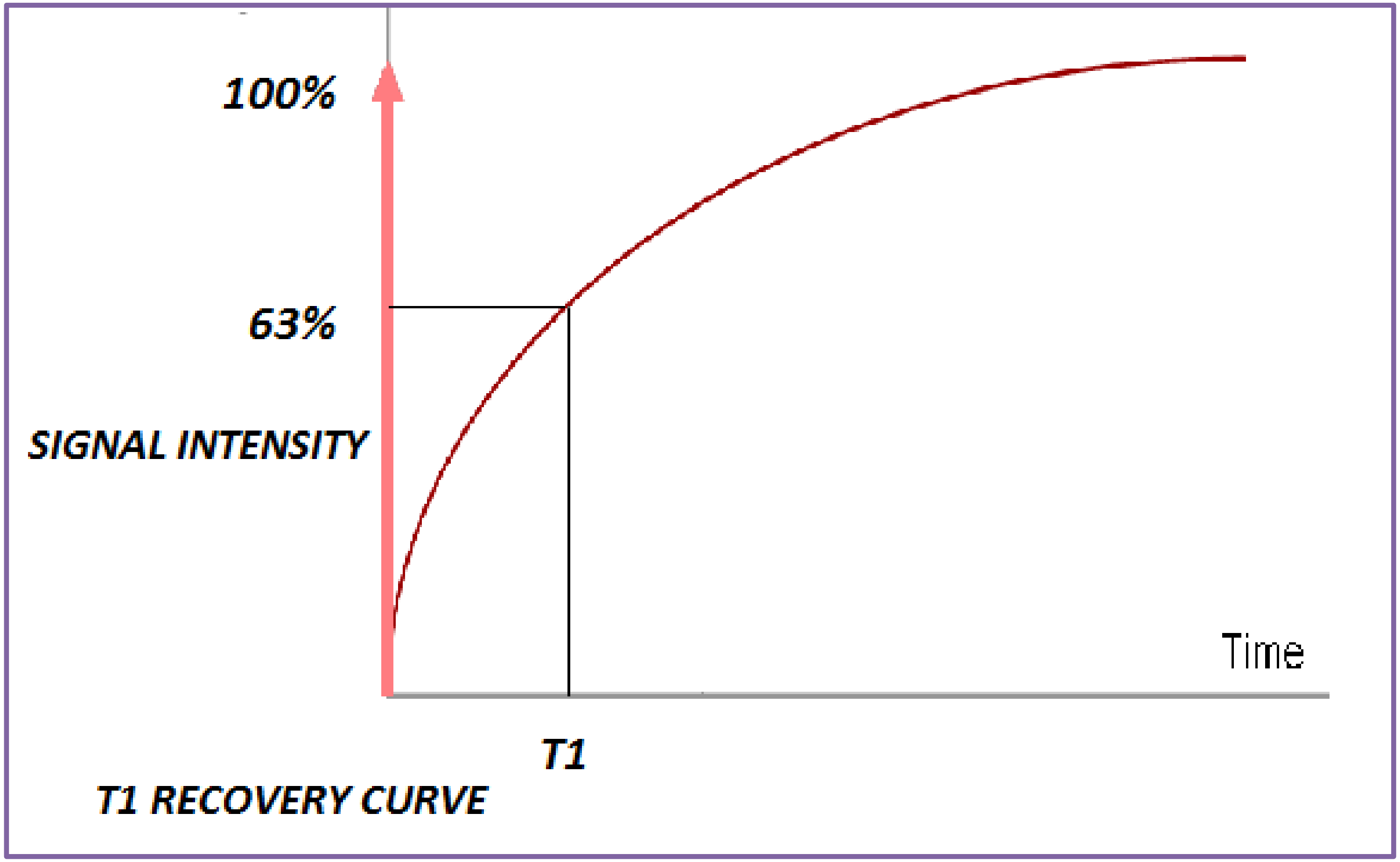
After 90^0 pulse:

Recovery of Longitudinal Mz and decay of Mxy



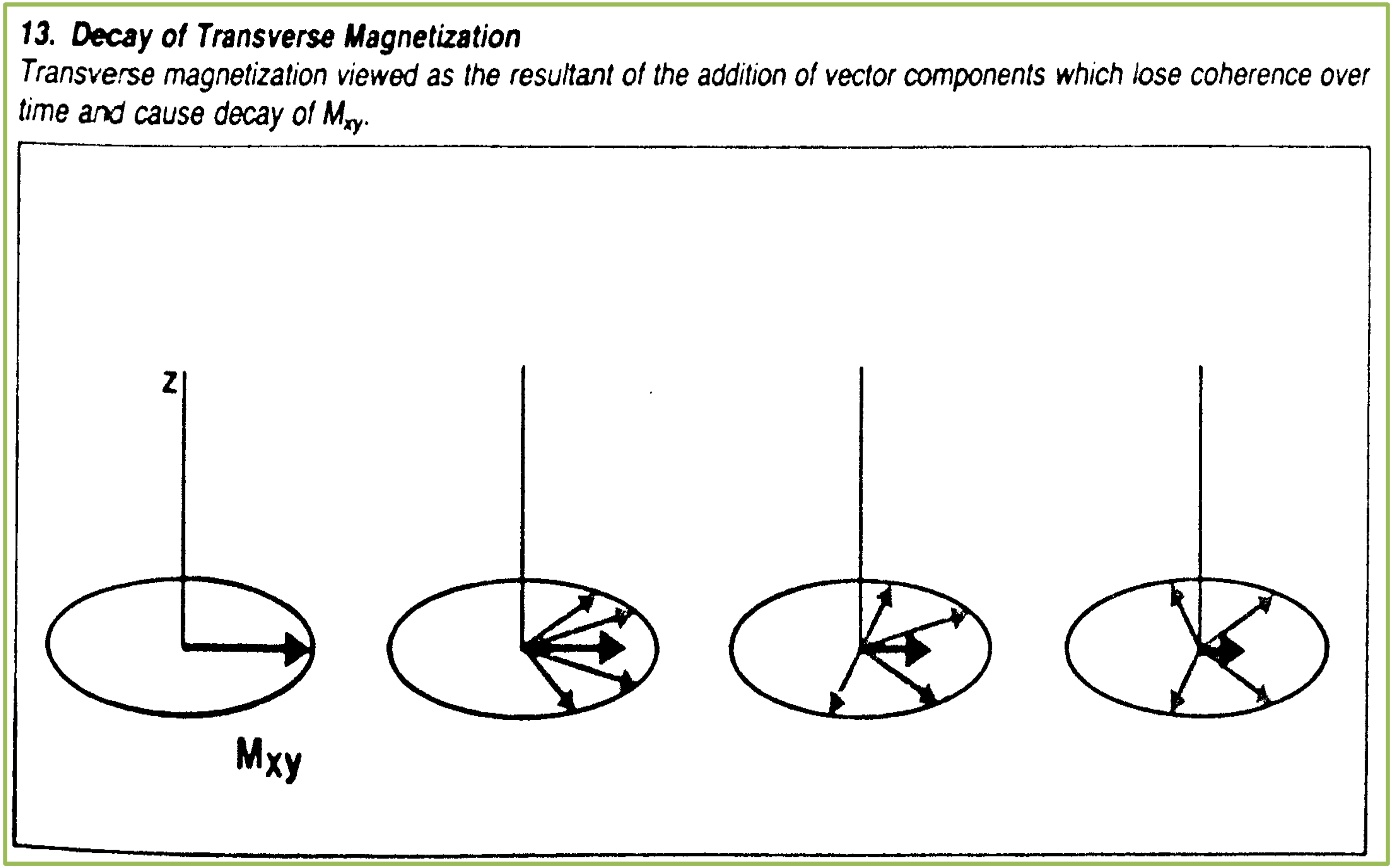
Longitudinal or Spin-Lattice Relaxation Time T1

- Longitudinal or Spin-Lattice Relaxation Time T1 is the time for Mz magnetization to recover to 63% of its magnitude M_0 after relaxing on z axis
- Mz increases exponentially with time constant T1
- T1 is greater than T2

100%
63%
SIGNAL INTENSITY
Time
T1
T1 RECOVERY CURVE

Transverse or spin – spin relaxation time T2

- Transverse or spin – spin relaxation time T2 represents the decay time constant of transverse magnetization Mxy, to reach 37% of its maximum magnitude, after 90^0 RF pulse
- Mxy decays exponentially with time
- T2 represents the duration of dephasing of μ_{xy} vectors from individual spins

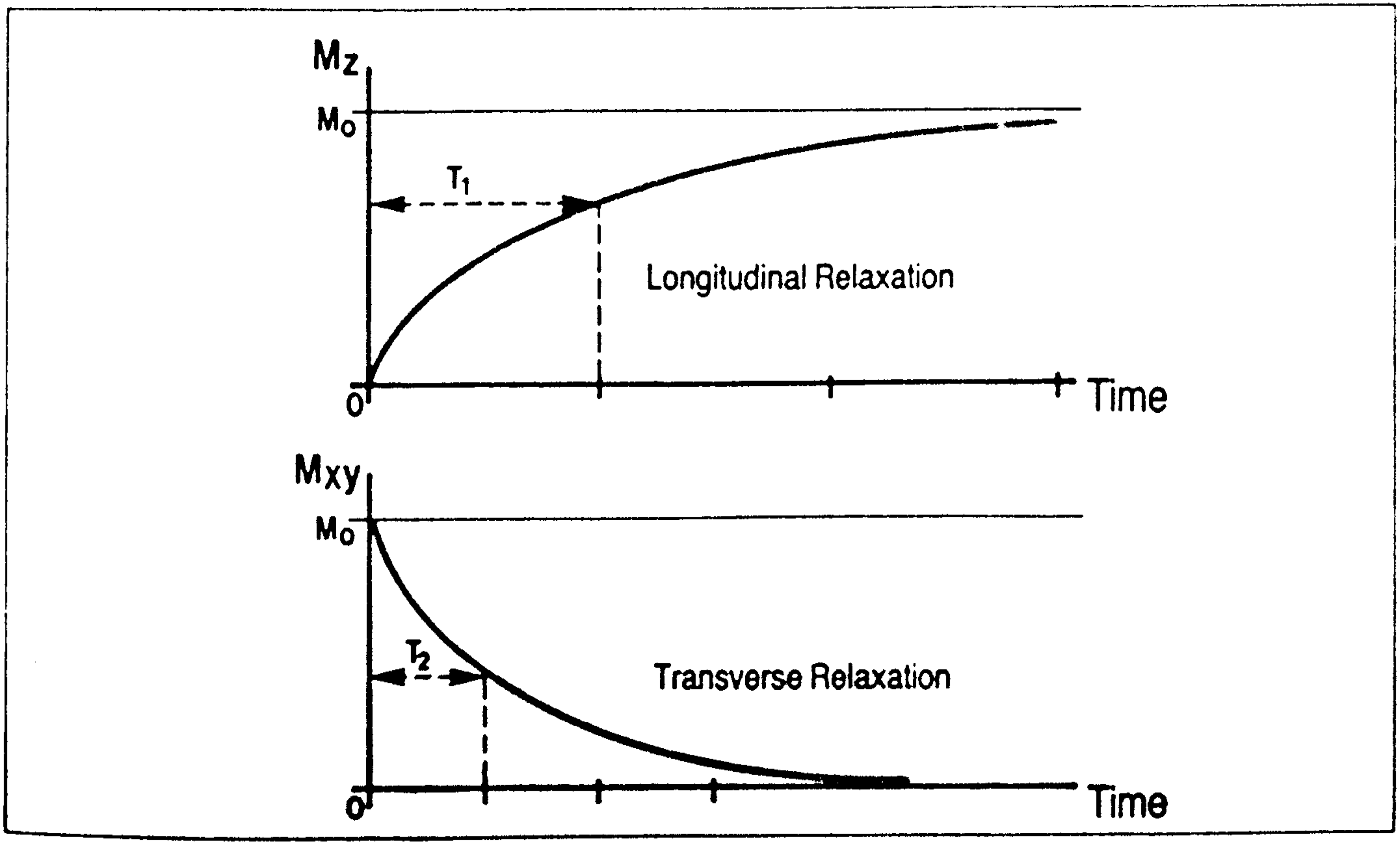


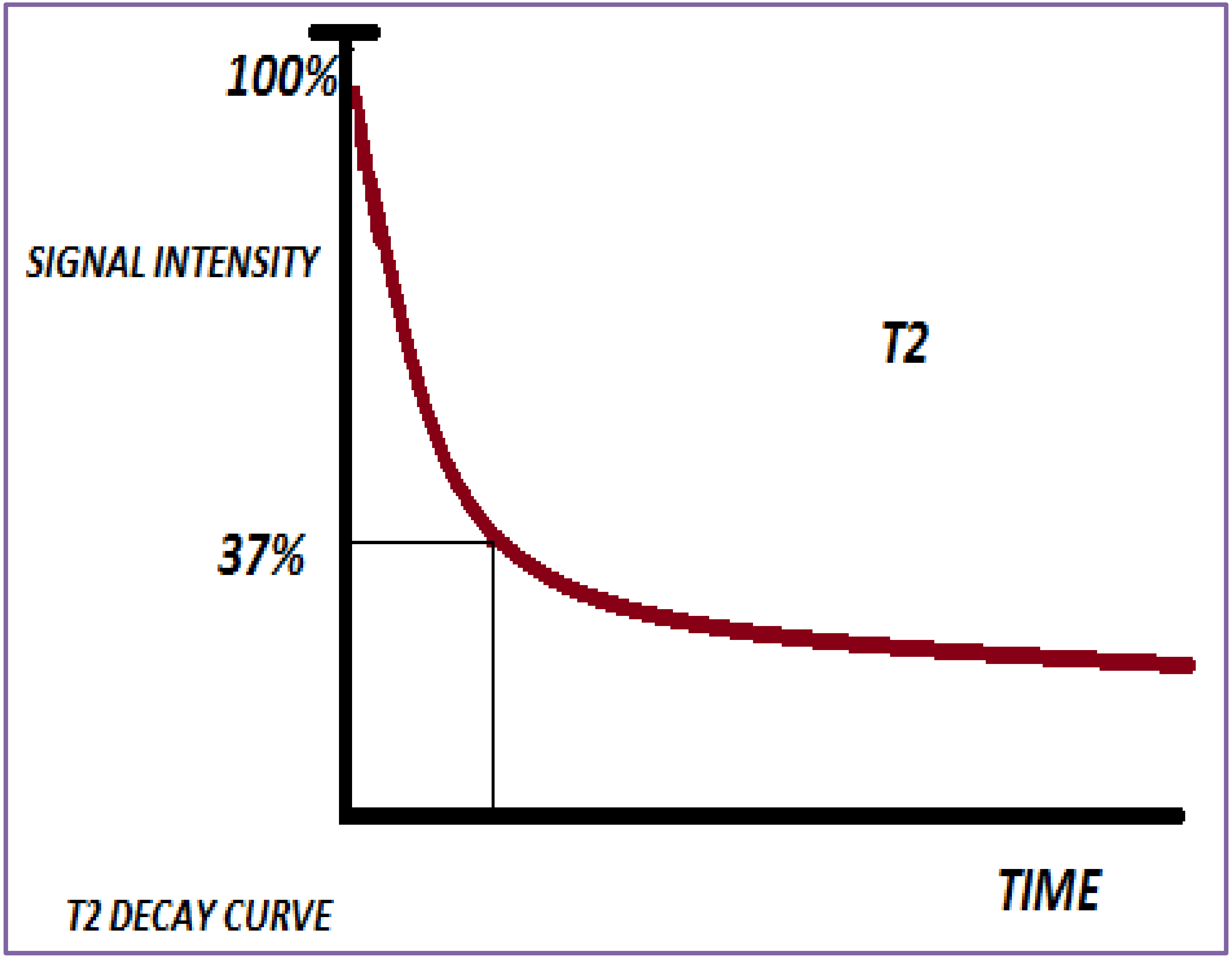
13. Decay of Transverse Magnetization

Transverse magnetization viewed as the resultant of the addition of vector components which lose coherence over time and cause decay of M_{xy}.

10. Longitudinal and Transverse Magnetization During Relaxation

Graphs showing the exponential decay of the transverse and longitudinal magnetization after excitation, and the relaxation times.




100%
SIGNAL INTENSITY
T2
37%
TIME
T2 DECAY CURVE

Bloch Equation

- Bloch equation describes the magnetization attributes of a nuclei magnetization vector M

$$\frac{d\overrightarrow{M}}{dt} = \gamma \overrightarrow{\mathrm{M}} \times \overrightarrow{\mathrm{B}}_o - \left(\mathrm{M}_x \vec{i} + M_y \vec{j}\right) / T_2^* - \left(M_z - M_o\right)\vec{k} / T_1$$

Bloch Equation

- Magnetic coordinates after RF excitation are given:

$$dM_x / dt = \gamma \cdot \mathrm{M}_y B_o - M_x / T_2^*$$

$$dM_y / dt = -\gamma \cdot \mathrm{M}_x B_o - M_y / T_2^*$$

$$dM_z / dt = -\left(M_z - M_o\right) / T_1$$

Bloch Equation

- Their solutions are given by next equations

$$M_y(t) = e^{-t/T_2^*}\left(M_x^o \sin\omega_o t - M_y^o \cos\omega_o t\right)$$

$$M_x(t) = e^{-t/T_2^*}\left(M_x^o \cos\omega_o t - M_y^o \sin\omega_0 t\right)$$

$$M_z(t) = M_z^o \exp(-t/T_1) + M_o(1 - \exp(-t/T_1))$$

Part II

Magnetic Resonance Imaging (MRI) Techniques

How an image is achieved

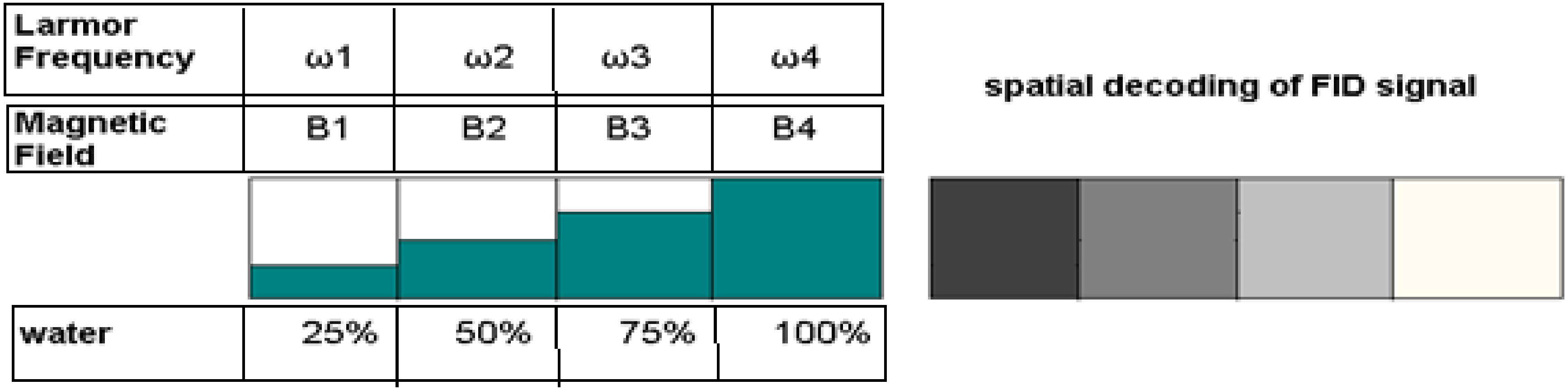
- MRI scanner or MRI tomographer is an imaging system of human body.
- It is based on NMR of Hydrogen atoms (protons) in human body, after excitation of chosen areas (slices) with RF pulses.
- FID signals are received by suitable coils and after amplification and decoded they translate the magnitude of FID to contrast for every point of scanning area.

How an image is achieved

- **Slice** selection of an image is achieved by a **gradient magnetic field G_z**, linearly changed on z direction
- **Voxel** selection on every point of slice is achieved by two **gradient magnetic fields G_x and G_y**, called the frequency and phase encoding gradients.

Magnetic Resonance Imaging (MRI) – proton density imaging example

Frequency encoding



Larmor Frequency	ω1	ω2	ω3	ω4
Magnetic Field	B1	B2	B3	B4
water	25%	50%	75%	100%

spatial decoding of FID signal

Image contrast

- Contrast is the difference in brightness between the light and dark areas of a picture. For MRI imaging, tissues with high signal are bright on the image and tissues with low signal are dark. Tissues with intermediate signal are gray.

Image contrast

- Tissues with a large transverse component of magnetisation give a large signal amplitude.
- Tissues with a small transverse component of magnetisation give a low signal amplitude.

MRI of head and dependence of contrast on NMR signal

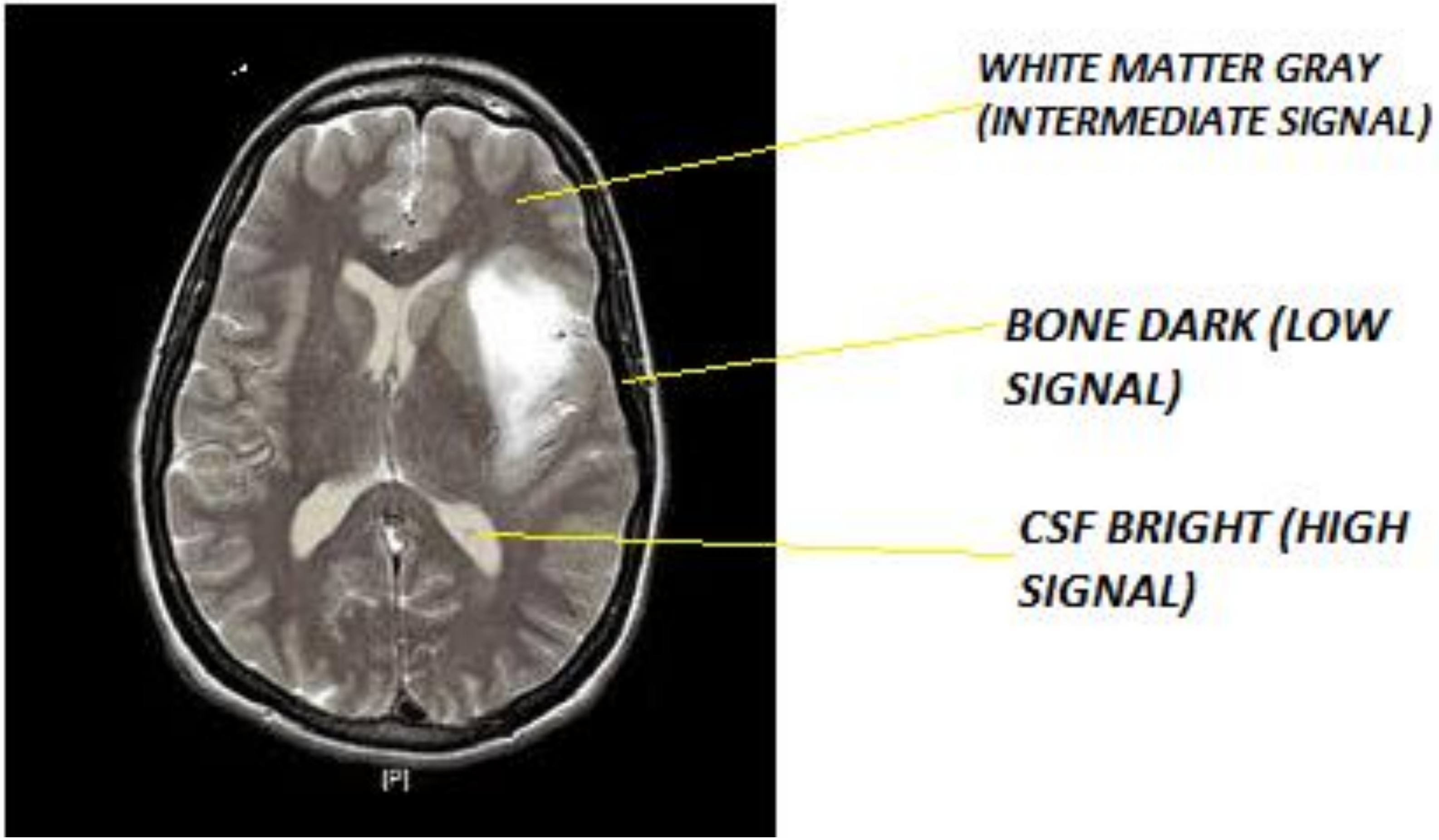


Image contrast

- Different kinds of tissues on human body have different T1 and T2 relaxation times, therefore image contrast is obtained through three mechanisms in MRI:
- T1 recovery,
- T2 decay and
- proton density.

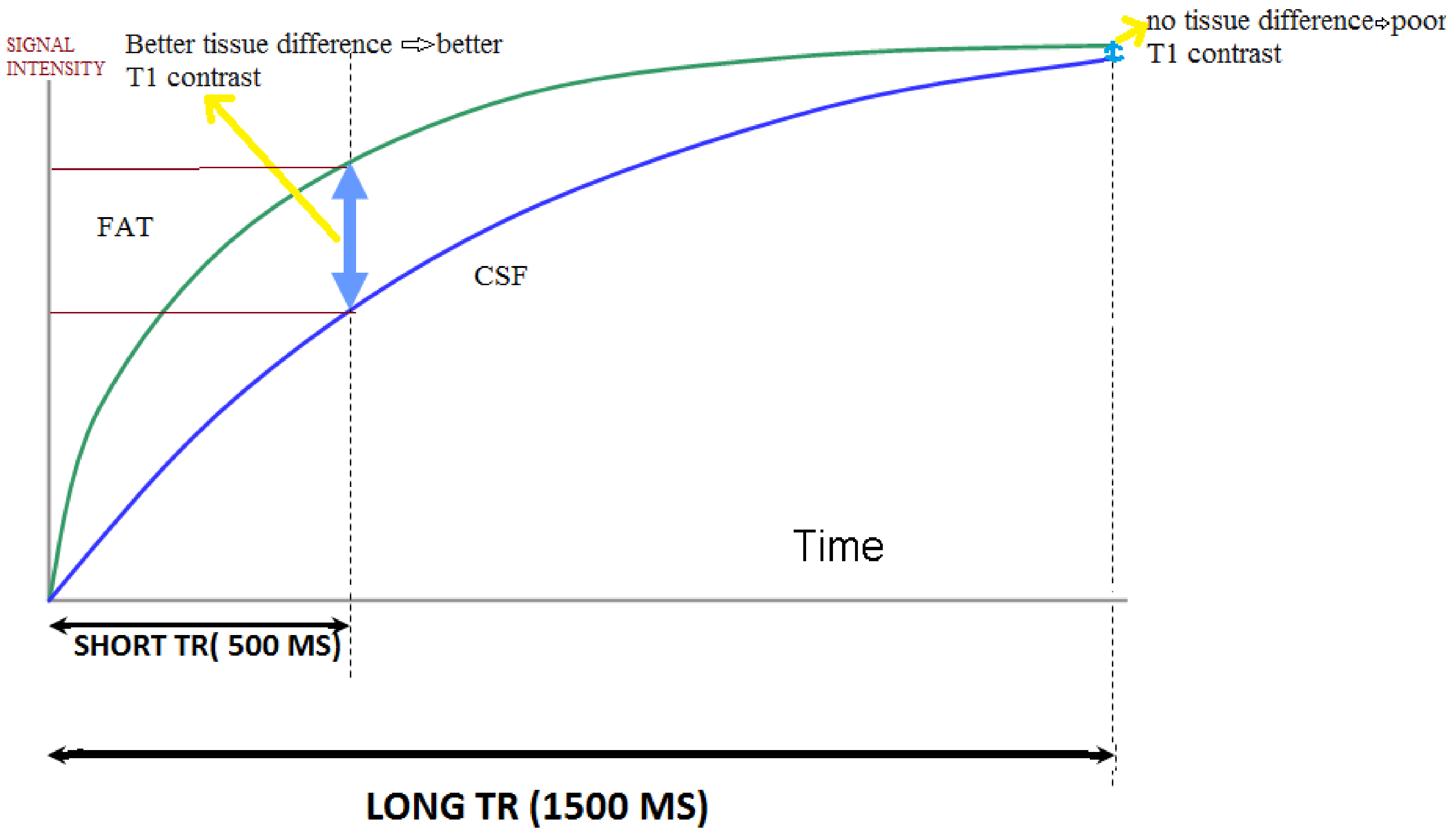
The image contrast depends on how we control these three parameters.

Image contrast

The corresponding MRI imaging is:

- T1 weighted imaging
- T2 weighted imaging
- Proton Density weighted imaging

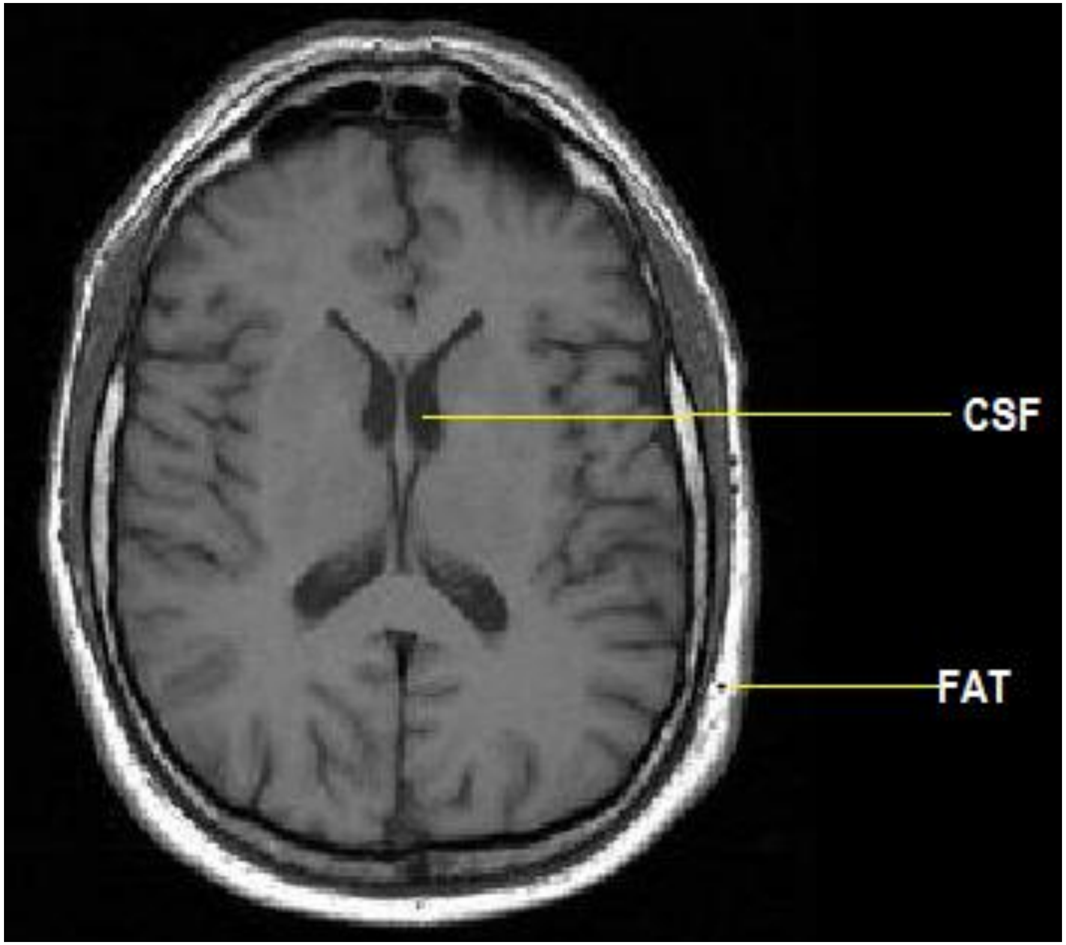
T1 weighted imaging for two different tissues (fat and cerebrospinal fluid CSF)



T1 for some brain tissues

BRAIN tissues	**T1 (ms) 1.5 T**
Gray matter	921
White matter	787
Tumours	1073
Meningioma	979
Glioma	959
Oedema	1090

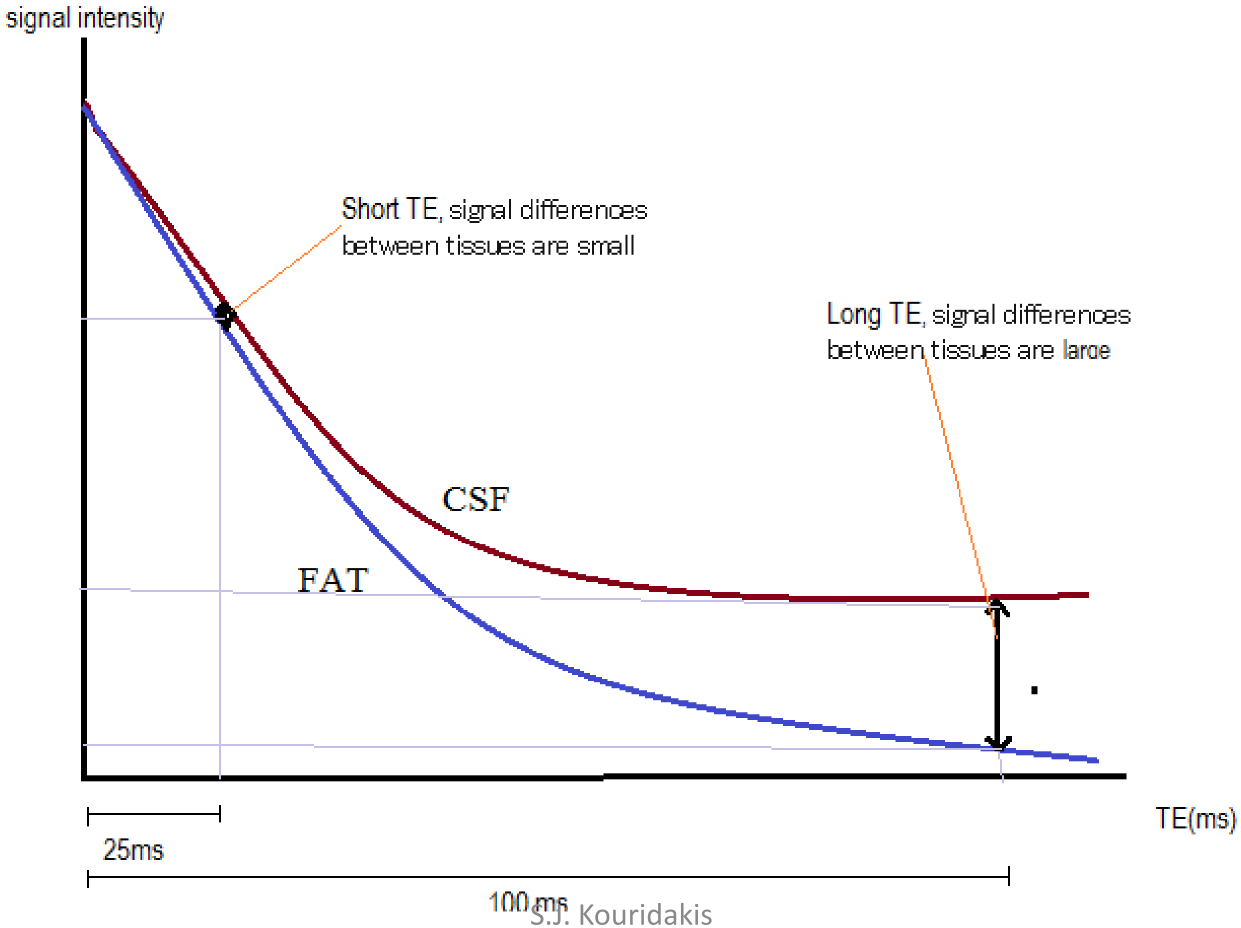
T1 weighted image (slice) of a head. Fat is bright, CSF is dark because of different T1



T1 weighted imaging

- Short TR → strong T1 weighting
  Long TR → low T1 weighting
- For T1 weighting we should choose a short TR.
- Tissues with a short T1 appear bright
- Tissues with a long T1 appear dark
- A typical T1-weighted spin echo (SE) sequence is acquired with a TR/TE of 400/15 msec

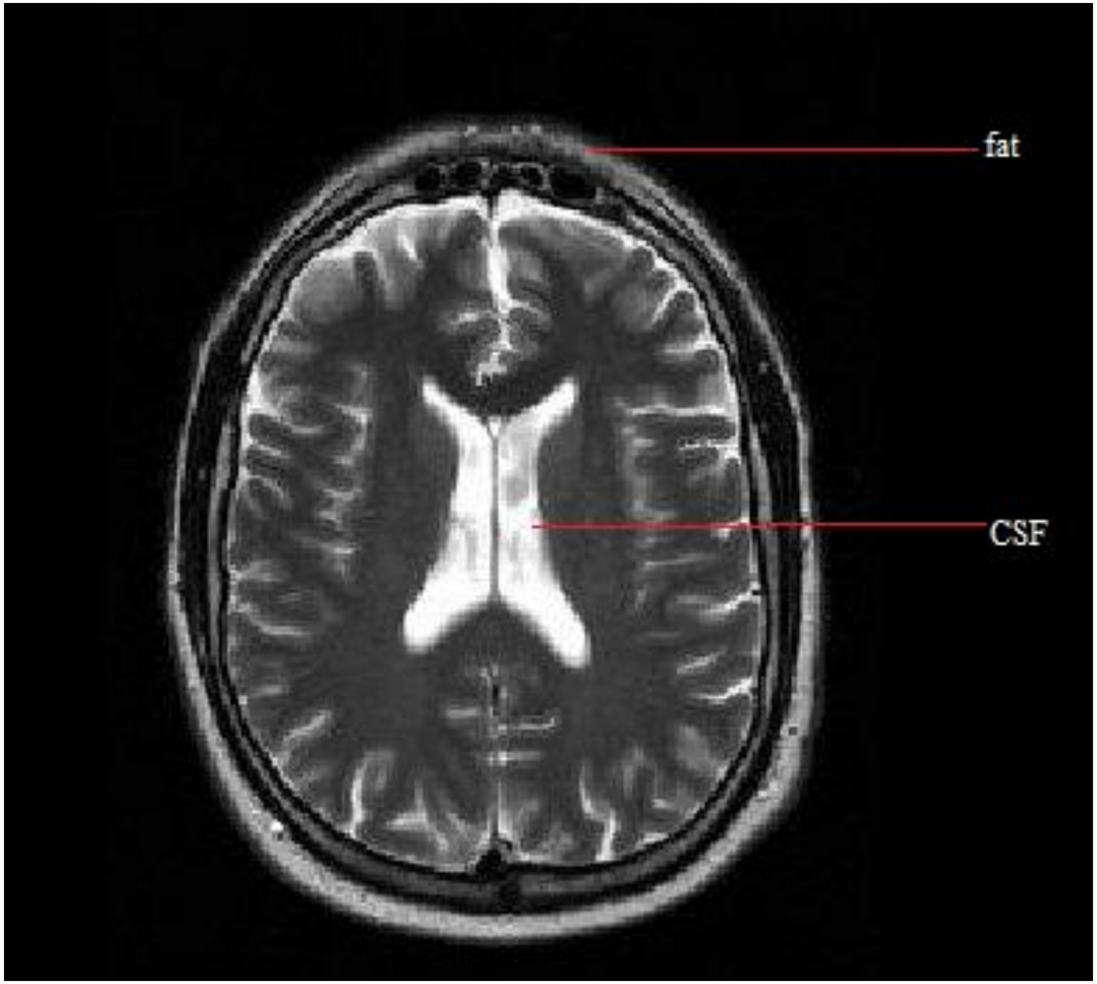
T2 weighted imaging for two different tissues (fat and cerebrospinal fluid CSF)



T2 for some brain tissues

BRAIN tissues	**T2 (ms) 1.5 T**
Gray matter	101
White matter	92
Tumours	121
Meningioma	103
Glioma	111
Oedema	113

T2 weighted image (slice) of a head. Fat is dark, CSF is bright because of different T2



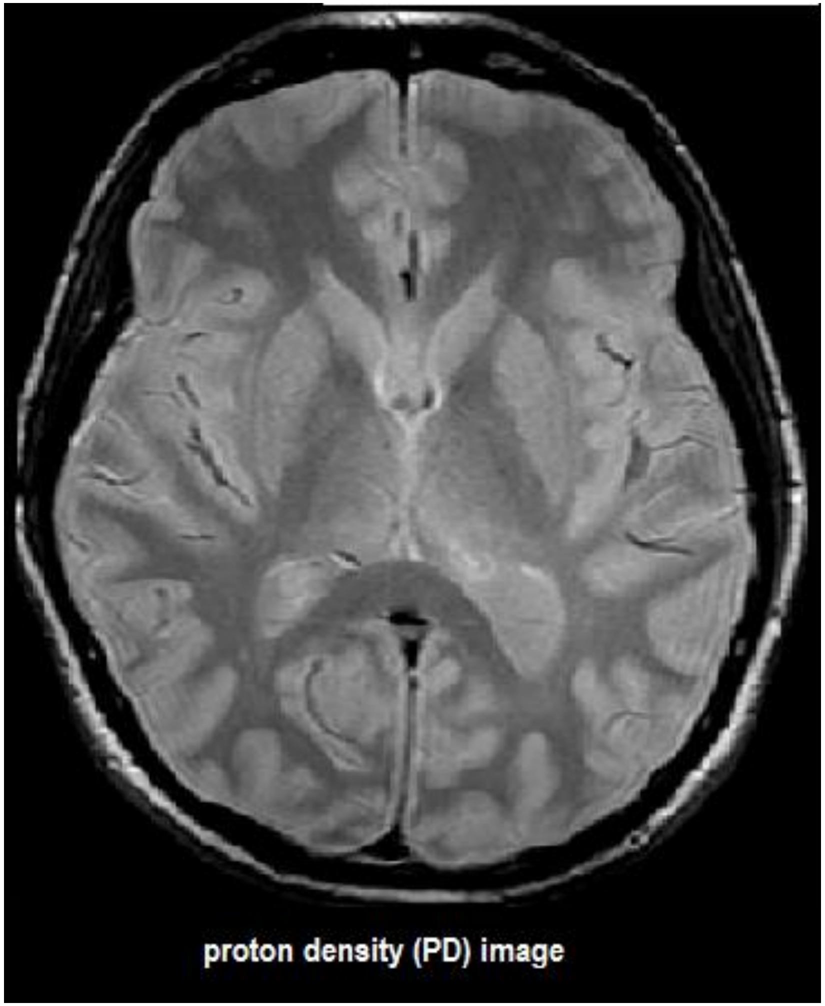
T2 weighted imaging

- Short TE → low T2 weighting
- Long TE → strong T2 weighting
- Tissues with a short T2 appear dark on T2-weighted images.
- Tissues with a long T2 appear bright on T2-weighted images.
- A T2-weighted fast spin echo (FSE) MR image can be acquired with a TR/TE of 3000/100 msec

Proton Density weighted imaging

- The image contrast in PD images is not dependent on T1 or T2 relaxation. The signal we receive is completely dependent on the amount of protons in the tissue
- Short TE → diminish T2 weighting.
- Long TR → diminish T1 weighting
- A typical PD weighted spin echo (SE) sequence is acquired with a TR/TE of 2500/15 msec.

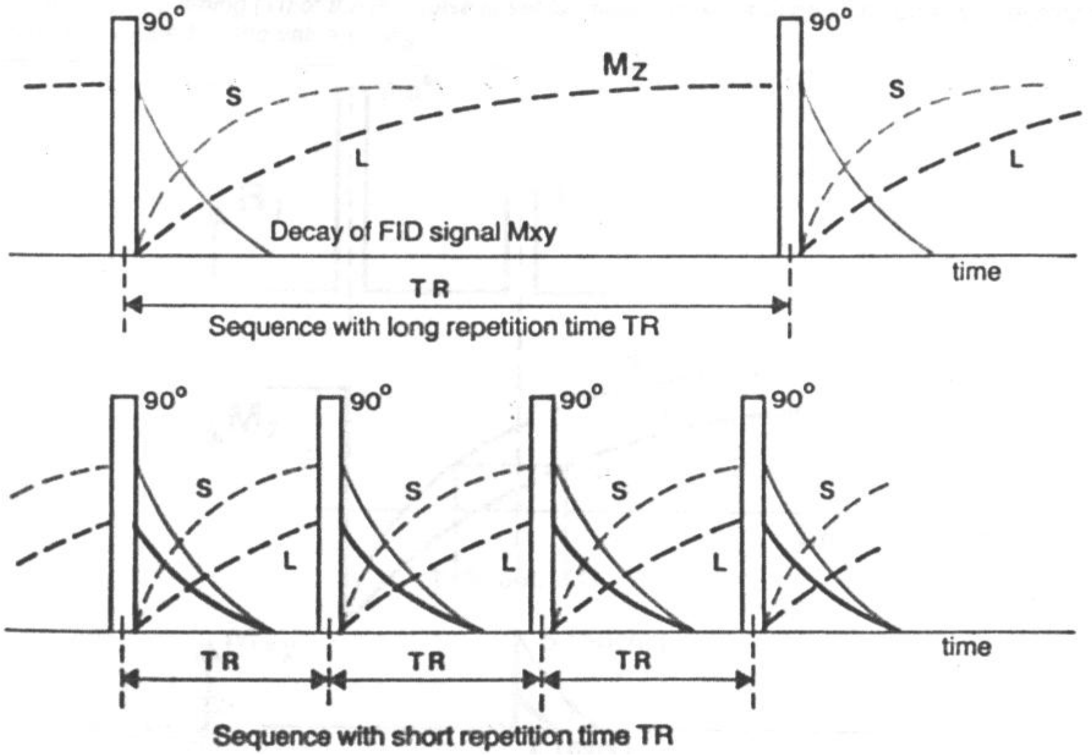
Proton Density weighted image (slice) of a head. Fat and CSF are grey because of different PD's



Pulse sequences for NMR-MRI

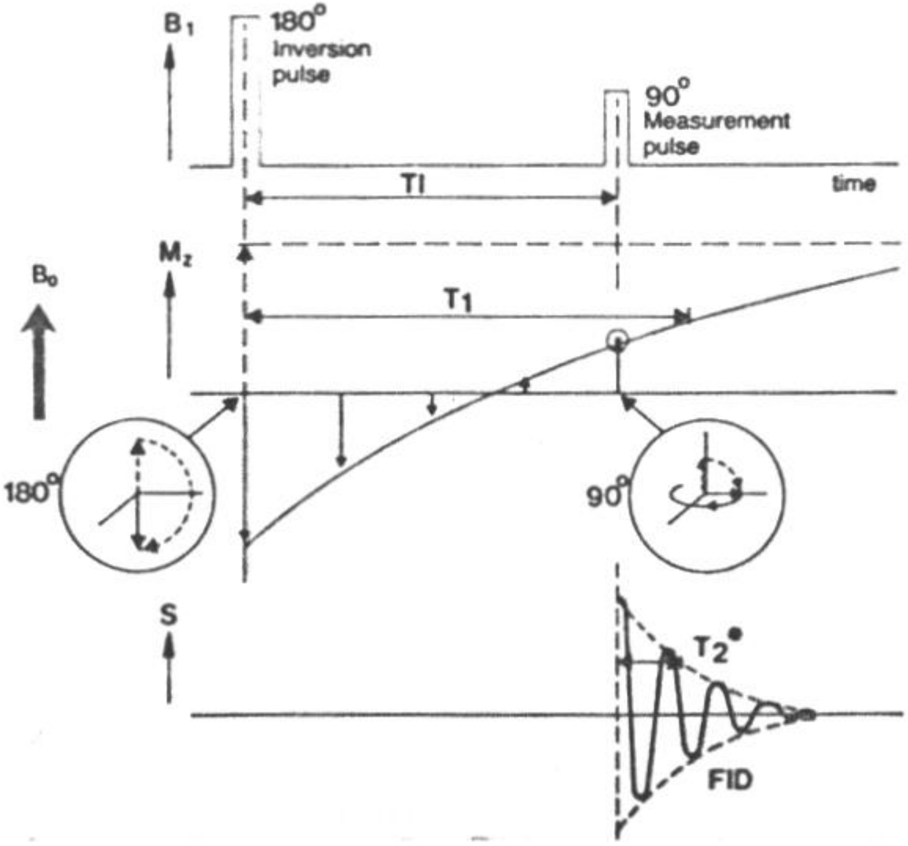
Partial Saturation recovery sequence

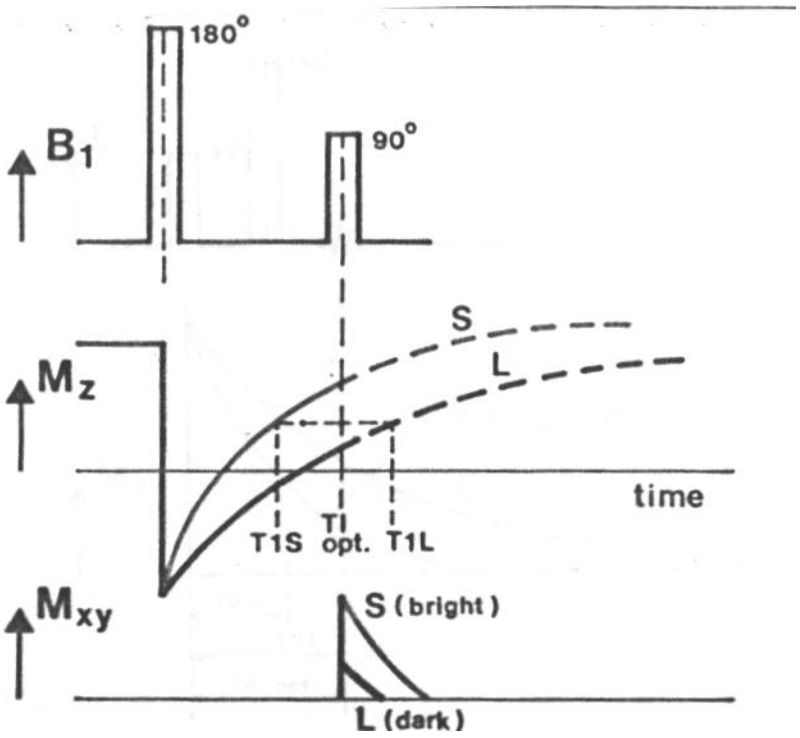
$$I \propto \mathrm{N(H)}(1 - e^{-T_R/T_1})$$



Inversion Recovery Sequence

$$I \propto \mathrm{N(H)}(1-2e^{-T_I/T_1}+e^{-T_R/T_1})$$



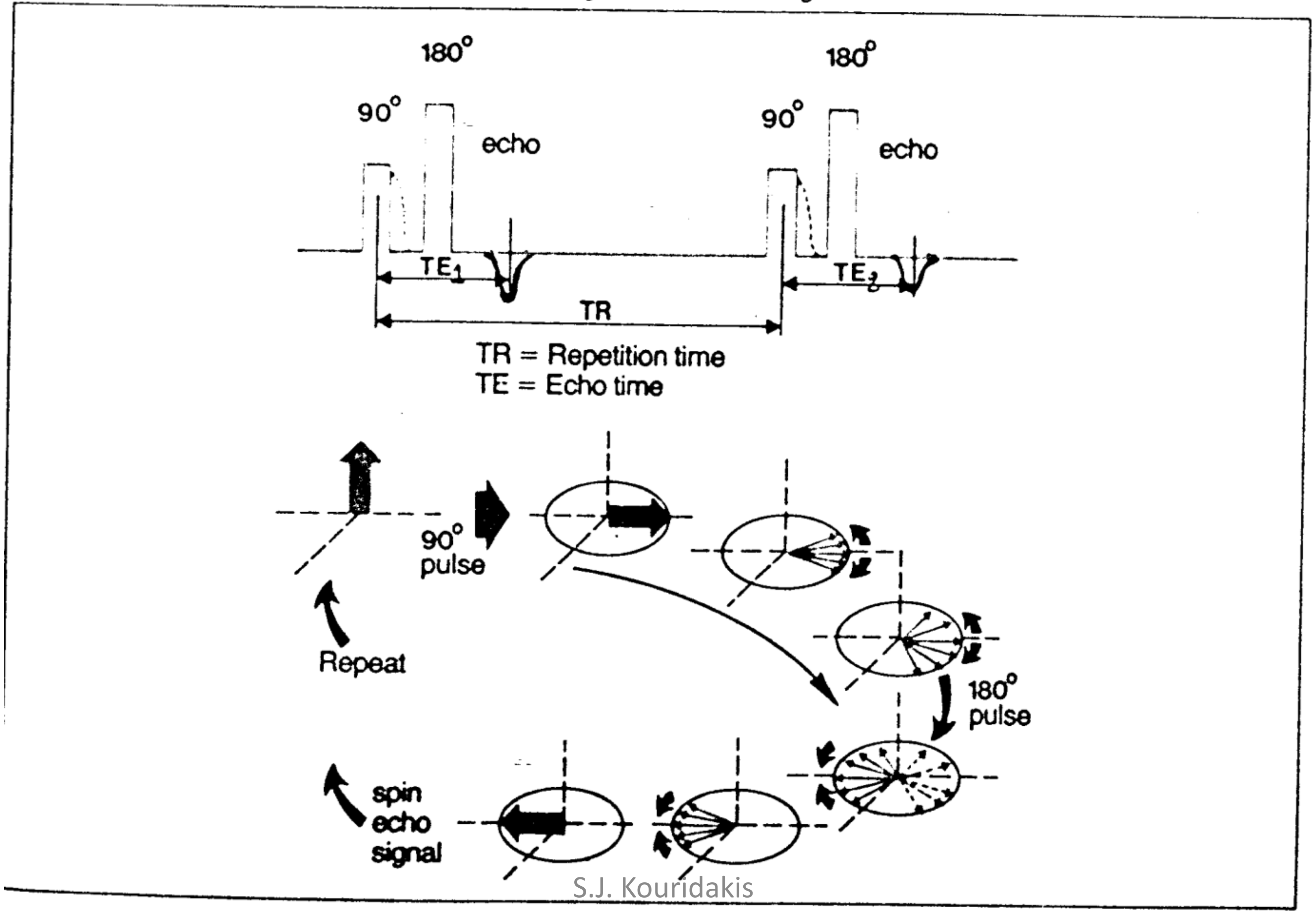


spin – echo sequence and multiple spin – echo sequence

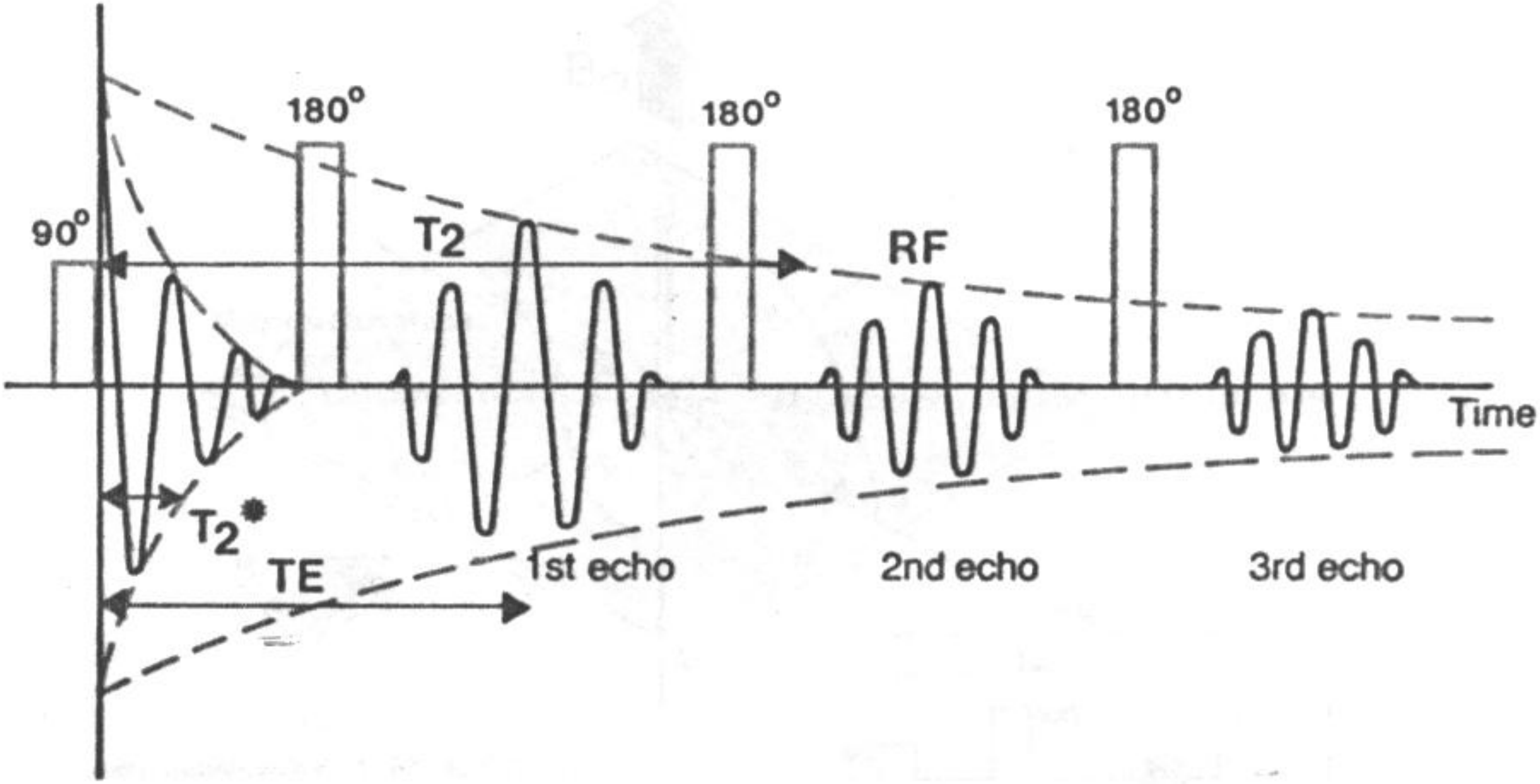
$$I \propto \mathrm{N(H)}\left(1-2e^{-(T_R-T_I)/T_1}+e^{-T_R/T_1}\right)e^{-T_E/T_2}$$

18. Spin Echo Sequence

The magnetization, having been put into the transverse plane by the 90° pulse, decays due to loss of coherence in the spins. The 180° pulse promotes re-phasing and regeneration of the signal as an echo.

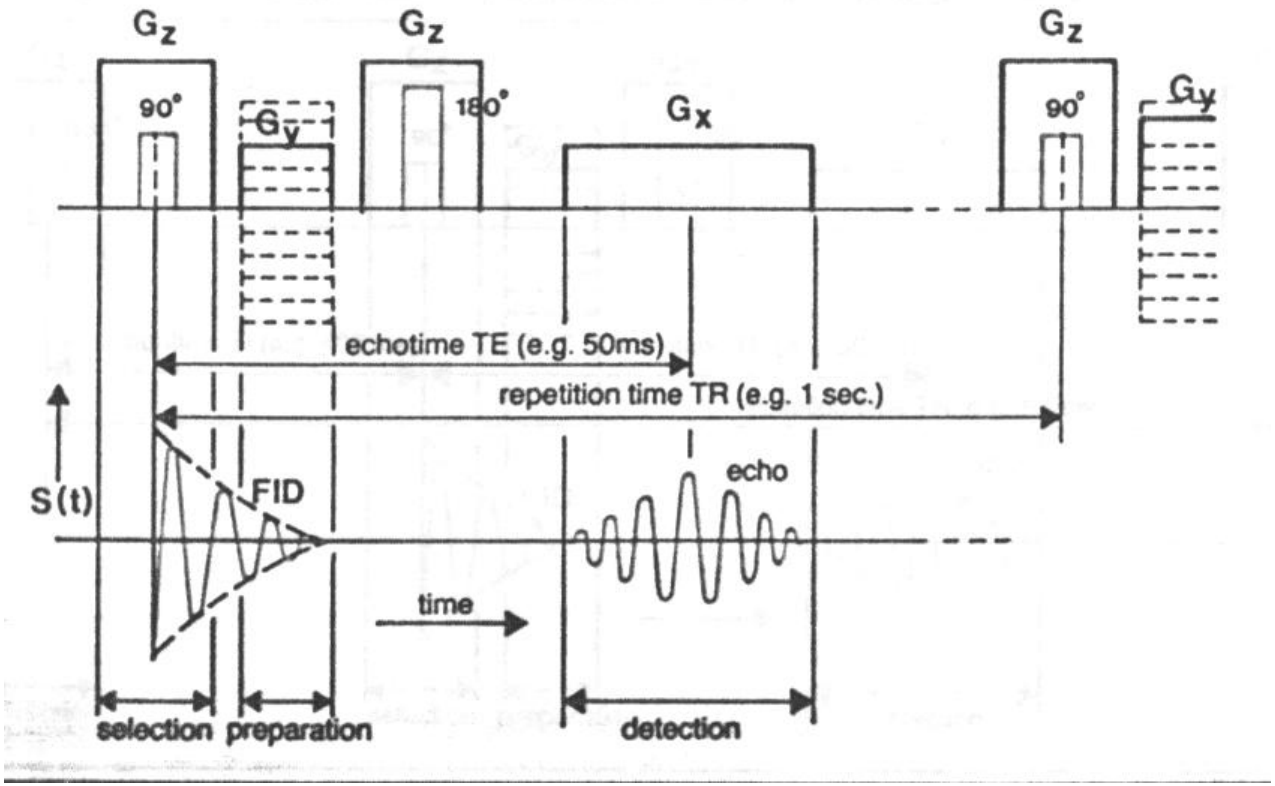


multiple spin – echo sequence

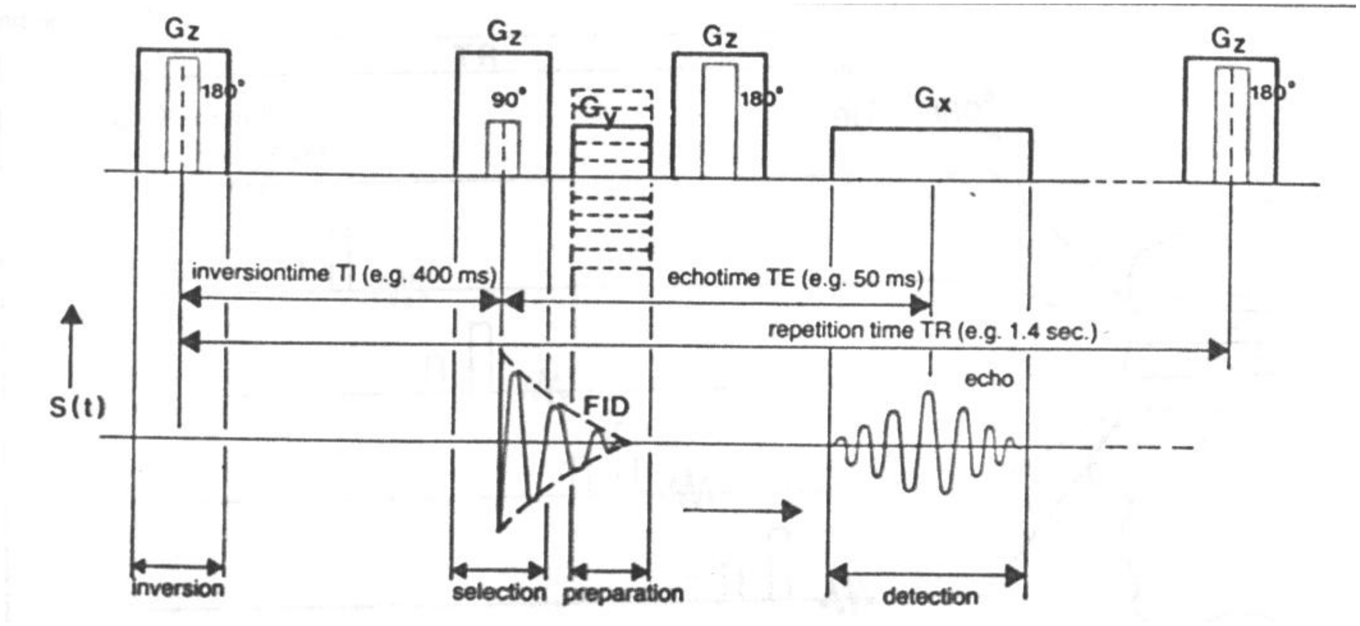


Imaging Techniques

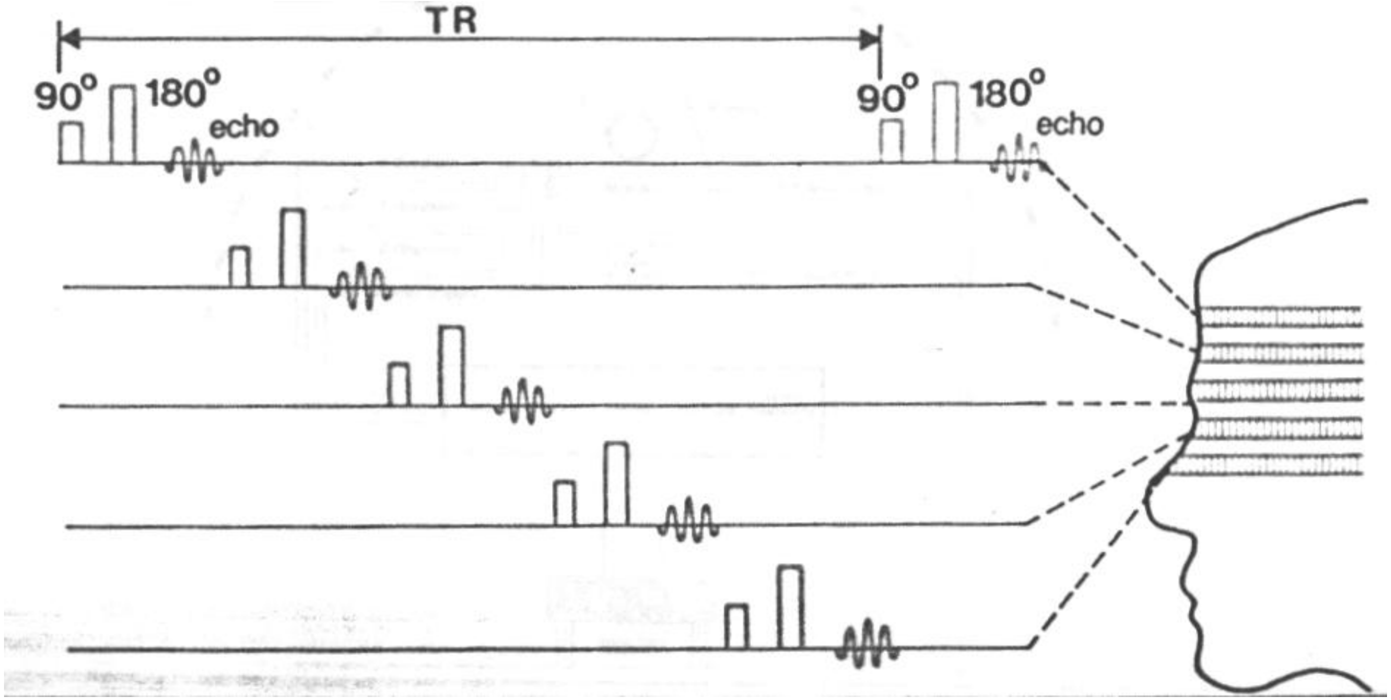
Spin echo imaging for T1, T2, PD weighted images



Spin echo Inversion recovery imaging

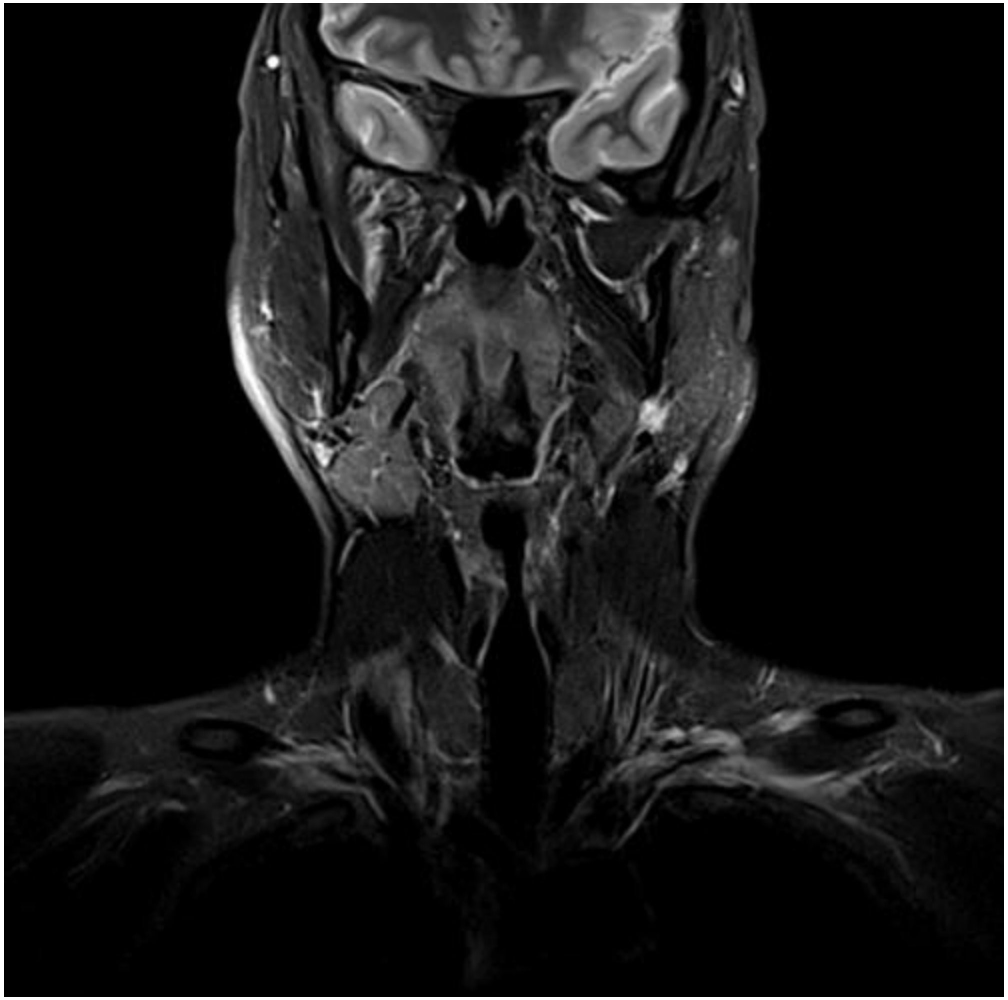


Multislice spin echo Imaging

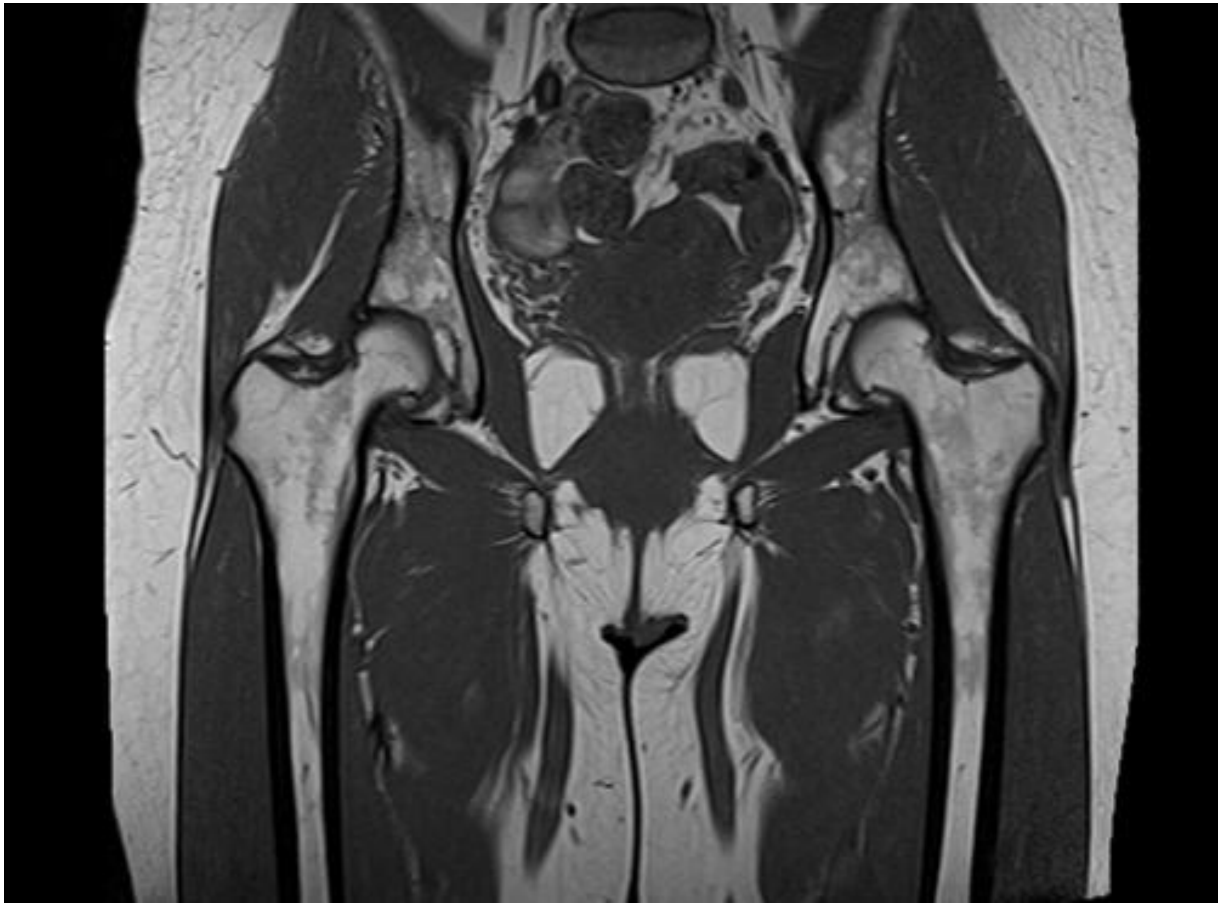


Some MRI images examples

MRI neck coronal STIR (Short Time Inversion Recovery) image

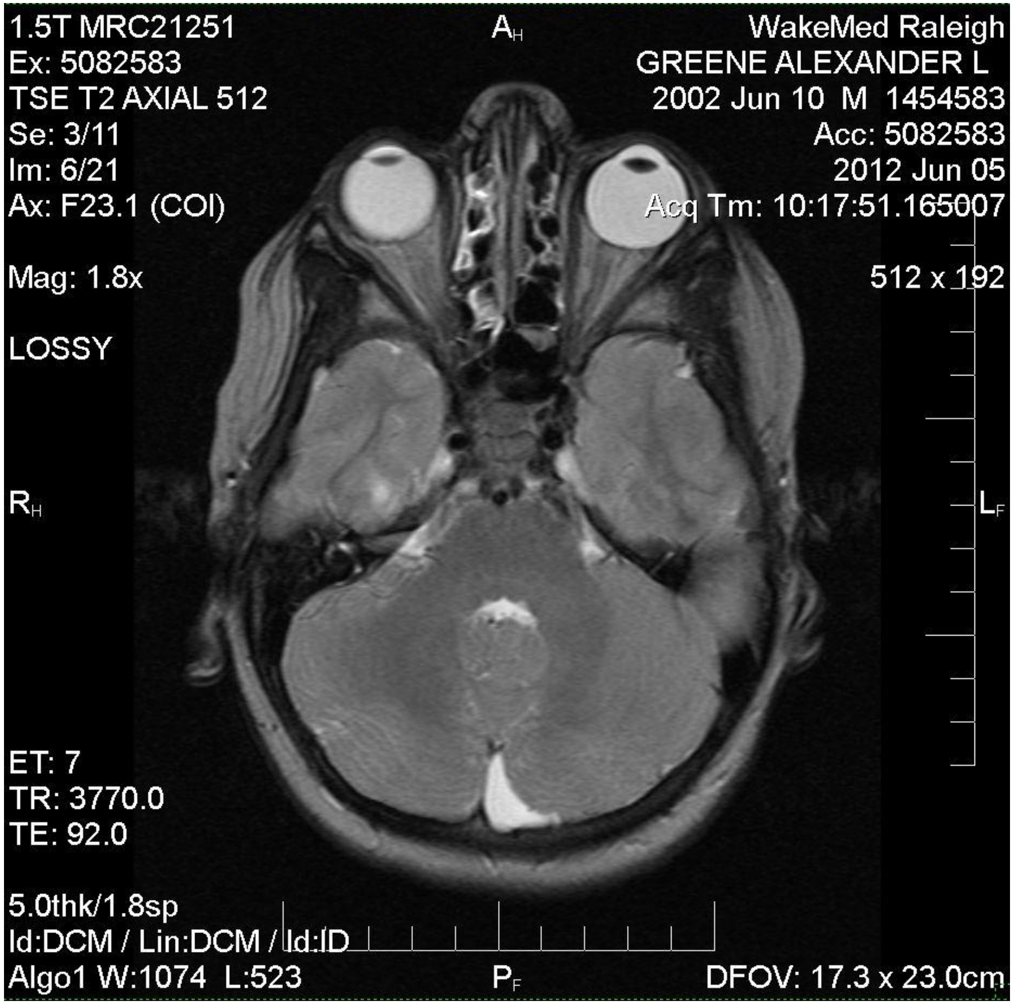


MRI Hips Coronal T1 Image



MRI spine sagittal T1 image

MRI head axial T2 weighted spin echo



MRI hand coronal T1 image

MRI knee sagittal T1 image

Knee T1 spin echo sagittal MRI

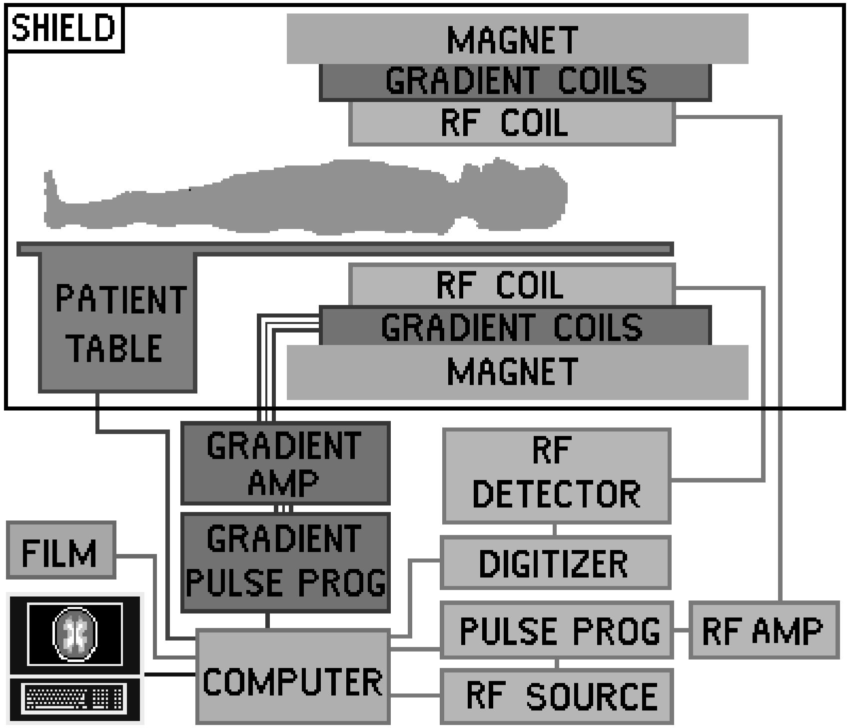
Knee T1 FLASH WE sagittal

Spine T1 TSE sagittal MRI

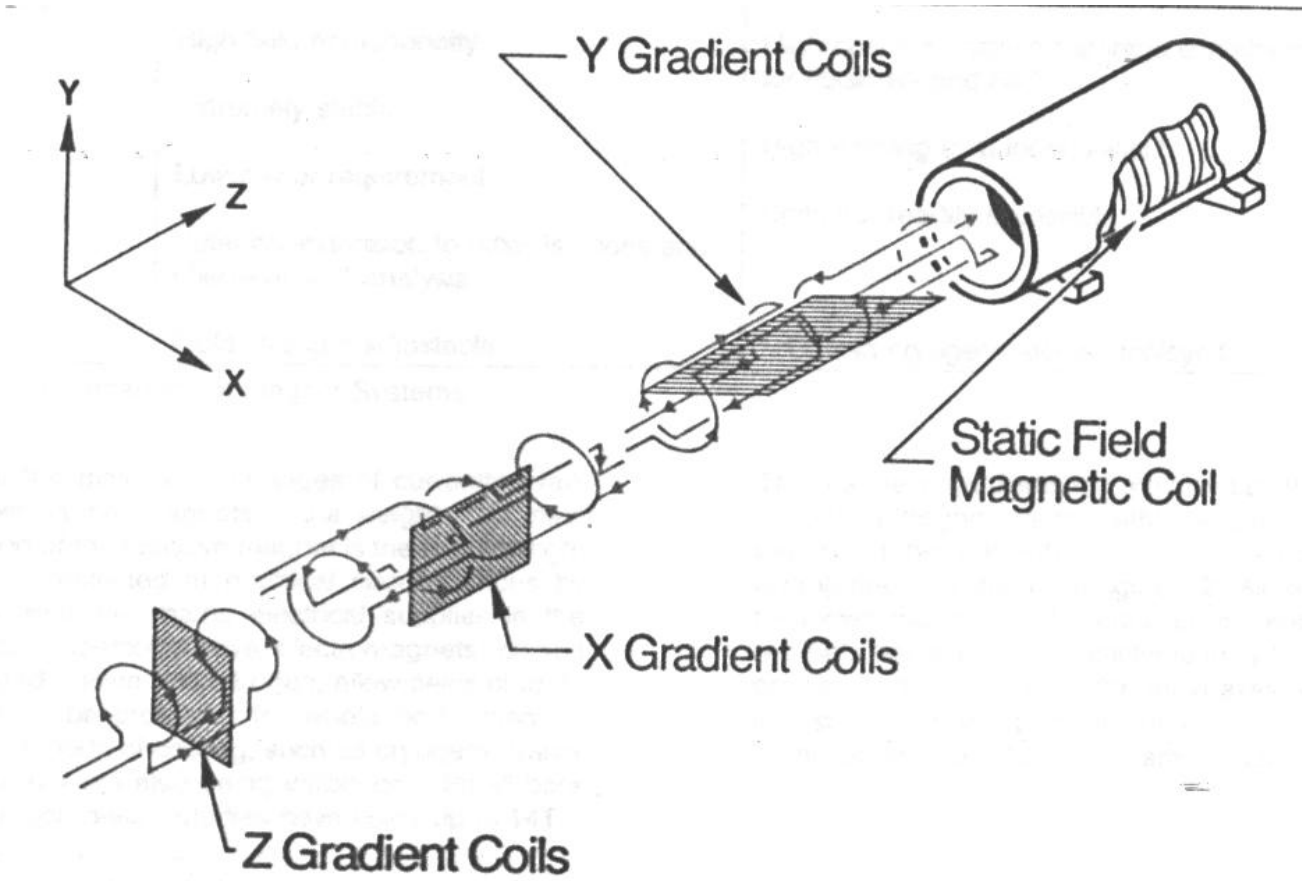
Head T2 TSE sagittal MRI (1)

Head T1 FLASH sagittal MRI (2)

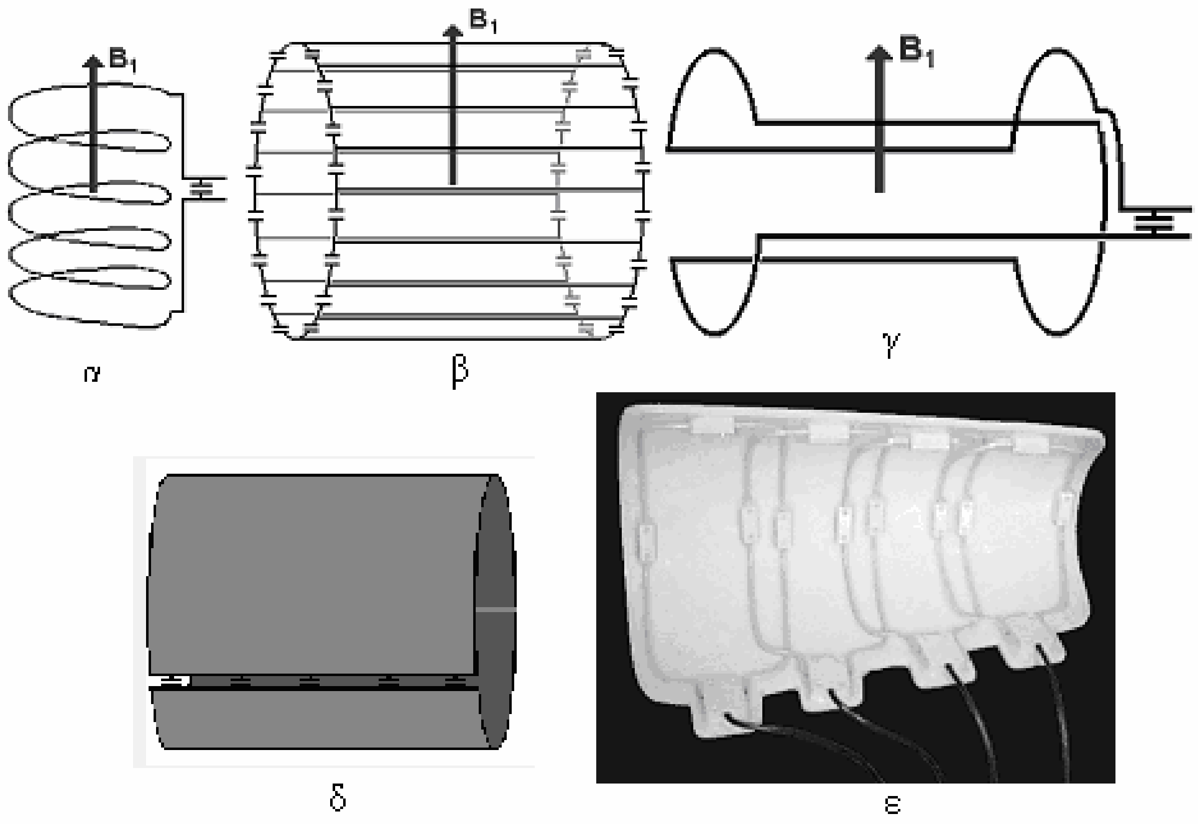
Magnetic tomographer (scanner)



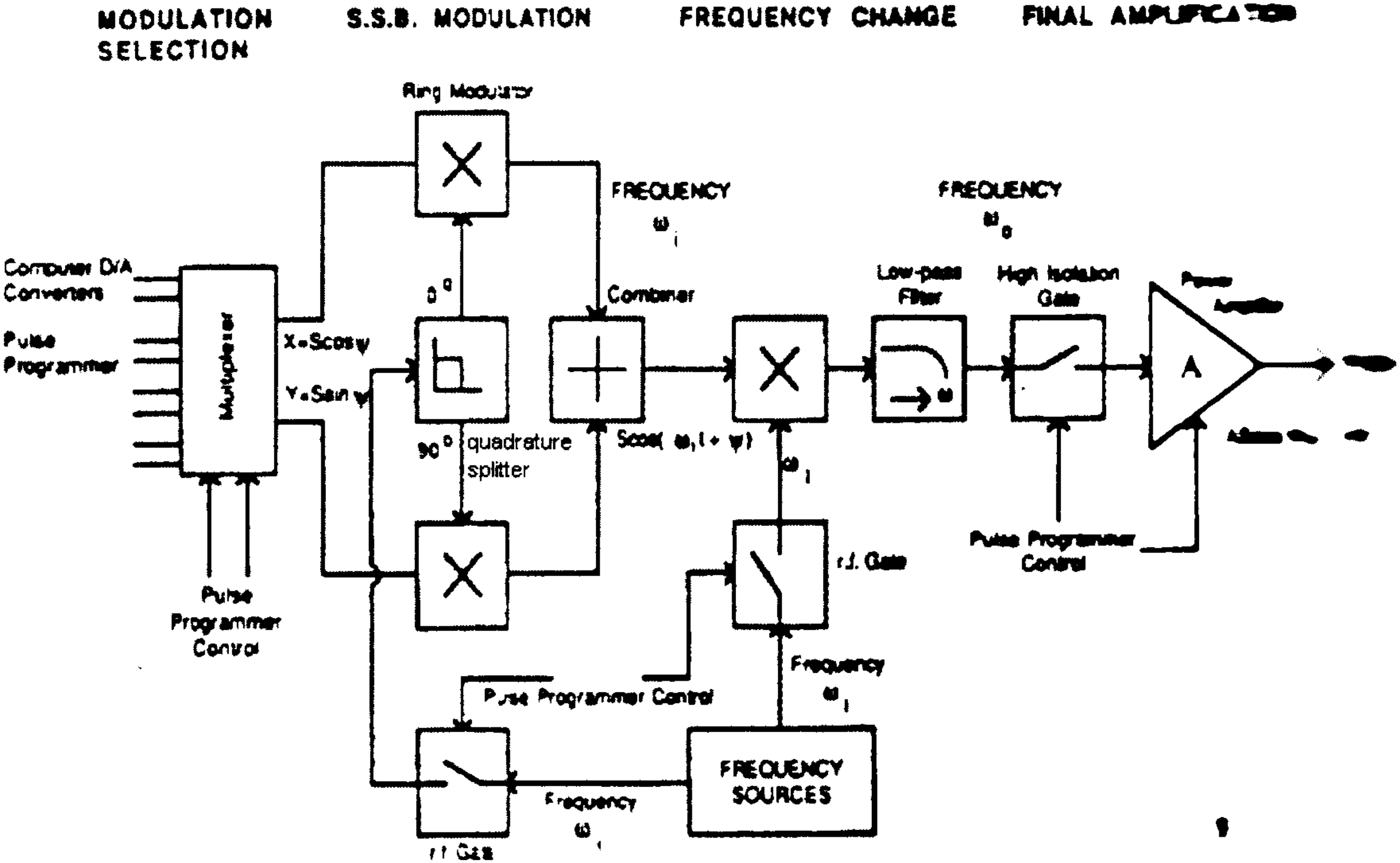
Magnet and gradient coils



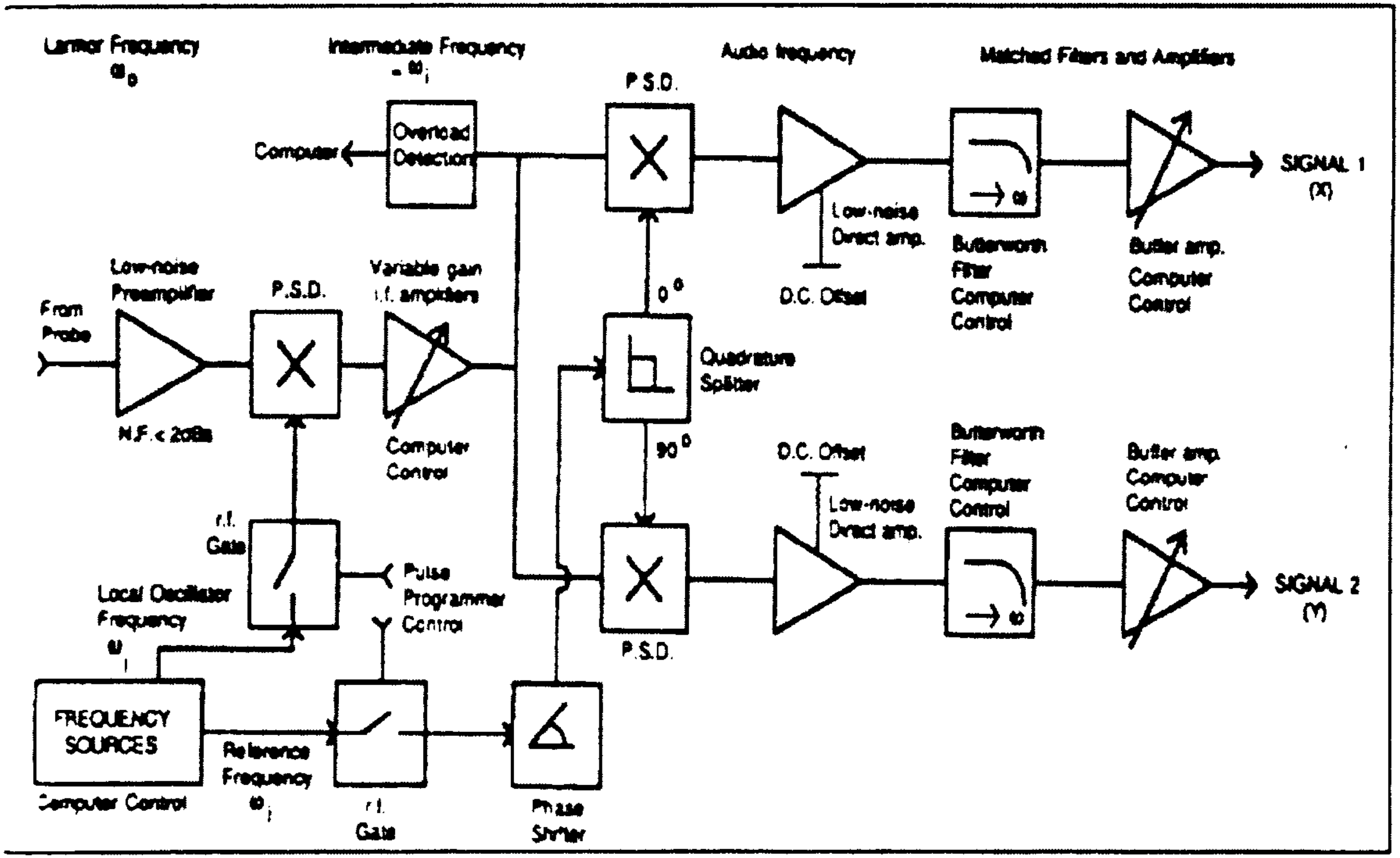
Types of exciting – receiving coils



The transmitter



The receiver



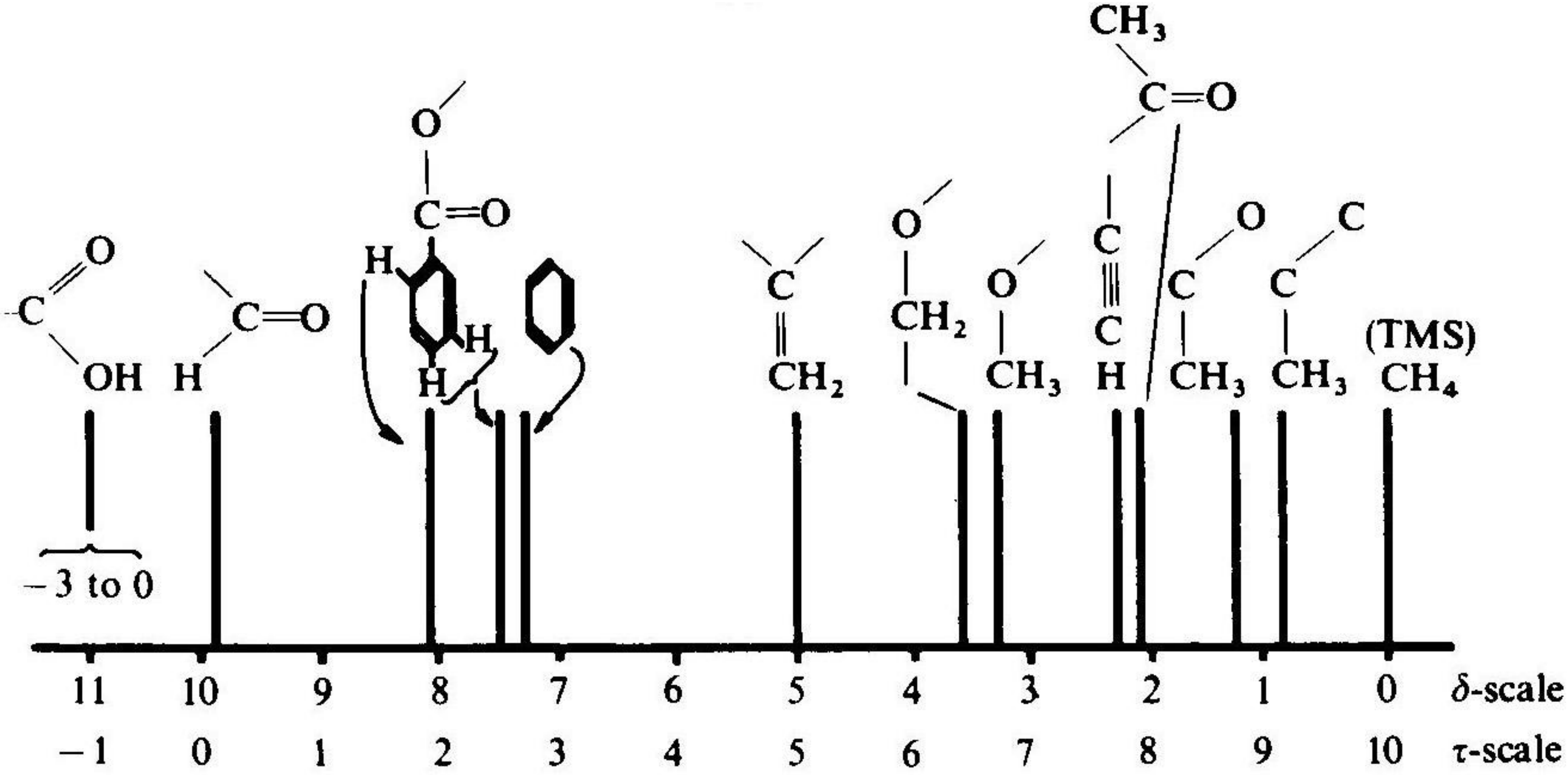
Spectroscopy

- Chemical shift is the variation in resonant frequency of a particular nucleus. It is caused by slight non uniformity in the local magnetic field ought to:

i. electronic shielding
ii. nucleus coupling
iii. interconnection between atoms in a molecule
iv. the surrounding molecular structure.

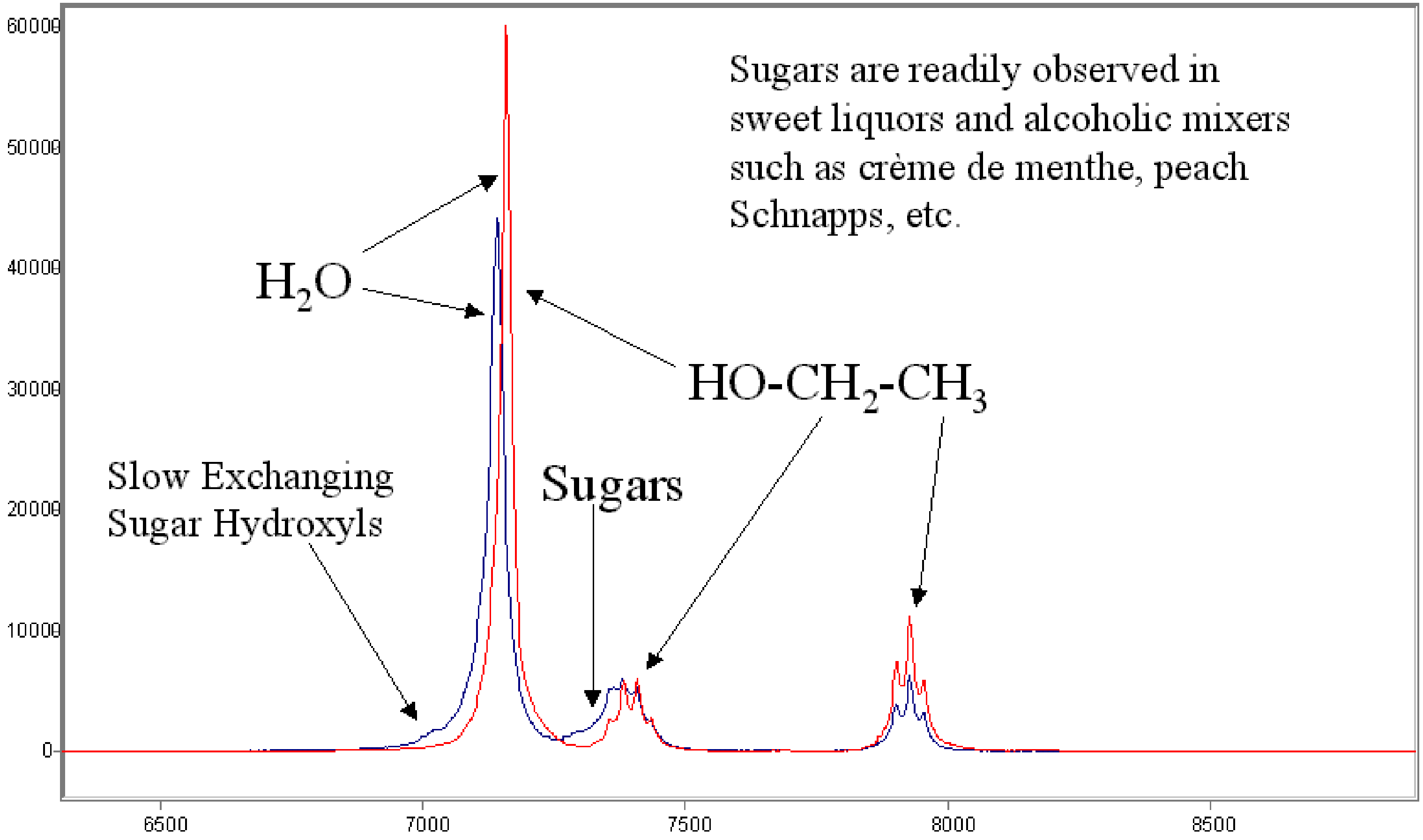
- NMR spectroscopy is a powerful tool to investigate and extract detailed molecular information
- It is used to investigate foods, alcoholic drinks, on chemistry, on biology, on genetics, on petroleum research and many other applications.

Proton chemical shifts of some simple molecules and groups

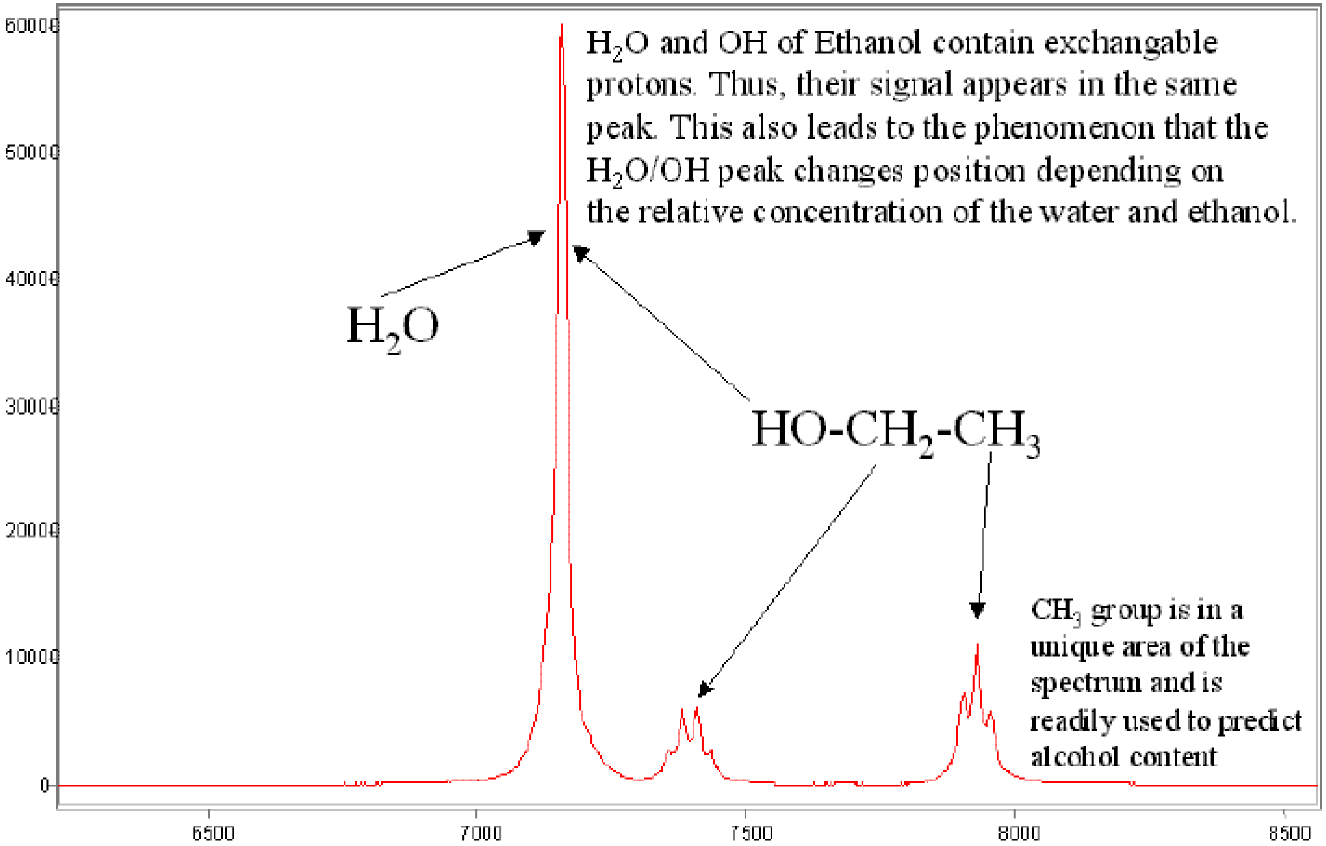


Some spectroscopy examples

Scotch and scotch liqueur spectrums



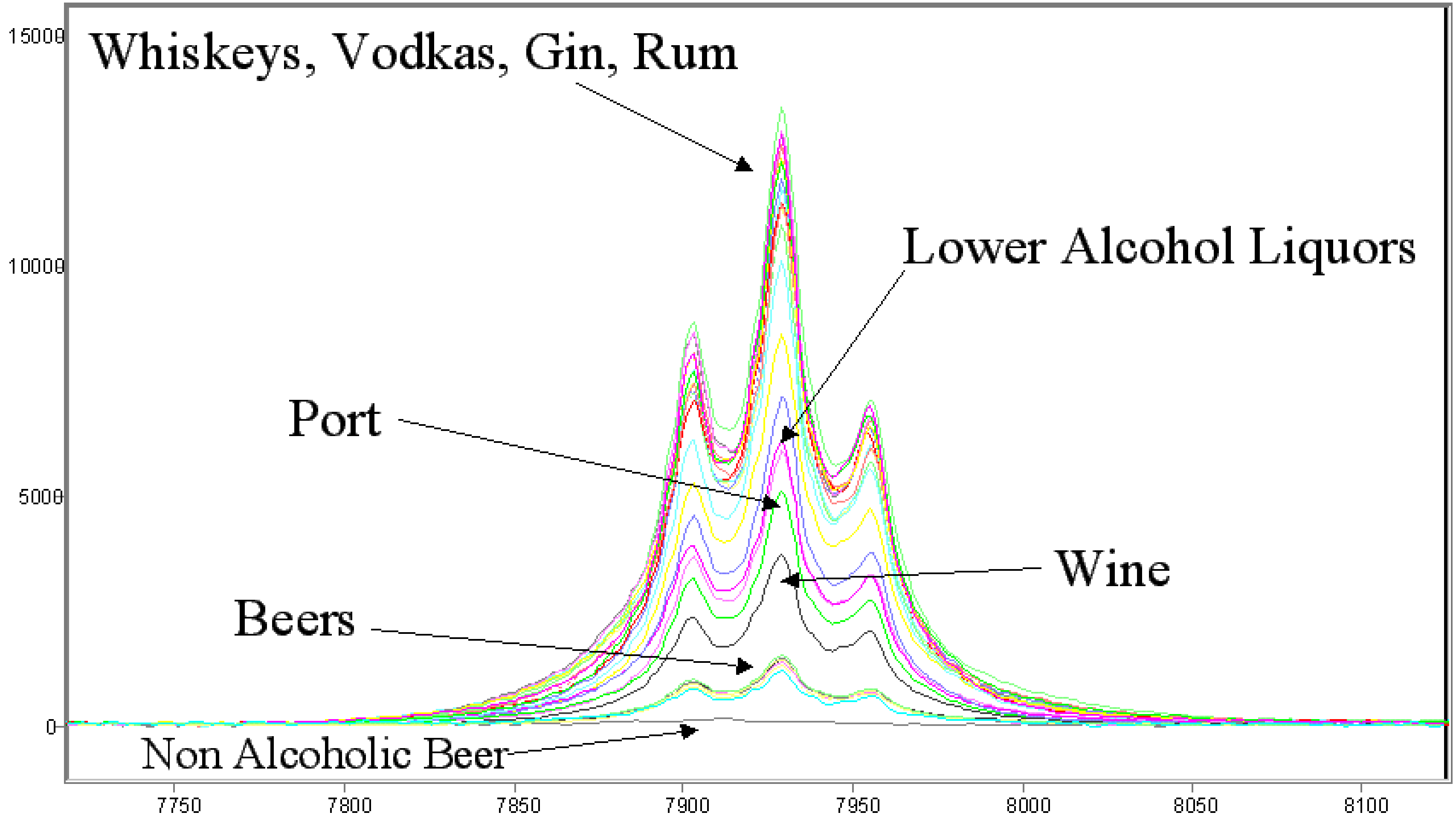
Ethanol solution spectrum



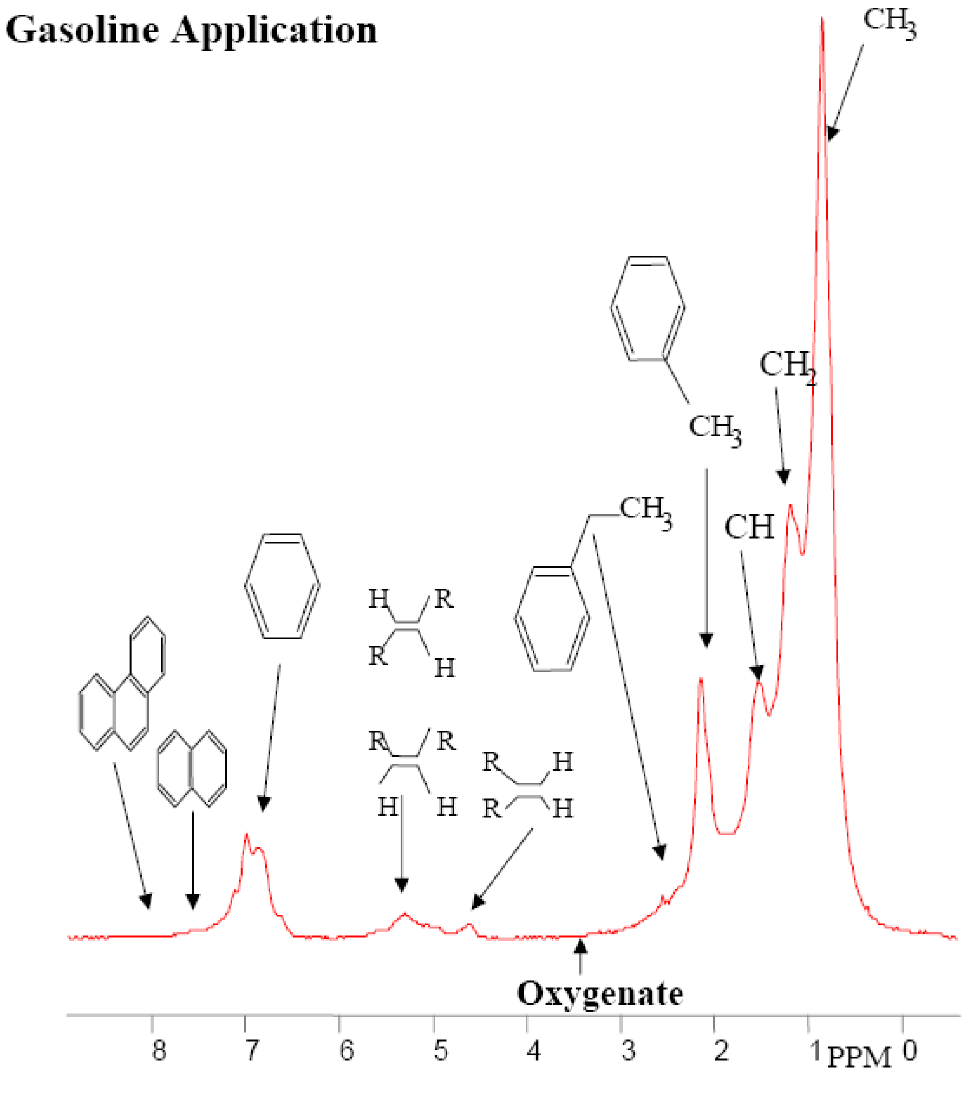
H_2O and OH of Ethanol contain exchangable protons. Thus, their signal appears in the same peak. This also leads to the phenomenon that the H_2O/OH peak changes position depending on the relative concentration of the water and ethanol.

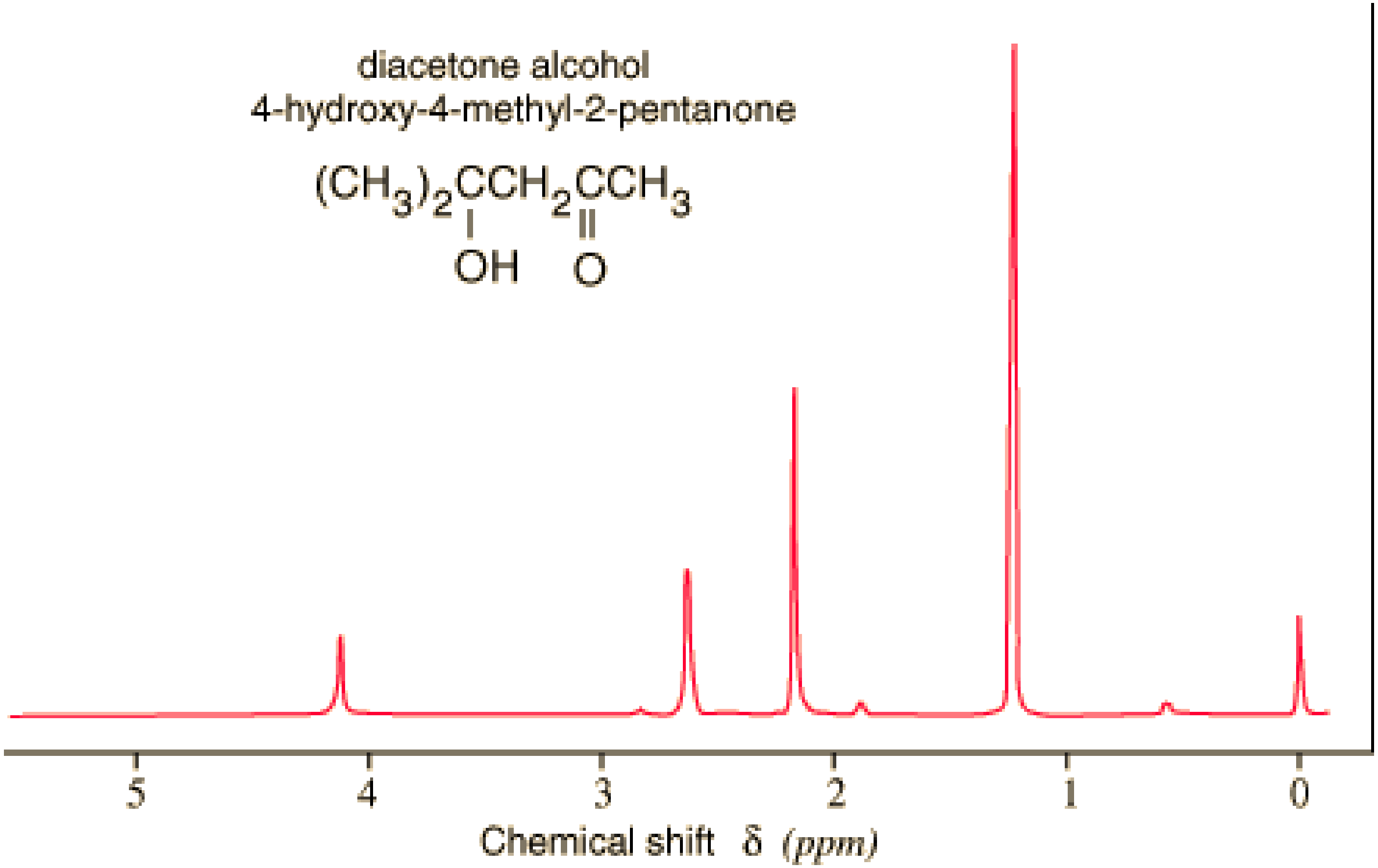
CH_3 group is in a unique area of the spectrum and is readily used to predict alcohol content

Alcoholic drinks spectrum



Gasoline spectroscopy




diacetone alcohol
4-hydroxy-4-methyl-2-pentanone
$(CH_3)_2C(OH)CH_2C(=O)CH_3$
5
4
3
2
1
0
Chemical shift δ (ppm)

Conclusions

- NMR is an important property of nucleus to help us on modern science of medicine, physics, chemistry, food technology, petroleum industry and on NDT.