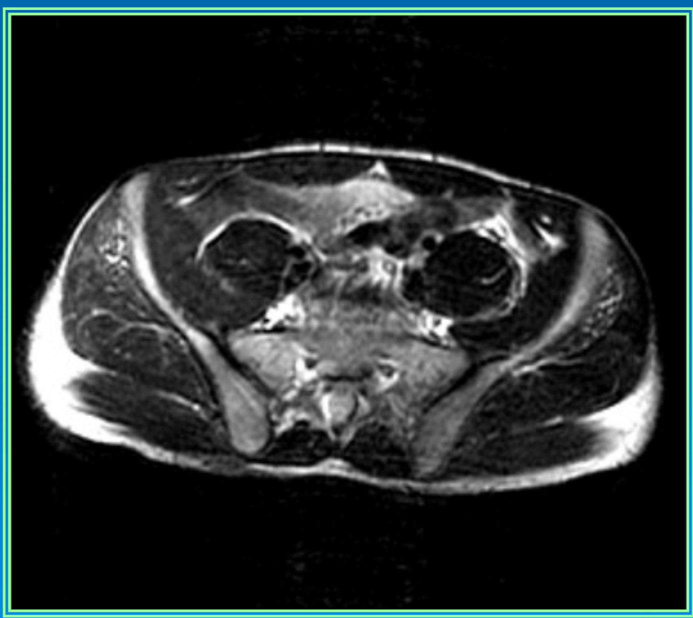
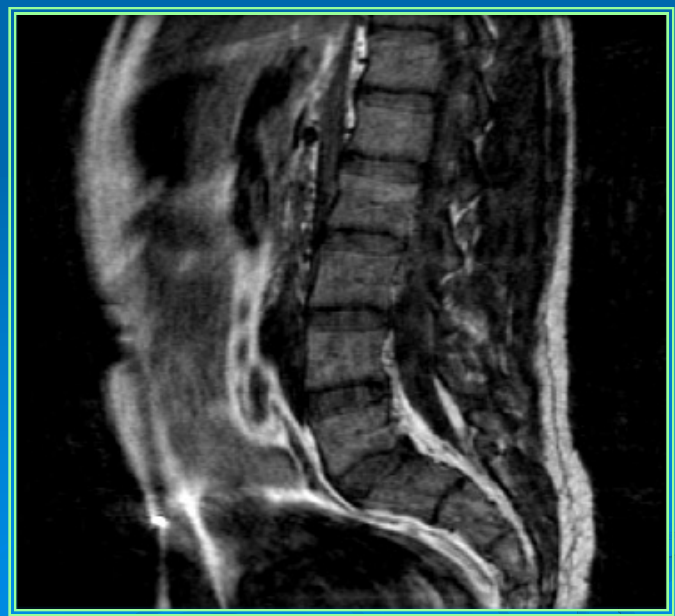
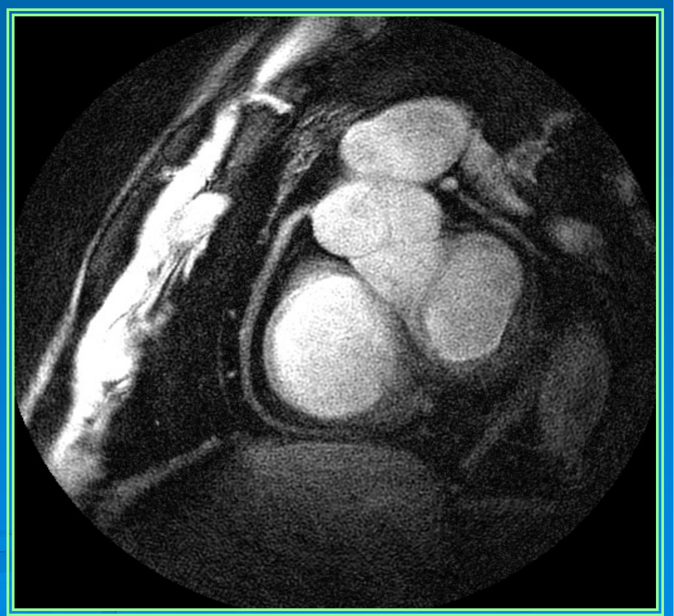
Magnetic Resonance Imaging (MRI)



Abdomen



Spine

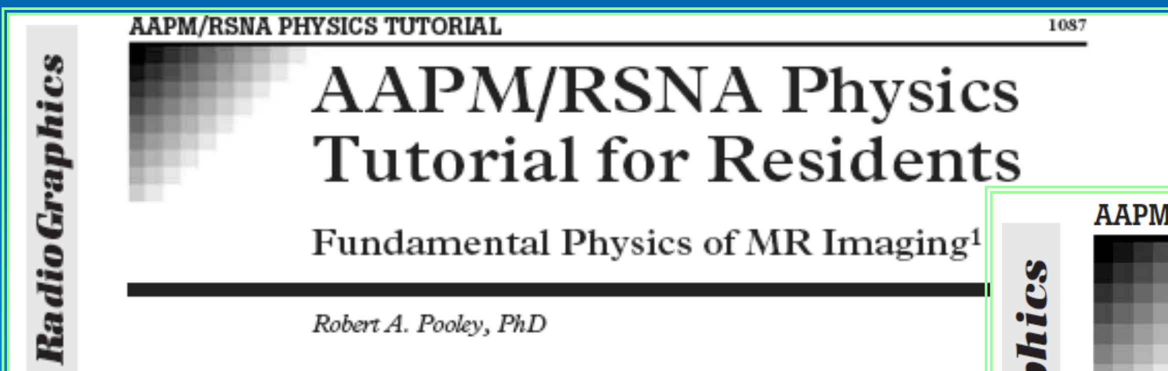


Heart / Coronary

MRI scanner

www.imaios.com/en/e-Courses/e-MRI

Free registration required



AAPM/RSNA PHYSICS TUTORIAL 1087

RadioGraphics

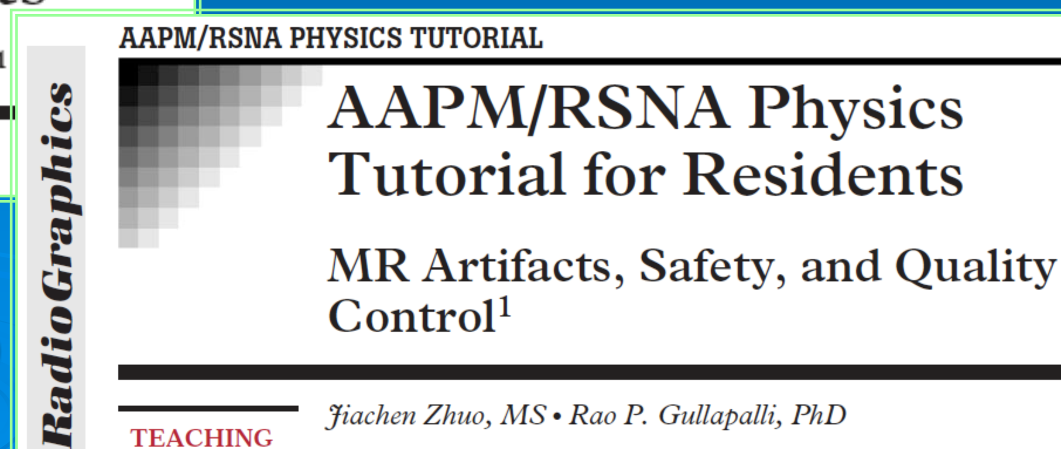
AAPM/RSNA Physics Tutorial for Residents

Fundamental Physics of MR Imaging[1]

Robert A. Pooley, PhD

RadioGraphics 2005; 25:1087–1099

RadioGraphics 2006; 26:275-297



AAPM/RSNA PHYSICS TUTORIAL

RadioGraphics

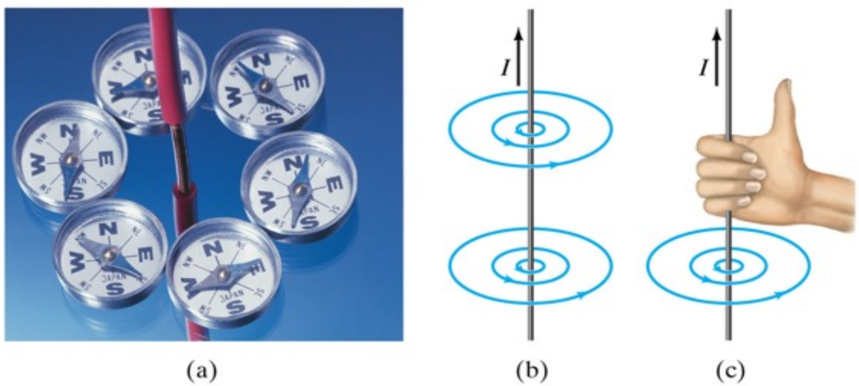
AAPM/RSNA Physics Tutorial for Residents

MR Artifacts, Safety, and Quality Control[1]

Jiachen Zhuo, MS • Rao P. Gullapalli, PhD

TEACHING

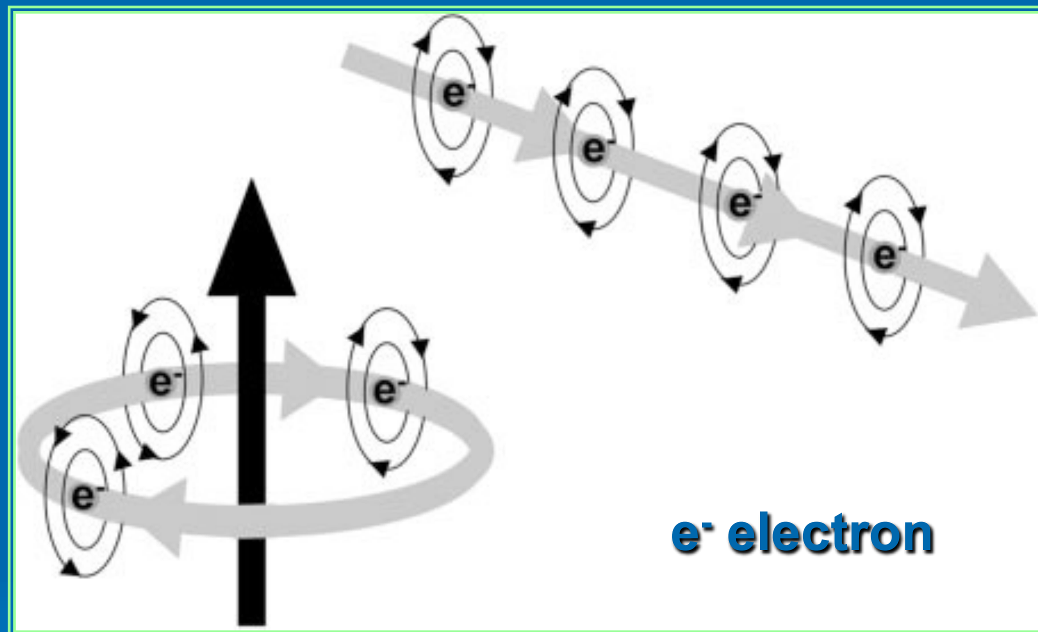
Initial Concepts
Magnetic Field



Magnetic needles map the magnetic field

- Electrons flowing along a wire produce a magnetic field
  - Continuous current, not oscillating !
- The earth magnetic field 0.5 G
- Magnetic field units: Tesla (T), Gauss (G) 1 T=10000 G

Initial Concepts
Production of a Magnetic Field



- An electric current in a loop of wire will produce a magnetic field (black arrow) perpendicular to the loop of wire

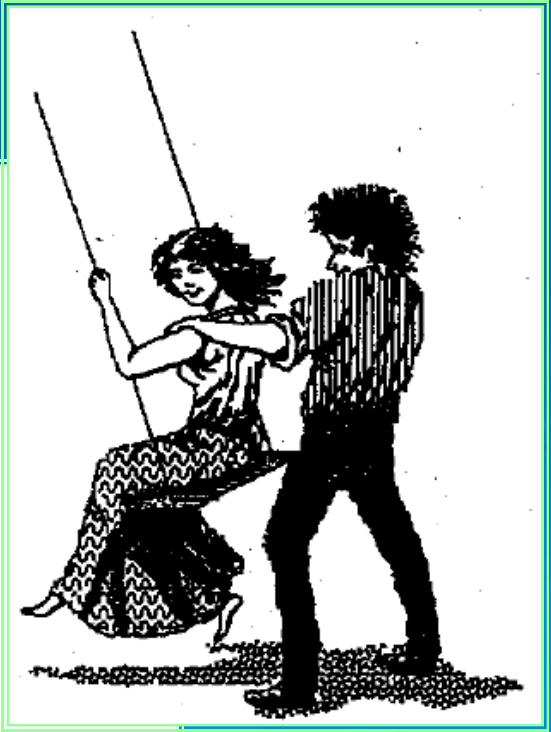
Initial Concepts
Resonance

Resonance aids an efficient transfer of energy

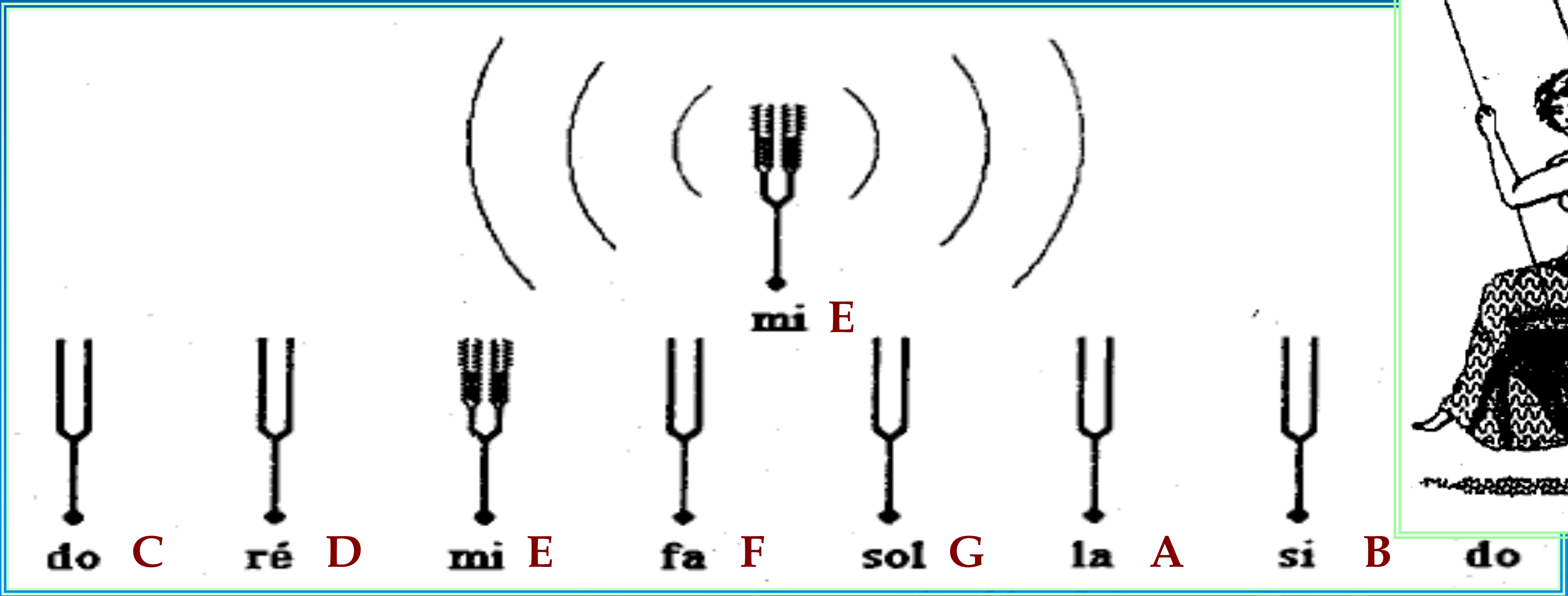
- ✓ Pushing a child on a swing

  The child swings back and forth at a particular frequency.

  By push the swing at the right time, an efficient transfer of energy to the swing happens

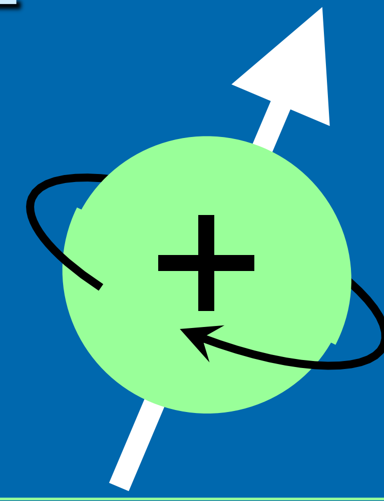


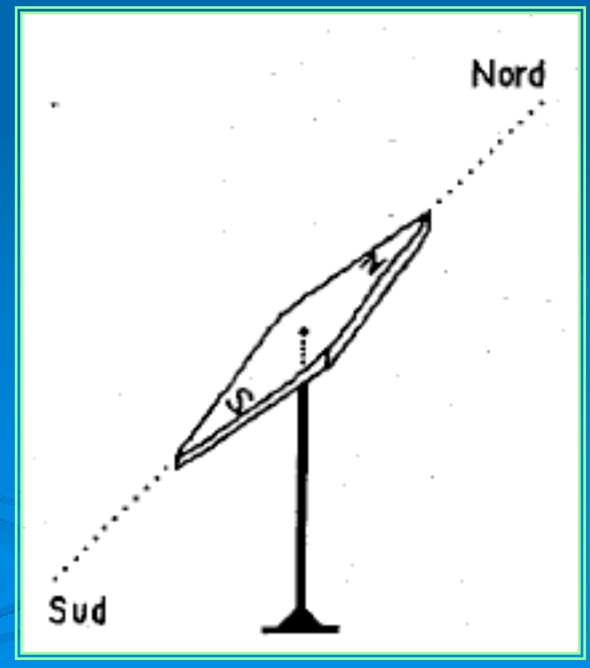
- ✓ The tuning fork



Initial Concepts
Hydrogen Protons

- To form our MR images it is necessary to have a source of hydrogen protons, which are associated with fat and water molecules
  - The hydrogen proton is positively charged and spins about its axis
  - This positively charged spinning proton acts like a tiny magnet
- The hydrogen protons in our body thus act like many tiny magnets

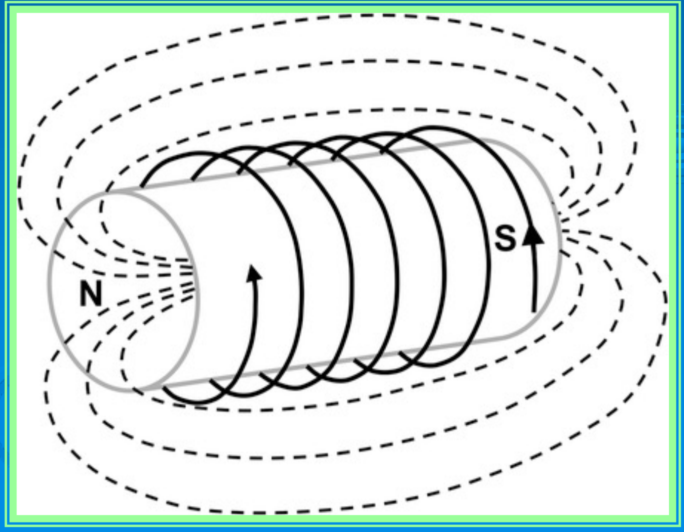




Initial Concepts
Magnetic Field

- Magnetic field strength of MRI system
  - Clinical system 1.5 T
  - Advanced and Research system 3 T
  - Very high field 7- 9.4- 11.7 T

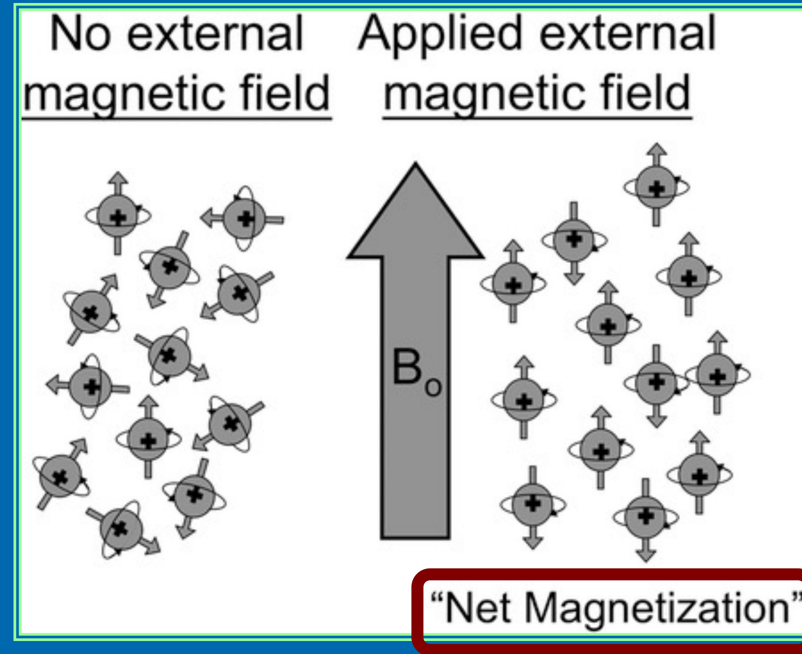
- The main magnetic field of an MR system comes from a large electric current flowing through wires that are formed into a loop in the magnet

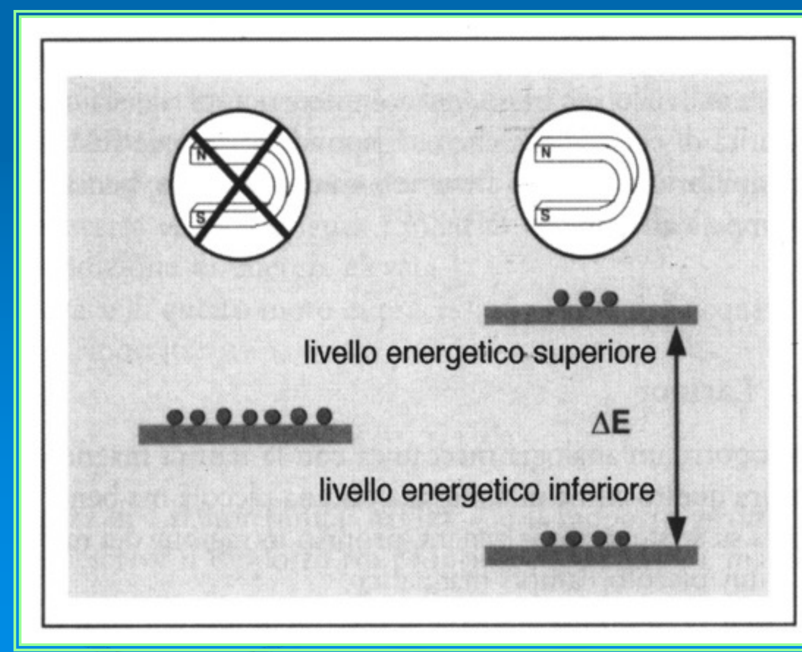


- The wires are at superconducting temperatures so that very large currents can be used to produce the strong magnetic field
  - Liquid N cooling
  - Field never switch off !!

Initial Concepts
Protons in magnetic field

- When placed in a magnetic field (called B_0), the protons tend to align in the direction of the magnetic field, but some protons tends to align in a direction opposite to the magnetic field
  - Quantum mechanics
  - Population of energy states: Boltzmann distribution



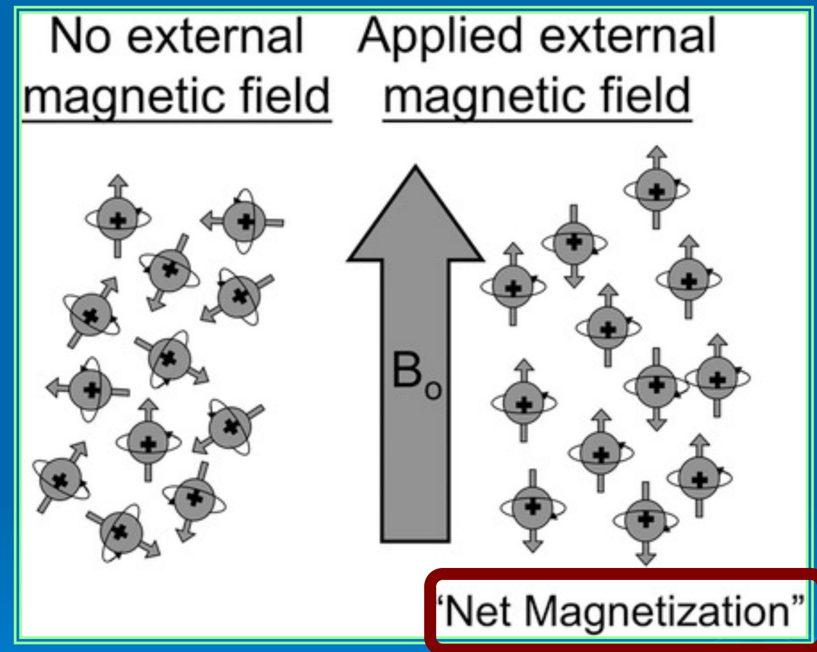


Initial Concepts

Protons in magnetic field

- The magnetic fields from many protons will cancel out, but a slight excess of the protons will be aligned with B_0 producing a **net magnetization** that is aligned parallel to B_0

- This net magnetization is the source of our MR signal
  - It is used to produce MR images
  - Higher B_0 -> Higher net magnetization

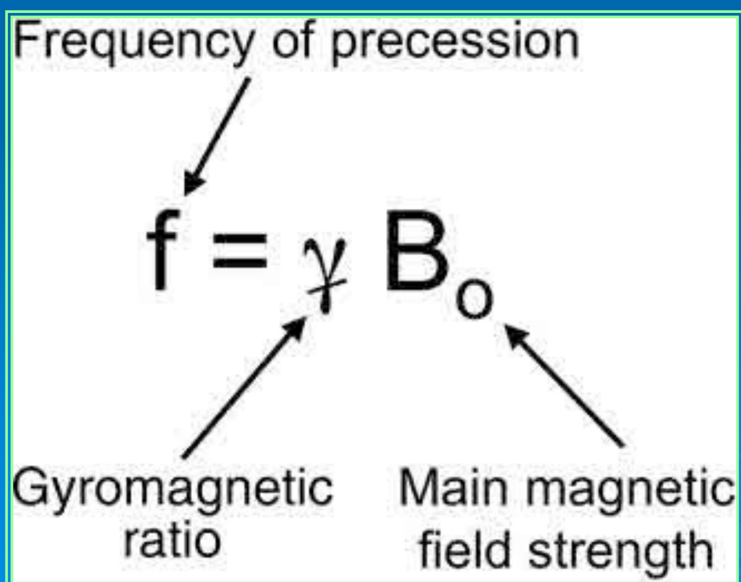


Magnetic Nuclei

- A nucleus has magnetic properties if it has an odd number of protons and/or neutrons
  - $^{1}H_{1}$ (proton), $^{2}H_{1}$ (Deuterium; odd-odd)
  - $^{7}Li_{3}$ (Lithium; even-odd)
  - $^{13}C_{6}$ (Carbon; even-odd)
  - $^{14}N_{7}$ (Nitrogen; odd-odd)
  - $^{19}F_{9}$ (Fluorine)
  - $^{23}Na_{11}$ (Sodium)
  - $^{31}P_{15}$ (Phosphor)
  - $^{35}Cl_{17}$ (Chlorine)
  - $^{63}Cu_{29}$ (Copper)
  - $^{127}I_{153}$ (Iodine)

Resonance frequency

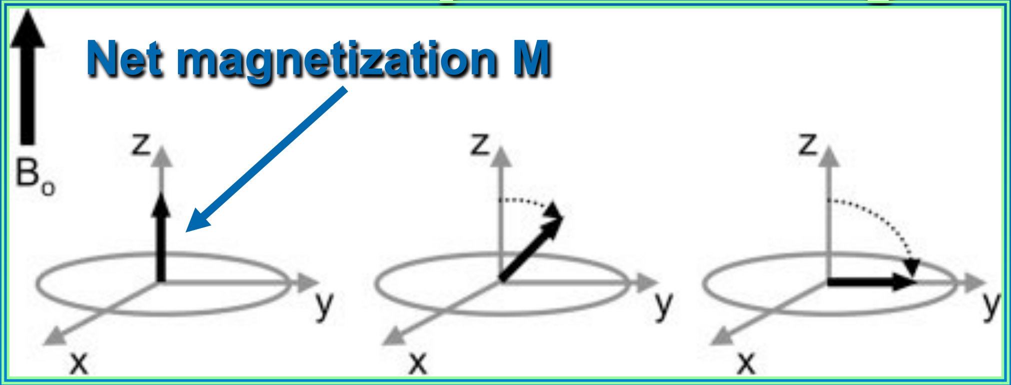
- ✓ The protons can absorb electromagnetic energy in the radiofrequency (RF) range
- ✓ The resonance frequency is proportional to B_0
  - For a typical clinical MR system, the magnetic field strength is 1.5 T and the resonance frequency is 64 MHz
    - 64 million times per second



- The Larmor equation determines the frequency resonance of a spin in B_0
- For hydrogen protons, the gyromagnetic ratio is equal to 42.6 MHz/T

Absorption of RF Energy

- When protons are placed in B_0, the magnetic fields from these protons combine to form a net magnetization
  - http://www.imaios.com/en/e-Courses/e-MRI/NMR/Net-magnetization
- This net magnetization points in a direction parallel to B_0
  - called the longitudinal direction
- As energy is absorbed from the RF pulse, the net magnetization rotates away from the longitudinal direction



  - ✓ The amount of rotation (termed the flip angle) depends on the strength and duration of the RF pulse
  - ✓ http://www.imaios.com/en/e-Courses/e-MRI/NMR/Excitation

Radiofrequency energy

- Radio and television stations broadcast at radio frequencies (RF) in units of megahertz
- not far from the proton Larmor frequencies of a 1.5 T magnet
  - MR systems must be shielded from external RF signals
- RF energy comes by oscillating flow of electrons through coils
  - loops of wire
  - antenna

Radiofrequency energy in MRI system

RF energy is transmitted

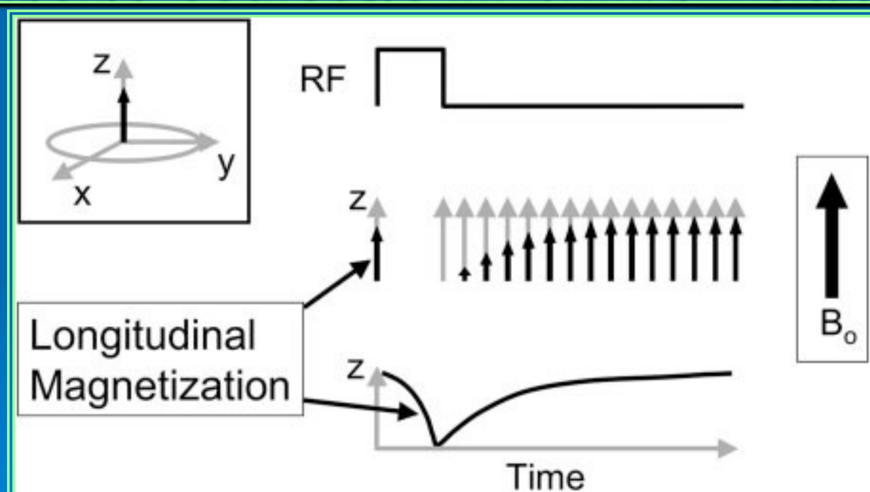
- by an RF transmit coil
- for a short period of time
  - called RF pulse

- The transmitted RF pulse must be at the resonance frequency of the protons

Head coil

T_1 Relaxation

- Net magnetization aligned with B_0 is called longitudinal magnetization
- A 90° RF pulse rotates the longitudinal magnetization into the transverse plane
  - this magnetization is called transverse magnetization
  - www.imaios.com/en/e-Courses/e-MRI/NMR/Excitation

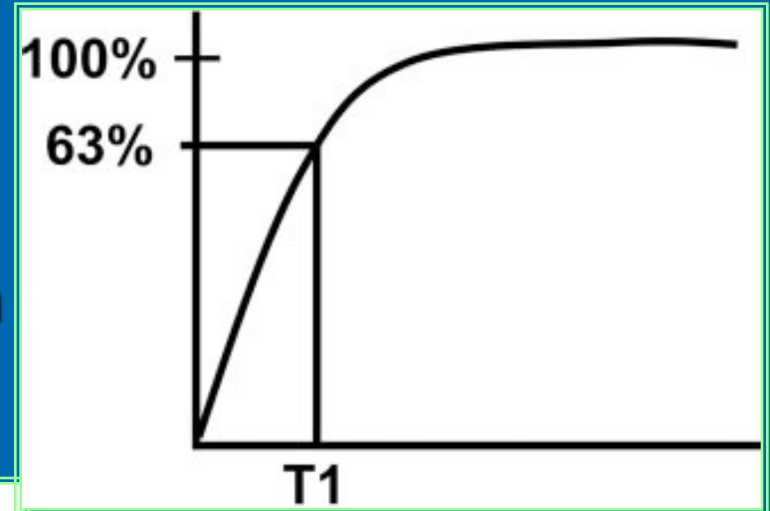


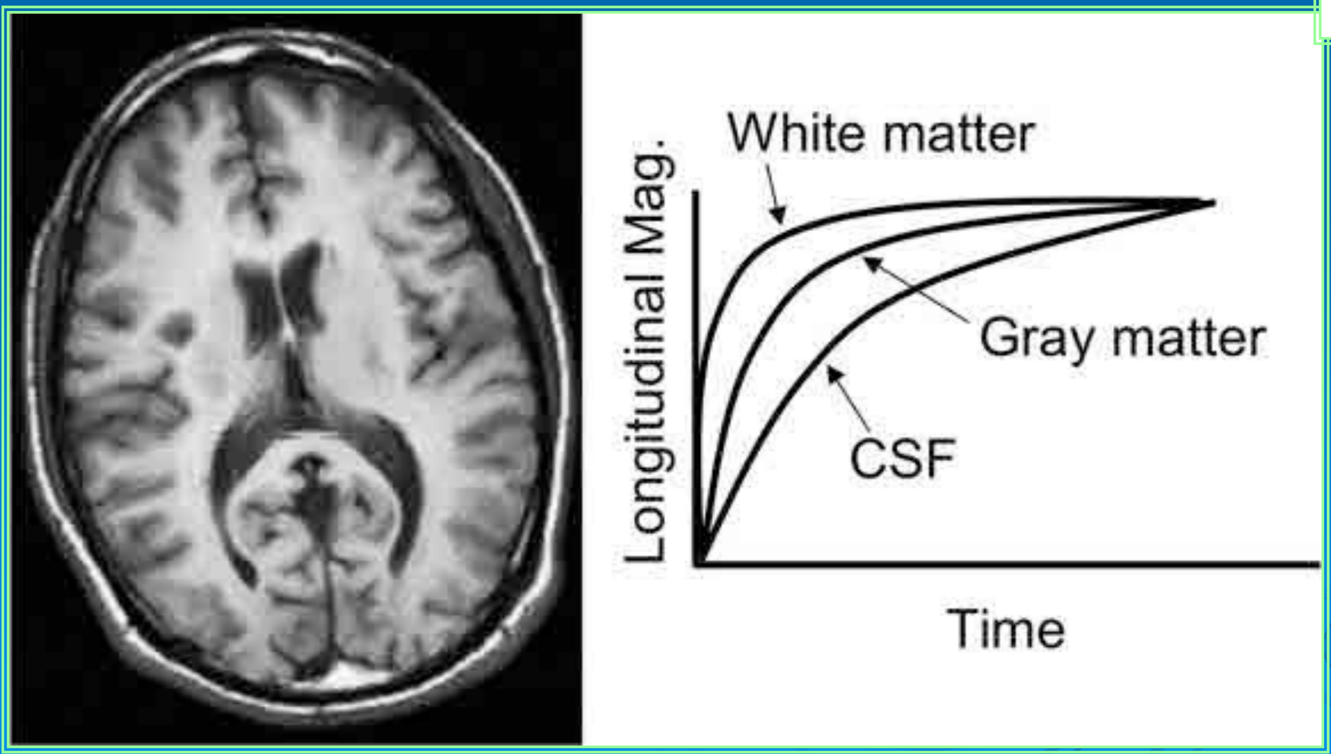
- After a 90° RF pulse, the longitudinal magnetization is zero
- The magnetization then begins to grow back in the B_0 direction: This is called T_1 relaxation
  - www.imaios.com/en/e-Courses/e-MRI/NMR/Relaxation-nmr

T_1 Relaxation and Contrast

The rate at which the longitudinal magnetization grows back is different for protons in different tissues

It is the fundamental source of contrast in T1-weighted images

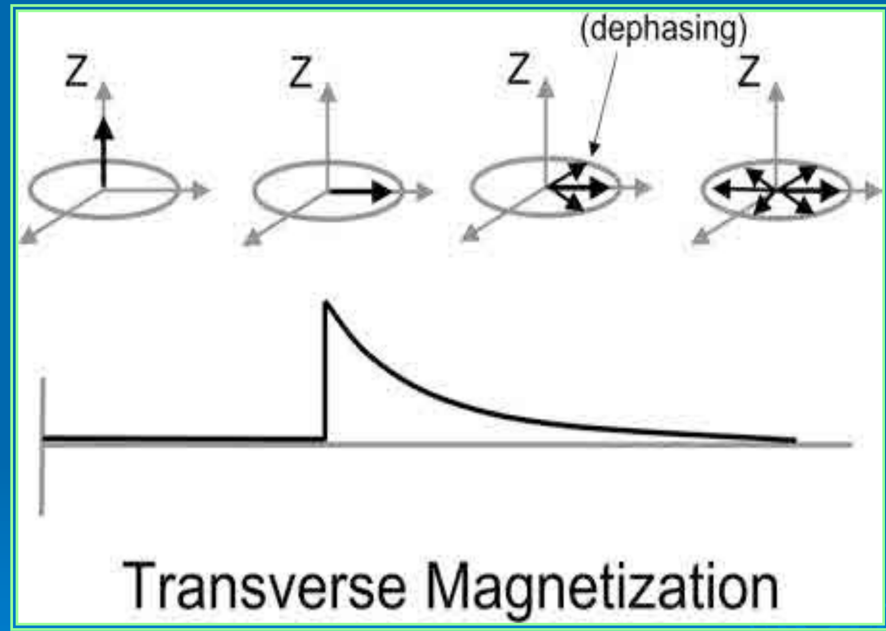




T_1 is a characteristic of tissue and is defined as the time that it takes the longitudinal magnetization to grow back to 63% of its final value

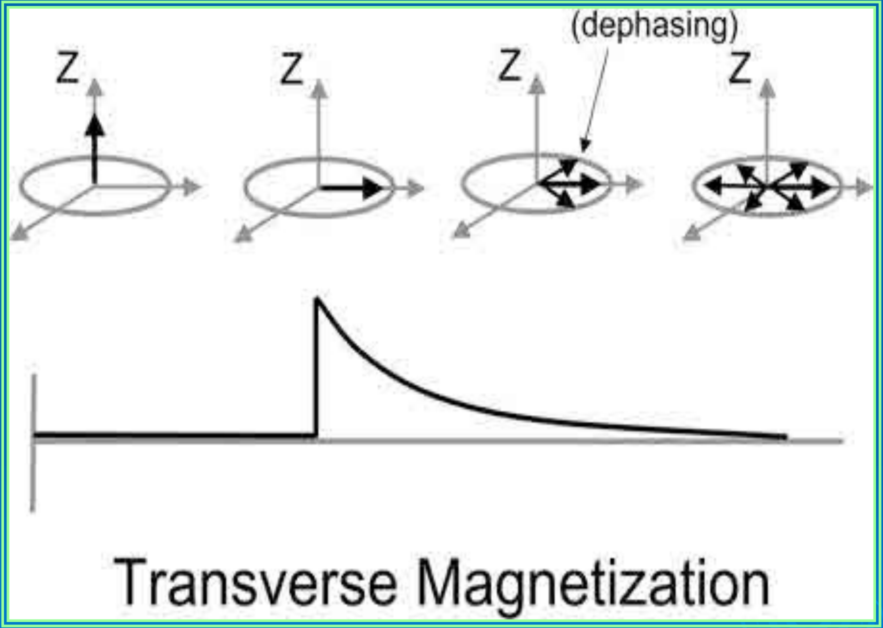
T_2 Relaxation

- After application of a 90° RF pulse, transverse magnetization is maximized
- The intensity of the transverse magnetization decreases rapidly
  - T_2 relaxation
- Faster than the recovery of the longitudinal magnetization
  - T_1 relaxation



T_2 Relaxation

- The net magnetization is made up of contributions from many rotating protons
  - Resonance frequency
- During the RF pulse the protons become “in phase”
  - Protons precess together
- Immediately after the 90° RF pulse, begin to dephase due to several effects

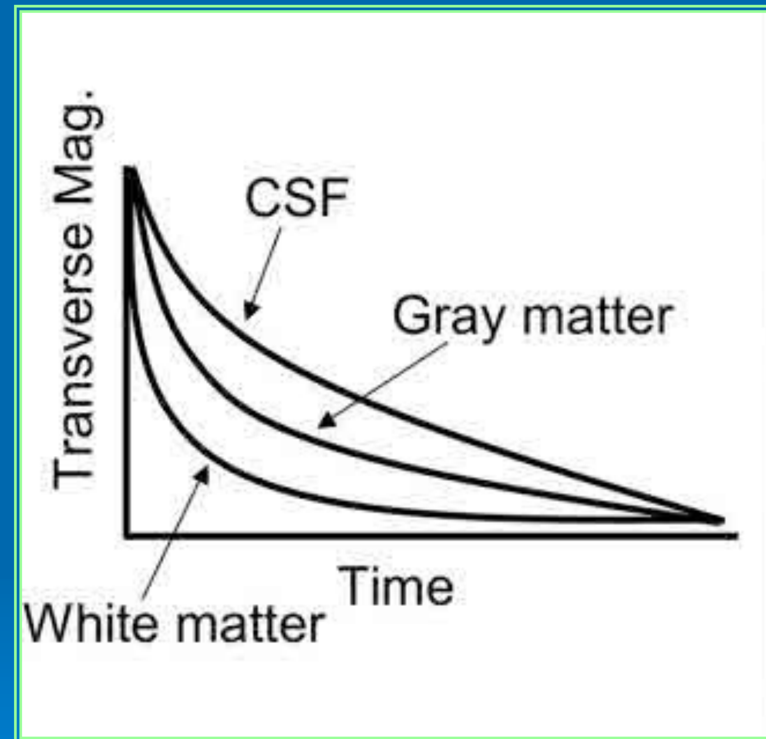


Look carefully the animations !!!!

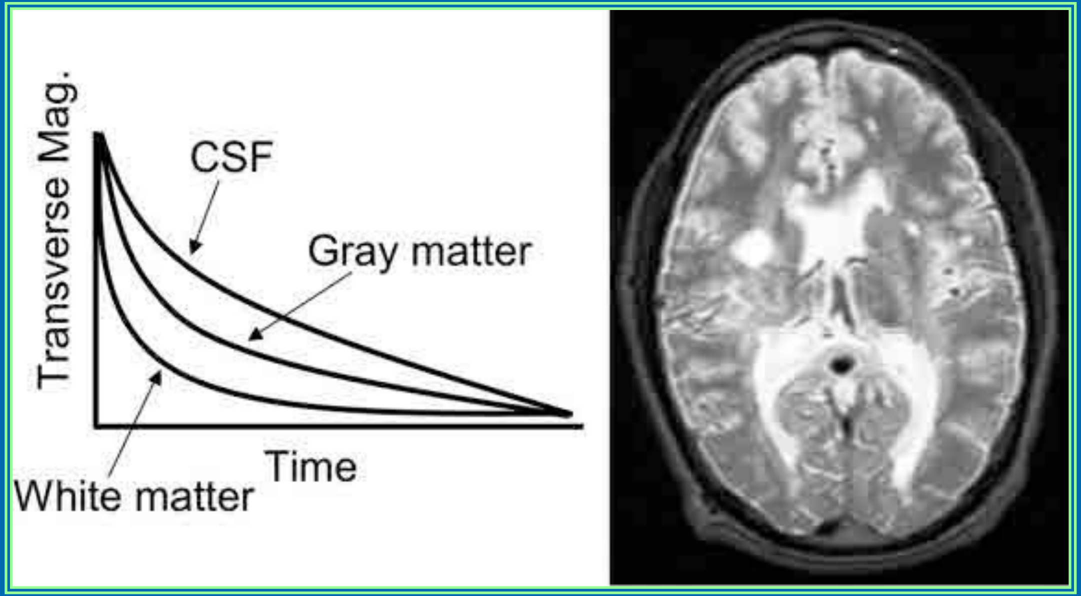
www.imaios.com/en/e-Courses/e-MRI/NMR/Net-magnetization

T_2 Relaxation and Contrast

- When the transverse magnetization begins to dephase, measured MR signal begins to decrease until the magnetization is completely dephased
  - at which time the measured MR signal is zero
- Different tissues have different rates of T2 relaxation
  - Mag = magnetization



T_2 Relaxation and Contrast



- Different tissues have different rates of T2 relaxation
- If an image is obtained in a conditions when the relaxation curves are widely separated, T2-weighted contrast will be maximized
  - Mag = magnetization

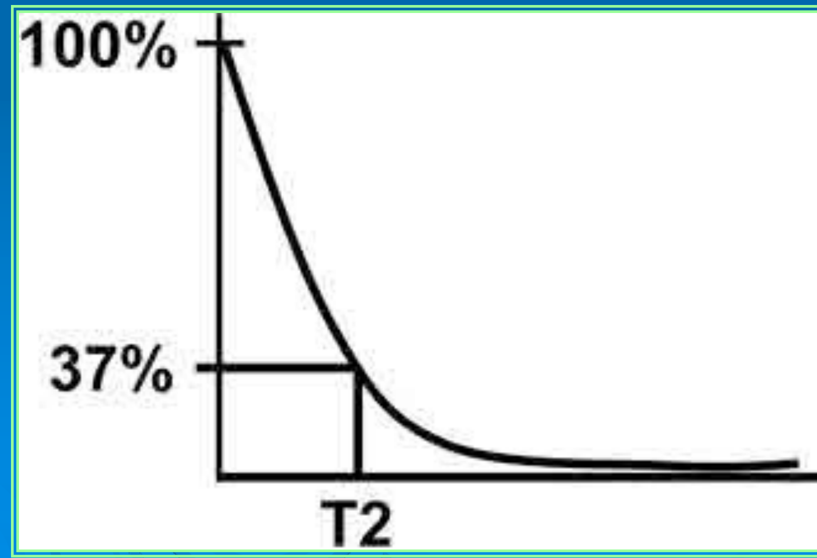
T_2 Relaxation

Effects That Cause T2* and T2 Dephasing

Causes of T2* Dephasing	Causes of T2 Dephasing
Spin-spin interactions	Spin-spin interactions
Magnetic field inho-mogeneities	
Magnetic susceptibility	
Chemical shift effects	

- T_2 is a characteristic of tissue and is defined as the time that it takes the transverse magnetization to decrease to 37% of its starting value

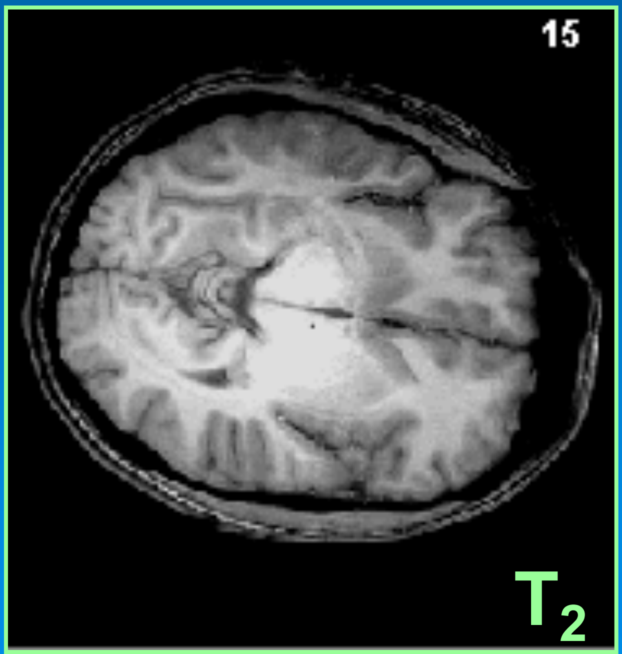
- Dephasing normally occurs due to all four effects, and in this case, the dephasing may be called T2* relaxation
  - The dephasing due to three of the effects can be reversed through a special "trick" discussed later

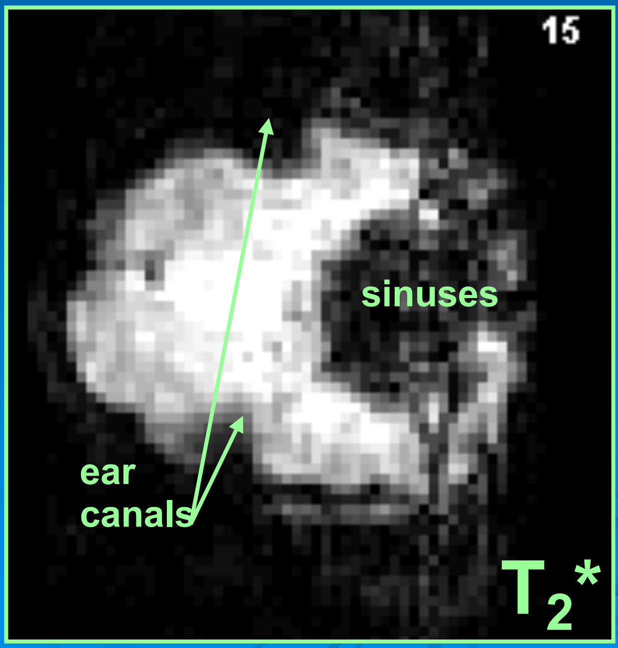


www.imaios.com/en/e-Courses/e-MRI/NMR/Relaxation-nmr

Susceptibility and Susceptibility Artifacts

- ✓ Adding a nonuniform object (like a person) to B_0 will make the total magnetic field B nonuniform
- ✓ This is due to *susceptibility*: generation of extra magnetic fields in materials that are immersed in an external field





Susceptibility Artifact near junctions between air and tissue

- sinuses
- ear canals

Source: Robert Cox's web slides

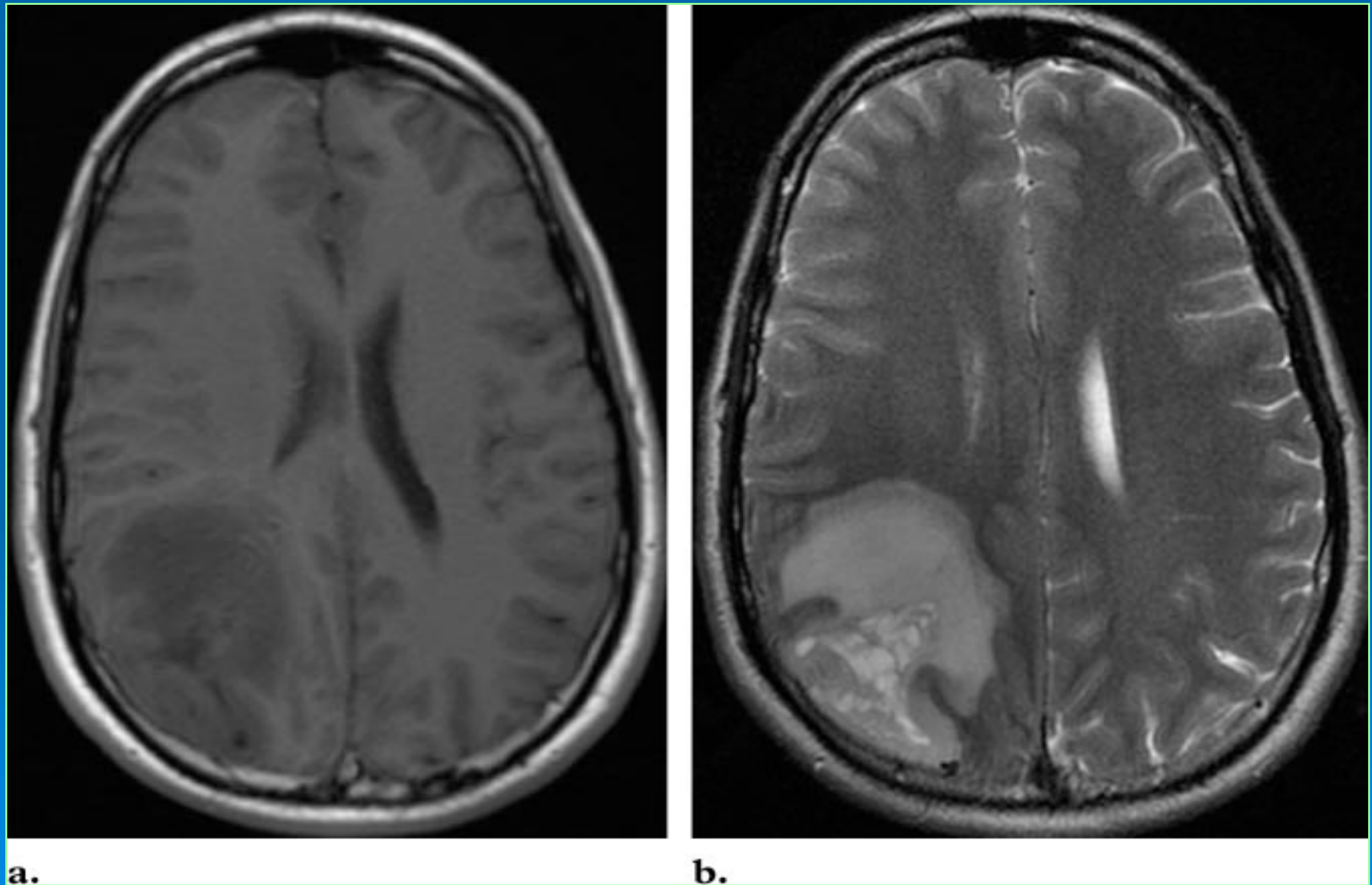
Image contrast
Proton density, T_1, T_2 weighted

T_1 weighted   Density weighted T_2 weighted

- ✓ By 'weighting' the pulse sequence different images of the brain are obtained
- ✓ Weighting is achieved by manipulating acquisition parameters:
  - TR time to repetition of the pulse sequence
  - TE time to echo

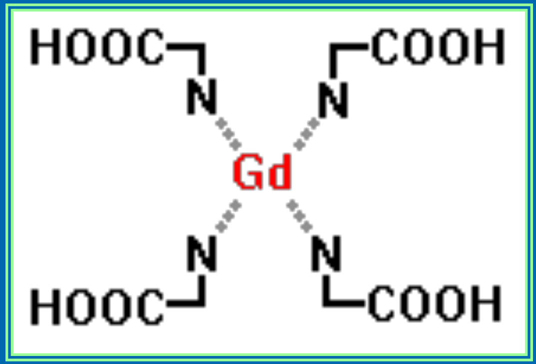
Image contrast
T_1, T_2 weighted

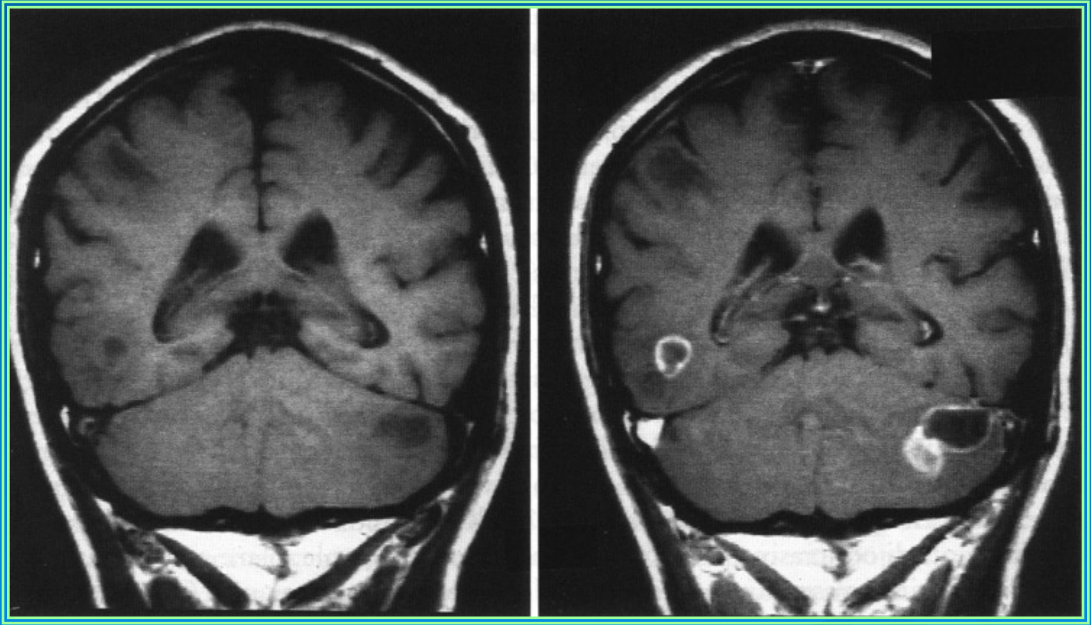
- **Axial T1-weighted (a) and T2-weighted (b) images show a low-grade glioma**
- **Because of hypercellularity, the tumor appears with hypointense signal in (a) and hyperintense signal in (b)**
- **The cystic components and edema are better depicted in (b) than in (a)**



R. Bitar et al. RadioGraphics 2006; 26:513–537

Contrast agents





- Contrast agents in many cases improves our sensitivity and/or specificity
  - Gadolinium based
- Paul Lauterbur and his associated were the first to demonstrate the feasibility of using paramagnetic contrast agents to improve tissue discrimination in MRI

www.imaios.com/en/e-Courses/e-MRI/Improving-MRI-contrast-Contrast-agents/contrast-agents

Localization and gradients

- Localization of the MR signal is obtained by applying a gradient that produces a controlled linear spatial variation of the B_0 magnetic field (z direction), which creates small perturbations to the field in three directions (x, y,and z)
- www.imaios.com/en/e-Courses/e-MRI/MRI-instrumentation-and-safety/gradients

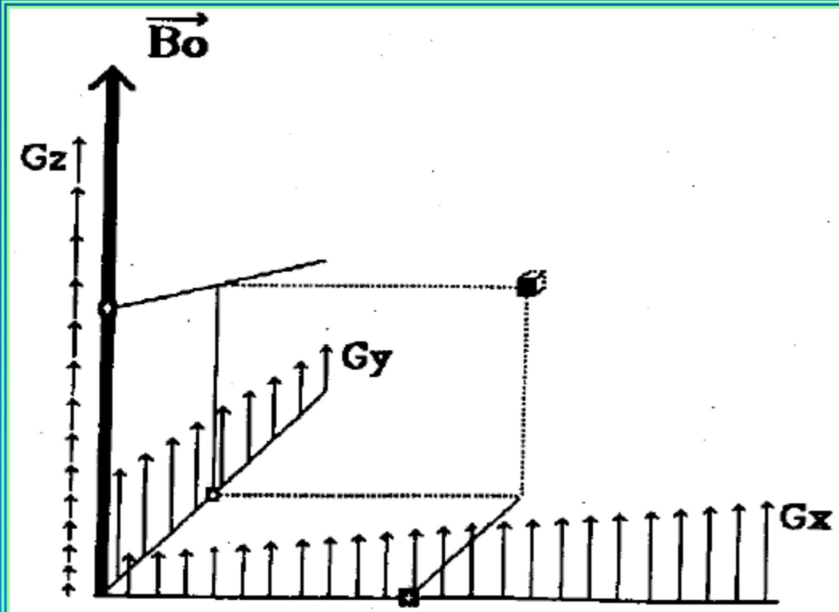


Fig. 4.1 La localizzazione spaziale dell'informazione necessita la codificazione delle tre dimensioni dello spazio: X, Y e Z. Questo si può effettuare per mezzo dei tre gradienti di campo magnetico Gx, Gy, Gz applicati successivamente secondo le tre direzioni studiate.
Non si dovrà confondere la **direzione di campo**, che resta la medesima per ciascun gradiente e la **direzione dei gradienti** definita da quella della progressione.

The spatial localization of the signal

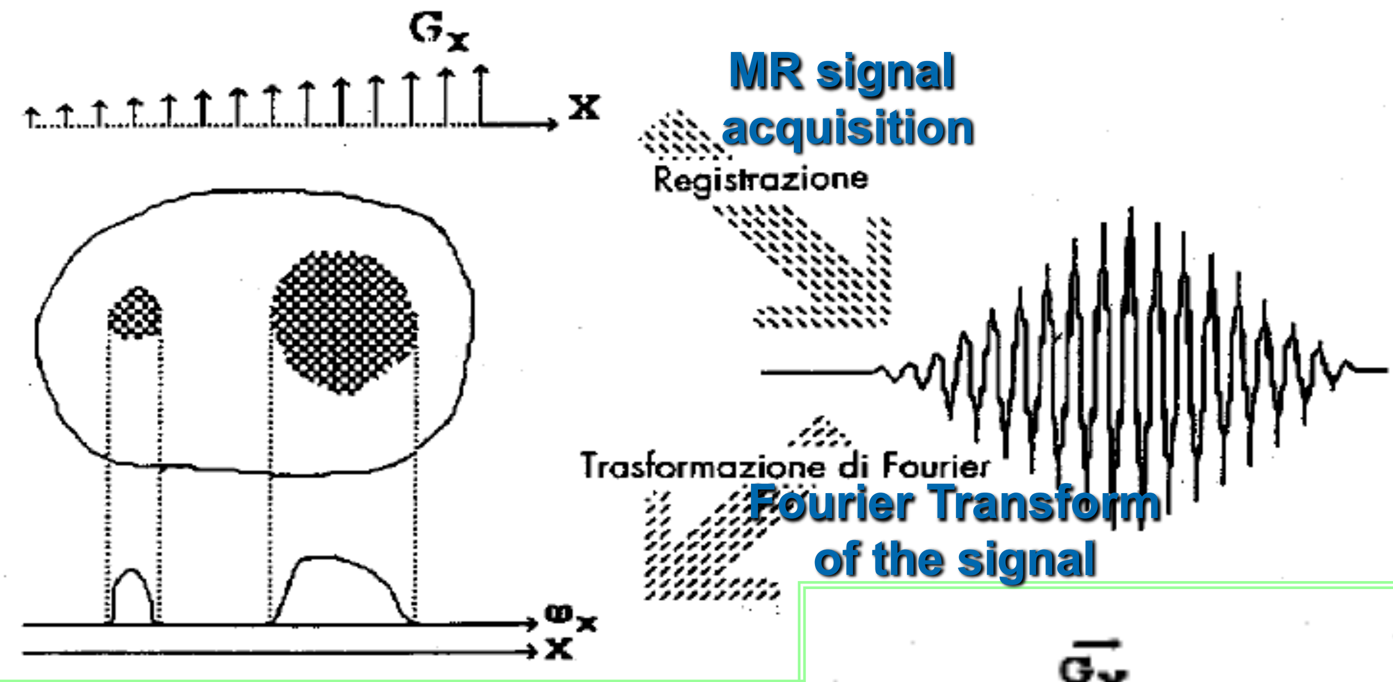
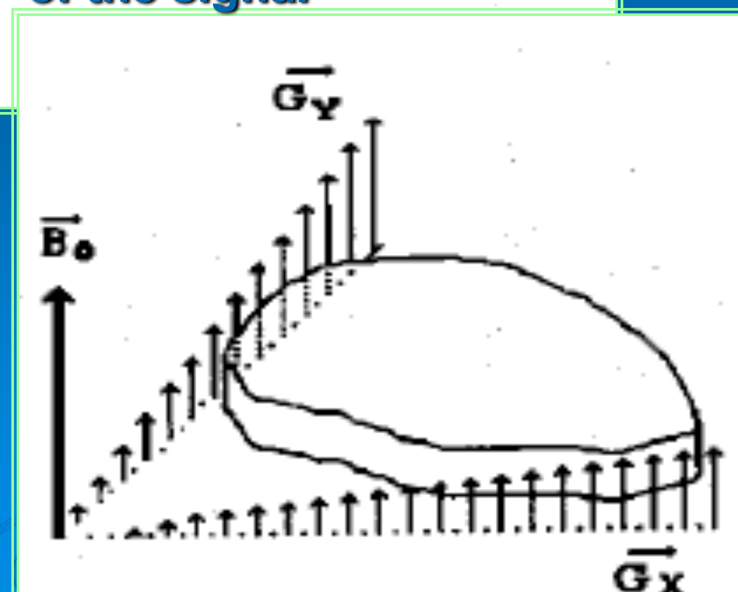


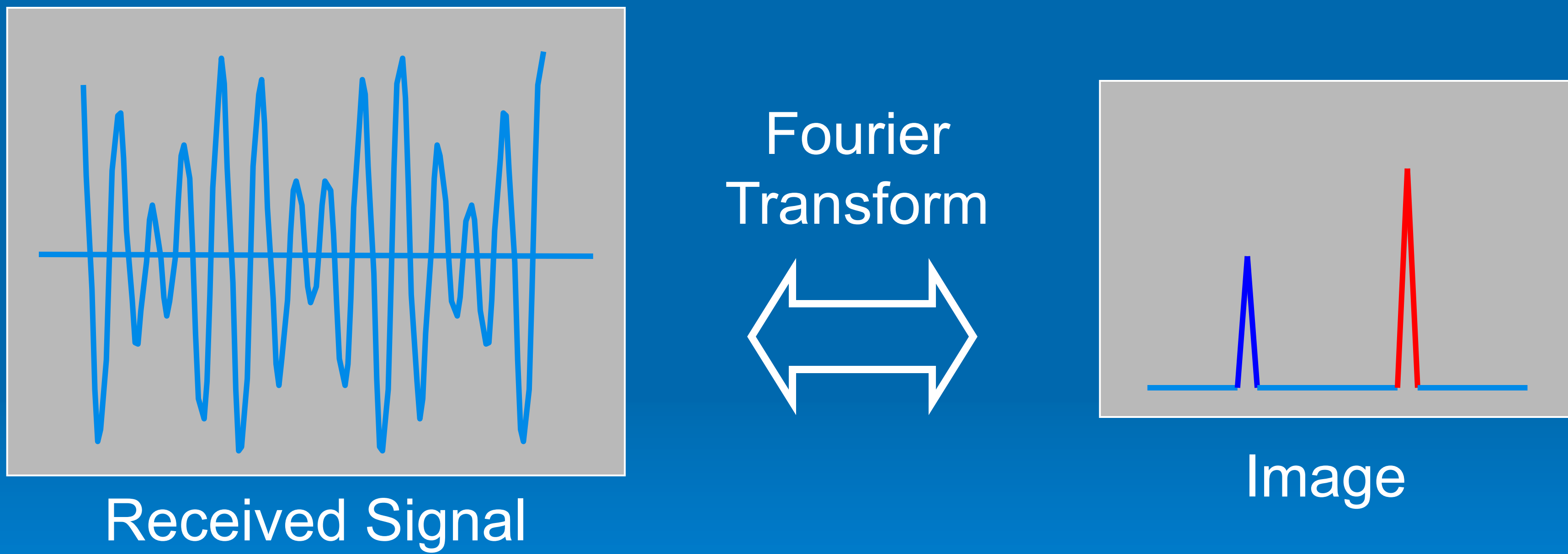
Fig. 4.5 L'applicazione di un gradiente Gx durante la registrazione conduce ad un interferogramma che, per trasformata di Fourier determina una proiezione della sezione su un'asse parallelo alla direzione delle X.



- 1D and 2D examples

www.imaios.com/en/e-Courses/e-MRI/spatial-encoding/Frequency-encoding

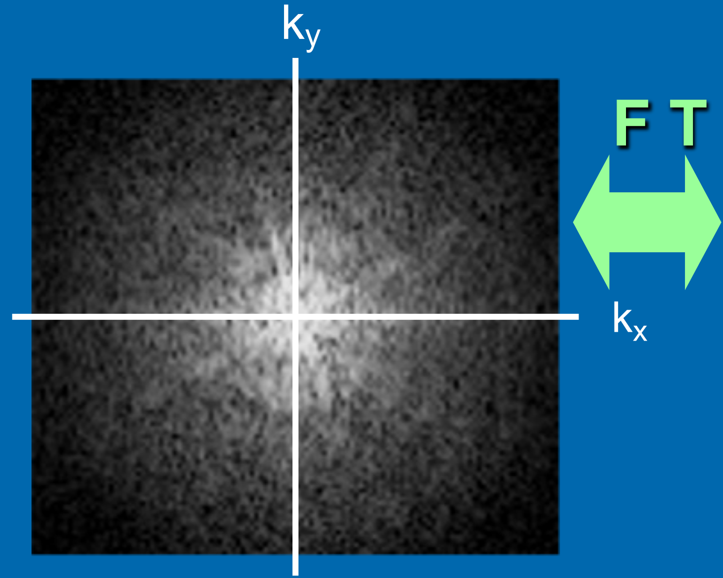
The Fourier transform and the spatial localization



www.imaios.com/en/e-Courses/e-MRI/image-formation/Fourier-transform
www.imaios.com/en/e-Courses/e-MRI/image-formation/spatial-frequency

- *Brian Hargreaves* *Stanford University*

MR image acquisition



Frequency-space
(k-space)

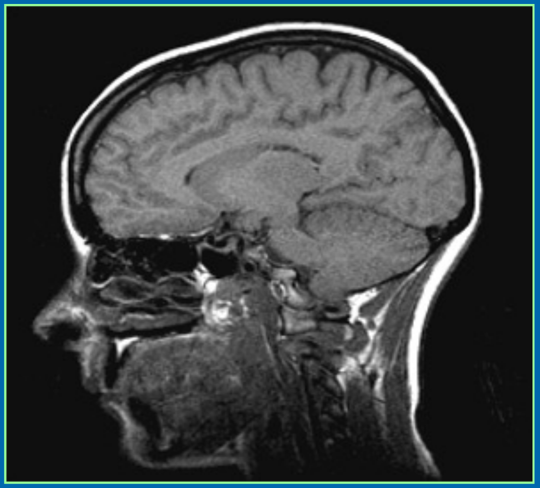
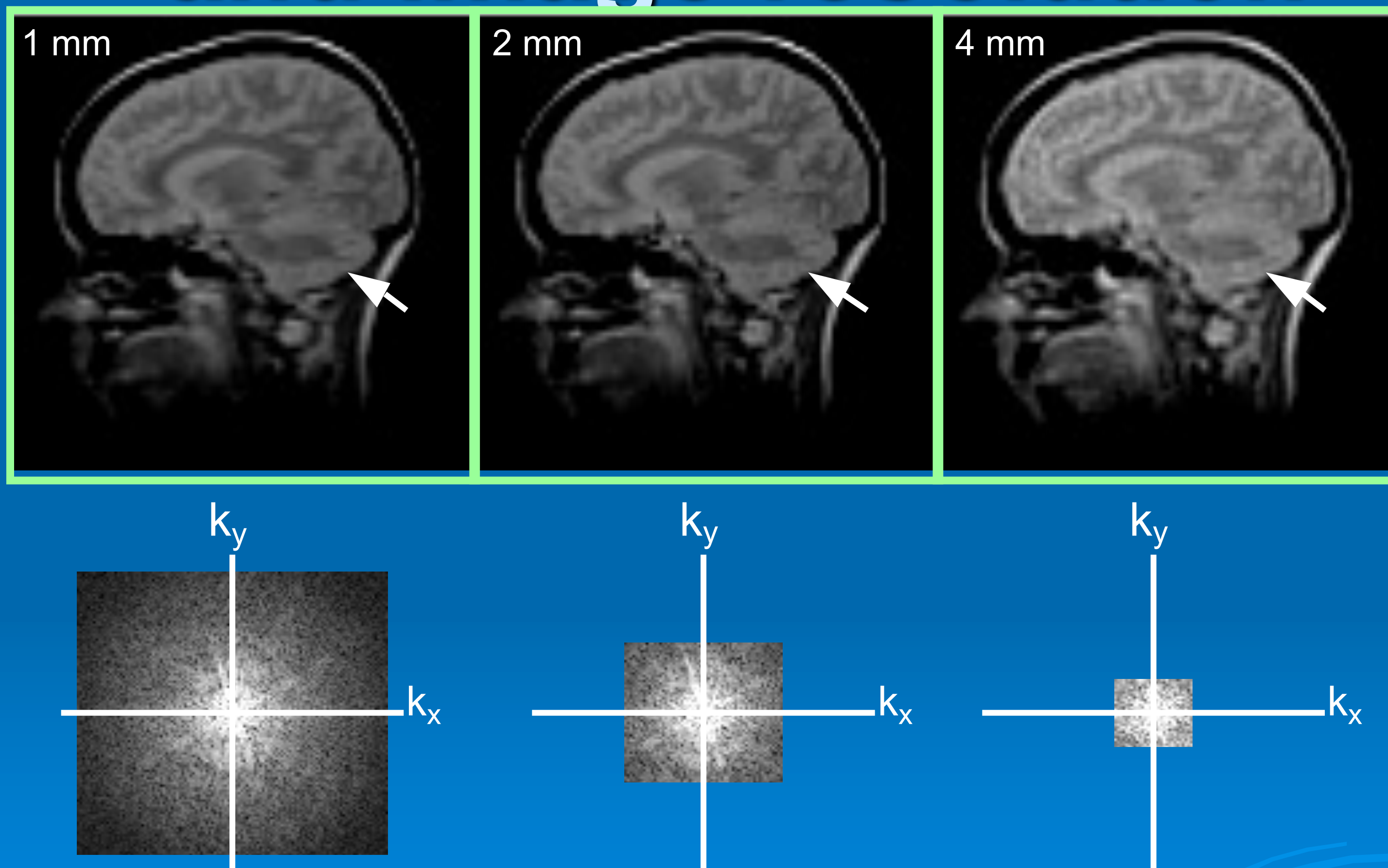


Image space

- Image is acquired in the frequency space
- Each row is filled after an excitation RF pulse
  - The flip angle may be different from 90º
- The excitation pulse is repeated in order to acquire the whole matrix
  - The repetition time (Tr) is the time between 2 RF pulse
  - Tr ~ 100-1000 ms
  - Acquisition time (Tacq) minutes

www.imaios.com/en/e-Courses/e-MRI/image-formation/K-space

Dimension of the acquisition matrix and image resolution

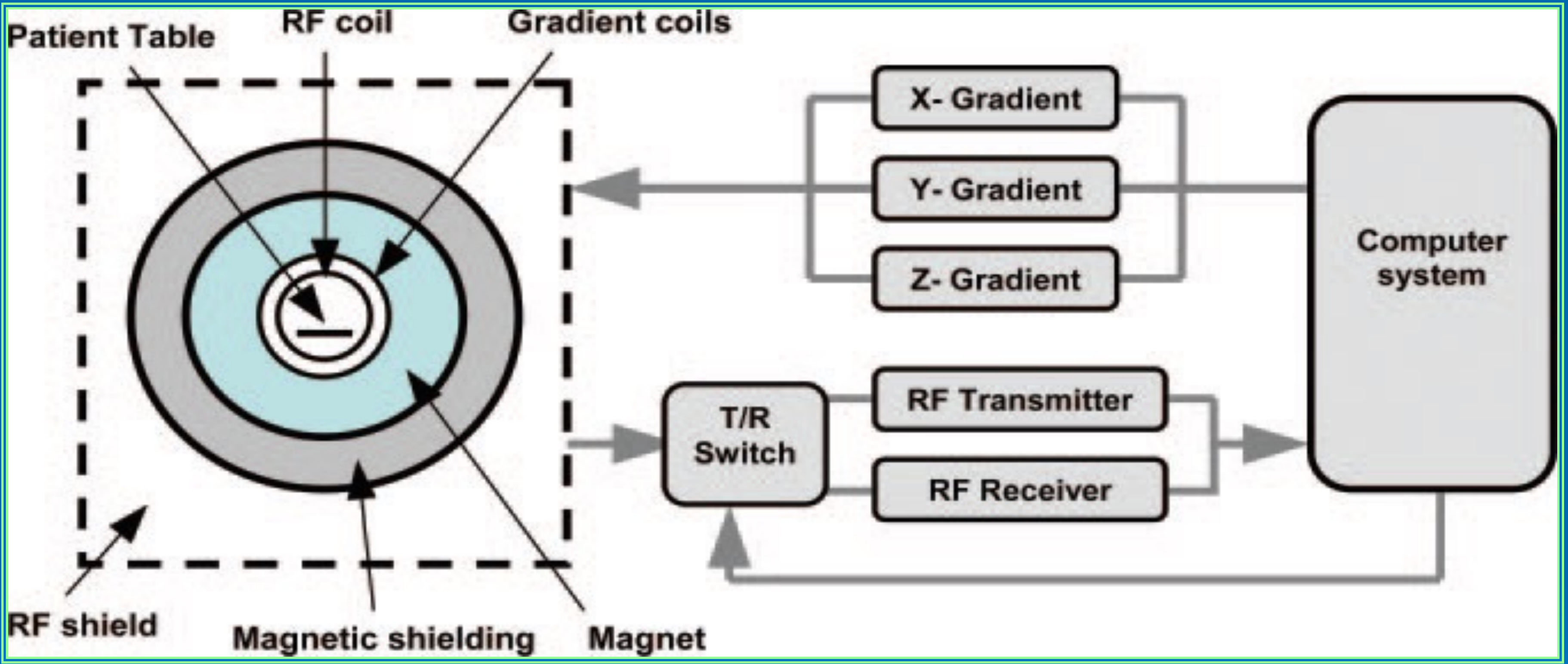


The acquisition time depends from the spatial resolution and from the field of view

www.imaios.com/en/e-Courses/e-MRI/image-formation/Spatial-frequency-image-contrast-and-resolution

- *Brian Hargreaves* *Stanford University*

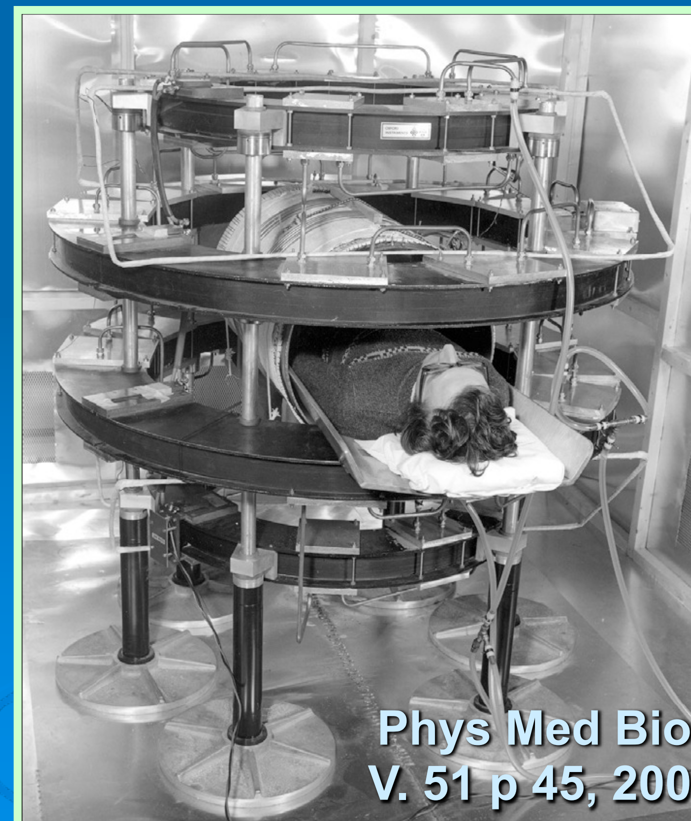
MRI system



- The main subsystems are the magnet, RF generator, gradient coil, and computer, the last of which controls the interplay between subsystems and the reconstruction, storage, and display of the images.
- https://www.youtube.com/watch?v=djAxjtN_7VE

The MR imager

- The Aberdeen NMR Mark I machine as it was in 1979
- Dr J M S Hutchison lying in the position of the patient, inside the 4 horizontal coils of the main electromagnet which provides the magnetic field of 0.04T



Phys Med Biol
V. 51 p 45, 2006

The MRI exam … in practice

- During the exam multiple acquisition sequences are applied, each of them a few minutes long: any motion during acquisition determines artifacts
- Acquisition sequences are different in contrast and spatial orientation
- The approximate duration of the whole exam is 30 minutes
  - https://www.youtube.com/watch?v=8m_RUVrxhew

Limitation:

- No space in the magnet for very fat body
- Claustrophobic subjects can not tolerate the position

Safety

- No ionizing radiation
- The magnetic field is 10000 times higher than our Earth field !

Safety

- Static magnetic field strengths greater than 1.5 T may induce mild sensory effects when a person moves within the field
- Time-varied gradient field strength may cause peripheral nerve stimulation
  - measured in gauss per centimeter per second
- The RF pulses have the potential to heat tissue
  - Due to the conductivity of the tissues

Safety

- Prior to MR imaging examinations, technologists and clinicians should carefully question patients about whether they have ferromagnetic implants such as surgical clips, coils, stents, and pacemakers

- Such implants are ferromagnetic: the static magnetic field may <u>torque</u> the object and exert a <u>translational force</u>

Safety

- Fatal accidents in MR imaging were caused by the failure to identify subjects with a cardiac pacemaker

- The FDA recently received several reports of serious injury, including coma and permanent neurologic impairment in patients with neurologic stimulators

Safety

Projectile effect

- Magnetic objects are attracted at high speed to the scanner
- Severe or fatal injury to the patient is possible

https://educationalgames.nobelprize.org/educational/medicine/mri/