NCC 2020 의학물리 아카데미 교육프로그램

Physics of MRI Basic Principle

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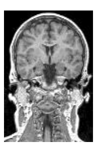
Imaging Modalities in Medical Field

Anatomical Imaging

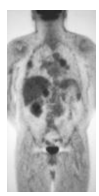

X-Ray

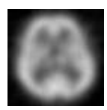

CT


US


MRI

Functional Imaging


PET

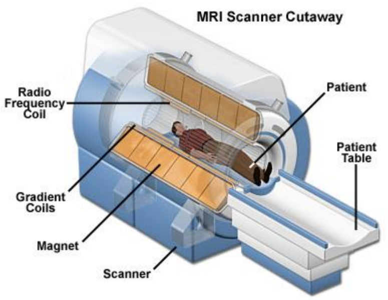

SPECT

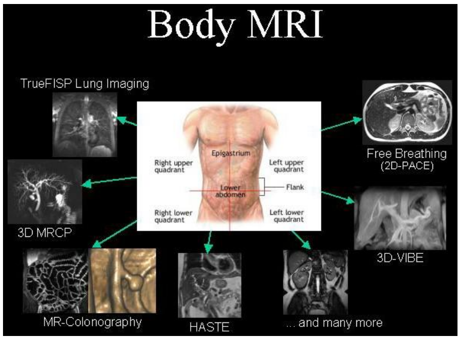

fMRI

CT	- Computer Tomography	MRI	- Magnetic Resonance Imaging
fMRI	- Functional Magnetic Resonance Imaging	US	- Ultra-Sound
PET	- Positron Emission Tomography	SPECT	- Single Photon Emission CT

Magnetic Resonance Imaging

MRI: Magnetic Resonance Imaging

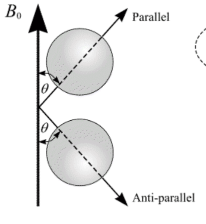


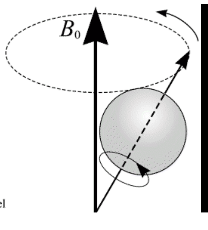


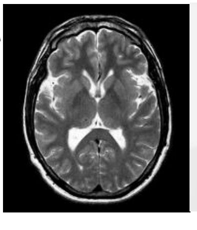
3

M R I

- **MRI** is the image acquisition equipment by using Nuclear Magnetic Resonance (NMR) phenomena.
- **MRI** displays the density of hydrogen atom (proton), relaxation time, blood flow velocity information, functional activation of brain regions in mainly human body.
- **MRI** provides anatomical evidence information, biochemical information, chemical shift information, functional image information etc..



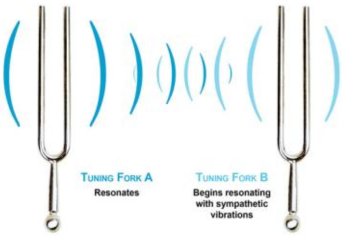


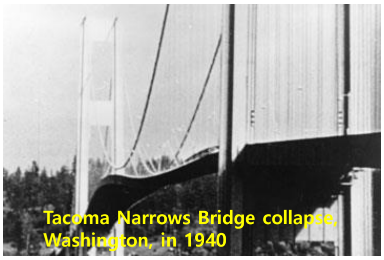


4

What is Resonance?

Resonance: A phenomenon that occurs when the frequency at which a force is periodically applied, is equal or nearly equal to one of the natural frequencies of the system on which it acts.

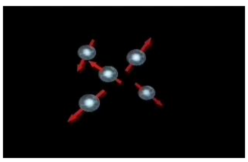


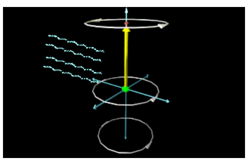


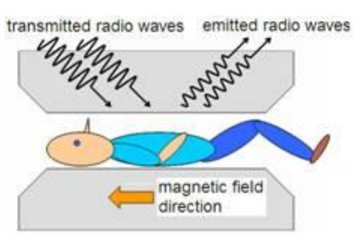
What is the NMR?

Nuclear Magnetic Resonance

A physical phenomenon in which nucleus **absorb and emit** the electromagnetic wave of natural frequency determined by the nucleus and the intensity of static magnetic field, when the electromagnetic wave of radio frequency is transmitted to the spin system located in static magnetic field.







History of MRI

- 1946: F. Bloch and E. M. Purcell released the principle of NMR, individually.
- 1950: Discovery the phenomena of spin echo signal.
- 1952: Novel prize for NMR (F. Bloch and E. M. Purcell).
- 1960's: Discovery of Fourier Transform (FT) NMR spectrometer by Richard R. Ernst.

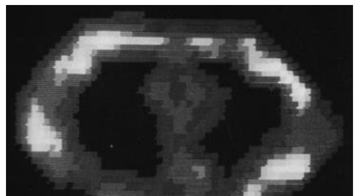
  → NMR phenomenon was applied to physical/chemical analysis equipment at the very first, FT NMR spectrometer was used in chemical structure analysis with a FT infrared spectrometer.
- 1971: R. Damadian and P. Lauterbur reported the possibility of cancer detections by using the measurement of the relaxation time of tumor.

  → Suggest the medical utilization of NMR phenomenon.

History of MRI

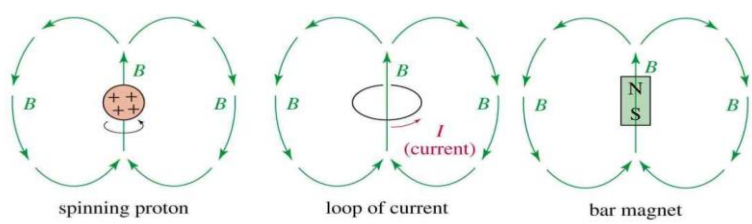
- 1973: Development of NMR projection reconstruction algorithm based on principle of CT image reconstruction.
- 1974: Discovery of NMR FT image reconstruction method.
- 1977: Firstly, MRI is used to human.
- 1979: Practical use of whole body MRI scanner.
  - In early stage, low spatial resolution and long acquisition time compared to CT.
  - Achieve the rapid imaging enhancement with the development of superconducting magnetic technology.
- 1988: Advent of MR Angiography.
- 1991: Richard. R. Ernet (Switzerland) Nobel prize in chemistry: for FT NMR spectroscopy.
- 1992: Advent of (functional) fMRI.
- 2003: P. C. Lauterbur & P. Mansfield: Nobel prize in physiology or medicine: discoveries concerning MRI.

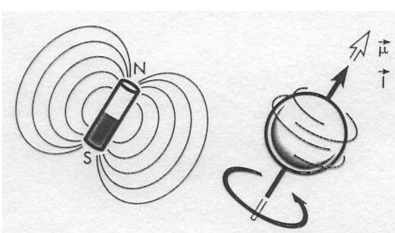
Early Human MR Images (from Damadian)

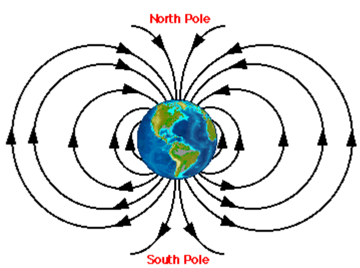


Mink5 Image – Damadian (1977)

Magnets & Magnetic Fields

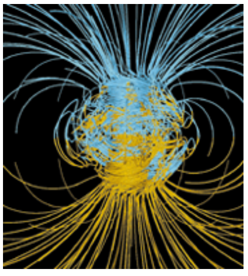




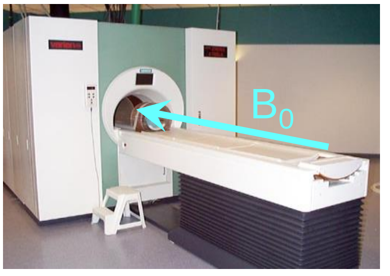


Magnetic Strength of MRI

- Earth's magnetic field = 0.5 Gauss
  1 Tesla (T) = 10,000 Gauss
  - 3 Tesla → 3 x 10,000 ÷ 0.5
    = 60,000 x Earth's magnetic field



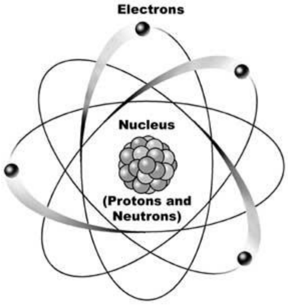
x 60,000 =



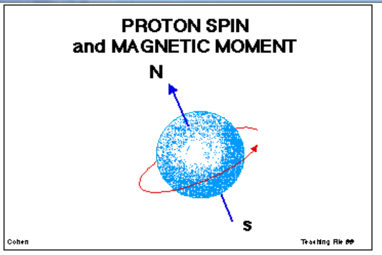
Magnetic Strength of MRI

Proton Spin

Atom:
nucleus + orbital electrons



The Atom.



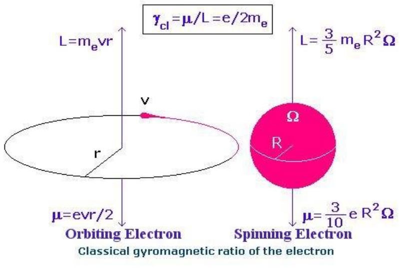
- Positive charges in atomic nucleus have mass and spin **angular momentum** (**L**)
- Also, the atomic nucleus having the odd members of protons and neutrons have **nuclear magnetic moment**:

$$\mu = \gamma hI/2\pi,$$

(where, γ: ratio of the magnetic moment, h: plank constant, I: quantum number)

3

Gyromagnetic Ratio (γ)



The ratio of the magnetic moment (μ) to the intrinsic angular momentum (L) of a spinning particle:

$$\gamma = \mu / L$$

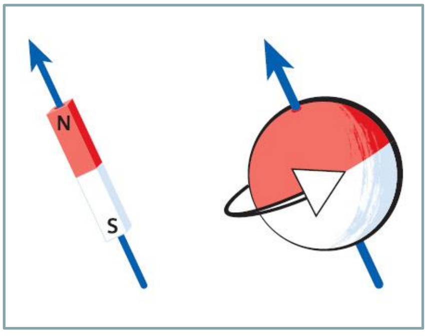
In general, following γ factor (magnetic angular momentum operator) is used: Angular momentum(**L**)/Magnetic moment(μ)= 2mc/γ'e

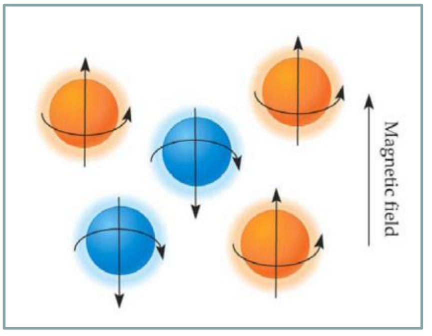
(*where, e and m are electron charge and mass, respectively, c: speed of light, γ' operator: "gyromagnetic ratio"*)

14

Magnetic Dipole Moment (MDM)

Protons have a spin and therefore, a magnetic dipole moment (MDM).	They can align to external magnetic fields in two ways: parallel or anti-parallel.





Gyromagnetic Ratios (γ) of Nuclei

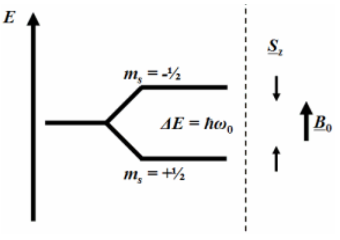
Nucleus	Abundance(%)	Sensitivity*	γ(MHz/T)
^{1}H	99.98	1	42.58
^{2}H	0.015	0.00965	6.53
^{13}C	1.07	0.016	10.71
^{19}F	100	0.830	40.05
^{23}Na	100	0.093	11.26
^{31}P	100	0.066	17.23
^{39}K	93.1	0.000508	1.99

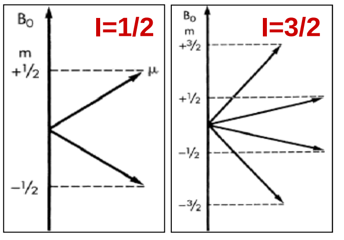
*At constant field for equal number of nuclei.

Quantization of Nuclear Spin

- If atomic nucleus having magnetic moment are put in the static magnetic field of $H_{0,}$ the energy levels of atomic nucleus are separated into the levels of (2I+1) to according to quantum number by Zeeman effect, and the energy difference between near levels is:

$$\Delta E = \gamma h H_0 / 2\pi$$

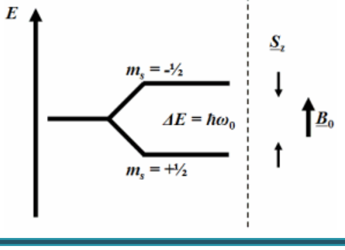


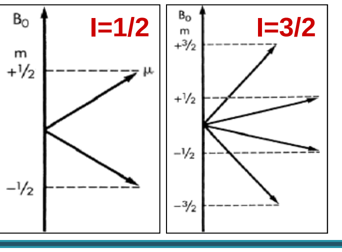


Based on QM, # of energy state were generated by the formula of 2I+1 in present of magnetic field (Zeeman effect)

Quantization of Nuclear Spin

- If electromagnetic wave having the frequency of $\omega_0 = 2\pi\cdot\Delta E/h$ corresponding to this energy difference is applied from exterior, energy transfer (resonance) is occurred to the nuclear spin system.
- Because the spin of proton nucleus is I = 1/2, there are two energy states: the low energy state E_1 having same direction to magnetic $H_{0,}$ and the high energy state E_2 having opposite direction to magnetic H_0 in a static magnetic field.





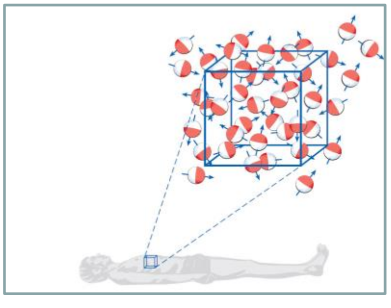
Spin Quantum # for Various Nuclei

Number of Protons	Number of Neutrons	Spin Quantum Number	Examples
Even	Even	0	^{12}C, ^{16}O, ^{32}S
Odd	Even	1/2	**^{1}H**, ^{19}F, ^{31}P
"	"	3/2	^{11}B, ^{35}Cl, ^{79}Br
Even	Odd	1/2	^{13}C
"	"	3/2	^{127}I
"	"	5/2	^{17}O
Odd	Odd	1	^{2}H, ^{14}N

- The nucleus consisted with even number of proton and even number of neutron cannot use the NMR phenomenon, because spin quantum number is 0.
- Nuclides which can cause NMR phenomenon in a living body are H-1, Na-23, C-13, P-31, etc. Especially, the proton H-1 of hydrogen nucleus is the subject for imaging because of high natural abundance ratios.

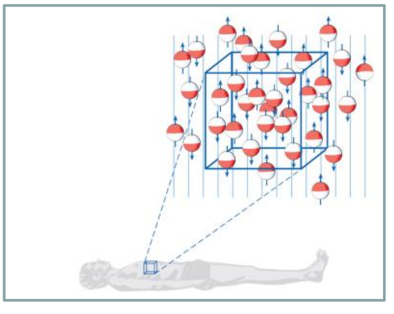
What Happens in MRI Scanner?

Random



Outside MRI Scanner

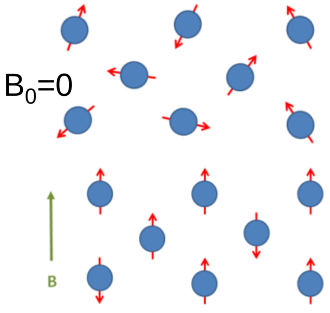
Align along B_0

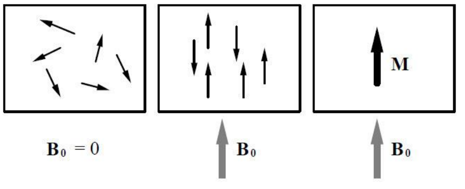


Inside MRI Scanner (B_0)

Net Magnetization (M_0)

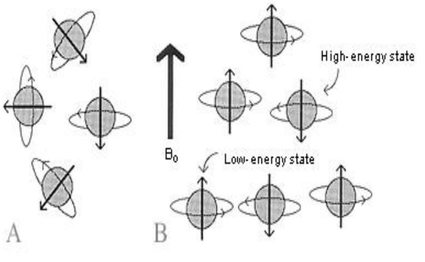
- In the present of static magnetic field: H_0, The directions of nuclear spin are random, and its vector sum is zero (net magnetization is not observed.)
- The net magnetization vector in static magnetic field: H_0 is the summation of all the magnetic moments of the individual nucleus spin magnets.

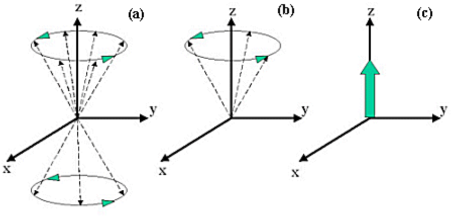




Net Magnetization (M_0) in Static Magnetic Field

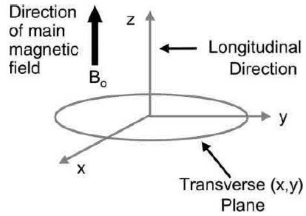
Vector sum of the individual spin vectors
= Macroscopic magnetization
= Bulk magnetization



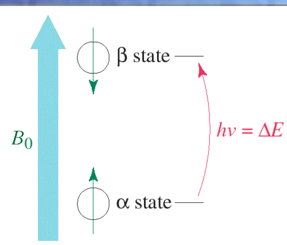


Where is the Magnetic Field in MRI Scanner?

Uniform Main Magnetic Field: B0
Direction of Magnetic Field: : z-axis
Magnetic Strength:1.5 T or 3 T



Nuclear Magnetic Resonance



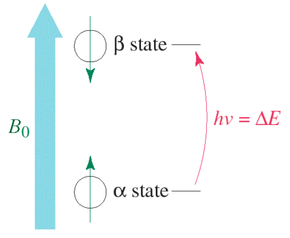
- If angular frequency (ω_0) corresponding to near energy difference is exposed from exterior, nuclear spin absorbed the energy and transformed from low energy state to high energy state.

  → This absorbed resonance frequency (ω_0) is called to **Larmor frequency** or **precession frequency**.

  $$\omega_0 = (E_2 - E_1)/(h/2\pi)$$

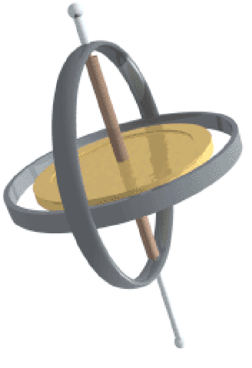
Nuclear Magnetic Resonance

- If the exposure of EM waves is stopped, nuclear spin transformed to high energy level come back to low energy state, and in this time, emit the EM waves having same frequency of absorbed energy.
  → **These are measured as to NMR signal → imaged by using these.**



25

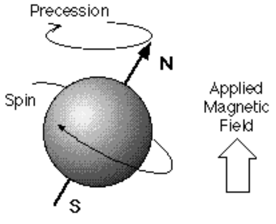
Gyroscope Precession



26

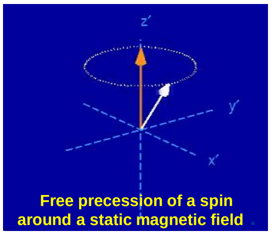
Precession

- When the spin of magnetic moment μ is put in static magnetic field of B_0, each nuclear spins are doing individual precessions corresponding to its Larmor frequency of ω_0 .
- Spins process is z-axis direction for applied magnetic field of B_0 .
- Larmor frequency is proportional to the applied magnetic field of B_0 .

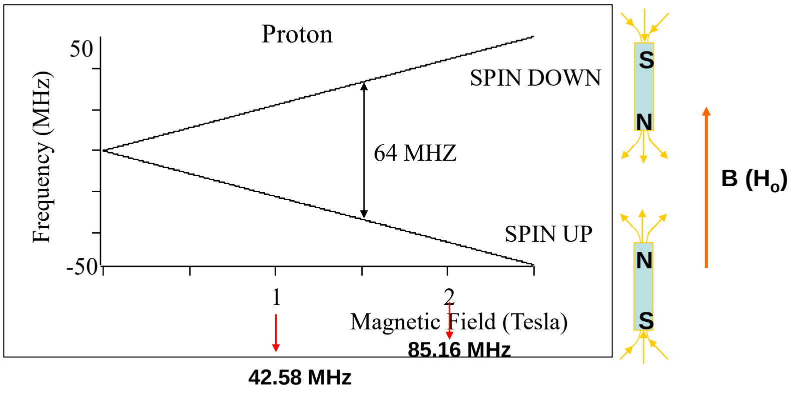


$$\omega = \gamma B$$

ω: Resonance Frequency
(=> 10^6 Hz = MHz)
(ex, 42.5 MHz/T)
γ : Gyromagnetic Ratio
B_0: External Magnetic Field (T)



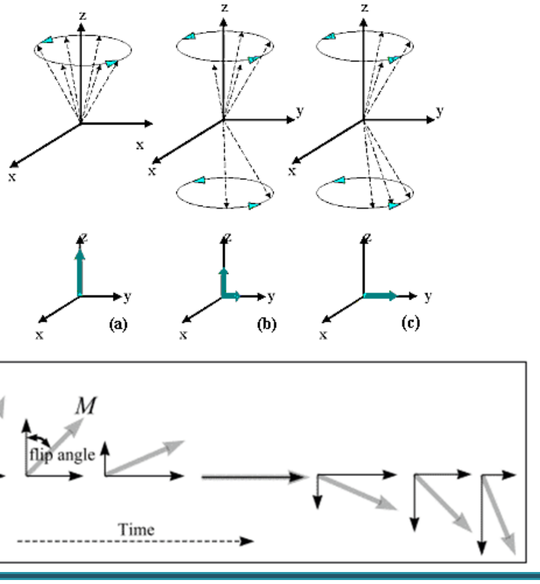
Larmor Frequency in Proton



Excitation of Net Magnetization

- In thermal equilibrium state *in which electromagnetic transmission from exterior is not applied*, the direction of net magnetization is same as the direction of static magnetic field (traditionally, z-axis).
- If Larmor frequency magnetic field (H_1: transmitting 90° RF pulse) is transmit from the vertical direction to static magnetic field → net magnetization fall down to x-y plain by gradual energy absorbing, → this vector sum of spins appears transverse magnetization. → the Larmor precession is started in z-axis around.
- Finally, the transverse magnetization having same phase is created.

Excitation of Net Magnetization

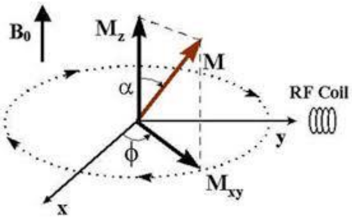


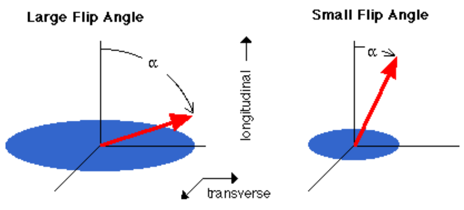
Flip Angle

- Flip angle is expressed as the product of the intensity of high frequency magnetic field and the transmit time (t_p):

$$\theta = \gamma H_1 t_p,$$

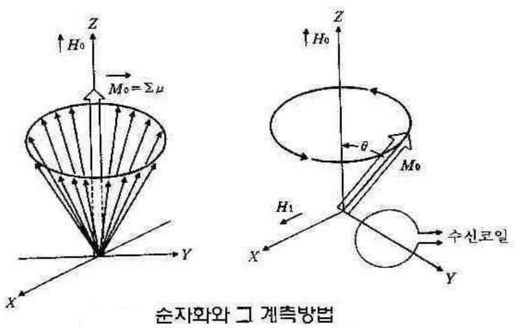
(where, H_1: intensity of high frequency magnetic field transmitted from exterior, t_p: transmit time of high frequency magnetic field, especially, at fixed t_p, RF pulse H_1 reaching to $\theta = \pi/2$ is 90^0 pulse, and RF pulse H_1 reaching to $\theta = \pi$ is 180^0 pulse.)



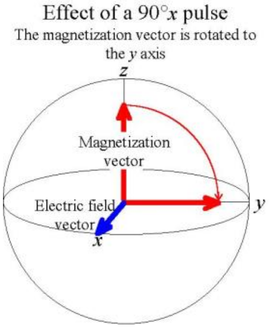


Relaxation

- If H_1 transmit is terminated, after that time, the absorbed resonance energy is released by emitting RF electromagnetic wave having Larmor frequency, which is proportional to exterior magnetic field, and the spin state return to original thermal equilibrium state. → **(Relaxation)**
  → MRI detect these RF signals and reconstruct image.

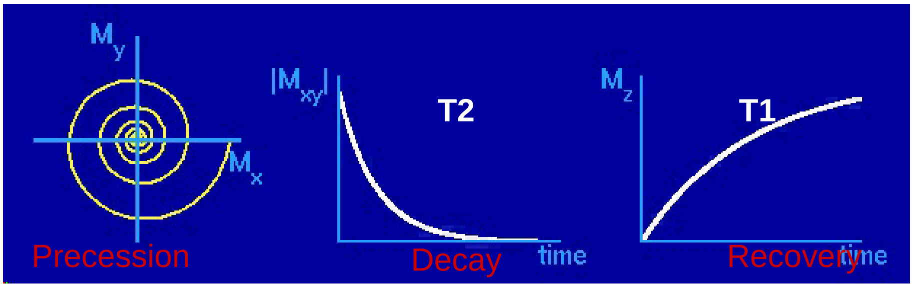


순자화와 그 계측방법



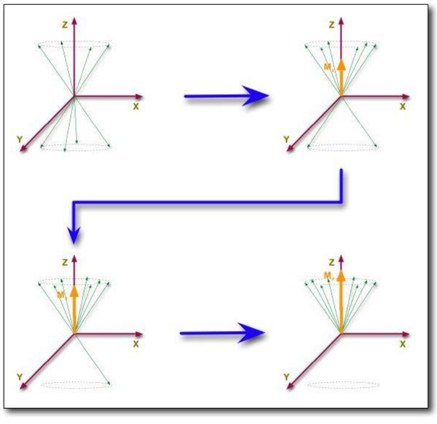
Relaxation Times

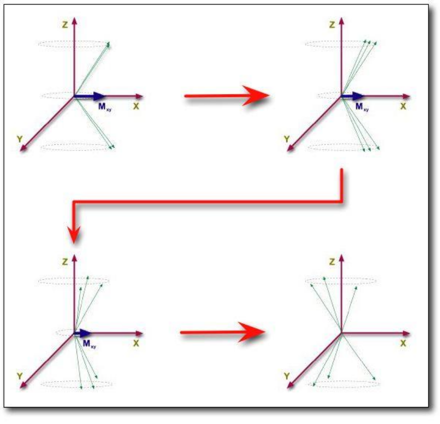
- **Magnetization exponentially return to equilibrium state.**
  - Longitudinal (z) recovery time constant: T_1
  - Transverse (xy) decay time constant: T_2
- **Relaxation and precession are independent.**



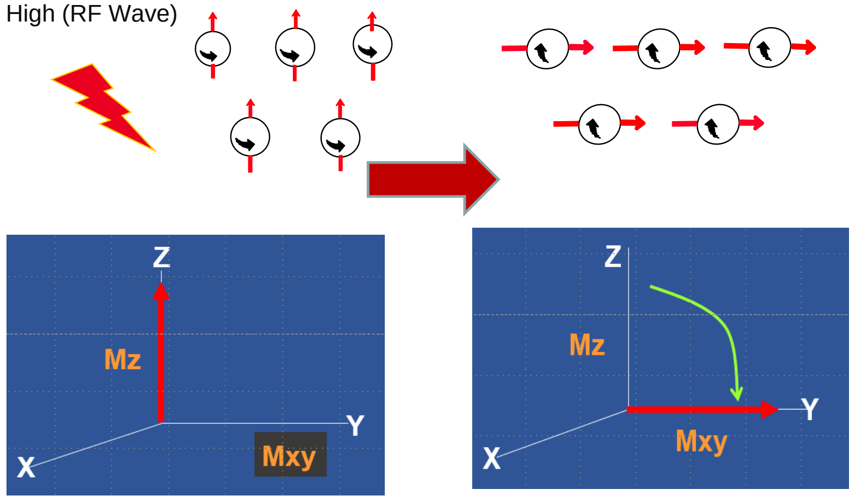
T1 & T2 Relaxation

Longitudinal Relaxation (T1)	Transverse Relaxation (T2)

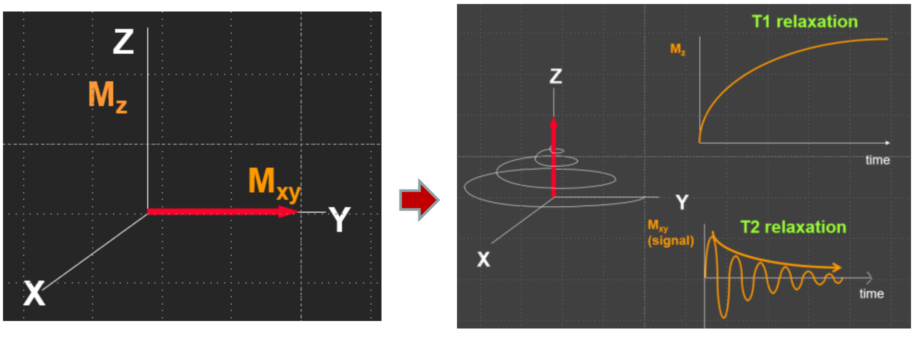




Excitation Process

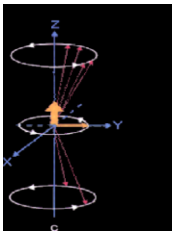


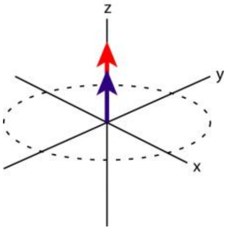
Relaxation Process

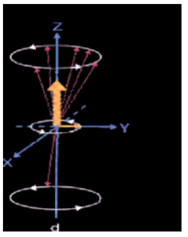


Spin-Lattice Relaxation Time (T1)

- The recovery rate of the longitudinal magnetization by the interaction of the proton spins with their surroundings.
- T1 (*longitudinal relaxation time or spin-lattice relaxation time*) represent the speed returning to original stable background state by emitting thermal vibration energy to surrounding lattice with resonance energy which is absorbed by spin.







Spin-Lattice Relaxation Time (T1)

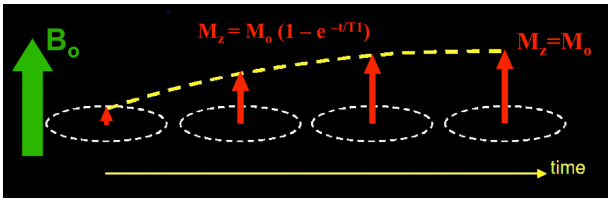
- In microscopic point of view, T1 is determined by surrounding local magnetic environments, viscosity, temperature, etc. in which nuclear spin is existed. Also, T1 of same material is varied according to static magnetic field, and T1 become longer as static magnetic field become higher.

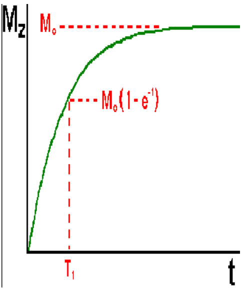
T1 

T1 Relaxation Time

Longitudinal / Spin-Lattice Relaxation Time

When 90^0 RF pulse is stopped, T1 can be viewed as the time required for the x-component of M to reach $(1-e^{-1})$ or 63% of its maximum value (M_0).

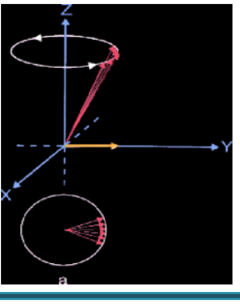


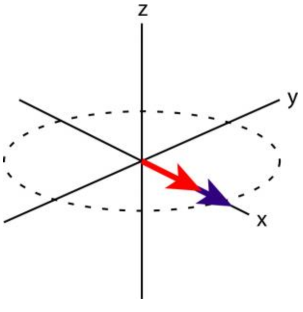


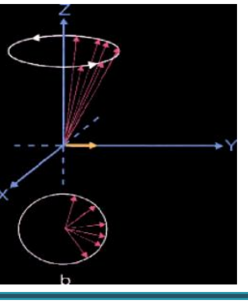
Spin-Spin Relaxation Time (T2)

- The decay rate of the transverse magnetization by the interactions between proton spins
- After the stop of 90^0 RF pulse transmit, the x-y components of net magnetization M_0 for time variation is:

$$M(t) = M_0 [\exp^{(-t/T2)}]$$

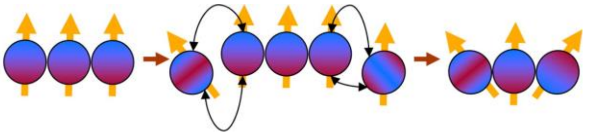






Spin-Spin Relaxation Time (T2)

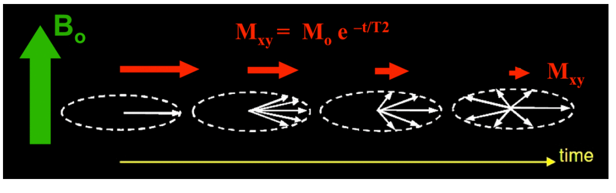
- This process is called "**Transverse Relaxation**". This time constant is "**Transverse Relaxation time**" or "**Spin-Spin Relaxation time**".
- T_2 depend on the exist of spin, and T_2 is different according to the types and sate of materials. However, T_2 value for same material is not depend on the intensity of static magnetic field.

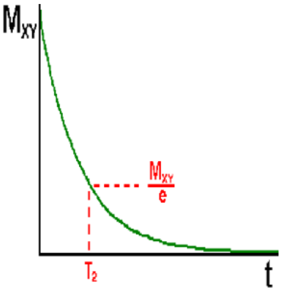
T2 

T2 Relaxation Time

Transverse / Spin-Spin Relaxation Time

When 90^0 RF pulse is stopped, T2 is the time required for transverse magnetization to fall to approximately 37% (1/e) of its initial value.





(T1) Relaxation Time

- In 1971, American Raymond Damadian annunciated that T1 (longitudinal relaxation time) in a malignant tumor is longer than T1 in a normal organization.
  → Promotion of clinical applied research of MRI
- In living body, T1 is shorter in a solid, and longer in a liquid. In other words, T1 values are varied according to the water content in a soft tissue.
  → TI become shorter in abundance of protein or fat tissue.
- The clinical effectiveness of MRI is that T1 value of lesion part is detected as signal intensities on image according to the magnitude of T1.
- In general, a water abundant region yield low signal, and a fat abundant region yield high signal in T1 weighed imaging.
- Lesion or tissue seen as high signal in T1 weighed imaging are hematoma, bone narrow, fat, etc.

(T2) Relaxation Time

- T2 (spin-spin relaxation time is time constant representing energy exchange between spins) is short for the proton coupled with a macromolecular of protein, and become longer in more pure water.
- In general, T2 is shorter than T1, and the maximum value of T2 is T1. Therefore, T2 have the characteristics that become shorter in solid state, and loner in liquid state.
- T2 value is very useful in the clinic. In general, The existence of lesion is roughly exanimated by T2 weighted image.
- Lesions seen as high signal in T2 weighted image are exanimated as cerebral infarction, hemorrhage, dehydration, tumor, edema, lipoma, etc.

T1 & T2 Properties for Body Tissues

MRI has high contrasts for different tissue types!

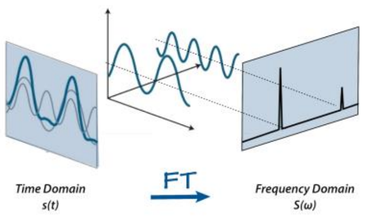
Tissue	T1 (ms)	T2 (ms)
Grey Matter (GM)	950	100
White Matter (WM)	600	80
Muscle	900	50
Cerebrospinal Fluid (CSF)	4500	2200
Fat	250	60
Blood	1200	100-200

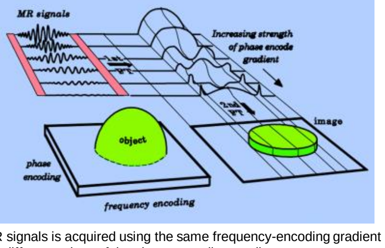
MRI Image Reconstruction

- NMR signals contain the information of proton density, T_1, T_2, chemical shift, blood, etc. but they not have the information of position.
- 1973, Lauterbur developed zeugmatography method, which is first NMR imaging method, as like as CT image reconstruction algorithm.
- In present, Fourier Transformation (FT) image reconstruction method is mainly used.

Fourier Transform (FT) Imaging

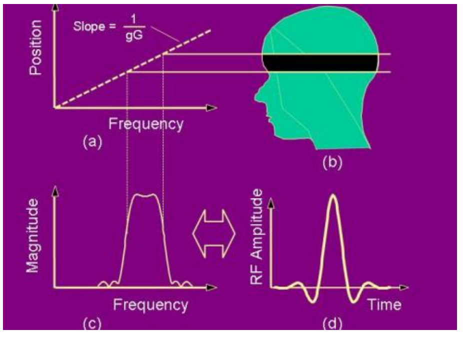
- Fourier Transform (FT) image reconstruction: It is required to transform the frequency signal with spatial signal, because the detected signals are varied according to time changes.
- To acquire two dimensional image, two dimensional FT should be performed with two dimensional data by varying phase encoding gradient with other magnitudes, in addition.

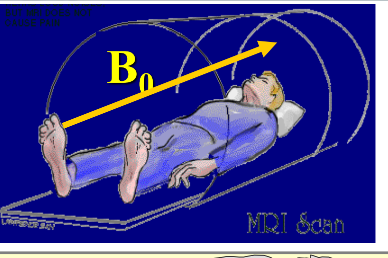


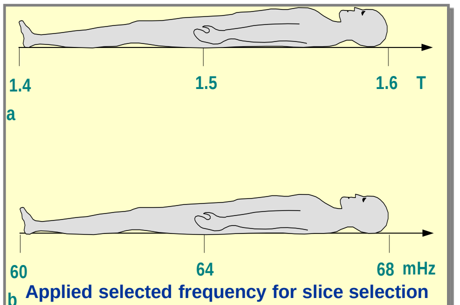


MR signals is acquired using the same frequency-encoding gradient but different values of the phase-encoding gradient.

Slice Selections of the Body



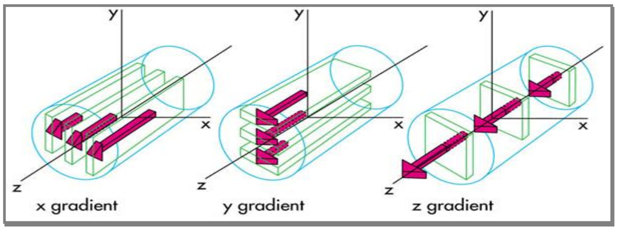




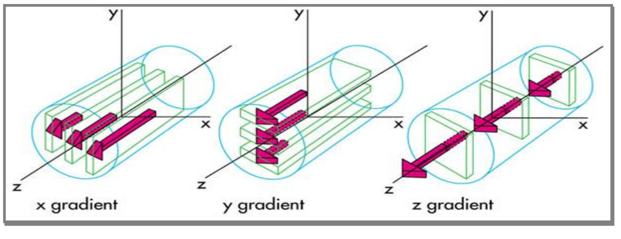
Applied selected frequency for slice selection

Magnetic Field Gradients

- To image the NMR phenomenon occurred in living body, there are needs to distinguish the positions of the MR phenomenon.
  → Because NMR phenomenon is related to frequency, the intensities of magnetic field for various positions should match with resonance frequencies by applying linearly varied gradient magnetic fields.



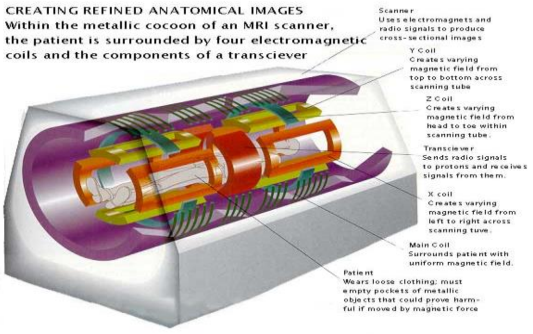
Magnetic Field Gradients

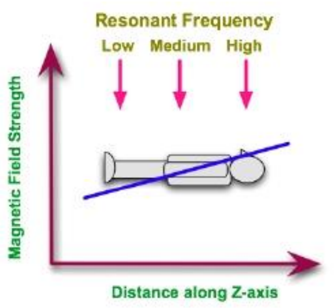


- Magnitude and direction of arrows denotes the magnitude and direction of magnetic field B.
- The gradient magnetic fields are halving same direction to the static magnetic field.

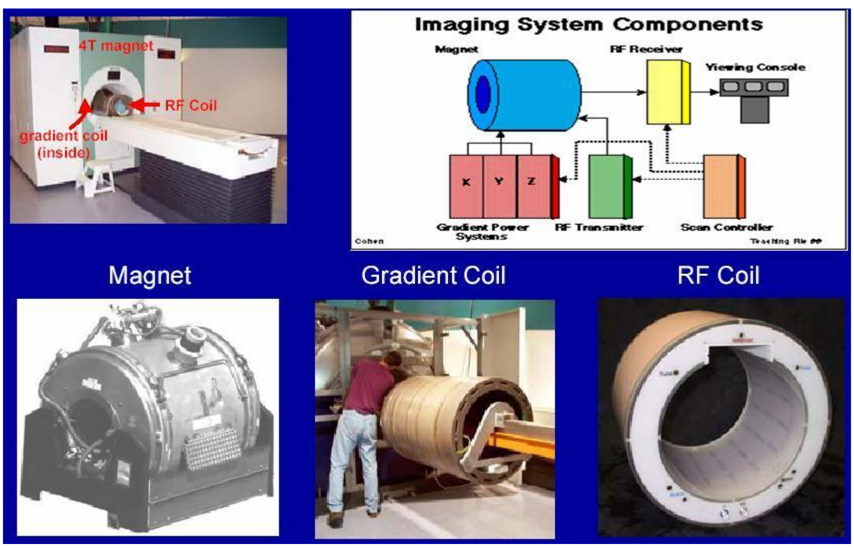
Generation of NMR Signal

- **Main Magnet** generating static magnetic field.
- **RF Transmit coil** emitting high frequency magnetic field. (single type and cross type).
- **RF Receive coil** for signal detection by receiving NMR signal.
- **Three gradient coils** generating gradient magnetic field of X, Y, Z directions.



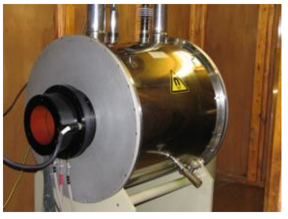
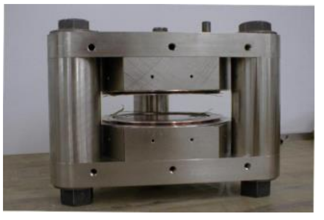


MRI Imaging System Components



MRI Magnets

- Static Magnetic Field Generation:
  - Superconductive magnet.
  - Resistance magnet.
  - Permanent magnet.

53

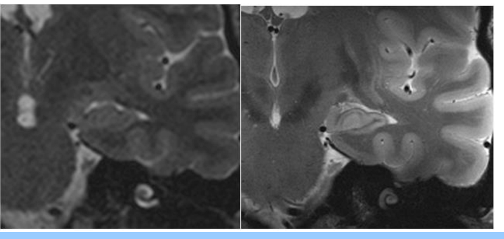
Requirements of MRI Magnets

- **High Magnetic Field:**
  - Image quality of MRI is basically depend on the intensity of static magnetic field,
  - The MRI adopting superconducting magnet, which generates uninform and spacious high magnetic field (0.5 – 2.0 T), is high quality instrument.
  - Resistance magnet type MRI, which generates medium/low magnetic field (0.02 – 0.38 T) and permanent magnet type MRI are used in popular level.
- **High Uniformity:** Static magnetic equipment is used to coincide the direction of spin in materials and the uniformity of magnet is important factor.
- **High Stability:** The temporal stability of static magnetic field is important. If static magnetic field is varied during MRI operations, Image quality is degraded from the position disagreement of image and the occurrence of phase ration.

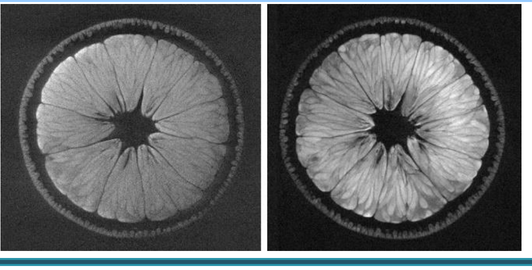
54

High Magnetic Field MRI

Human Hippocampus at 1.5 and 7 T



Images of Orange using Nottingham 3 T and 7 T Philips scanners

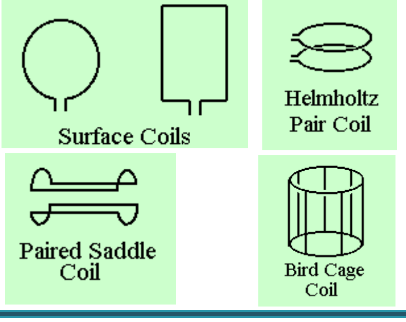


55

RF Receive Coils

Receive coils are ready as exclusive use or flexible use for head, neck, shoulder, breast, body, patella, and TMJ (temporomandibular joint) according to body regions.

Horizontal magnet type MRI: Saddle coil
Vertical magnet type MRI: Solenoid coil



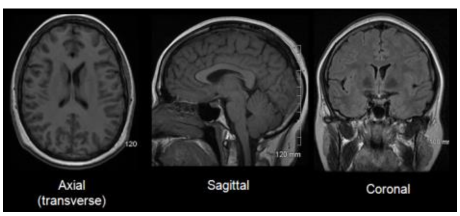
56

Factors Affecting MR Image Quality

Echo Time (TE)	Repetition Time (TR)
Slice Thickness	Interslice Gap
Slice Order	Field of View
Bandwidth	No. of Echoes
Imaging Matrix	Motion Comp
Patient Motion	Window Level
Surface Coil	Equipment Performance

57

General MRI Images



- MRI is a relatively new diagnostic imaging technique that has substantially affected the diagnosis of a multitude of disease.
- It has became the imaging modality of choice for a number of pathologic process, especially in the central nervous system.
- Also, It has became the useful imaging modality in radiotherapy treatment planning field.

58

Characteristics of MRI

Advantages

- No risks of radiation exposure.
- Excellent of contrast resolution in soft tissue.
- Noninvasive and high stability.
- Blood flow information availability without contrast media.
- No image artifacts for bone and air.
- Chemical shift information availability.
- Simultaneous imaging and spectra measurements (high magnetic apparatus).
- Imaging availability for another nucleus, except of hydrogen atomic nucleus (high magnetic apparatus).
- Functional imaging availability observing activation area in brain.

Characteristics of MRI

Disadvantages

- Longer image acquisition time.
- Moving artifact availability.
- No information for calcification lesion.
- Effect of leakage magnetic field to the environments.
- High price of instrument and high operating cost.
- Limitation for Imagine acquisition objects (metal).


THANK
YOU