OUTLINE AND GOALS

- The MR system
- History of MRI
- Magnetic fields
- Internal components of MRI and RF coils
- Magnetic properties of materials and nuclear characteristics
- The Larmor equation and precession
- Magnetic moment and flip angles
- Longitudinal and transverse relaxation
- T1, T2, and T2*

HISTORY OF MRI DEVELOPMENTS

1938	Nuclear magnetic resonance by I.I. Rabi
Mid-1940s	First detection of NMR in bulk matter
1950s	Discovery of chemical shift and spin-spin coupling
1960s	Development of pulse Fourier-transform NMR
1973	First NMR image by Paul Lauterbur, who shared the Nobel Prize in medicine in 2003
1975	2D NMR by Ernst, which earned him the 1991 Nobel Prize in chemistry
1977	First study performed on human
1980s	*k*-space formalism

THE PRINCIPLES OF MRI

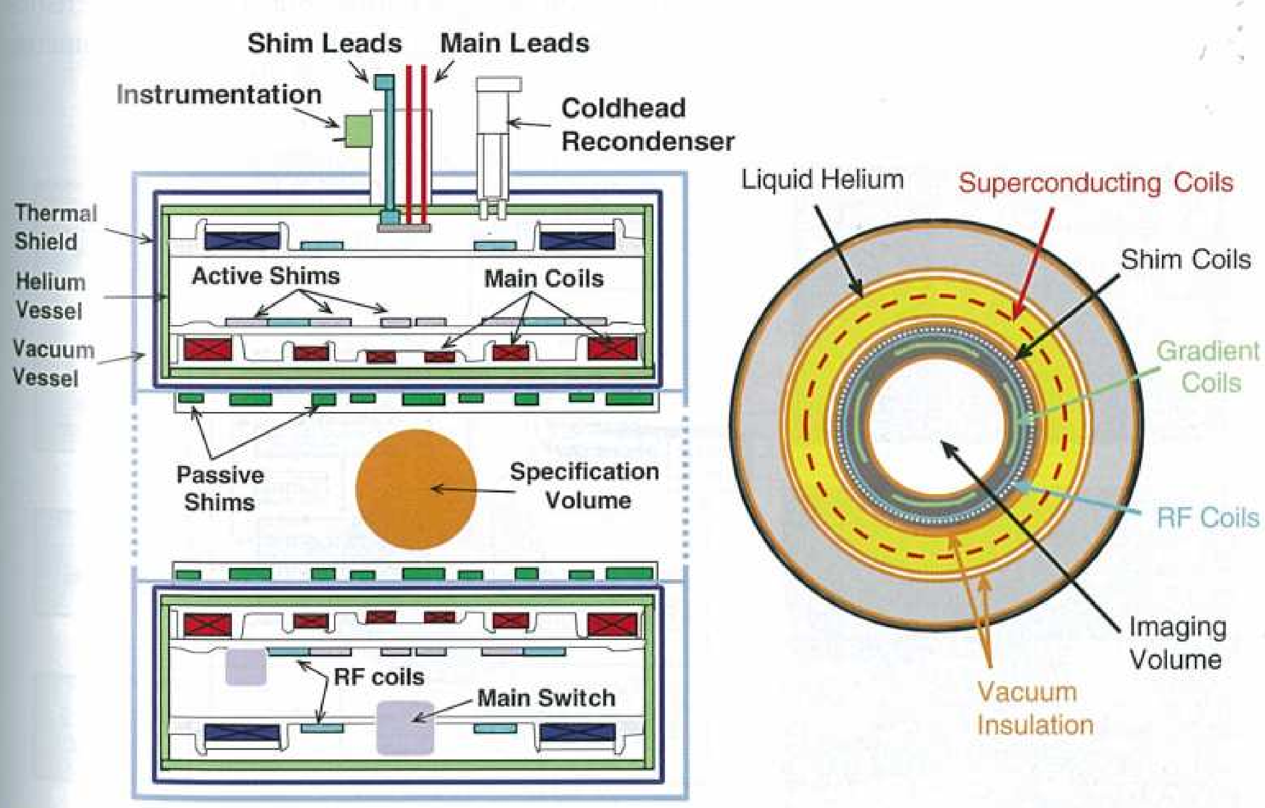
involves three sequential steps:

- The alignment (polarization) of the magnetic nuclear spins in an applied, constant magnetic field $\mathbf{B}_0$.
- The perturbation of this alignment of the nuclear spins by a weak oscillating magnetic field, usually referred to as a radio-frequency (RF) pulse set at the Larmor frequency, which is dependent upon the static magnetic field ($\mathbf{B}_0$) and the nuclei of observation.
- The detection of the NMR signal during or after the RF pulse is possible due to the current induced in a detection coil by precession of the nuclear spins around $\mathbf{B}_0$.

BASIC MRI INGREDIENTS

– Non-zero magnetic moment nuclei	*N*uclear
– Static magnetic field, B_o	*M*agnetic
– Radiofrequency field, B_1	*R*esonance
– Magnetic field gradients, $G_{x,y,z}$	

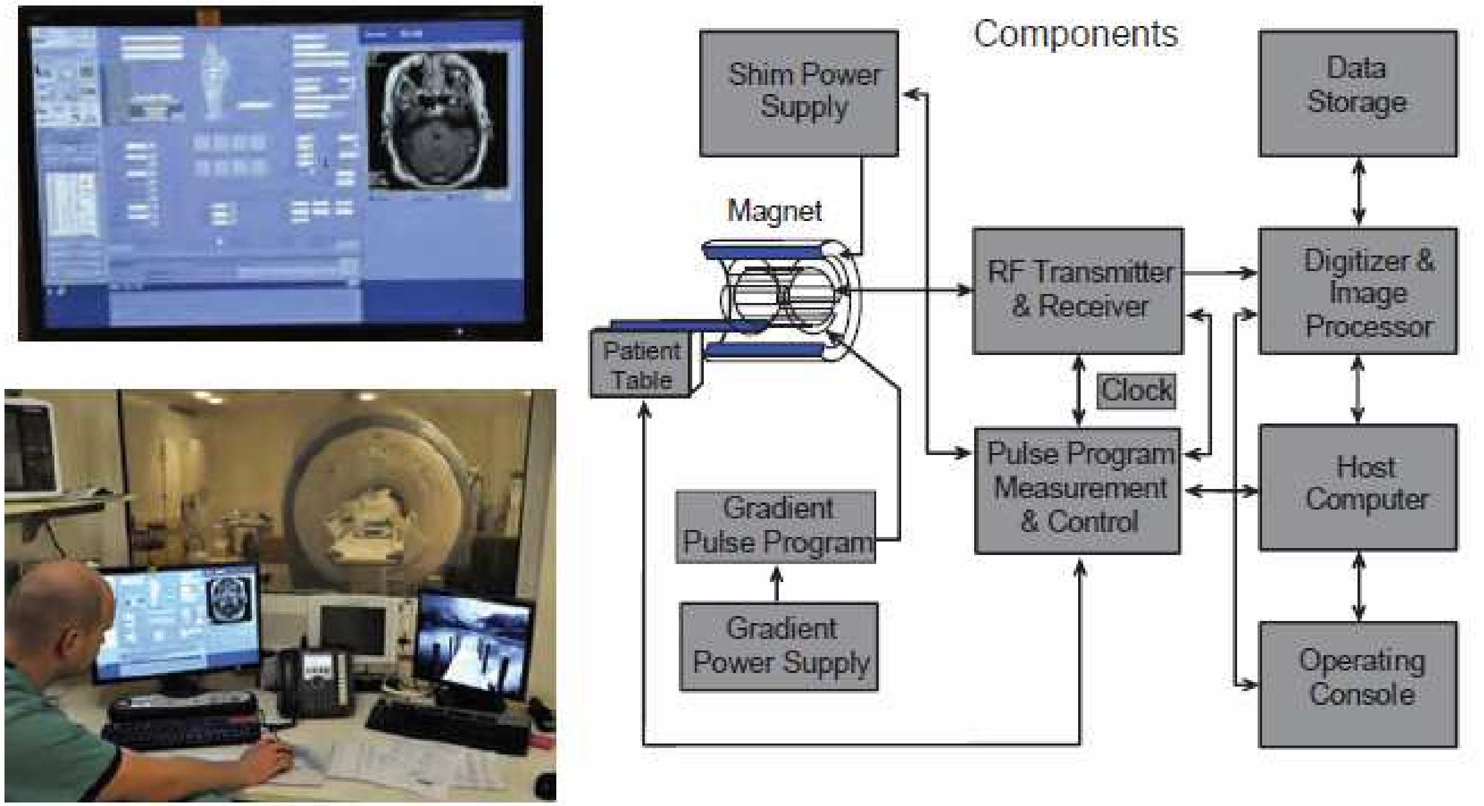
INTERNAL COMPONENTS



■ FIGURE 12-3 Internal components of a superconducting air-core magnet are shown. On the left is a cross section through the long axis of the magnet illustrating relative locations of the components, and on the right is a simplified cross section across the diameter.

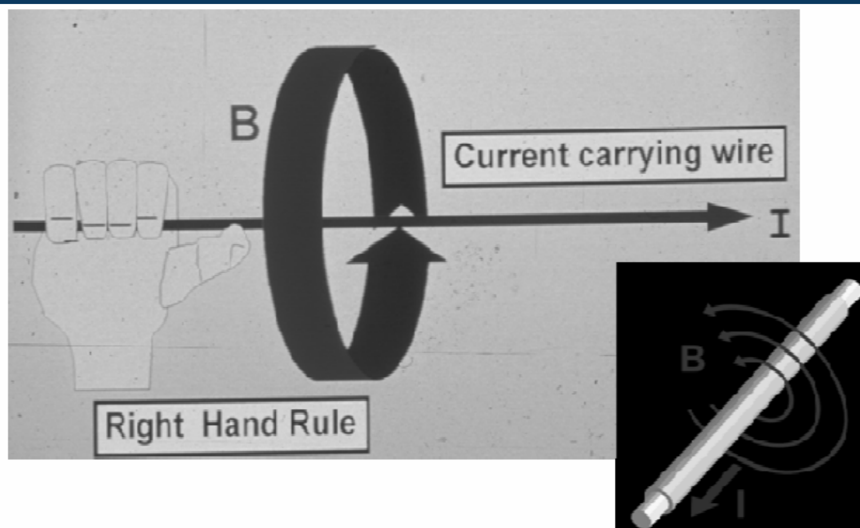
- Superconducting coils of the main are cooled with a cryogenic liquid (Helium)
- RF coils are used to transmit and receive offset fields.
- Gradient coils (3D) produce linear variation across the imaging volume. (0.01-1.0 Gauss/cm)
- Shim coils (passive or active) interact with the main magnet to improve homogeneity over the imaging volume.

THE MRI SYSTEM



■ **FIGURE 12-5** The MR system is shown **(lower left)**, the operators display **(upper left)**, and the various subsystems that generate, detect, and capture the MR signals used for imaging and spectroscopy.

MAGNETIC FIELDS



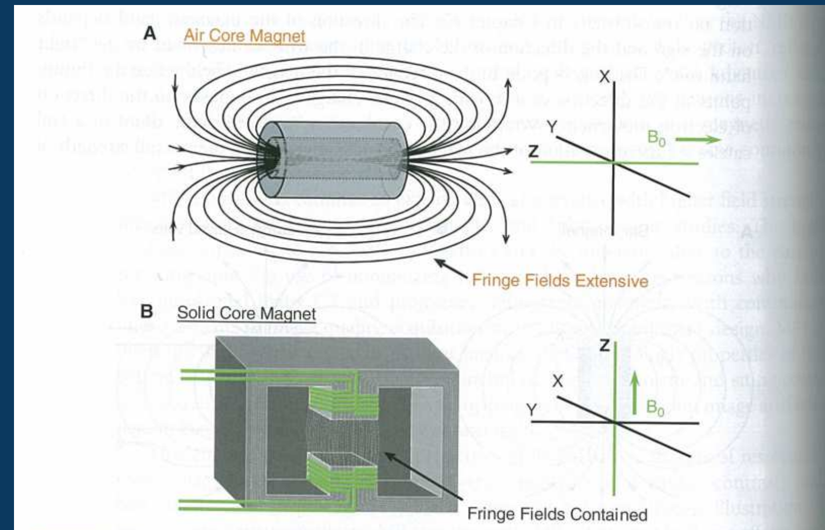


FIGURE 12-2 **A.** Air core magnets typically have a horizontal main field produced in the bore of the electrical windings, with the z-axis (B_0) along the bore axis. Fringe fields for the air core systems are extensive and are increased for larger bore diameters and higher field strengths. **B.** The solid core magnet has a vertical field, produced between the metal poles of a permanent or wire-wrapped electromagnet. Fringe fields are confined with this design. In both types, the main field is parallel to the z-axis of the Cartesian coordinate system.

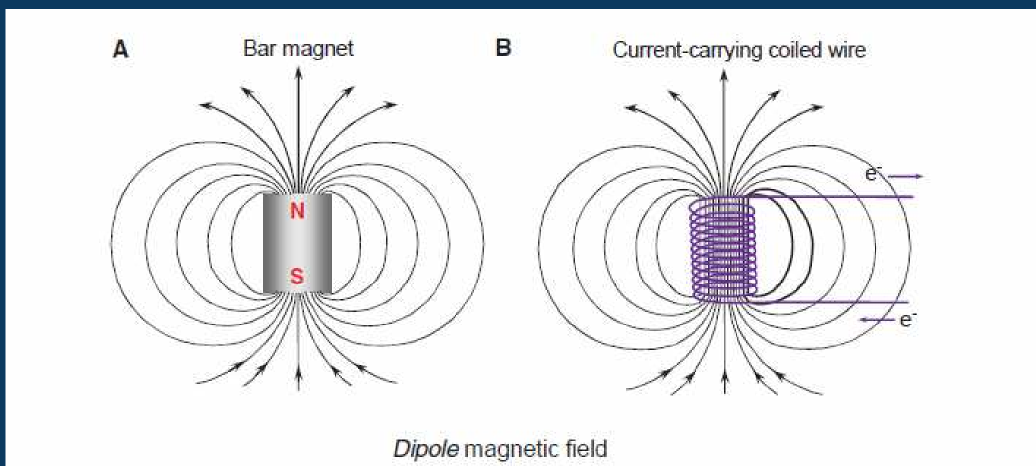
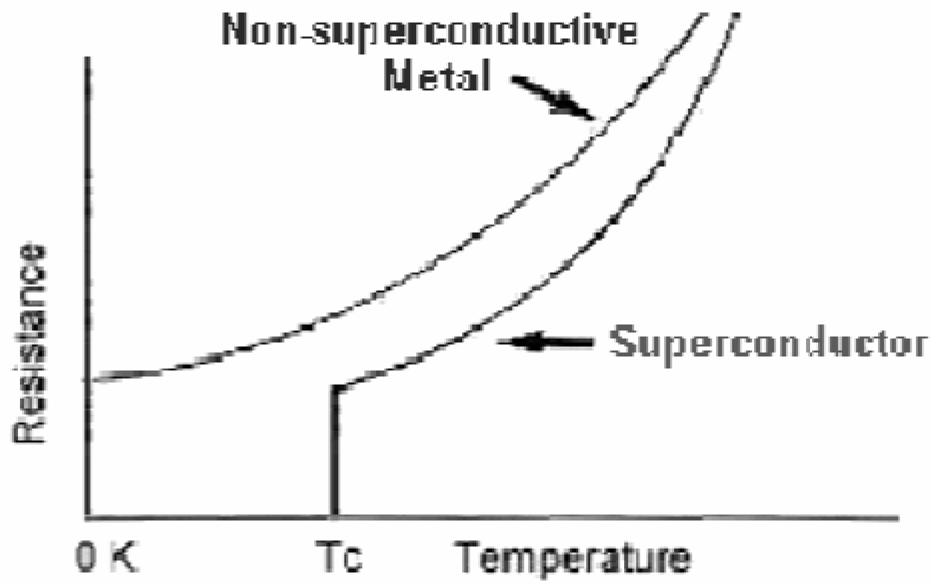


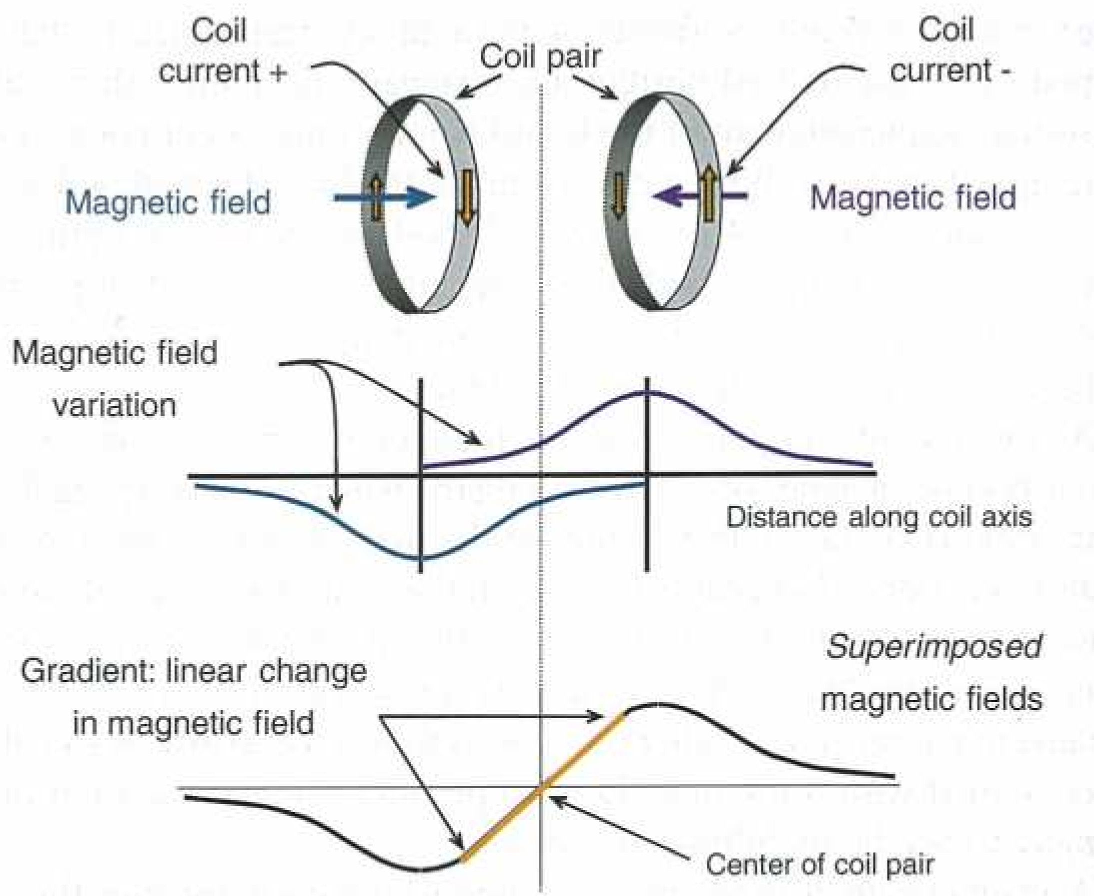
FIGURE 12-1 **A.** The magnetic field has two poles with magnetic field lines emerging from the north pole (*N*), and returning to the south pole (*S*), as illustrated by a simple bar magnet. **B.** A coiled wire carrying an electric current produces a magnetic field with characteristics similar to a bar magnet. Magnetic field strength and field density are dependent on the amplitude of the current and the number of coil turns.

Superconductivity

- Niobium-Titanium alloys commonly used for MRI
- Zero electrical resistance below 4° K (-452° F)
- Magnet is “ramped up” then disconnected from B_0 coil power

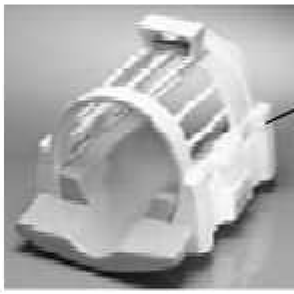


GRADIENT MAGNETIC FIELDS



■ **FIGURE 12-4** Gradients are produced inside the main magnet with coil pairs. Individual conducting wire coils are separately energized with currents of opposite direction to produce magnetic fields of opposite polarity. Magnetic field strength decreases with distance from the center of each coil. When combined, the magnetic field variations form a linear change between the coils, producing a linear magnetic field gradient, as shown in the lower graph.

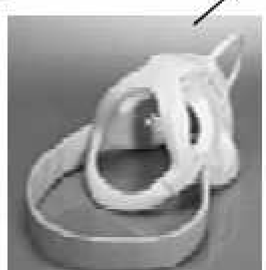
Examples of RF Coils

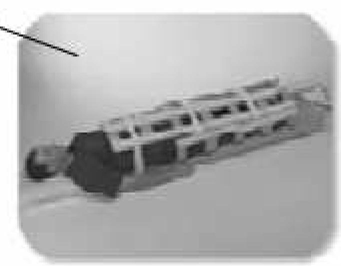


Head coil *Birdcage design most common*

Body coil

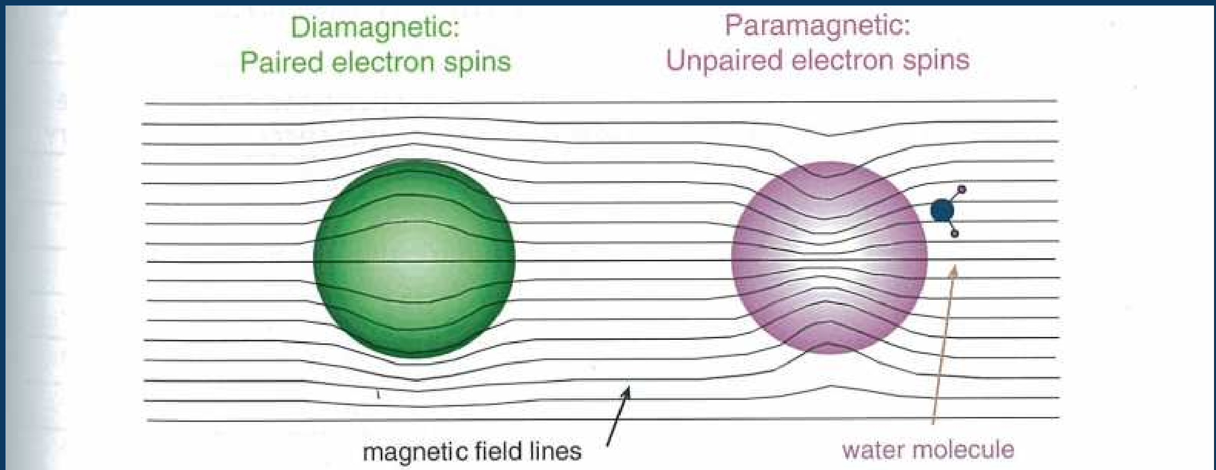
Surface coils





MAGNETIC PROPERTIES OF MATERIALS

- Diamagnetic materials have slightly negative susceptibility and oppose the applied magnetic field.
  - Due to paired electrons in the surrounding orbitals
  - E.g. Calcium, water, most organic materials
- Paramagnetic have slightly positive susceptibility and enhance the local magnetic field but have no ‘self-magnetism.
  - O_2, deoxyhemoglobin, some blood degradation products (methemoglobin), and Gadolinium-based contrast agents.
- Ferromagnetic can produce very strong self-magnetism
  - Iron, cobalt, nickel



■ FIGURE 12-6 The local magnetic field can be changed in the presence of diamagnetic (depletion) and paramagnetic (augmentation) materials, with an impact on the signals generated from nearby signal sources such as the hydrogen atoms in water molecules.

MAGNETIC CHARACTERISTICS OF THE NUCLEUS

- Magnetic properties are influenced by spin and charge distributions intrinsic to the proton and neutron.
- The proton has magnetic dipole with positive charge
- The neutron is uncharged, but associated nuclear spin result in a magnetic field of opposite direction and approximately the same strength as the proton.
- The net nuclear characteristics yield the nuclear magnetic moment.

TABLE 12-1 PROPERTIES OF THE NEUTRON AND PROTON

CHARACTERISTIC	NEUTRON	PROTON
Mass(kg)	1.674×10^{-27}	1.672×10^{-27}
Charge (coulomb)	0	1.602×10^{-19}
Spin quantum number	½	½
Magnetic moment (J/T)	-9.66×10^{-27}	1.41×10^{-26}
Magnetic moment (nuclear magneton)	−1.91	2.79

NUCLEAR MAGNETIC CHARACTERISTICS OF THE ELEMENTS

- Nuclei with odd number (if A is odd) of nuclear elements can be used to generate MRI signals
  - Hydrogen with a single proton is most commonly used have a very large magnetic moment and abundance.

TABLE 12-2 MAGNETIC RESONANCE PROPERTIES OF MEDICALLY USEFUL NUCLEI

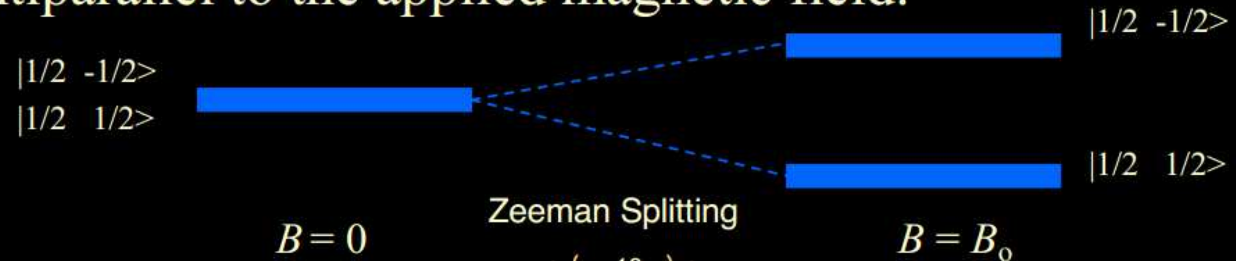
NUCLEUS	SPIN QUANTUM NUMBER	% ISOTOPIC ABUNDANCE	MAGNETIC MOMENT[b]	% RELATIVE ELEMENTAL ABUNDANCE[a]	RELATIVE SENSITIVITY
^{1}H	½	99.98	2.79	10	1
^{3}He	½	0.00014	−2.13	0	–
^{13}C	−½	0.011	0.70	18	–
^{17}O	$^{5}/_{2}$	0.04	−1.89	65	9×10^{-6}
^{19}F	½	100	2.63	<0.01	3×10^{-8}
^{23}Na	$^{3}/_{2}$	100	2.22	0.1	1×10^{-4}
^{31}P	½	100	1.13	1.2	6×10^{-5}

[a]moment in nuclear magneton units = 5.05×10^{-27} J T^{-1}.

[b]*Note:* by mass in the human body (all isotopes).

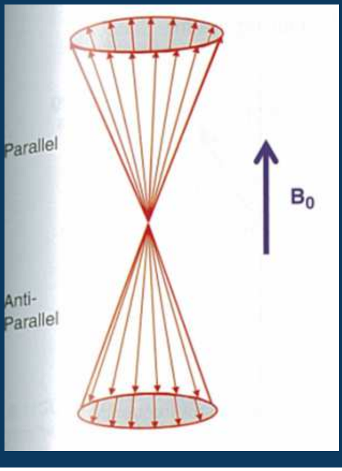
ZEEMAN SPLITTING

- Without an external magnetic field, the magnetic moments in a sample, or patient, are randomly distributed, *i.e.*, there is no *net* magnetization.
- In an externally applied field, protons, which have a spin quantum number of 1/2, have two allowed states: parallel or antiparallel to the applied magnetic field.



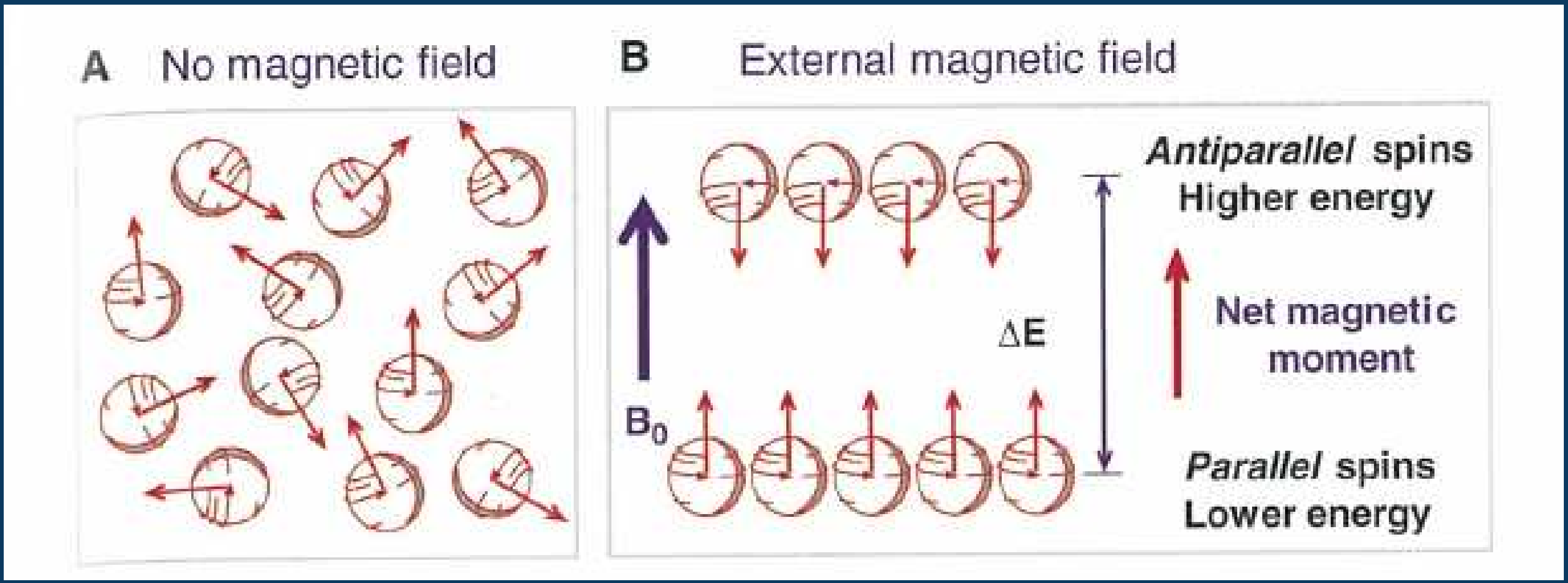
- The equilibrium distribution of spin up and spin down protons is given by the Boltzmann distribution,

$$N^0_- / N^0_+ = e^{-\frac{\gamma\hbar B_0}{kT}}$$



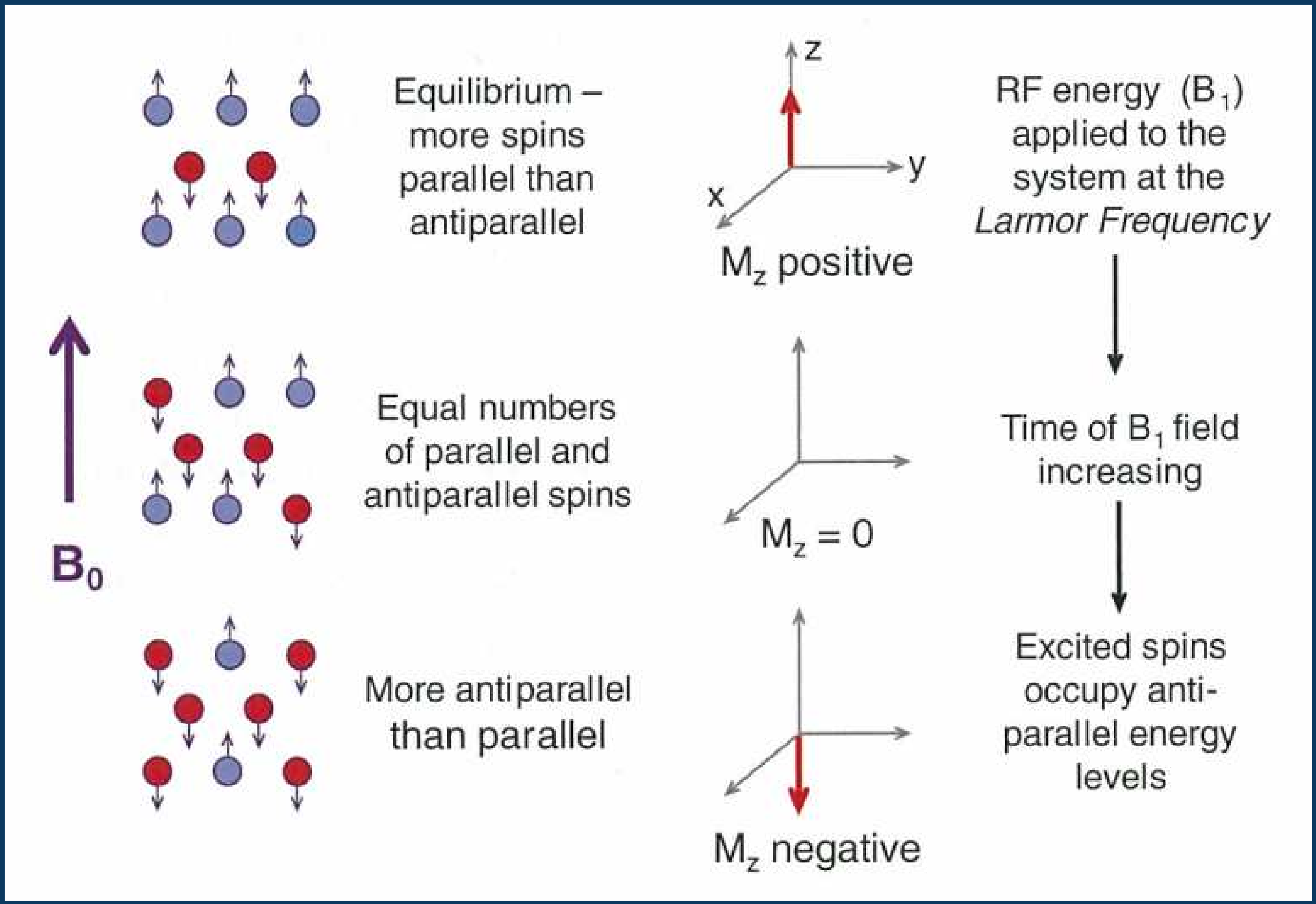
NMR ENERGY LEVELS

- At 1 T the number of excess protons in the low energy state is ~3 per million.
- Therefore, in one voxel containing 10^{21} protons, 3×10^{15} are in the lower state.
- The energy separation is determined from the magnetic field and the magnetic moment, μ.



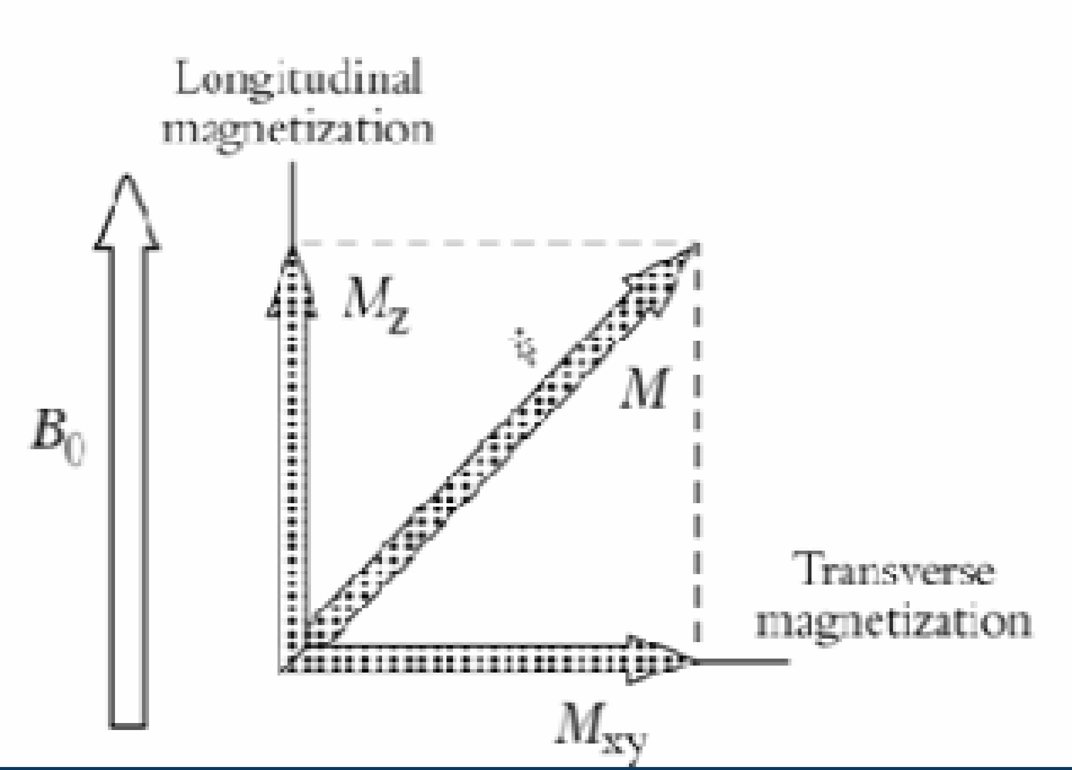
ADDING ENERGY TO THE SYSTEM

- Add RF energy at Larmor frequency (resonance)
- Magnetic field component of RF is referred to as B_1

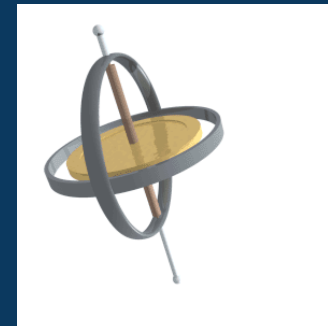


SUM OF NUCLEAR MAGNETIC MOMENT

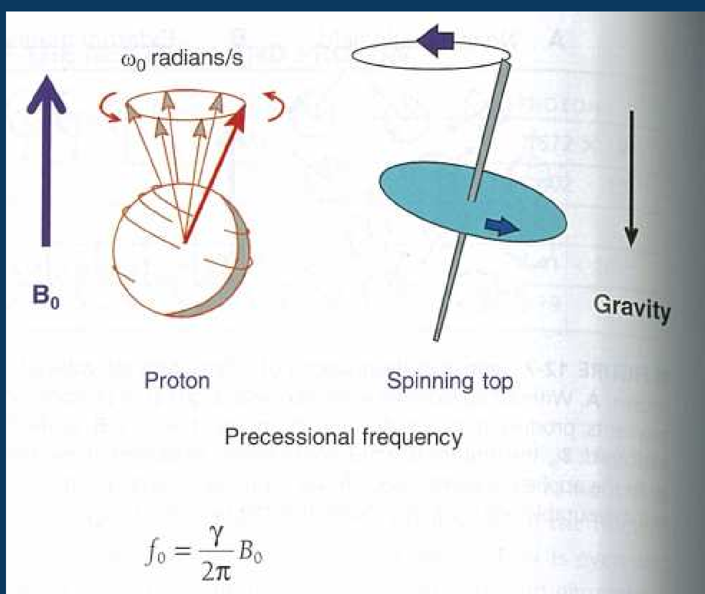
- M is a vector sum of all the individual magnetic moments of each nuclei
- M parallel to B_0 is the *longitudinal* component
- M perpendicular to B_0 is the *transverse* component



THE LARMOR EQUATION



- Describes the dependence between the magnetic field, B_0, and the angular precessional frequency, ω_0.
-
  - $\omega_0 = \gamma B_0$.
  - Where γ is the gyromagnetic ratio unique to each element.



Nuclear Gyromagnetic Ratio

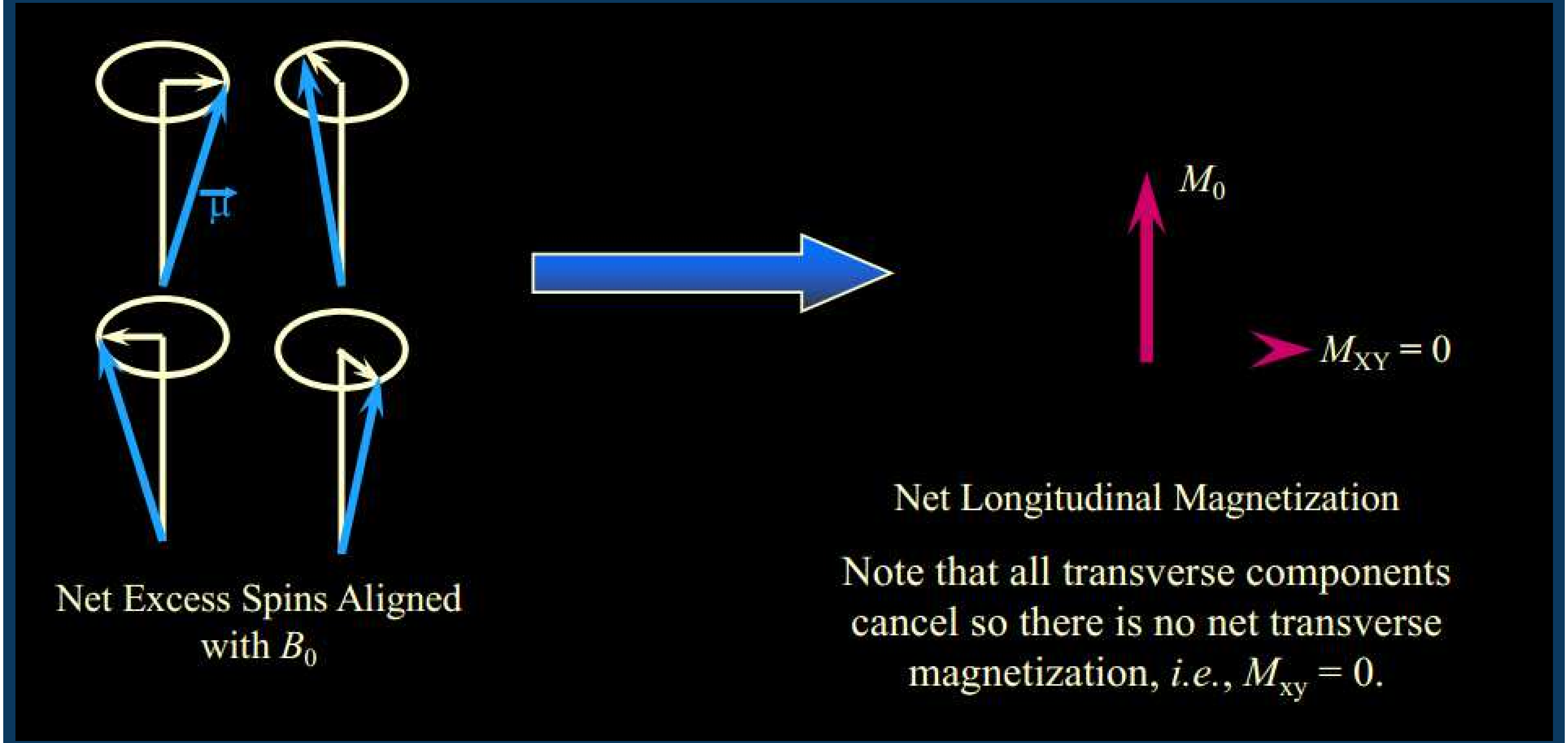
$\gamma =$ nuclear gyromagnetic ratio

$$\gamma = \frac{\text{magnetic moment}}{\text{spin angular momentum}}$$

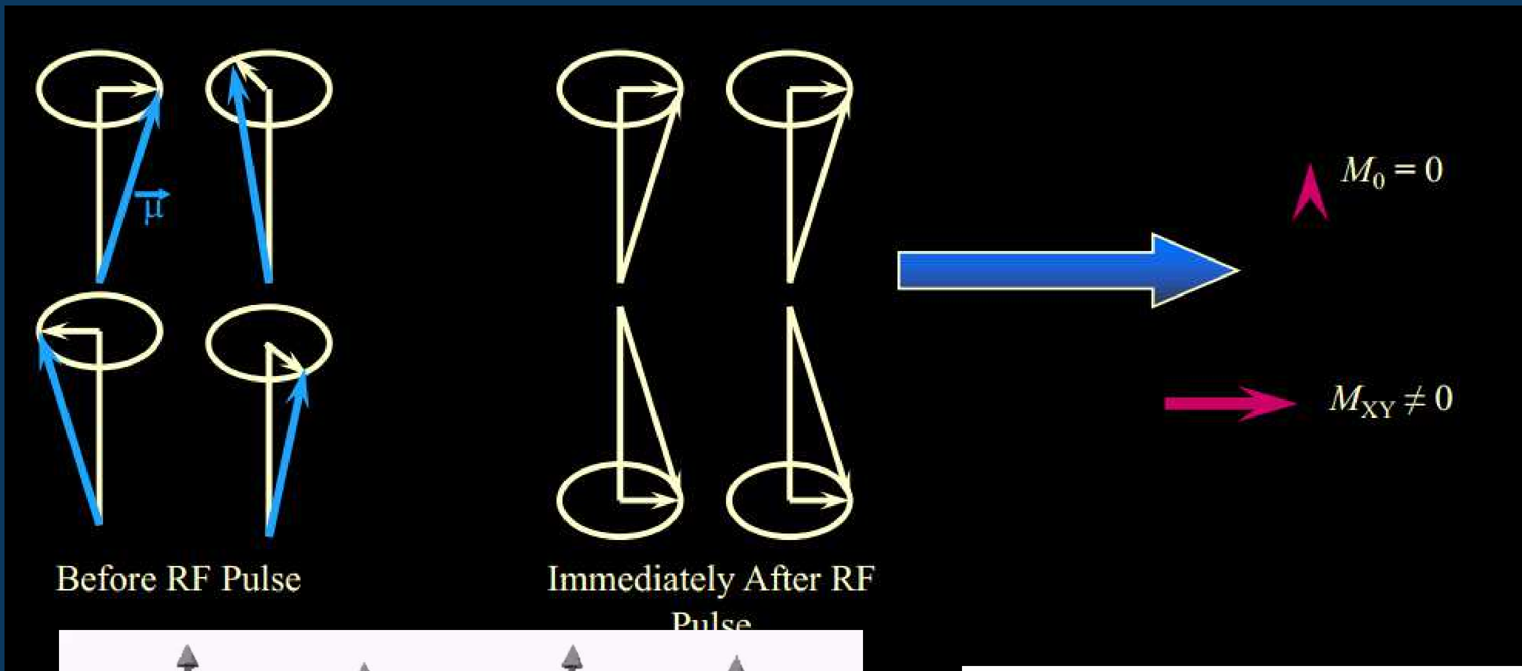
$$\gamma = \frac{\mu}{\frac{1}{2}\hbar}$$

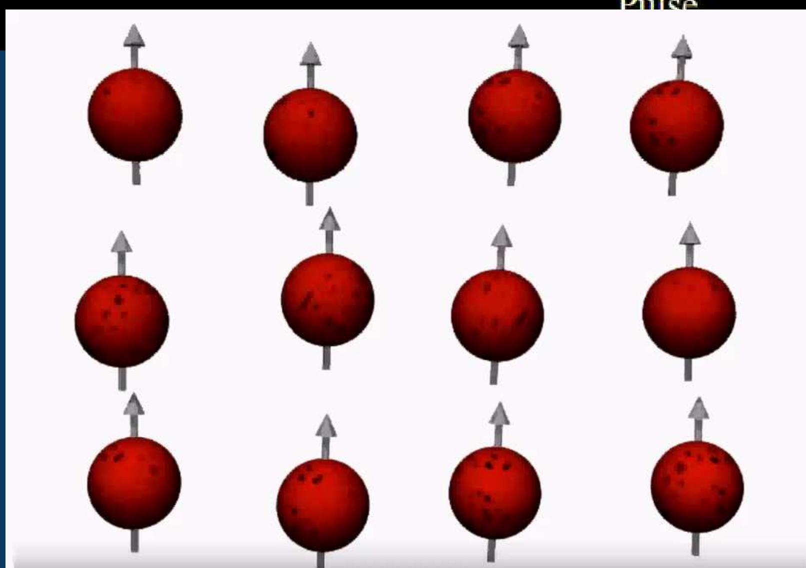
Nucleus	$\gamma/2\pi$ (MHz/T)
^{1}H	42.58
^{13}C	10.7
^{17}O	5.8
^{19}F	40.0
^{23}Na	11.3
^{31}P	17.2

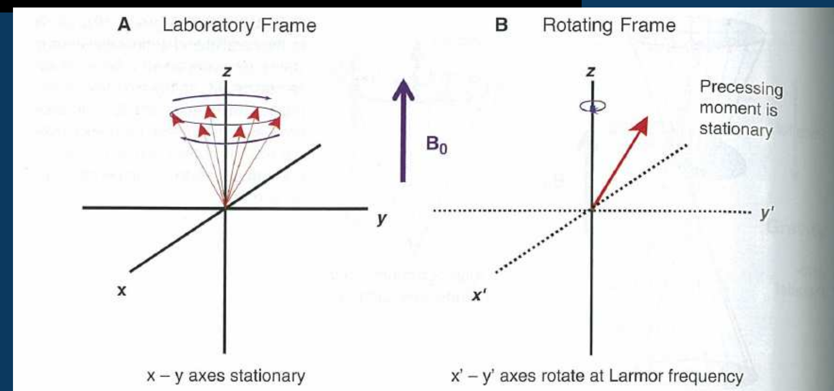
WITHOUT TRANSVERSE MAGNETIZATION



WITH TRANSVERSE MAGNETIZATION (B_1)



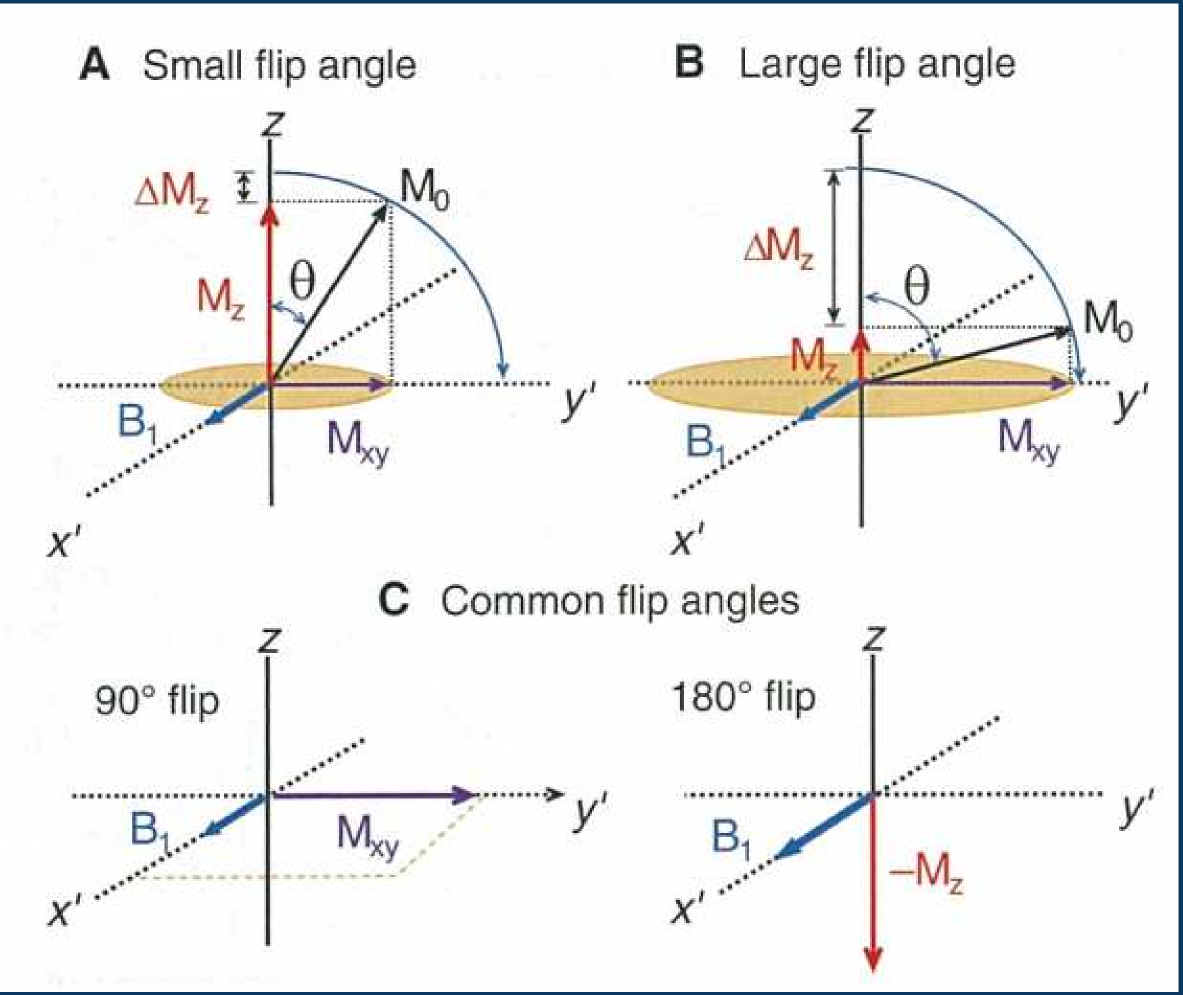




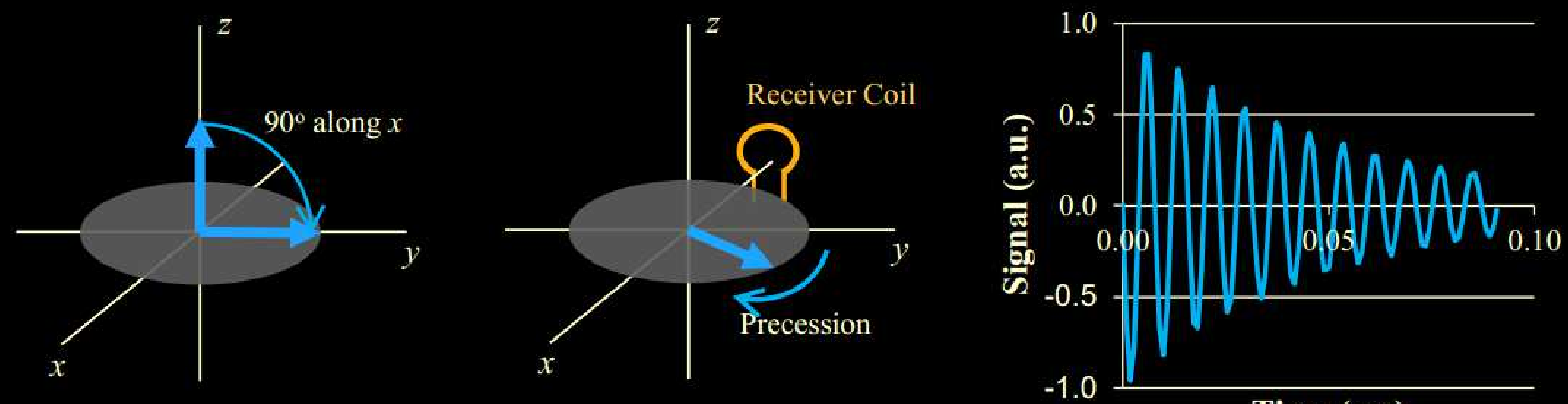
■ FIGURE 12-10 **A.** The *laboratory frame of reference* uses stationary three-dimensional Cartesian coordinates: x, y, z. The magnetic moment of the proton precesses around the z-axis at the Larmor frequency as the illustration attempts to convey. **B.** The *rotating frame of reference* uses rotating Cartesian coordinate axes that *rotate about the z-axis* at the Larmor precessional frequency, and the other axes are denoted: *x'* and *y'*. When precessing at the Larmor frequency, the proton magnetic moment is stationary.

THE FLIP ANGLE VS. B1 AND TIME

- Size of the flip angle depends on the duration and magnitude of B_1.
- Common flip angles are 90^o for maximum transverse magnetization, while 180^o flip angle will invert the longitudinal magnetization.



FREE INDUCTION DECAY



Creation of M_{xy} from M_0

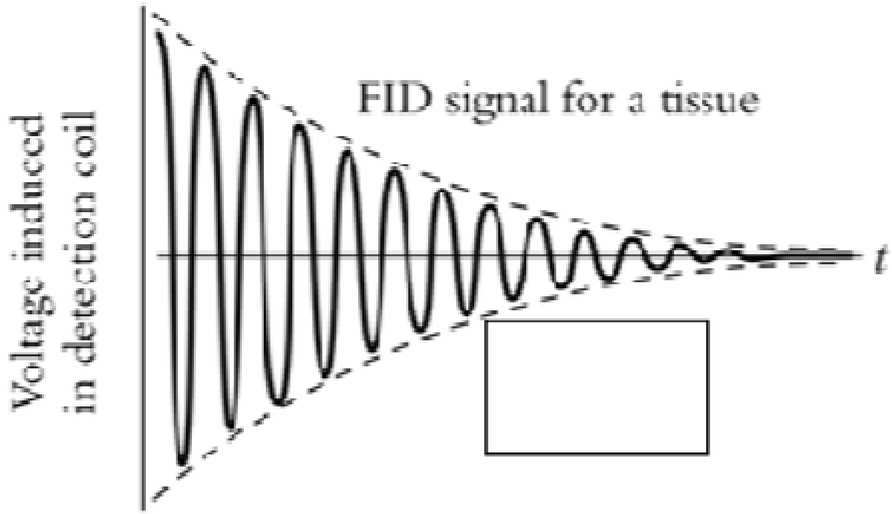
Precession of M_{xy} about B_0

Free Induction Decay (FID)
(with T_2* decay envelope)

$Signal \propto \omega_0 M_0 \propto \omega_0^2 \propto B_0^2$

$Noise \propto \omega_0 \propto B_0$

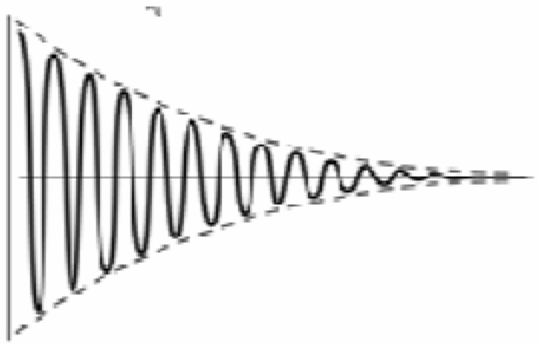
SUMMARY - NMR IN A NUTSHELL



Free Induction Decay (FID)

- **Water nuclei act like little bar magnets that align with the magnetic field of the scanner**
- **Nuclei absorb radiofrequency (RF) energy and flip over (go to a higher energy level)**
- **When they flip back (return to their ground state), RF energy is given off**
- **The signal (FID) results and contains information regarding the proton density and chemistry (T1 & T2) of the local tissue**

THE FID SIGNAL



Relaxation !!!

- After 90 degree pulse, FID signal diminishes due to decreasing transverse component of M
  - Longitudinal relaxation (T1 – Spin Lattice)
  - Transverse relaxation (T2 – Spin Spin)
- Amplitude also depends on proton density

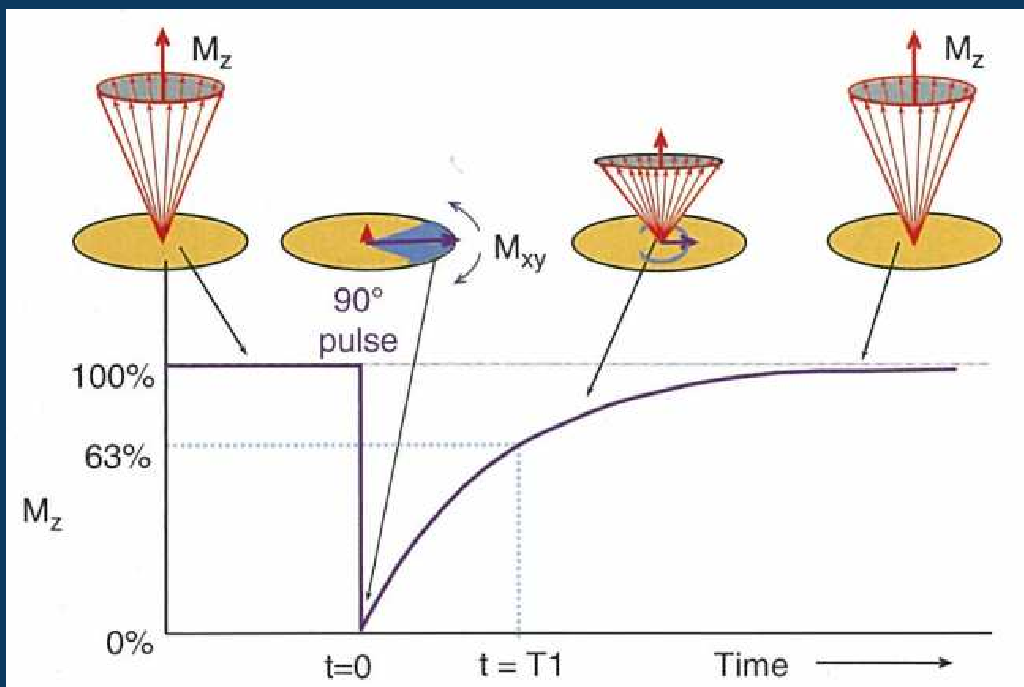
MORE ON RELAXATION AND DECAY

- Immediately following the 90^0 pulse, the magnetic moments precess *in phase*, and $N_+ = N_-$. This gives rise to the detected transverse magnetization, M_{xy}.

- Following the B_1 pulse, two effects are observed:
  - The transverse magnetization (M_{xy}) returns to the equilibrium longitudinal direction (M_o), and
  - The magnetic moments begin to dephase.

RETURN TO EQUILIBRIUM: T1 RELAXATION

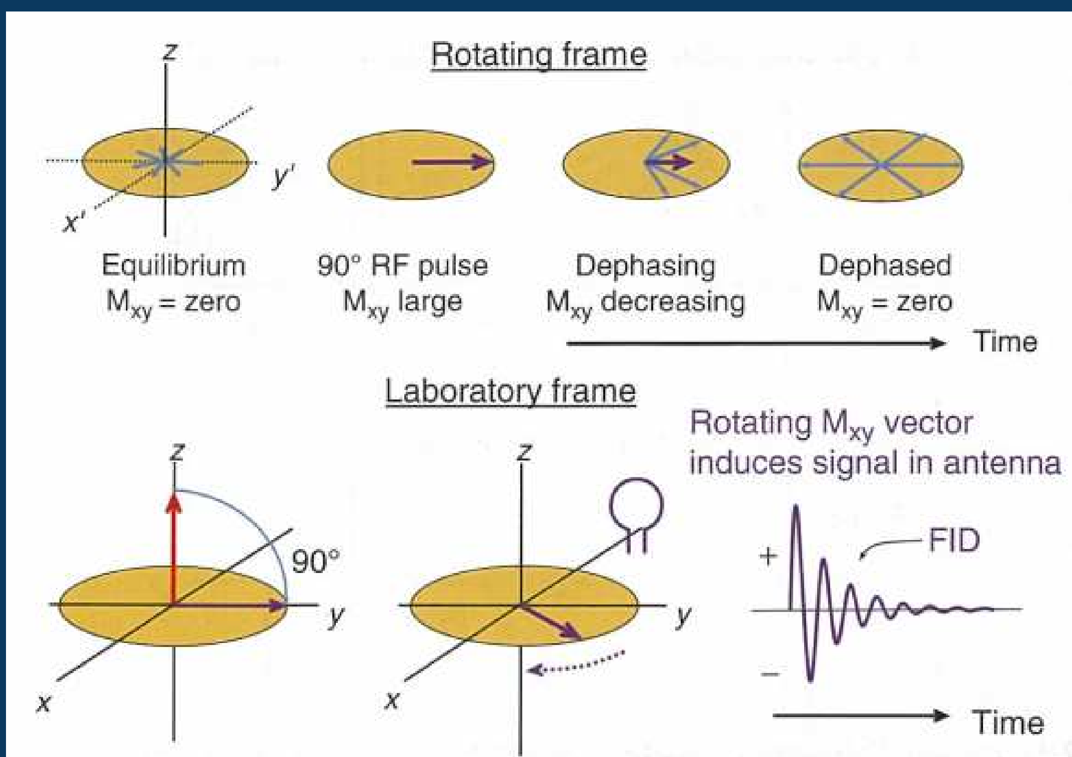
- T1 Longitudinal (Spin-lattice) relaxation describes the release of energy back to the lattice after the excitation pulse and the regrowth of M_z.
  - When t=T1, then e^{-1}=0.37 and $M_z = 0.63M_0$, or 63% recovery.



$$M_z(t) = M_0(1 - e^{-t/T1})$$

TRANSVERSE MAGNETIZATION

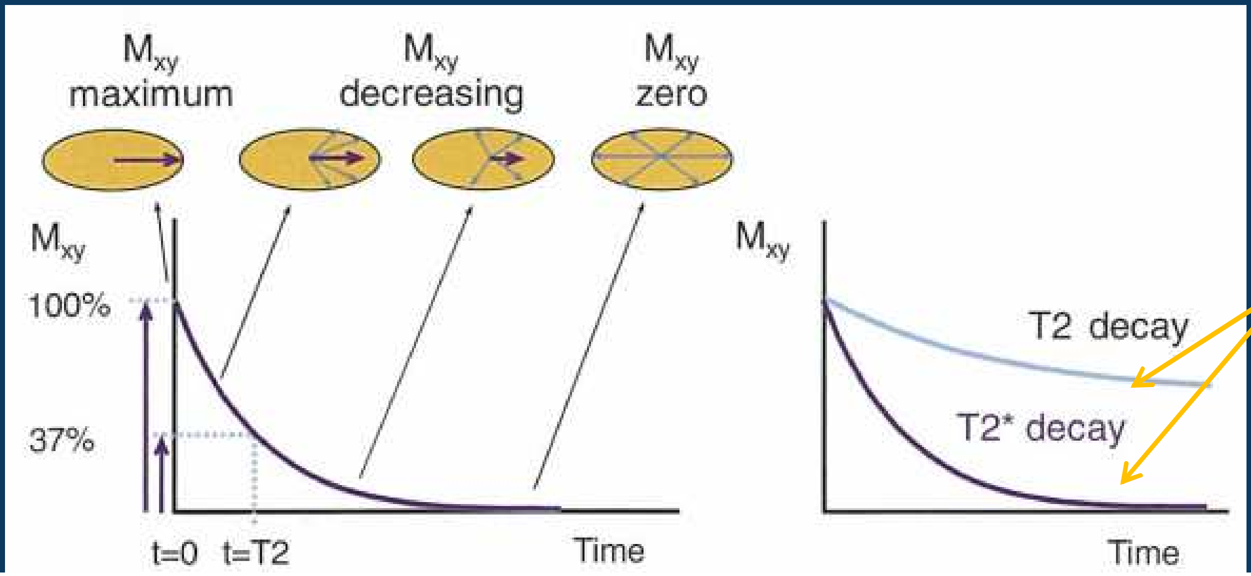
- T2 Transverse (spin-spin) relaxation describes the dephasing of the coherent signal immediately after the RF pulse
-
    - RF signal (at the Larmor frequency) when engaged aligns all the magnetic moments to become coherent
    - When t = T2, then e^{-1}=0.37 and $M_{xy} = 0.37M_0$



$$M_{xy}(t) = M_0 e^{-t/T2}$$

MAGNETIC INHOMOGENEITIES

- $T2^*$ contain both intrinsic and extrinsic contributions.
- T2 contain only *intrinsic inhomogeneities* (in the hydration layer).
  - Amorphous materials lack a hydration layer and result in long T2 values. (e.g. CSF or edematous tissue)
  - Larger molecules and the presence of a hydration layer produce magnetic fields and increase dephasing leading to a short T2 (e.g. bone)
- Extrinsic inhomogeneities include MR contrast materials, paramagnetic inhomogeneities, and static external field inhomogeneities



T2* always less than T2

INTRINSIC AND EXTRINSIC PARAMETERS

Image contrast in MRI depends on an extensive list of *intrinsic* and *extrinsic* parameters.

- Intrinsic parameters include, among others:
  - *proton density*
  - *spin-lattice relaxation time* (T_1)
  - *spin-spin relaxation time* (T_2)
  - *chemical environment*
  - *velocity*
  - *diffusion*
  - *temperature*
- Extrinsic parameters include, among others:
  - *echo time* (*TE*)
  - *repetition time* (*TR*)
  - *flip angle* (α)
  - *contrast agents*
  - *saturation pulses*
  - *inversion pulses*
  - *flow compensation pulses (GMN)*
  - *diffusion sensitization pulses*

T1 & T2 OF VARIOUS TISSUES

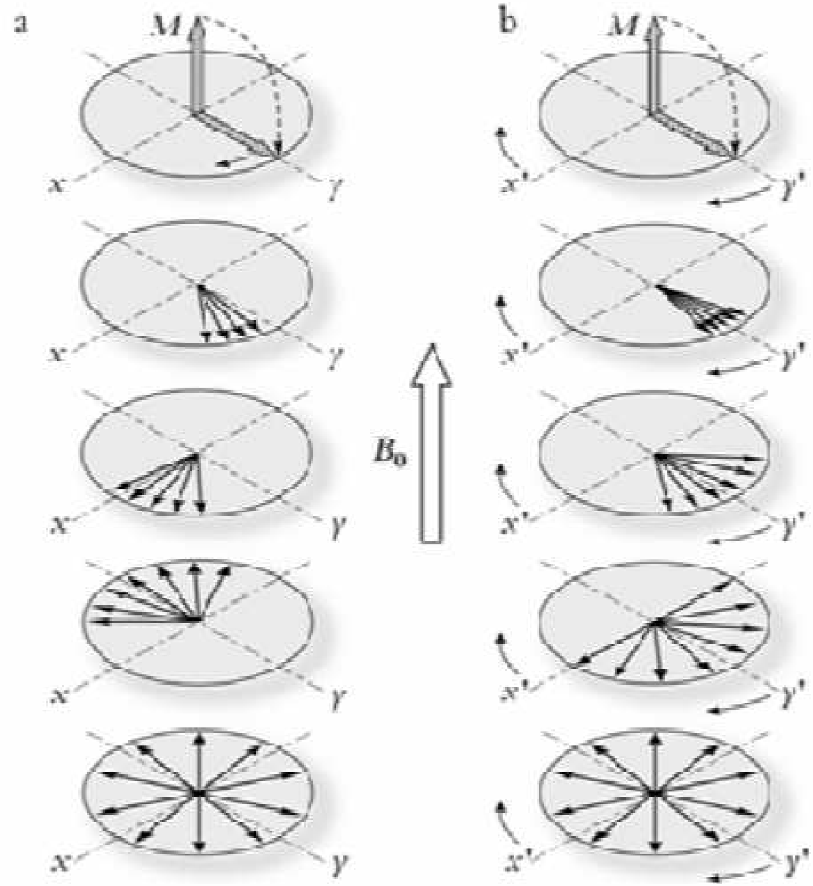
Tissue Type	T1 (msec) @ 0.5 T	T1 (msec) @ 1.0 T	T2 (msec)
Fat	210	260	80
Liver	350	500	40
Muscle	550	870	45
White Matter	500	780	90
Gray Matter	650	900	100
CSF	1800	2400	160

DEPHASING

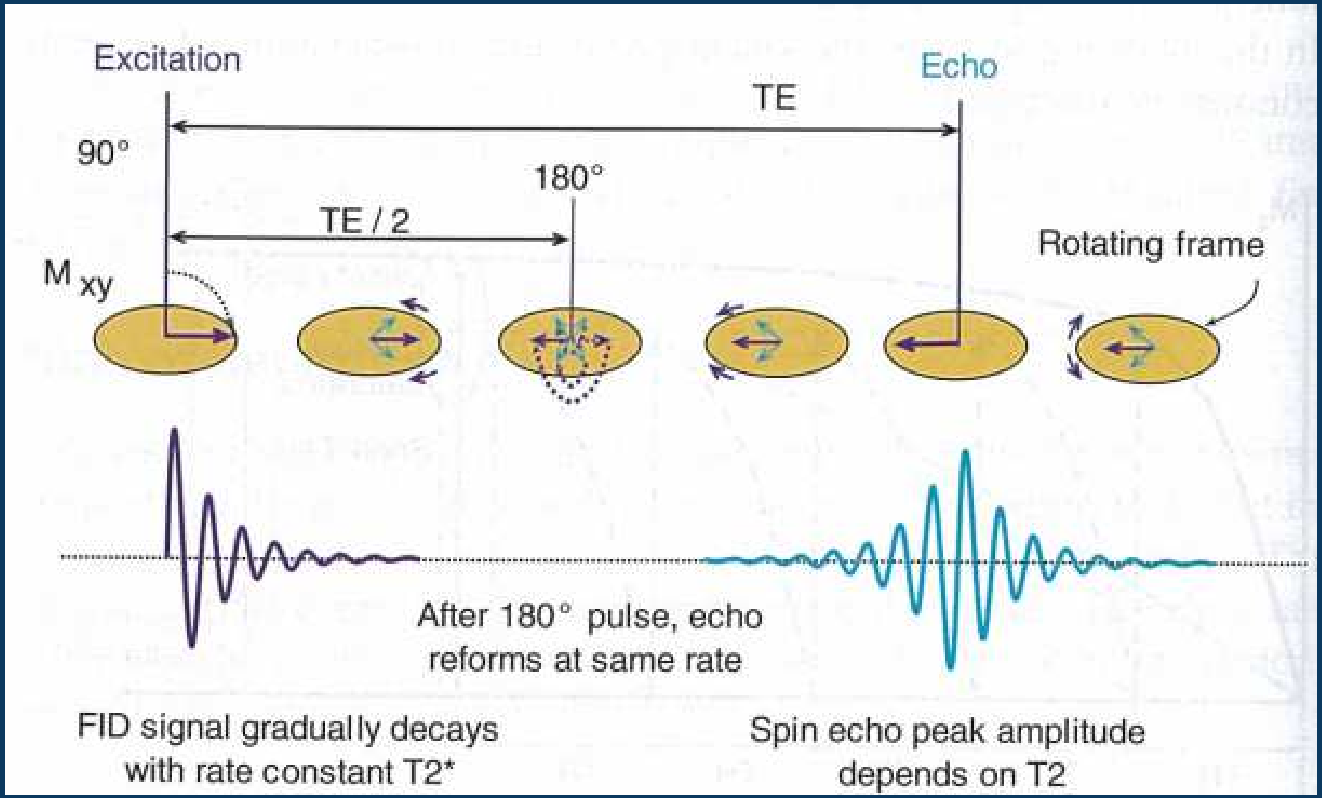
Reference Frames

Laboratory Frame

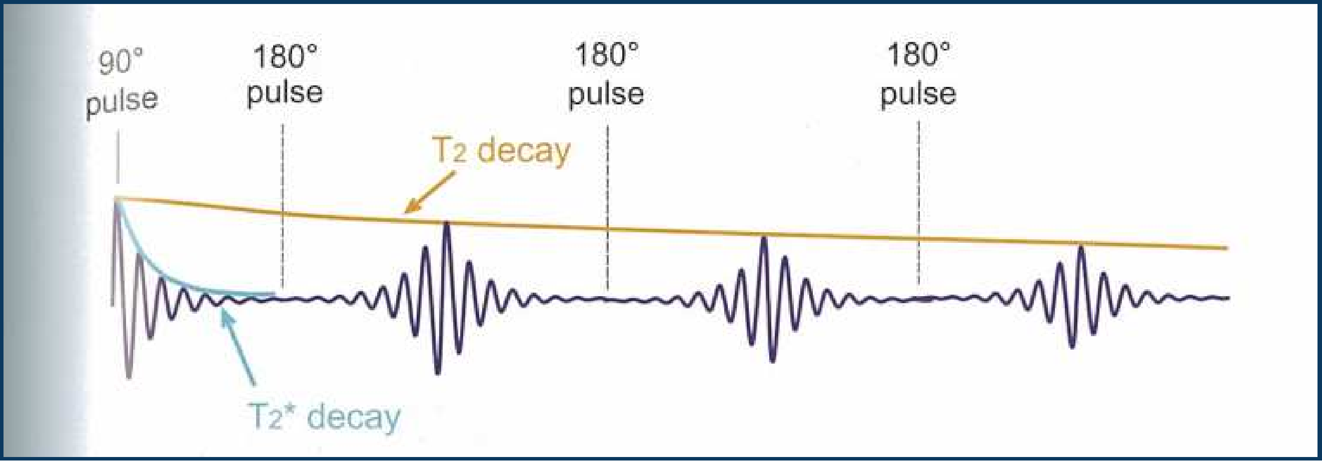
Rotating Frame



T2 AND T2*

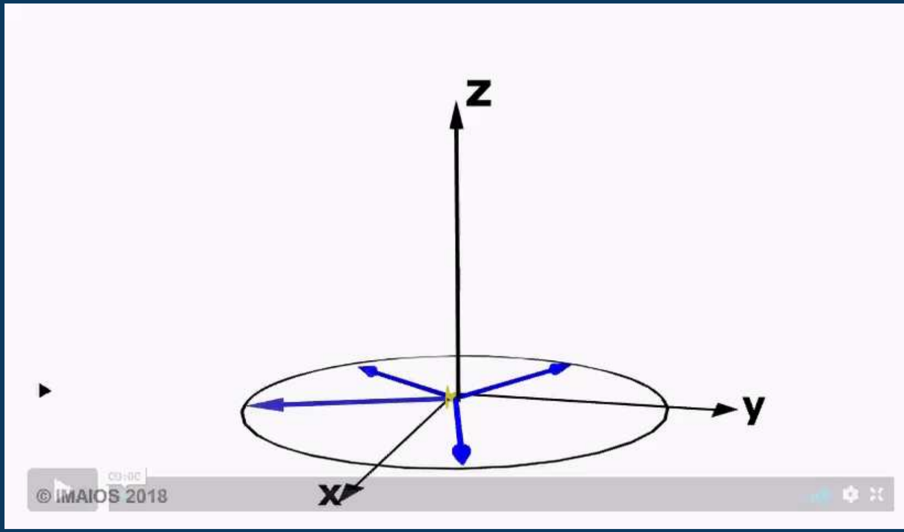


Excitation
Echo
TE
90°
180°
TE / 2
Rotating frame
M xy
After 180° pulse, echo
reforms at same rate
FID signal gradually decays
with rate constant T2*
Spin echo peak amplitude
depends on T2



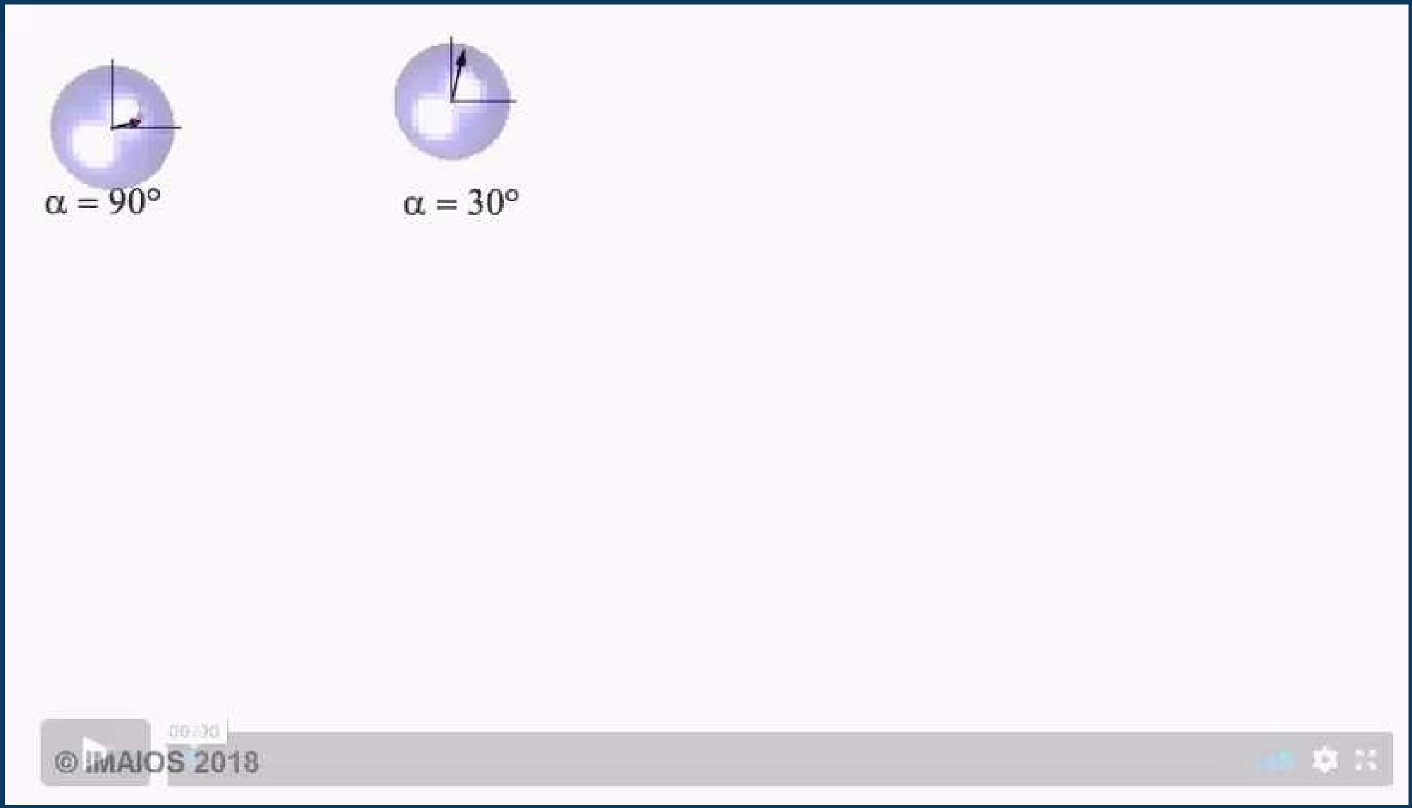
90° pulse
180° pulse
180° pulse
180° pulse
T2 decay
T2* decay

RELAXATION AND INVERSION VIDEOS



https://www.imaios.com/en/e-Courses/e-MRI/MRI-signal-contrast/180-RF-pulse

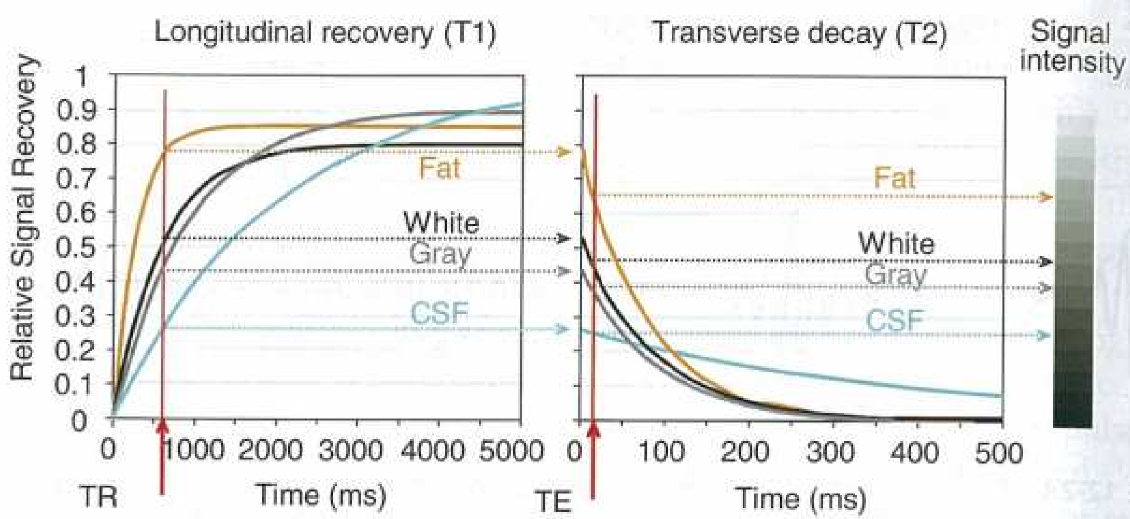
FLIP ANGLE DEPENDENCE



https://www.imaios.com/en/e-Courses/e-MRI/MRI-signal-contrast/180-RF-pulse

T1 WEIGHTED IMAGE

- Short TR, short TE



■ FIGURE 12-24 T1-weighted contrast: Longitudinal recovery (**left**) and transverse decay (**right**) diagrams (note the values of the x-axis time scales) show four brain tissues and T1 and T2 relaxation constants. T1-weighted contrast requires the selection of a TR that emphasizes the differences in the T1 characteristics of the tissues (e.g., TR = ~ 500 *ms*), and reduces the T2 characteristics by using a short TE so that transverse decay is reduced (e.g., TE ≤ 15 *ms*).

T2 WEIGHTED IMAGE

- Long TR, Long TE

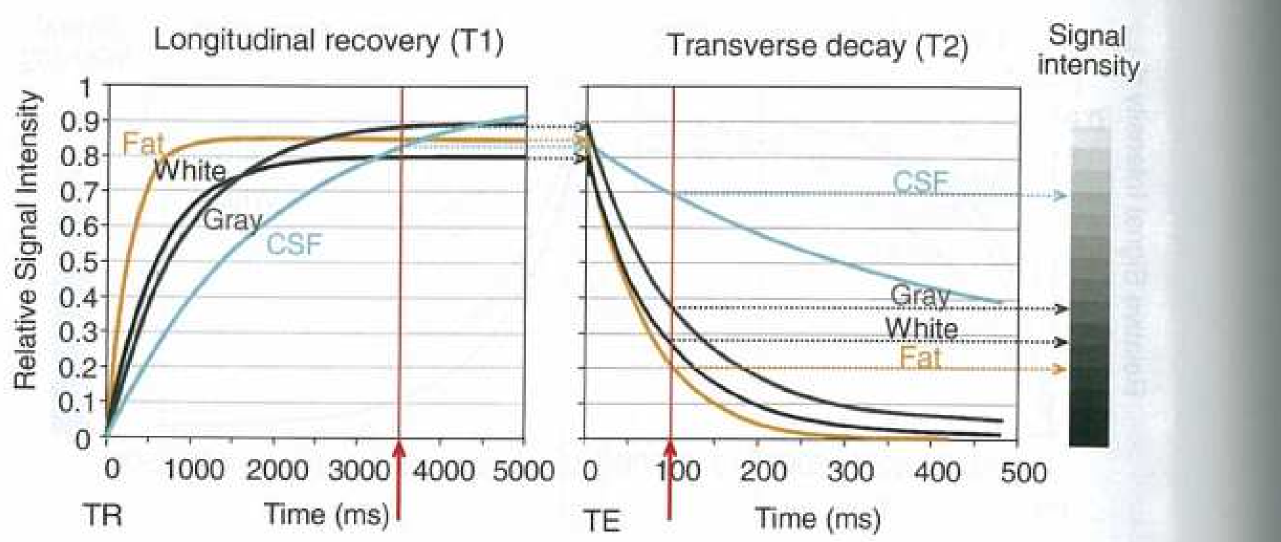
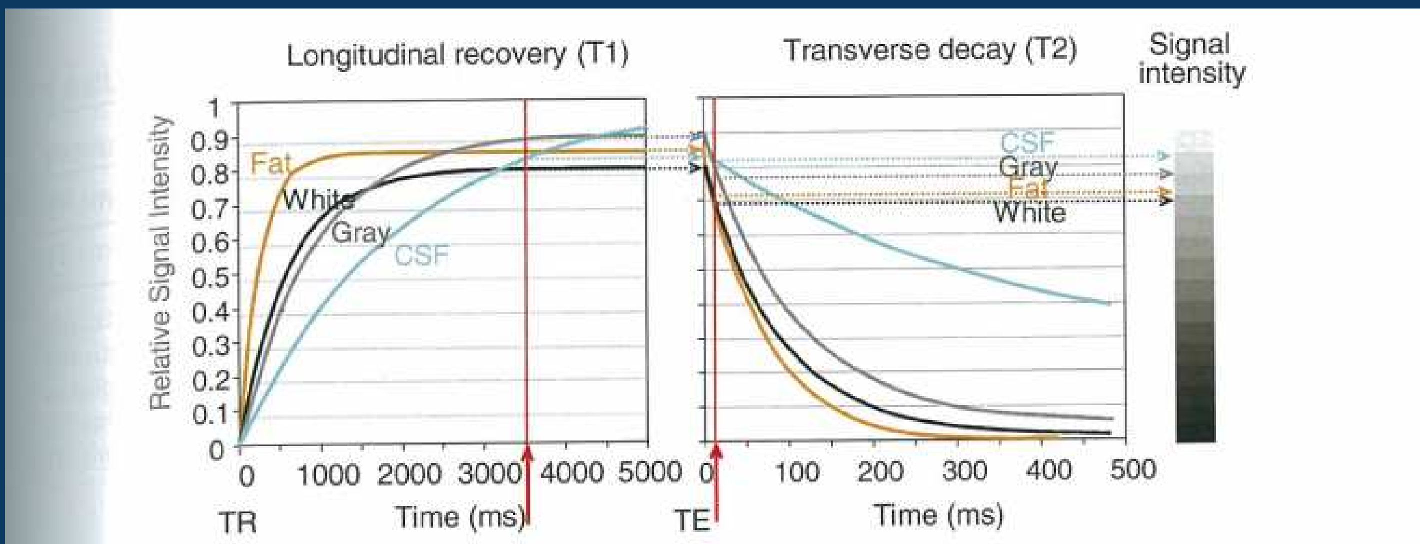


FIGURE 12-28 T2 weighted contrast requires the use of a long TR (e.g., greater than 2,000 ms) to reduce T1 influences, and a long TE (e.g., greater than 80 ms) to allow for T2 decay to evolve. Compared to the proton density weighting, the difference is with longer TE.

PROTON DENSITY WEIGHTED IMAGE

- Long TR, short TE



■ FIGURE 12-26 Proton density weighting: Proton (spin) density weighted contrast requires the use of a long TR (e.g., greater than 2,000 *ms*) to reduce T1 effects, and a short TE (e.g., less than 35 *ms*) to reduce T2 influence in the acquired signals. Note that the average overall signal intensity is higher.

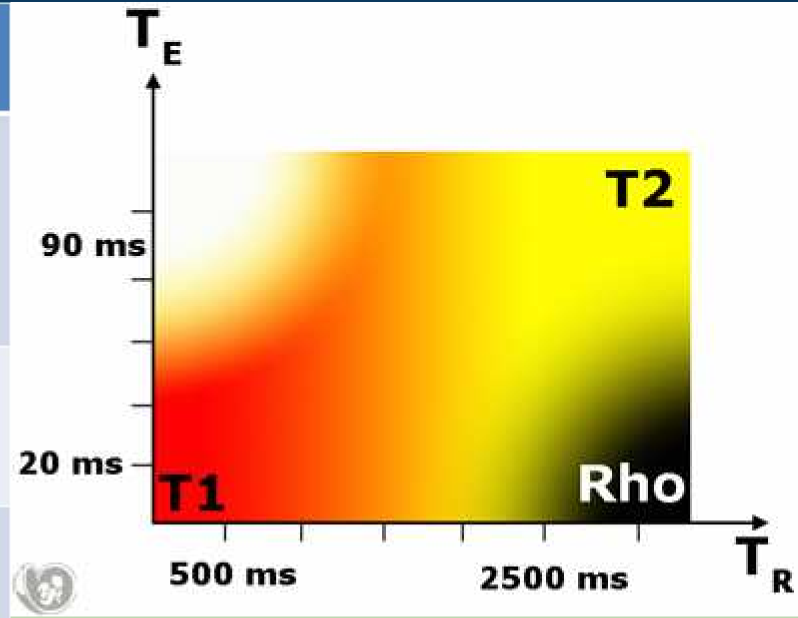
HELPFUL CHARTS

MR Signal Intensities

	T2WI	PD/FLAIR	T1WI
Solid mass	Bright	Bright	Dark
Cyst	Bright	Dark	Dark
Subacute blood	Bright	Bright	Bright
Acute & chronic blood	Dark	Dark	Gray
Fat	Dark	Bright	Bright

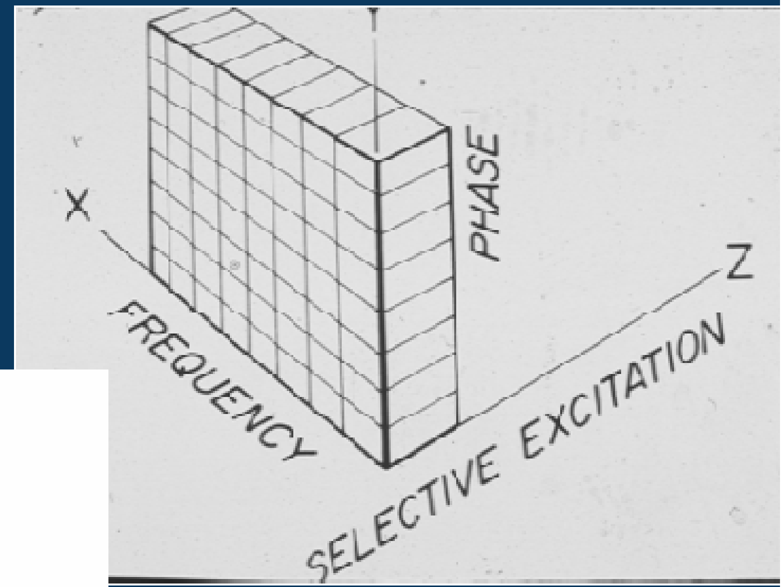
TISSUE	T1W	T2W
FAT	BRIGHT	INT/DARK
BRAIN		
WHITE MATTER	BRIGHT	DARK
GREY MATTER	DARK	BRIGHT
CSF	VERY DARK	VERY BRIGHT
GADOLINIUM CHELATE		
LOW CONCENTRATION	VERY BRIGHT	BRIGHT
HIGH CONCENTRATION	INT/DARK	VERY DARK
HEMATOMA		
HYPERACUTE(<6 HRS)	INT	INT
ACUTE(6-24 HRS)	INT/DARK	DARK
SUBACUTE(1DAY-1MONTH)	BRIGHT RIM	BRIGHT
CHRONIC(>1 MONTH)	DARK RIM WITH OR WITHOUT A BRIGHT CENTRE	DARK RIM WITH OR WITHOUT A BRIGHT CENTRE

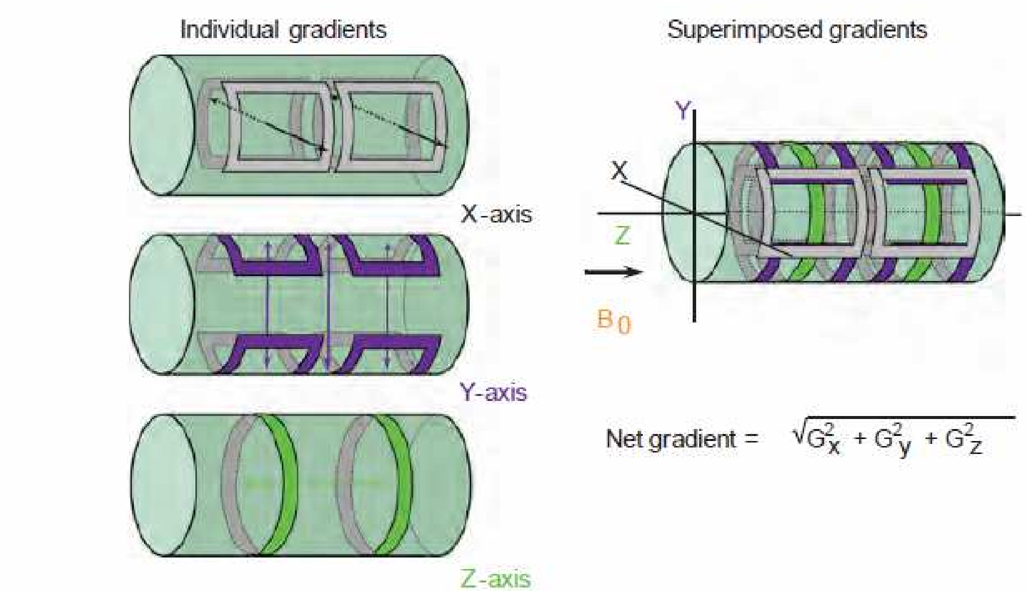
Desired Image Contrast	Parameter Selection	Reason
T1-Weighting	Short TR (5-10 ms) Short TE (2-5 ms) Intermediate α (30-50°)	T1 contrast would theoretically be better with α = 60-90°, but signal would be weak because far from Ernst angle; α = 30-50° is compromise for good signal and T1-weighting at short TR values
[H]-Weighting	Long TR (100-400 ms) Short TE (2-5ms) Small α (5-20°)	Long TR and small α minimize T1 weighting; short TE minimizes T2* effects
T2*-Weighting	Long TR (200-800 ms) Long TE (20-50 ms) Small α (5-20°)	Long TR and small α minimize T1 weighting; long TE maximizes T2* effects.



SPATIAL ENCODING OF MR SIGNALS

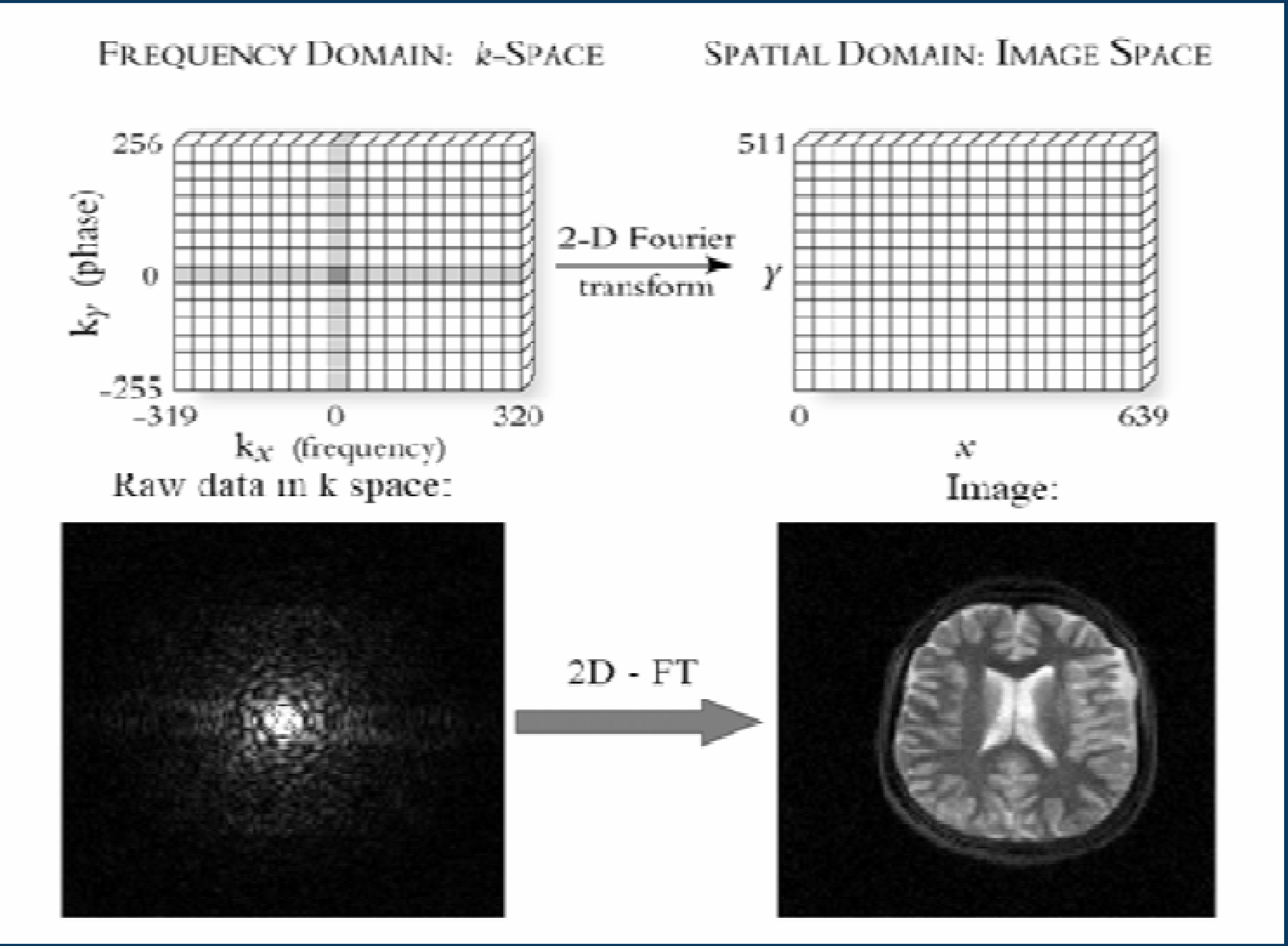
- Determination of M_z, M_{xy} as a function of the spatial variable (x,y,z)





■ FIGURE 12-48 Within the large stationary magnetic field, field gradients are produced by three separate coil pairs placed within the central core of the magnet, along the *x, y,* or *z* directions. In modern systems, the current loops are distributed across the cylinders for the x-, y- and z- gradients, which generates a lower, but more uniform gradient field. Magnetic field gradients of arbitrary direction are produced by the vector addition of the individual gradients turned on simultaneously. Any gradient direction is possible by superimposition of magnetic fields generated by the three-axis gradient system.

K-SPACE


FREQUENCY DOMAIN: k-SPACE
SPATIAL DOMAIN: IMAGE SPACE
256
0
-255
ky (phase)
-319
0
320
kx (frequency)
2-D Fourier
transform
511
y
0
639
x
Raw data in k space:
Image:
2D - FT

MRI – FIRST IMAGES

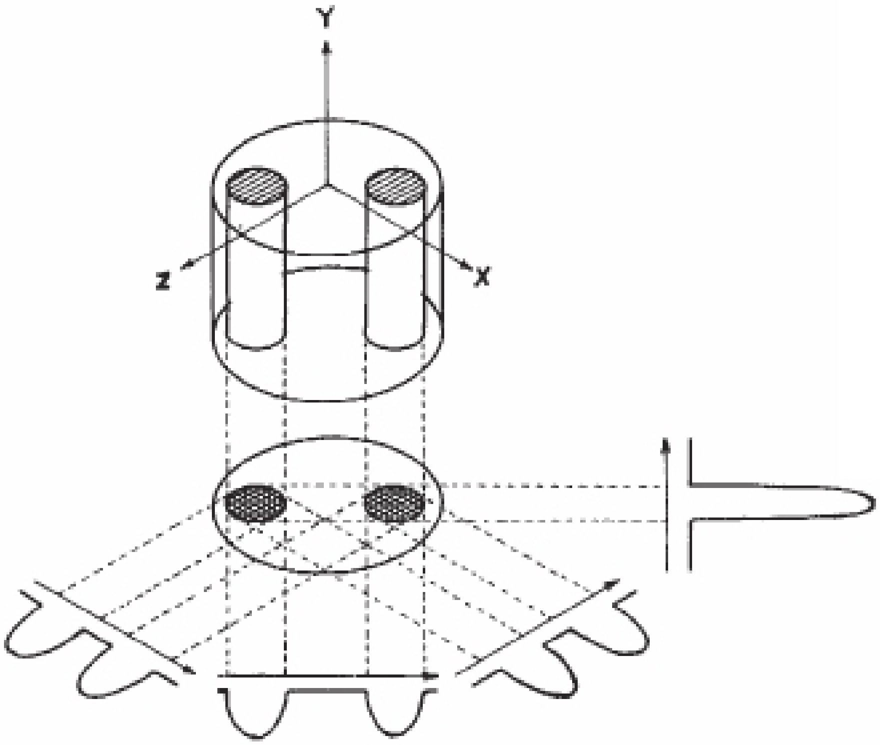
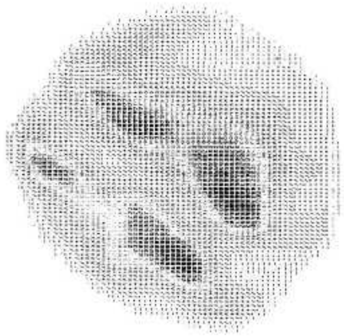


Fig. 1 Relationship between a three-dimensional object, its two-dimensional projection along the Y-axis, and four one-dimensional projections at 45° intervals in the XZ-plane. The arrows indicate the gradient directions.

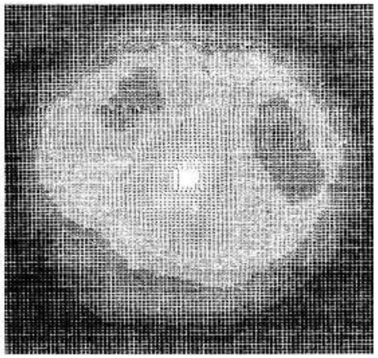
3.1 History of MRI developments

Paul Lauterbur's images



← Oil in peanuts

Cross-section of a mouse →
(shadows are lungs)



31

MR BIOEFFECTS AND SAFETY

- Strong magnetic fields, cryogenic liquids, claustrophobia, and loud acoustic noise
- Patients with implants, prostheses, aneurysm clips, pacemakers, heart values, etc.

- Heating of foreign objects.
- Unaccounted metal objects in the MR scanner room have lead to death.
- As such, proper signage is a requirement

https://www.youtube.com/watch?v=6BBx8BwLhqg&t=1s

MR SAFETY – THIS IS REAL

July 31, 2001

Boy, 6, Dies Of Skull Injury During M.R.I.

By DAVID W. CHEN

Outside of the X-ray, perhaps no other medical examination is as well known or as safe as the magnetic resonance imaging test, which is conducted eight million times a year in the United States on patients ranging from people with brain tumors to famous athletes with knee injuries.

But today, officials at the Westchester Medical Center announced that something went horribly wrong on Friday with an M.R.I. test on a boy, 6, who had just undergone surgery. Even though no metal objects are supposed to be in the testing area, because they will be pulled toward the 10-ton machine by its powerful electromagnet, a metal oxygen tank somehow made it into the examination room.

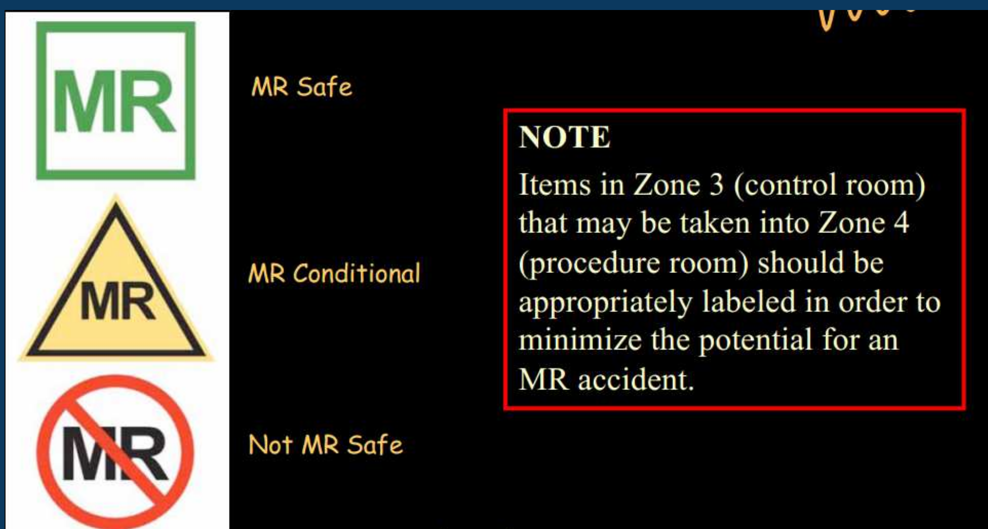
The tank, about the size of a fire extinguisher, became magnetized, then flew through the air at 20 to 30 feet per second and fractured the boy's skull.

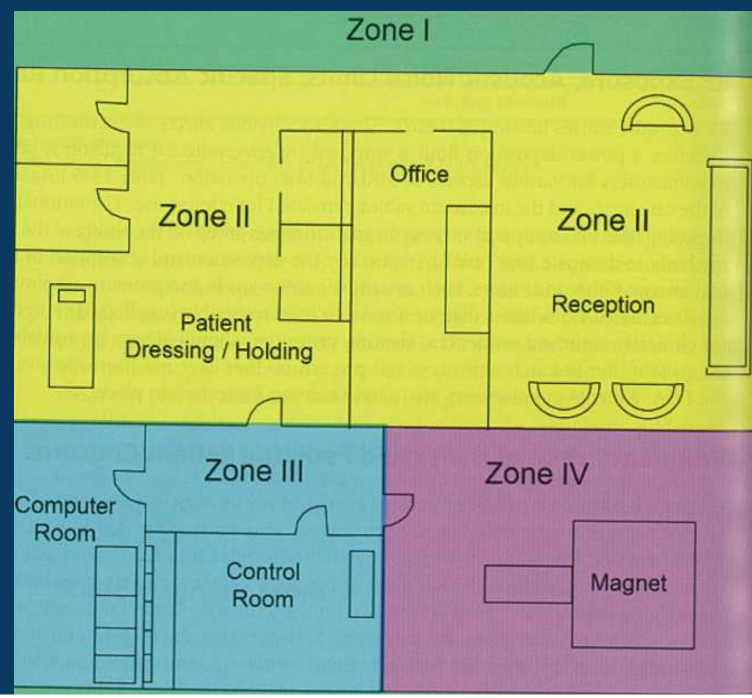
The boy died on Sunday. And today, an autopsy conducted by the Westchester County Medical Examiner's office confirmed that he had died of blunt force trauma, severe hemorrhaging and a contusion to the brain. The hospital and the State Department of Health are investigating, and the Westchester District Attorney's office is also reviewing the case.

MR PERSONNEL AND MR SAFETY ZONES

MR safety training requirements established for two levels:

- Level 1
  - maintain one's own safety in a limited set of conditions
  - limited experience / responsibility in the MR environment
  - REQUIRED to work in MR environment
  - Examples: nurses, (non-MR) technologists, *etc*.
- Level 2
  - highly trained and experienced personnel
  - work constantly in the MR environment
  - training qualifies staff to train/oversee others
  - Examples: MR technologist, MR radiologist, MR physicist, *etc*.





MR SAFETY

Each of the magnetic fields used in MR imaging can be a source of safety concerns:

- Static B_0 field (**always on**!)
  - Physiological effects, projectile motion, medical device displacement and/or interference with normal operation
- Radiofrequency B_1 field (on during scanning)
  - Tissue heating, heating of conductors, interference with patient monitoring equipment
- Gradient fields (on during scanning)
  - Peripheral nerve stimulation, excessive sound pressure levels, interference with patient monitoring equipment

The RF power required in MRI studies scales as the:

- square of the static magnetic field for a given flip angle
- square of the flip angle at a given static magnetic field
- size of the patient
- duty cycle of the RF pulses (# pulses per unit time)

ACR White Paper on MR Safety (2013)

- Available at www.acr.org
- Kanal, Barkovich, *et al.*, *J Magn Reson Imaging* 37:501-530, 2013
- Recommends facility design with respect to four zones, with increasing security / access control requirements.
- Updated version of original white paper (2002) and supplements (2004 and 2007).

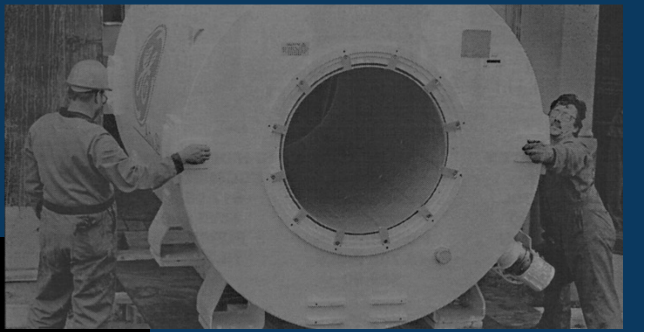
MR BIOEFFECTS AND SAFETY

- Long term biologic effects are not well known.
  - >4T, dizziness and disorientation have been reported.
  - >20 T, enzyme kinetic changes have been documented.
  - Fast switching gradients can induce nerves or tissues.
- Pregnancy is typically not an issue, but minimum exposure in the MR environment is recommended.
  - Contrast agents have been documented to pass the placental barrier and enter fetus.

- At 1.5 T, the Larmor frequency is ~ 64 MHz => good penetration and possible source of tissue heating.
- Tissue heating is primarily due to magnetic induction with a negligible electric field contribution.
- Measure: the specific absorption rate (SAR) - W/kg.
- The heating of the tissue is greatest at the periphery and minimal at the center of the body.

  Head equivalent phantom scans demonstrate significant changes in temperature during an MR only occur less than 4 cm from the edge and do not exceed 1-2^{o}C for 1.0 and 2.5 W/kg scans for 30 minutes[1].
- Tissues that are poorly perfused, such as the orbits, require particular attention.

FDA GUIDELINES



FDA Guidelines (6/20/2014):

Main static magnetic fields greater than 8 Tesla (4 Tesla for infants <1 mo) are considered significant risk investigations and require approval of an investigational device exemption (IDE) by the FDA Center for Devices and Radiological Health (CDRH).

Source:
http://www.fda.gov/downloads/MedicalDevices/DeviceRegulationandGuidance/GuidanceDocuments/ucm072688.pdf

FDA Guidelines (6/20/2014):

Specific absorption rates greater than

a. 4.0 W/kg averaged over the whole body for any period ≥15 min; or
b. 3.2 W/kg averaged over the head for any period ≥10 min

are considered significant risk investigations and require approval of an investigational device exemption (IDE) by the FDA Center for Devices and Radiological Health (CDRH).

Source:
http://www.fda.gov/downloads/MedicalDevices/DeviceRegulationandGuidance/GuidanceDocuments/ucm072688.pdf

$$\mathrm{SAR} = \frac{1}{V}\int_{\mathrm{sample}} \frac{\sigma(\mathbf{r})|\mathbf{E}(\mathbf{r})|^2}{\rho(\mathbf{r})} d\mathbf{r}$$

where

σ is the sample electrical conductivity

E is the RMS electric field

ρ is the sample density

V is the volume of the sample

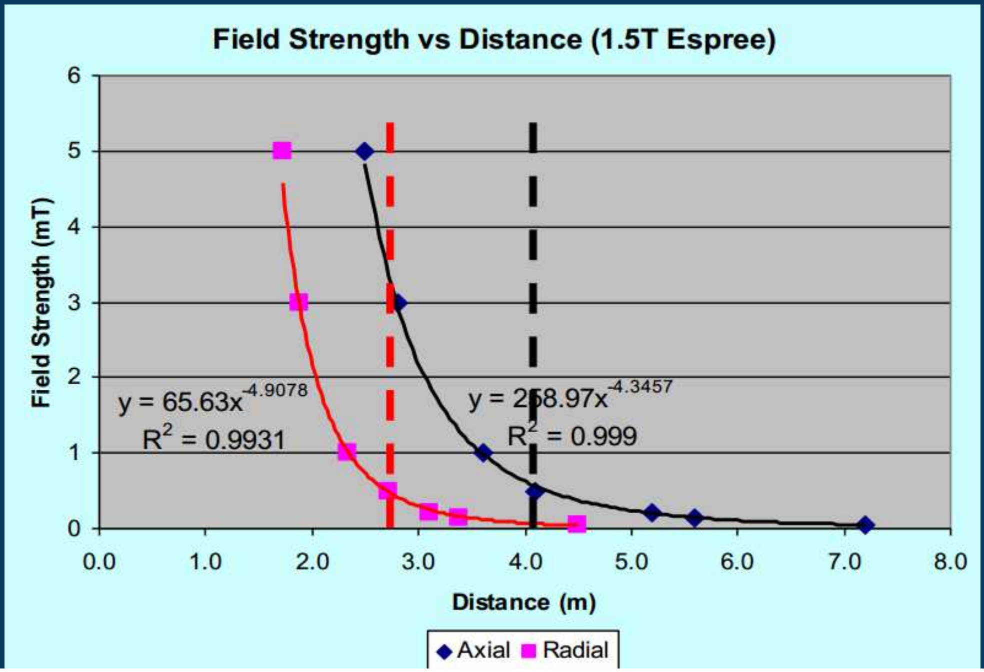
HELPFUL INFO

Magnetic Field Units:

- Gauss (G)
- Tesla (T)
- 1 T = 10,000 G
- Earth's magnetic field is ~0.5 G (0.05 mT)
- Posted exclusion zone (pacemakers/neurostimulators): 5 G (0.5 mT)
- 1.5T MR scanner ~30,000 times Earth's field
- 3.0T MR scanner (CABIR) ~90,000 times Earth's field
- ~3,000 – 9,000 times the 5 G exclusion zone field strength

Force of attraction at 1.5T:

- Near bore opening: can easily be ≥25-50x the weight of the object



END

- https://www.youtube.com/watch?v=djAxjtN_7VE
- https://www.youtube.com/watch?v=4dbQxyrhZ2A

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