MR Research Facility

MRI Physics – Brain Imaging Bootcamp

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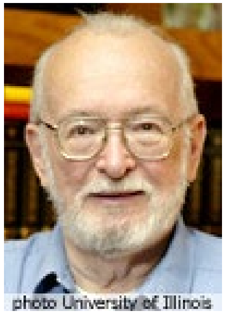
History of MRI

- MRI first proposed in 1974
- MRI introduced as a diagnostic tool in mid-1980's
- Most of the basic principles (as applied in NMR spectroscopy) known since 1945
- 2003 Nobel Prize in Medicine



Mansfield and Lauterbur

MR Scanner

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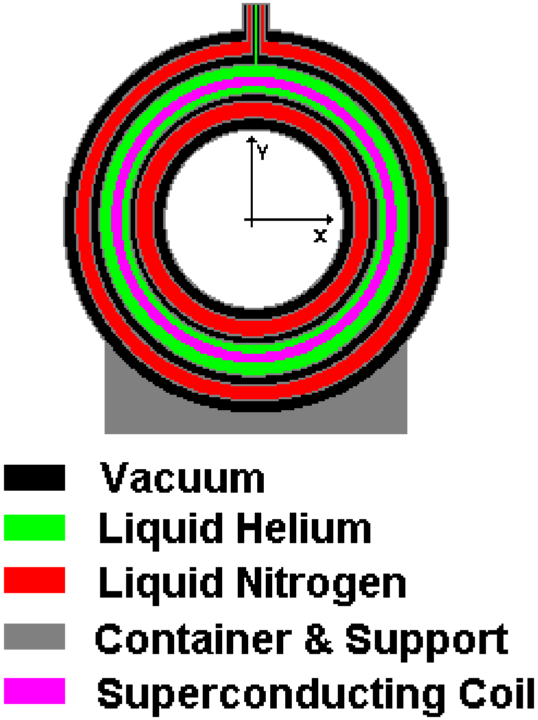
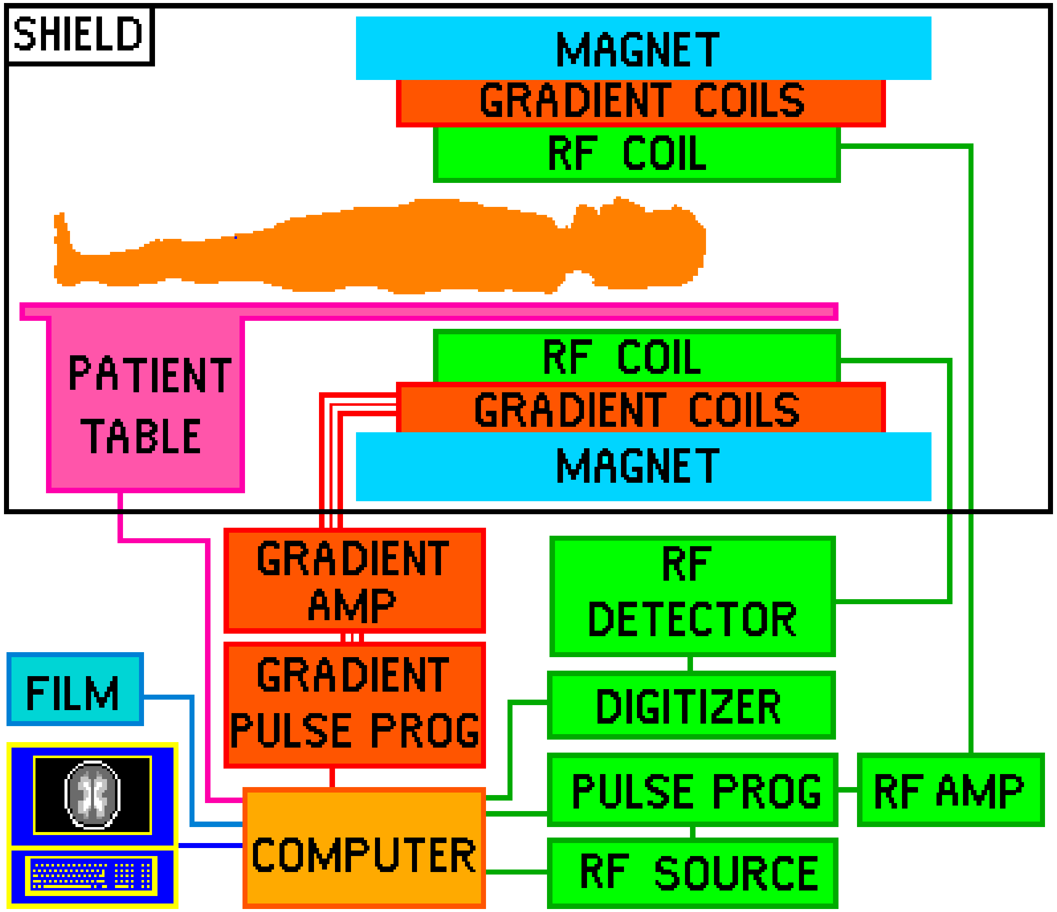
Inside the MR Scanner

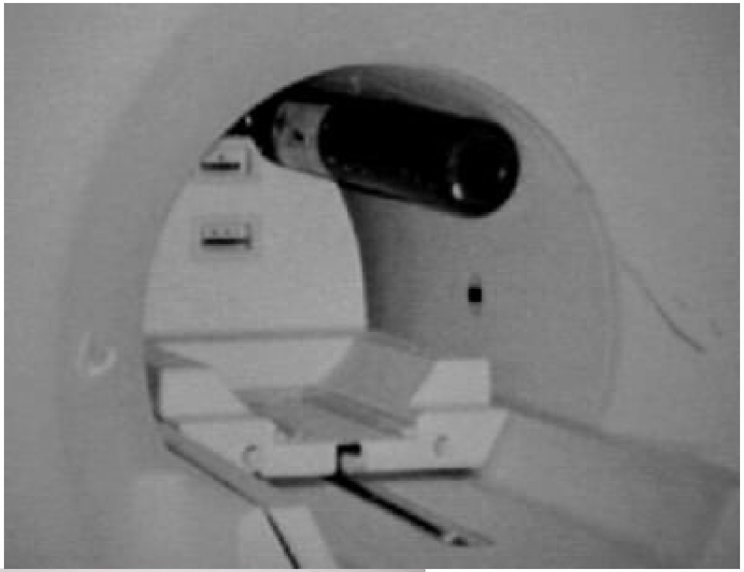


An MR Scanner

More than just the Magnet



Danger: Flying Objects



Nuclear Magnetic Resonance

- → Magnetic resonance imaging roots are in nuclear magnetic resonance (NMR)
  - Nuclear deals with the nucleus of then atom
  - Does not deal with radioactivity
- → Atom consists of protons, neutrons and electrons
- → Properties of nucleus include atomic number, atomic weight, and angular momentum
  - Atomic number = # of protons
  - Atomic weight = # protons + # neutrons
  - Angular momentum is a quantized number that depends on atomic number and atomic weight

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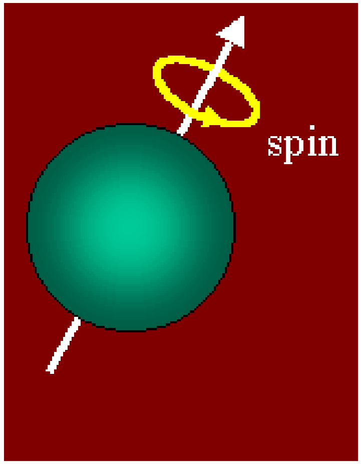
Nucleus Magnetic Field



- A moving electrical charge produces a magnetic field
  - The faster the speed, the larger the magnetic field
  - Magnetic field is parallel to the axis of rotation
  - Magnetic field similar to that in a “tiny” bar magnet
- The nucleus and the resulting magnetic field will be manipulated with the MR scanner to provide the basis for the MR signal

Source of MR Signal

- The protons in the body can be thought of as small bar magnets
- Water and fat make up the largest source of protons in the body
- Normally the direction of these protons is completely random
- Common imaged nuclei are ^{1}H, ^{13}C, ^{15}N, ^{19}F, ^{23}Na, and ^{31}P

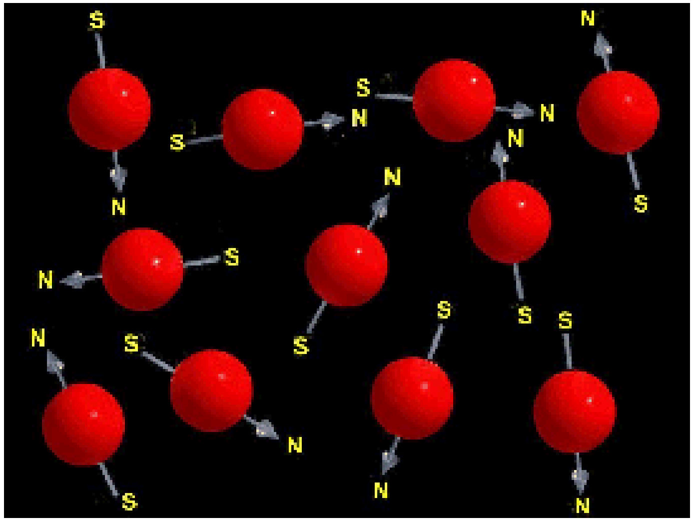
Views of MR Physics

- Classical Mechanics
  - Protons form little bar magnets that can produce a net field
  - $M_0 = \Sigma \mu_I$
- Quantum Mechanics
  - Protons can occupy different energy states with a preference for the lower energy state

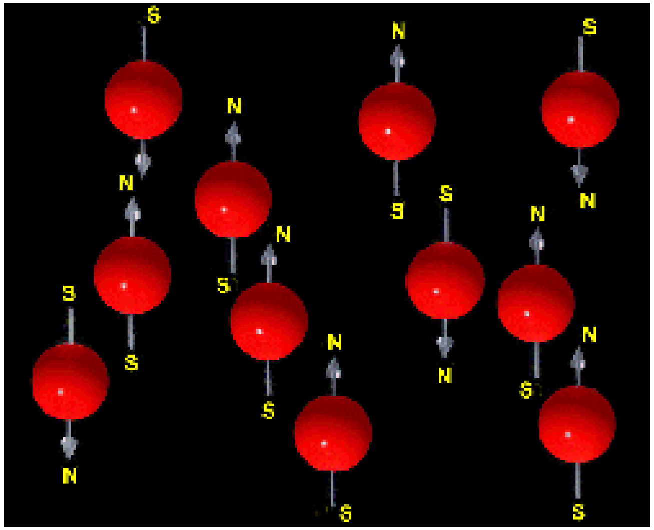
Protons in a Magnetic Field

- If protons are placed in a large magnetic field, B_0, they will align with the external field
  - Like a compass aligning with the earth's magnetic field (B_{earth} ~ 0.5 gauss or 10^{-4} T)
- Not quite that simple at the atomic level.
  - Some align with and some against the applied magnetic field
  - Slight excess of protons aligned with the magnetic field

Alignment of Protons



Random alignment of protons with no external magnetic field

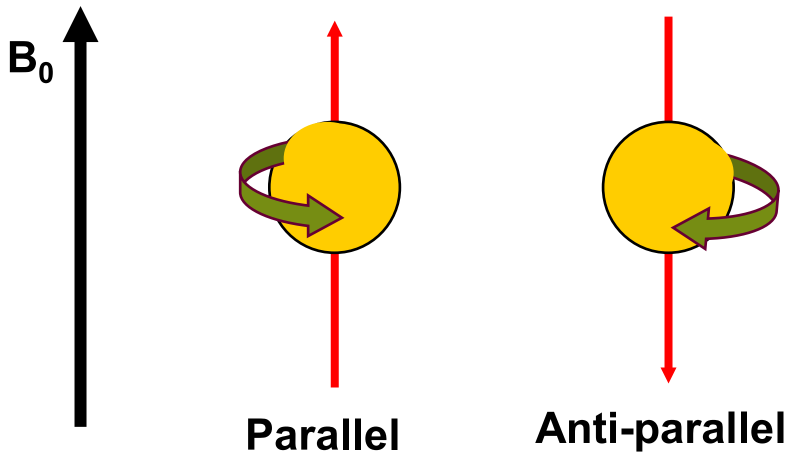


Protons aligned with external magnetic field

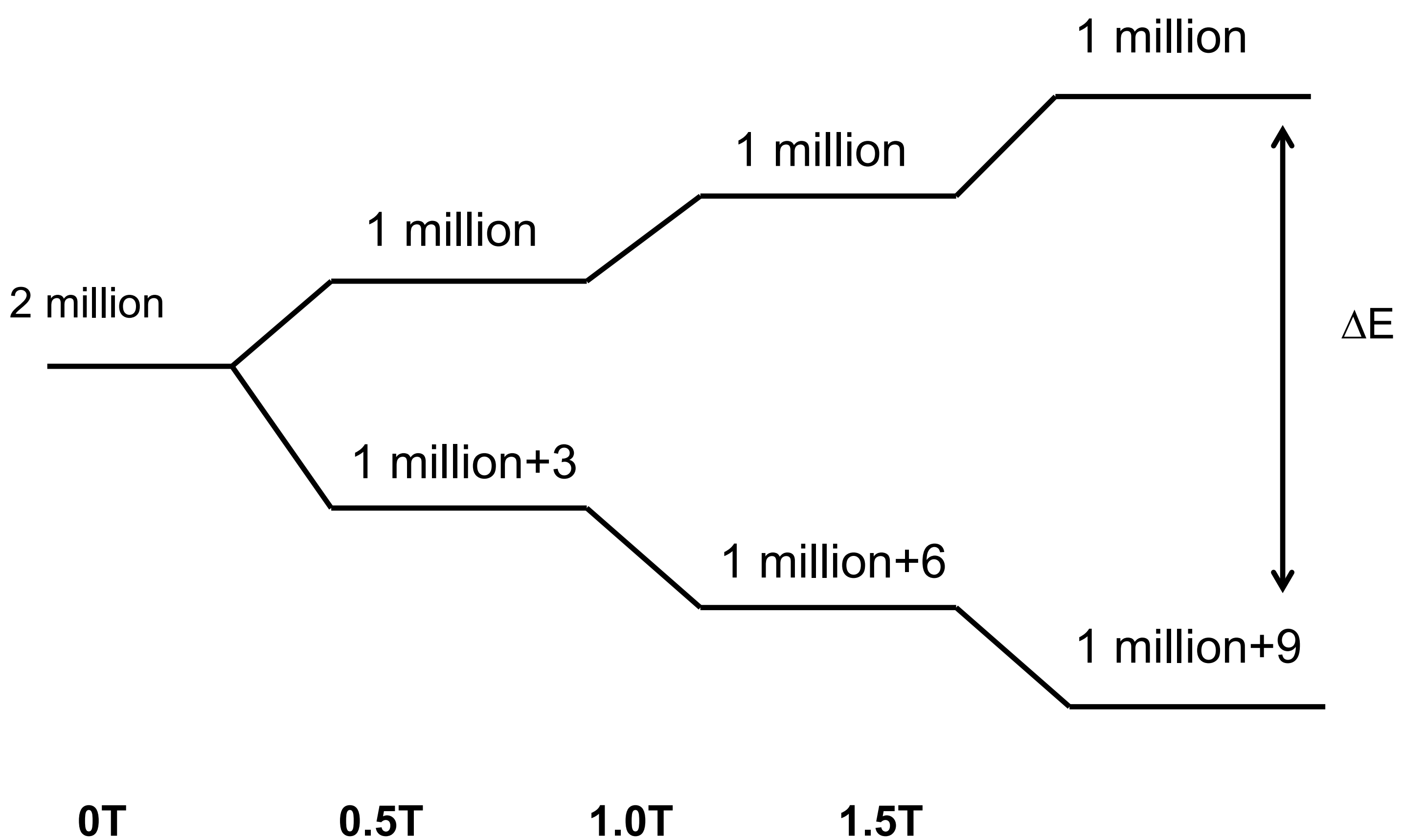
Quantum Alignment of Protons

→ Protons have two possible energy states that they may occupy: parallel and anti-parallel

- The energy difference between these two states is proportional to the applied magnetic field
- Preference to the aligned state is proportional to the applied magnetic field



Proton Energy Levels



Larmor Equation

- → The frequency of precession is directly proportional to the strength of the external magnetic field
- → Frequency of precession described by the Larmor Equation

Larmor Equation: $\nu = \lambda B_0$

- Gamma (λ) - gyromagnetic ratio and is a constant unique to each nuclei
- For hydrogen λ =42.56 MHz/Tesla
  - 1.5 T =42.56x1.5 = 63.84MHz
  - 3T = 42.56x3.0 = 127.68 MHz
  - 7T = 42.56x7.0 = 297.92 MHz

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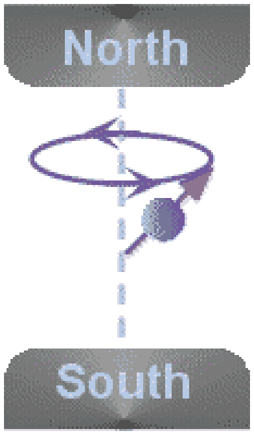
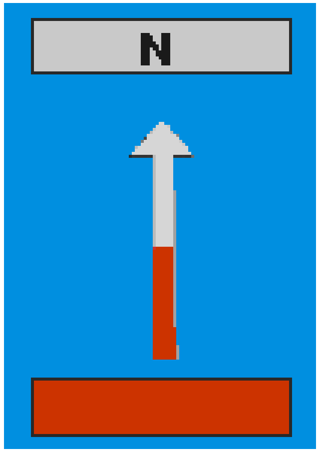
Precession of M_0





Standard MR Conventions

- Z axis in the direction of the large main static magnetic field (in the direction of the magnetic bore) and is known as the longitudinal direction
- M_0 is the vector sum of all of the protons in the magnetic field that results from the preferential alignment with the external magnetic field
- XY is known as the transverse plane

Application of RF Pulses

- If an electromagnetic RF pulse is applied to the resonance (Larmor) frequency then the protons will absorb the energy
  - At the macro level, to the observer in the external laboratory, the magnetization vector spirals down to the XY plane
  - If one is observing from the standpoint of the M_0 vector sees the world rotating about him. The magnetization appears to tip some angle towards the Y' axis
- The flip angle, alpha (α), is a function of the strength and duration of the RF pulse

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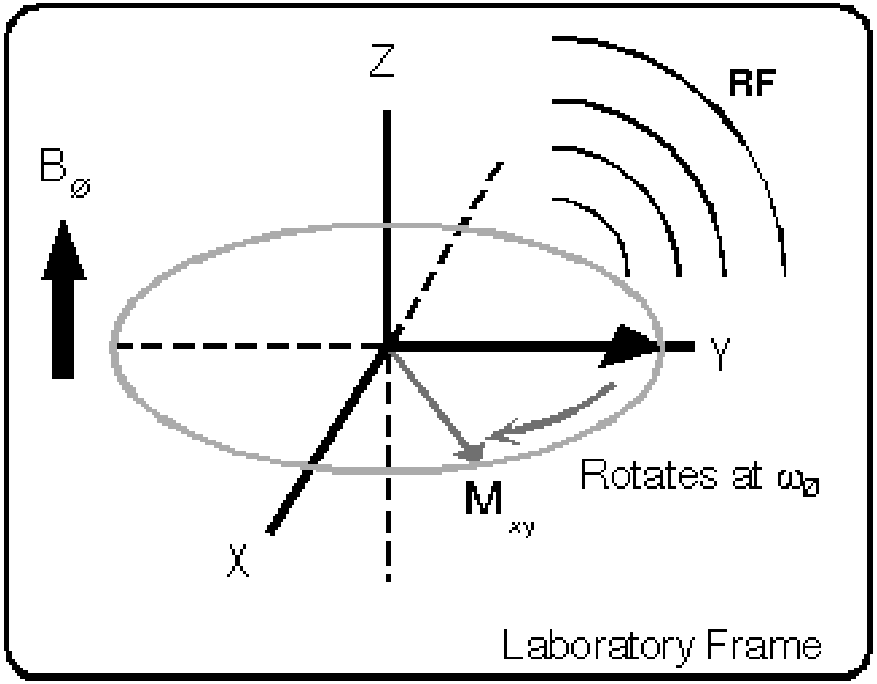
Proton Precession



Once the RF is Turned Off

- The absorb energy is retransmitted at the Larmor frequency
  - Signal proportional to the proton density
- The excited spins return to their original M_z orientation (T1 recovery)
  - Exponential recovery with a time constant called T1
  - Longitudinal or Spin-Lattice relaxation
- The in phase protons start to dephase (T2 and T2* relaxation)
  - Exponential decay with a time constant of T2 or T2*
  - Transverse or Spin-Spin relaxation

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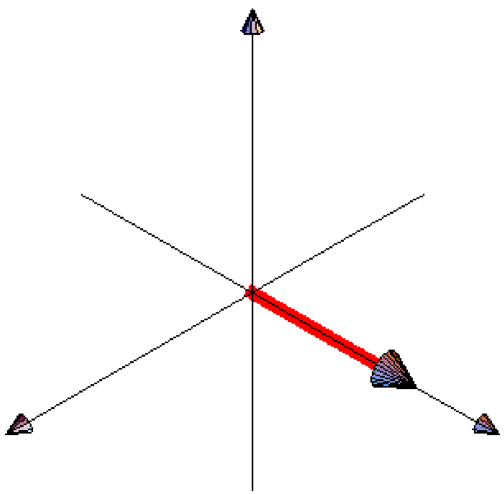
Magnetization Recovery



T1 Relaxation

- Spin-Lattice interaction results from spins returning to their equilibrium state
- In the classical sense the M_z component grows at the expense of the M_{xy} component
- The time course in which M_z returns to M_0 is described by an exponential curve whose time constant is unique to every tissue allowing for tissue differentiation
  - One T1 after the excitation pulse 63.2% of the magnetization has returned along the Z axis
  - Relaxation Equation?

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

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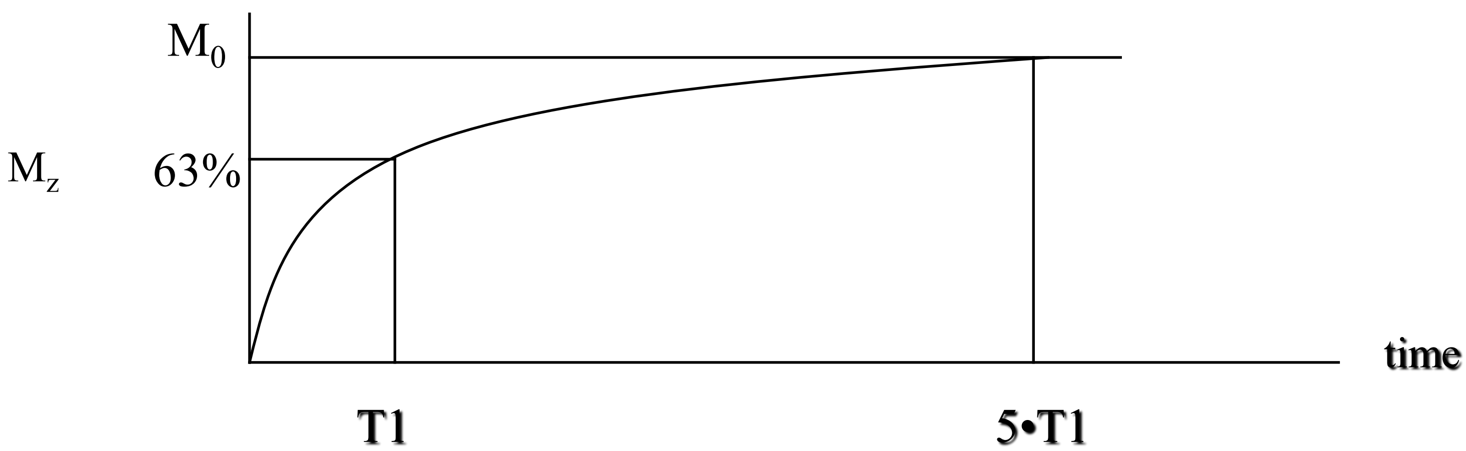
T1 Recovery



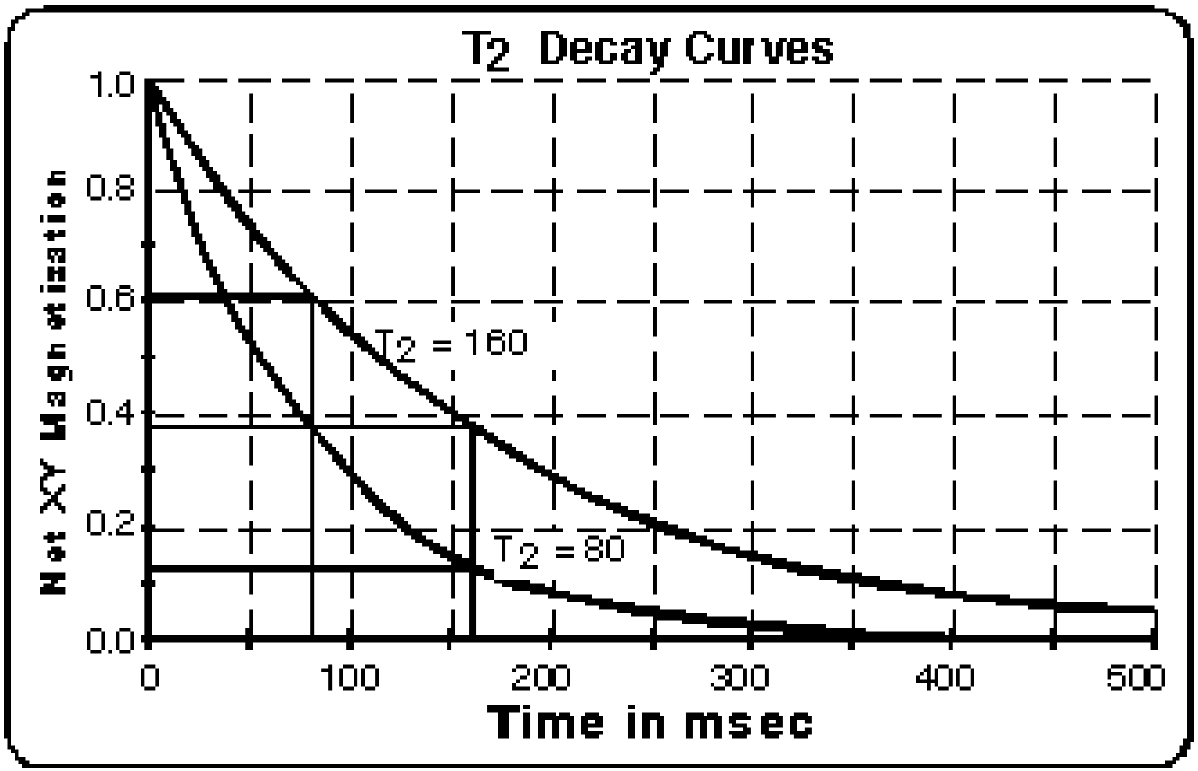
T2 Relaxation

- When magnetization first tilted into the XY plane all of the spins are in phase
- Start to dephase due to local variations in the magnetic field that the protons feel – some precess faster others precess slower
- As the spins dephase the magnitude of the MR signal fades

Spin-Spin Interaction

- An isolated proton feels main magnetic field B_0 only
- As protons move together, their magnetic fields interact
  - Field from one increases the field, precession speeds up
  - Field from one decreases the field, precession slows
- These temporary random interactions cause a loss of phase across the excited spins resulting in an overall signal loss

T2 Decay



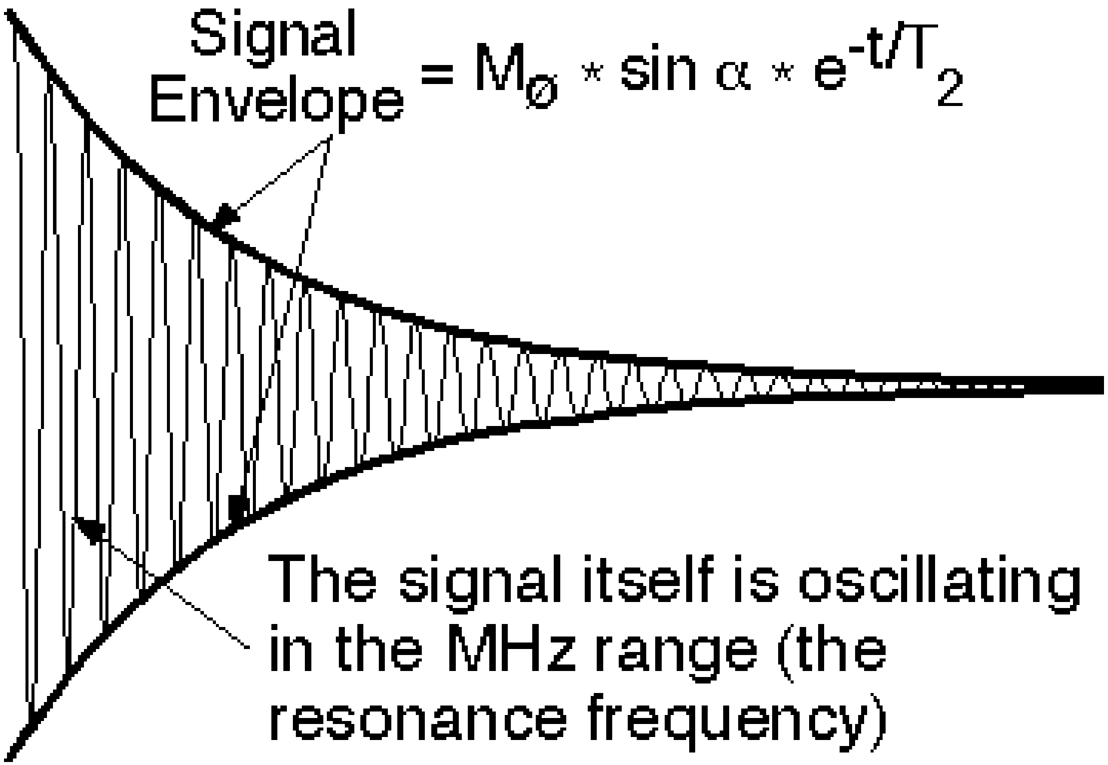
T2 Decay Curves
1.0
0.8
0.6
0.4
0.2
0.0
Net XY Magnetization
T2 = 160
T2 = 80
0
100
200
300
400
500
Time in msec

T2 Decay

- The decay of the signal due to loss of phase coherence is described by an exponential function
- The T2 time is the time after excitation that the signal has been reduced to 36.8% of its original magnitude
  - T2 is unique to every tissue and is in part determined by its chemical environment
  - T2 Decay Curve?

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

T2 Decay



Signal
Envelope
= Mø * sin α * e^-t/T2
The signal itself is oscillating
in the MHz range (the
resonance frequency)

Free Induction Decay

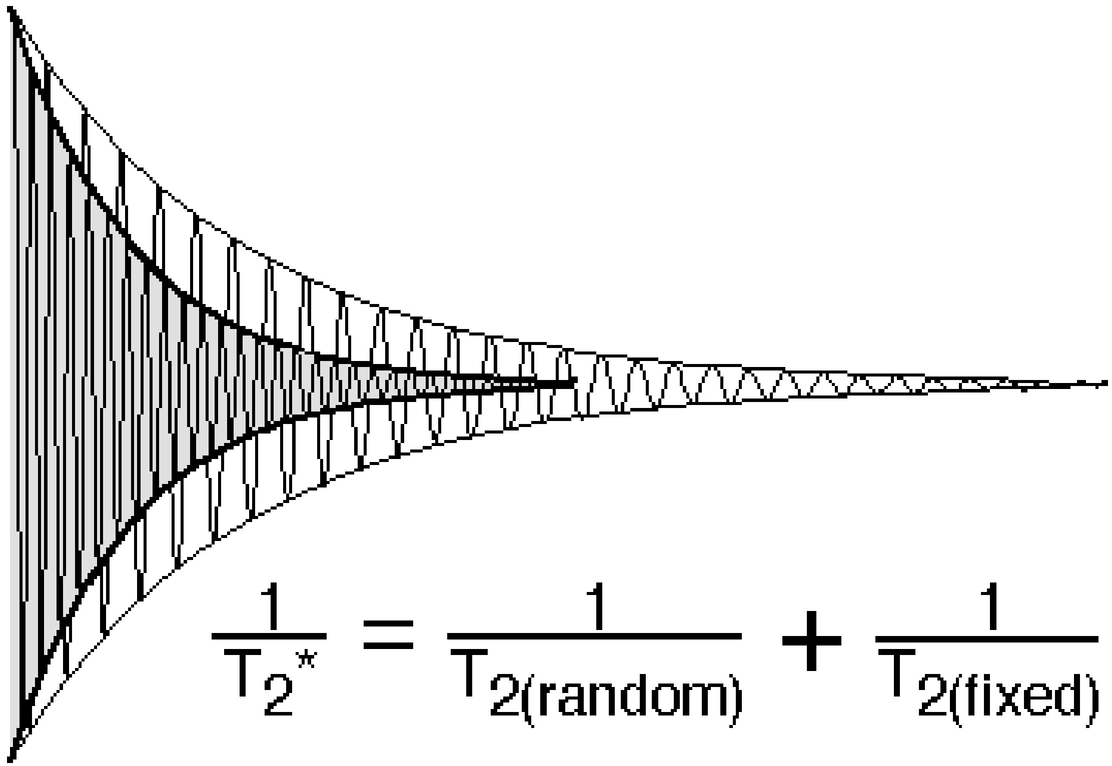
- After the RF transmitter is turned off, protons radiate RF energy
- The amplitude of the signal is based on the proportion of the M_0 tipped into the XY plane
  - Based on the sine of the flip angle
    - $\sin(0°) = 0$
    - $\sin(90°)=1.0$
- Signal unaffected by any gradients is known as the Free Induction Decay (FID)
  - Time constant of decay is related to T2
  - FID has no positional information

T2* Decay

- Decay of FID occurs faster than that predicted by T2
  - Slight imperfections in B_0 as well as magnetic susceptibility which distorts the field
- Sum total of all fixed T2 effects and random T2 effects is called T2*

$$1/T2^* = 1/T2_{random} + 1/T2_{fixed}$$

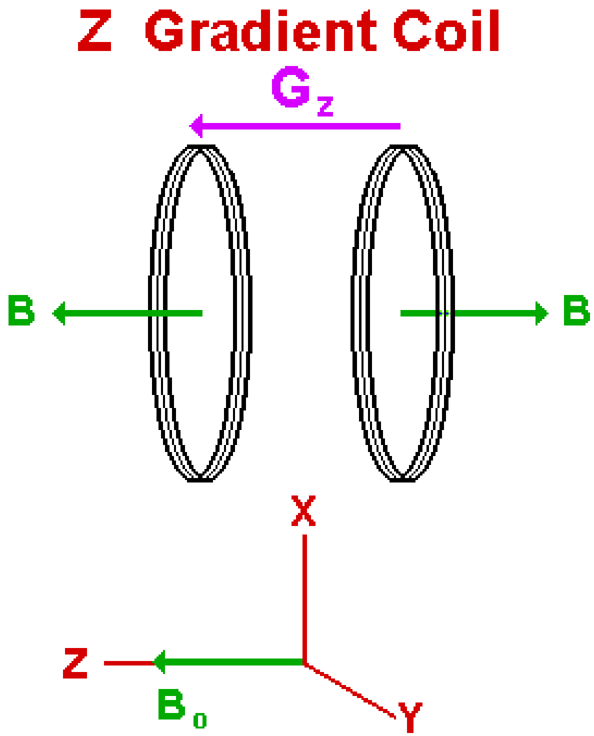
T2* Decay

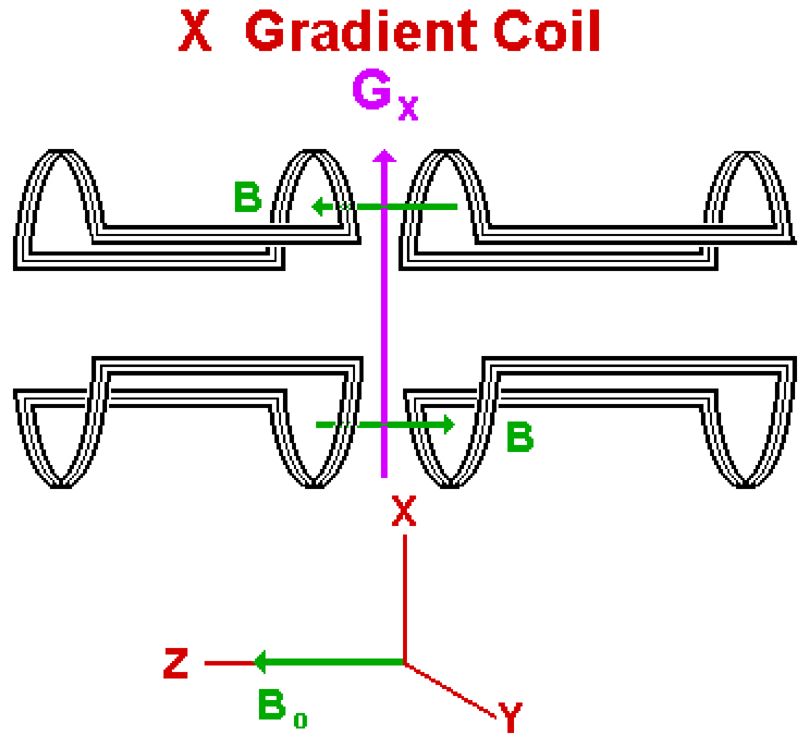


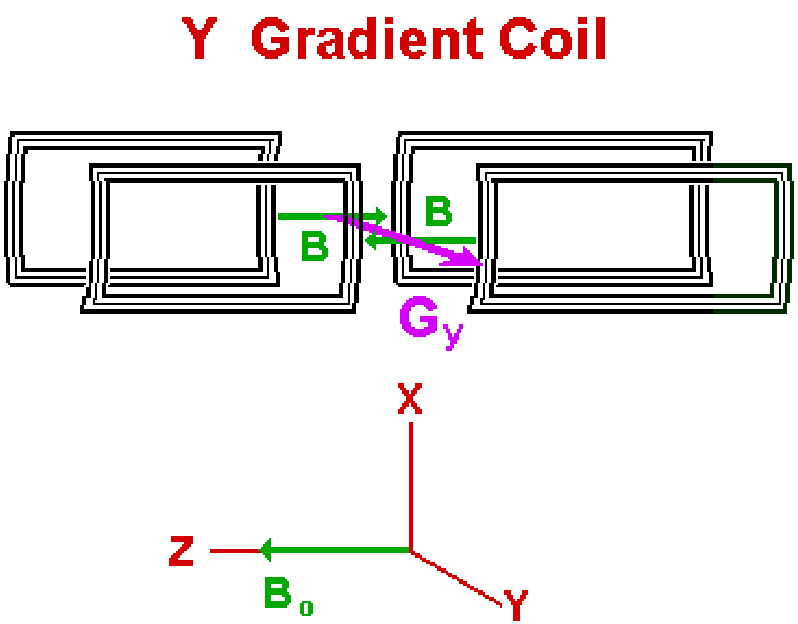
$$\frac{1}{T_2^*} = \frac{1}{T_{2(random)}} + \frac{1}{T_{2(fixed)}}$$

Gradient Coils

- There are three gradient coil sets in the scanner that create gradients along each of the axes
- When current is flowing on only one of the gradient coils then a gradient exists in that direction
- Gradient is a vector and when current flows in more than one coil then the gradient has a component in multiple planes
- Magnitude of gradient is the $\sqrt{(Gx^2+Gy^2+Gz^2)}$







Orthogonal Gradient Coils Used in MR Scanner

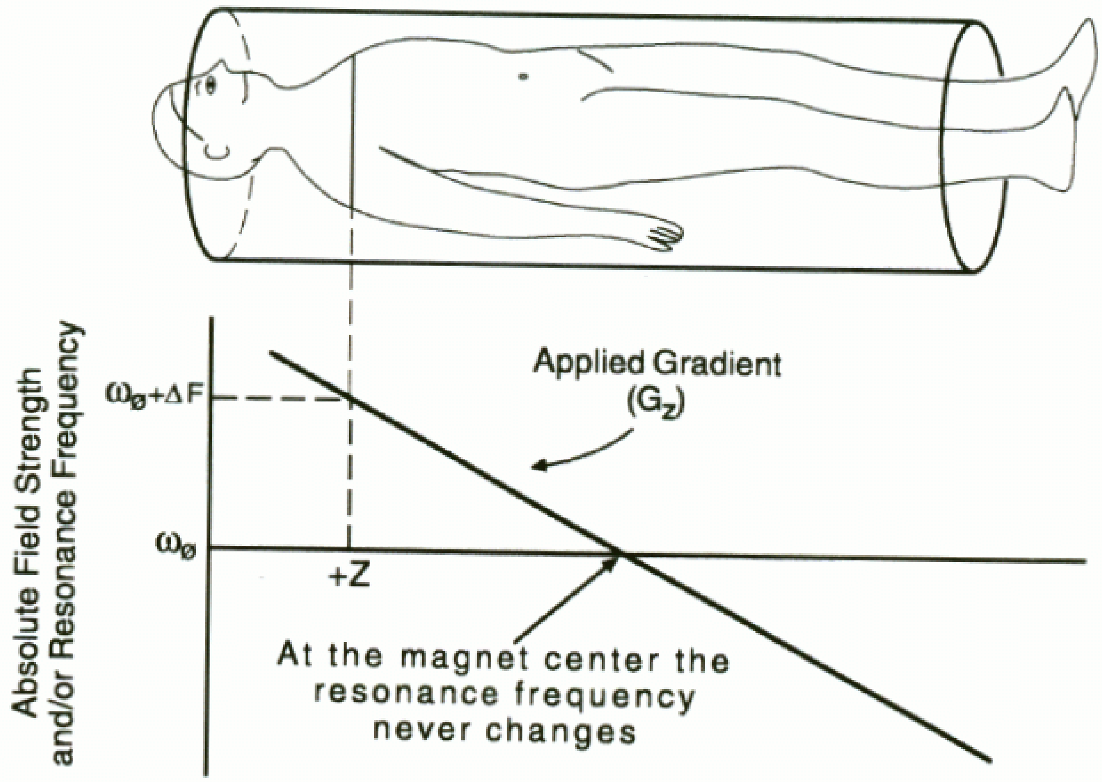
Gradient Properties

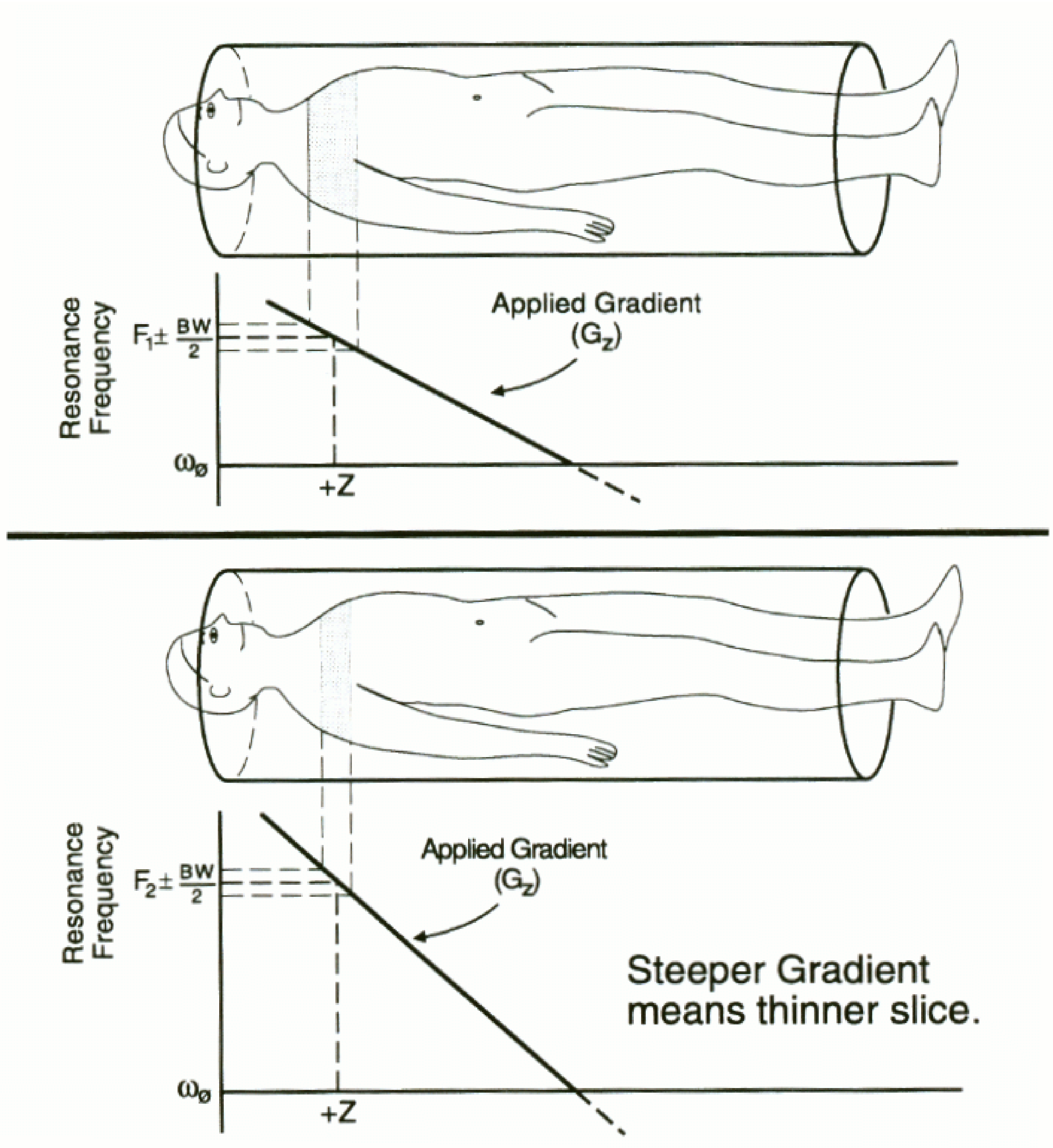
- Peak amplitude - i.e. Maximum gradient produced
  - Effect minimum slice thickness and FOV
- Slew rate - i.e. How fast the gradients can be ramped to peak amplitude
  - Faster gradients allow for shorter TE and TR times
  - Fast ramping gradients required for echo-planar scanning

RF System

- Center frequency - Placing the patient in the magnet affects the magnetic field and must retune to the new center frequency
- Transmitter gain - The amount of power to produce a 90 or a 180 degree pulse. Depends on the number of protons being flipped
- Receiver gain - The amount of signal reaching the receiver depends on the sequence and the amount of tissue in the sample
    - Gain too high, the signal is clipped
    - Gain too low, poor signal to noise ratios

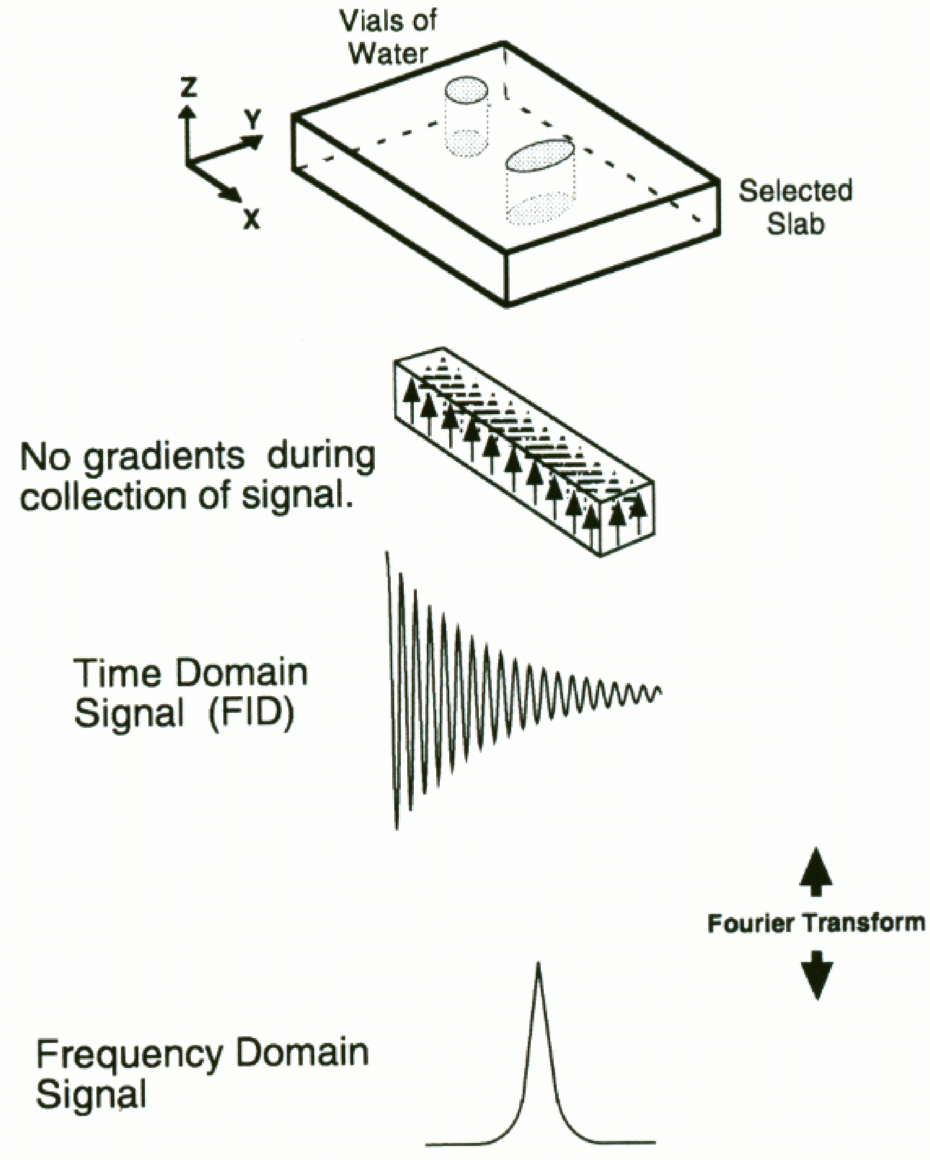
Slice Selection



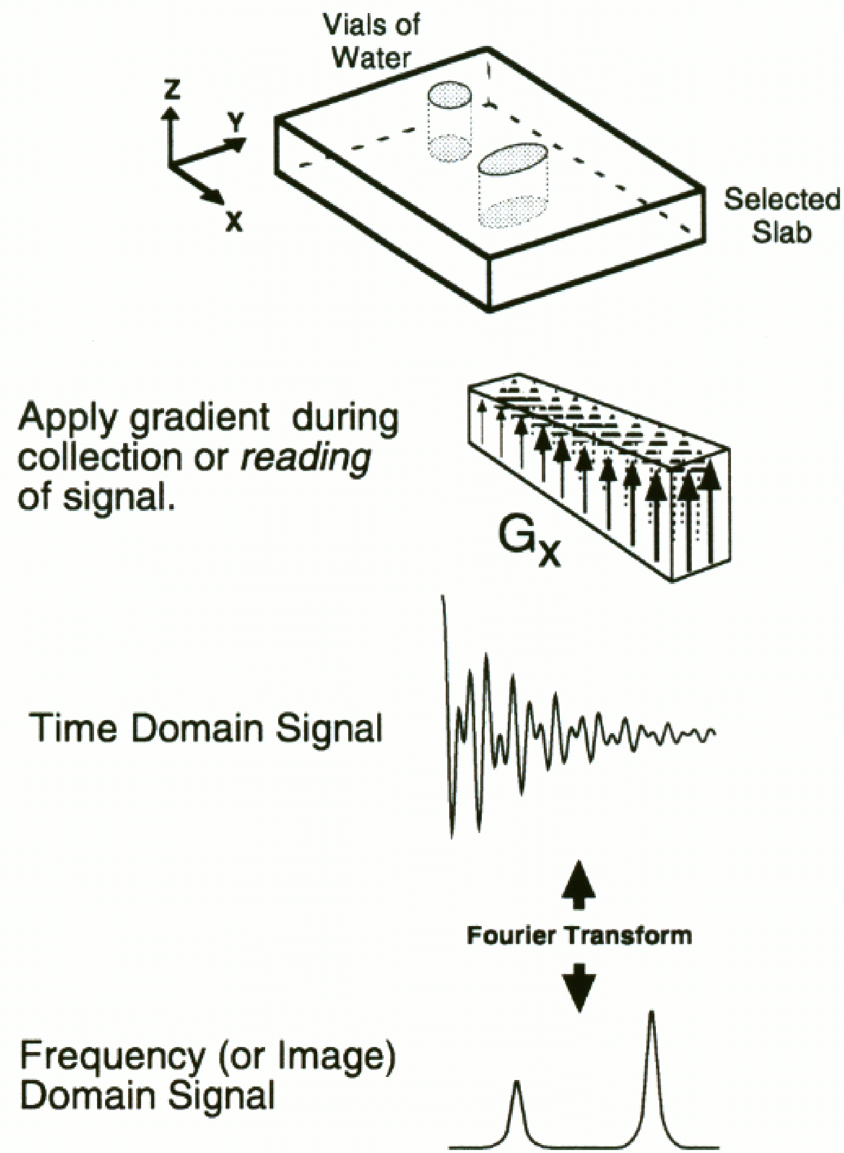


Slice Thickness

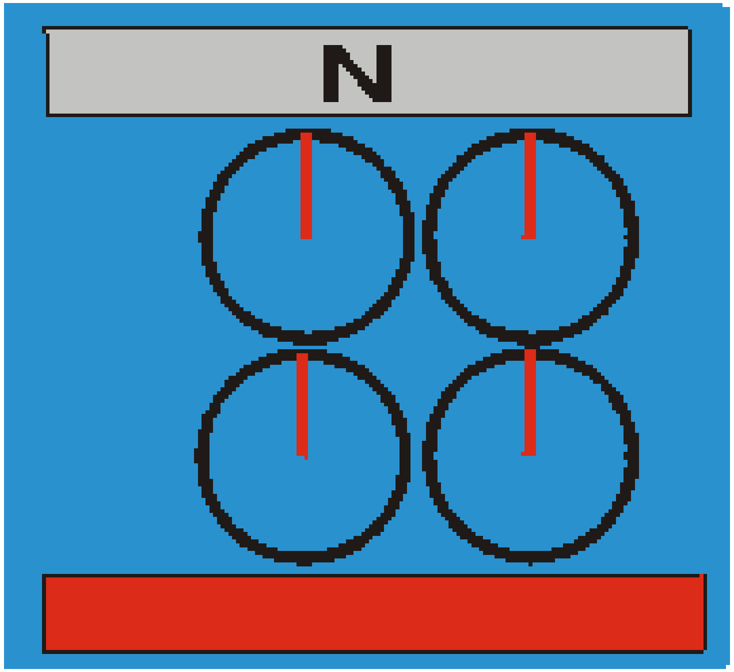
MR Signal without Any Applied Gradients



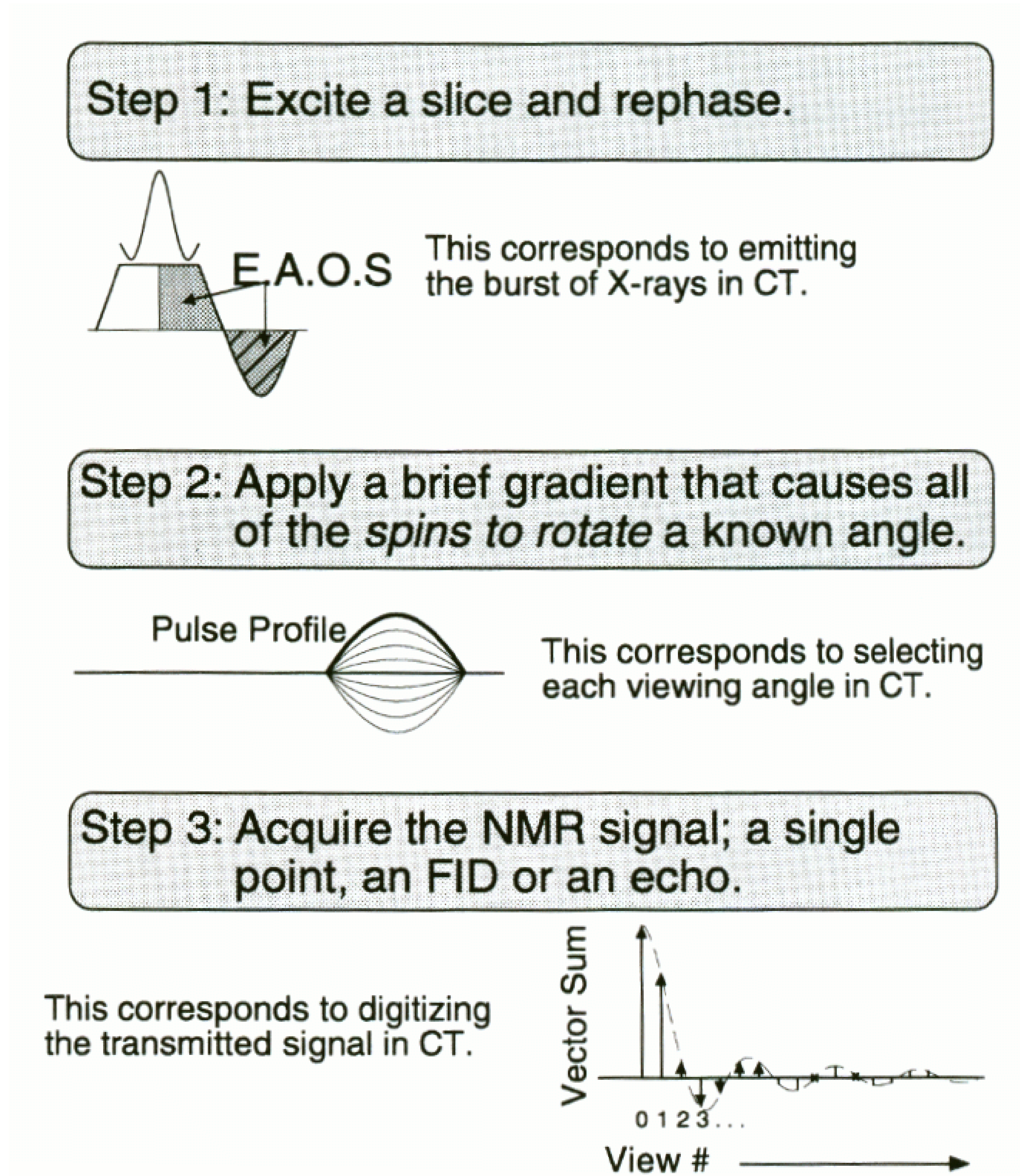
MR Signal With An Applied Gradient



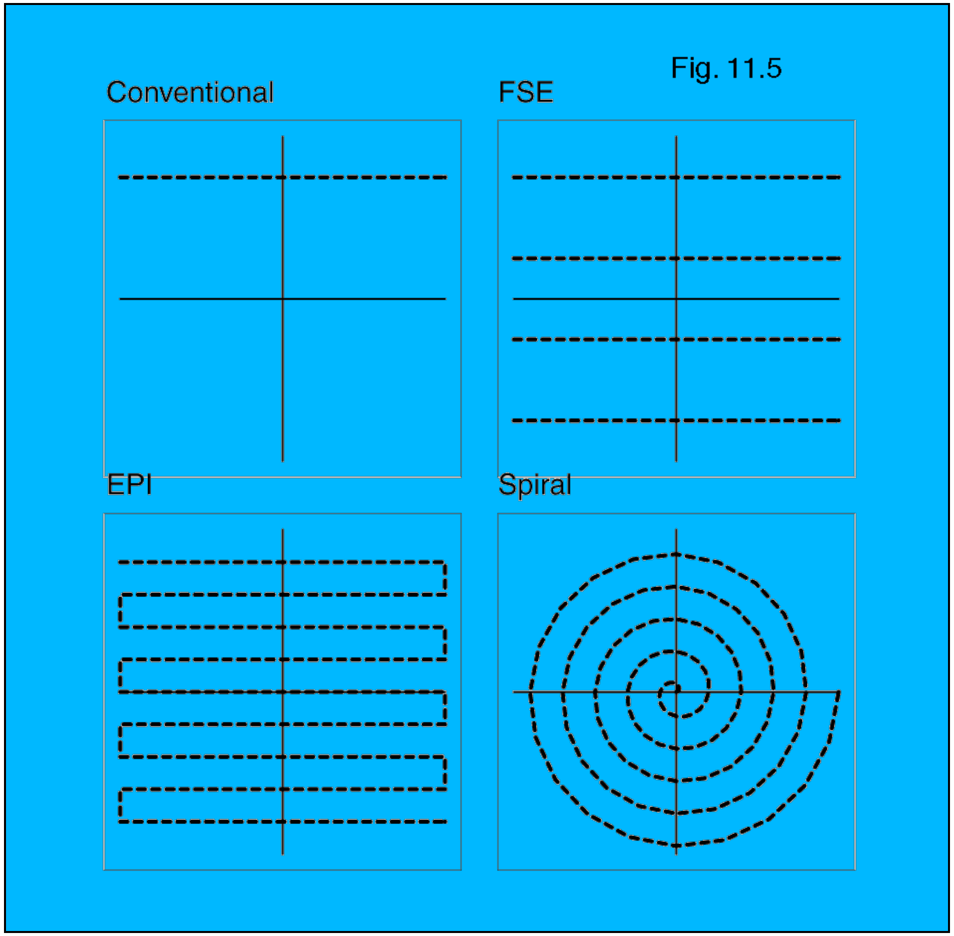
Phase Encoding



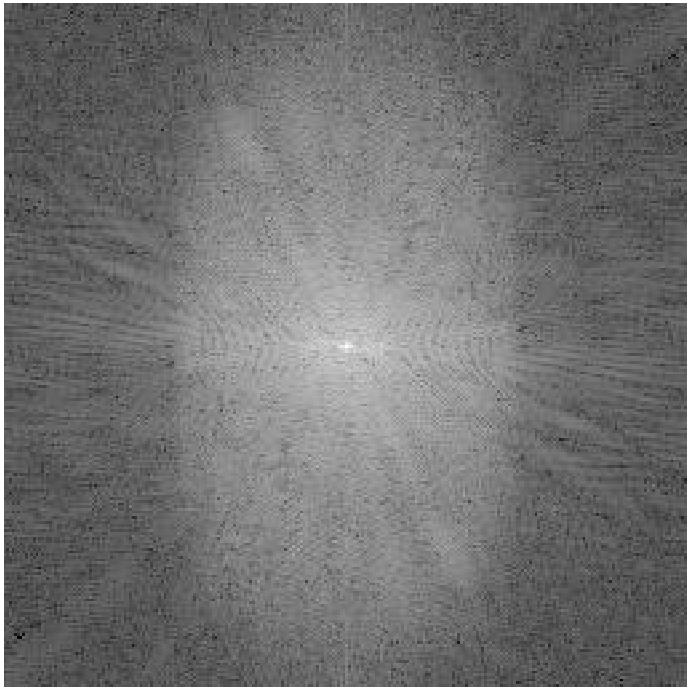
Standard Phase Encoding



K-Space Figure



Fourier Transform of Data



K-Space Data

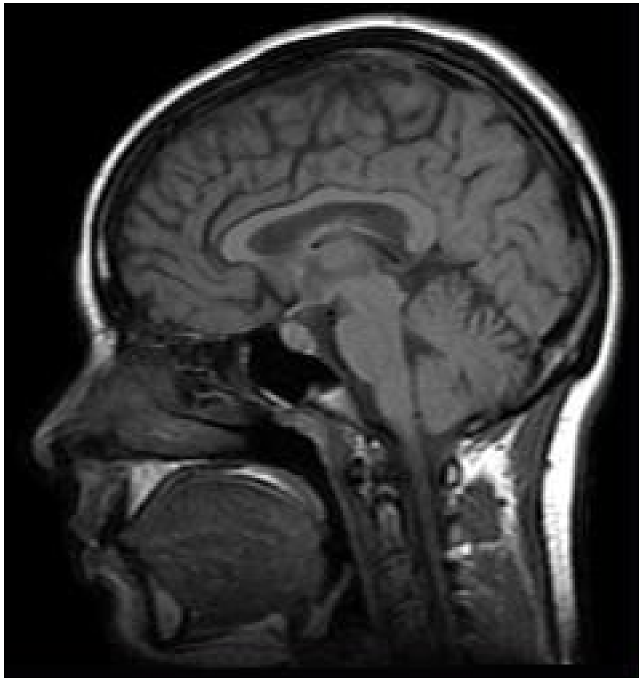
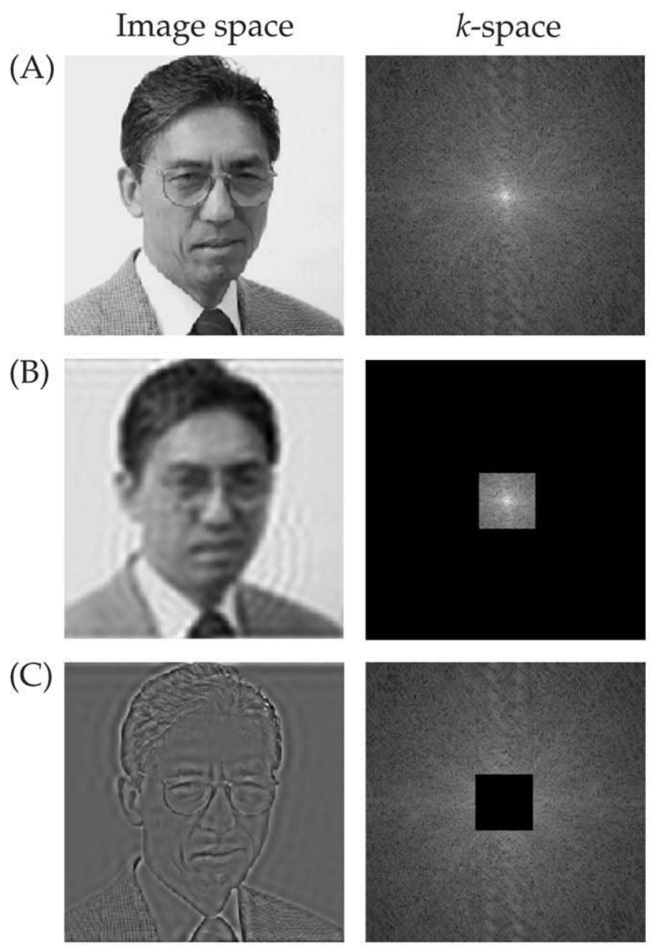


Image Data

→ Fourier Transform

How different parts of *k*-space contribute to image space.



FUNCTIONAL MAGNETIC RESONANCE IMAGING, Figure 4.7

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