Lecture 7: Magnetic Resonance Imaging

November 10, 2016

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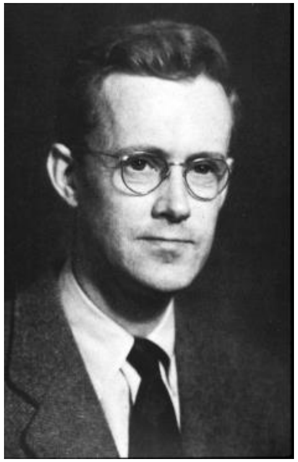


- **First successful NMR experiment in US in 1946**
- **Awarded Nobel Prize for Physics in 1952 for NMR discovery**
- **Found that nuclei placed in a magnetic field absorbed energy in the RF range of the electromagnetic spectrum and re-emitted this energy when they returned to their relaxed state**

Raymond Damadian

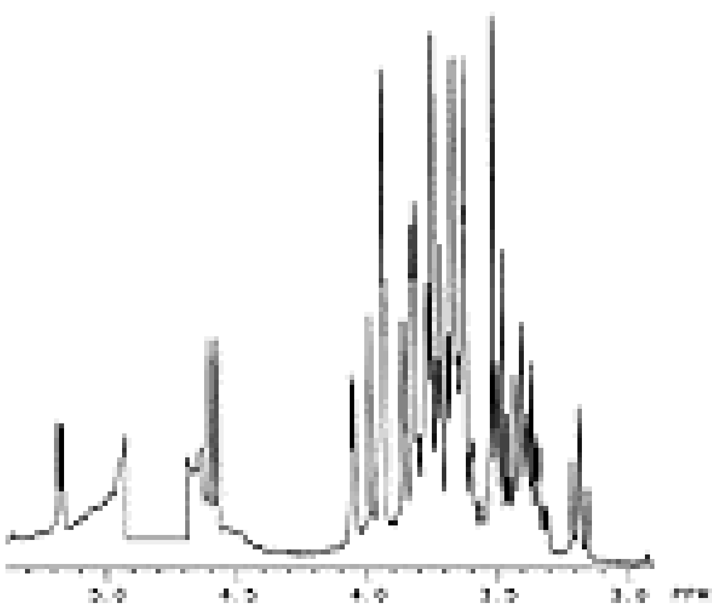
- **Demonstrated differences in NMR tissue parameters between normal tissue and tumor samples in late 1960’s and early 1970’s**

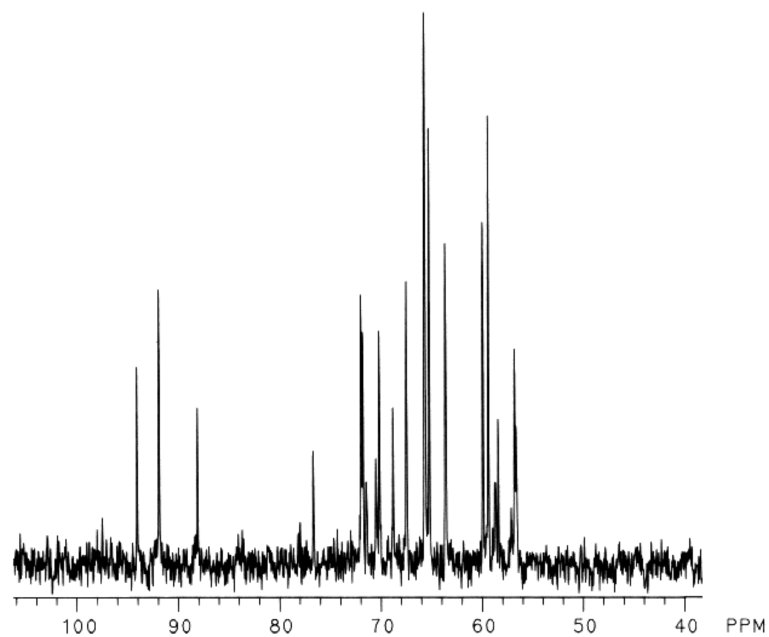
Paul Lauterbur
1929-2007

- **March 1973 published "Image formation by induced local interaction; examples employing magnetic resonance" in Nature**
- **Awarded 2003 Nobel prize in Physiology or Medicine with Peter Mansfield for his discoveries in MRI**

Uses of MR

NMR spectroscopy – determine chemical composition of materials





http://www.acts.org/roland/mt.dew/index.html

Uses of MR

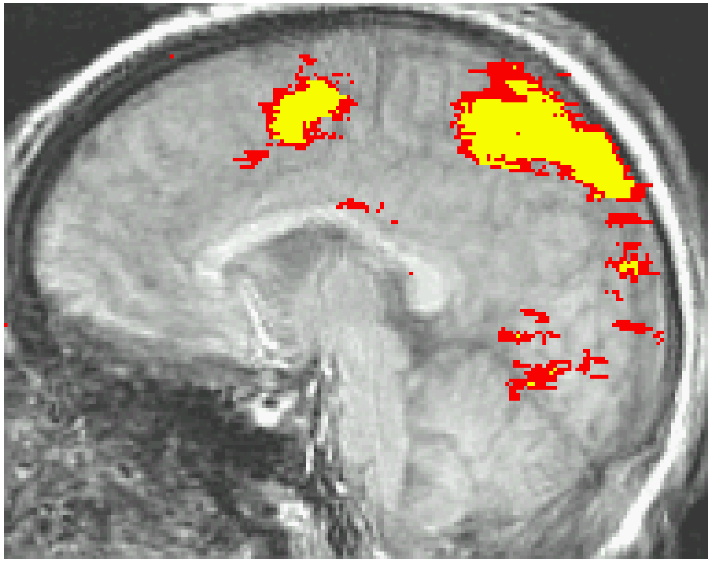
Magnetic Resonance Imaging

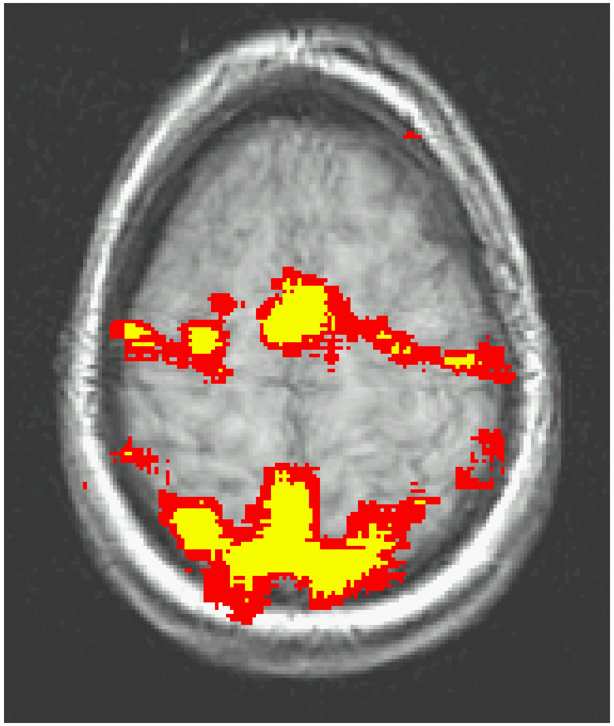
– high resolution anatomical imaging

www.nlm.nih.gov

Uses of MR

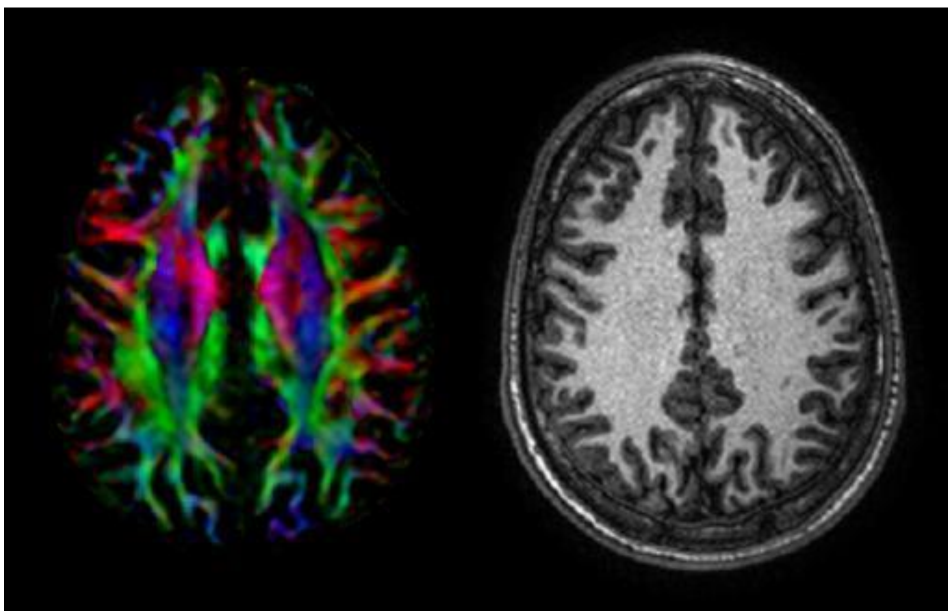
Functional MRI - imaging brain function by determining changes in blood flow



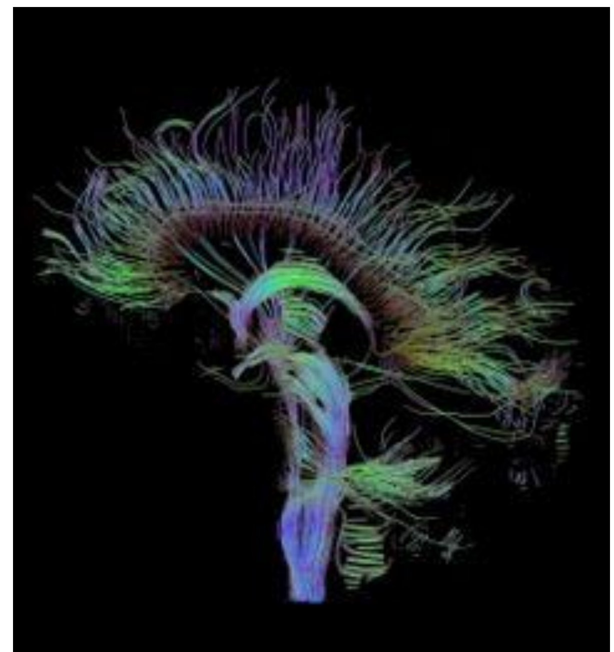


Uses of MR

Diffusion Tensor Imaging – used to image white matter in the brain by measuring the restriction and diffusion of water in tissue



www.ipam.ucla.edu



http://en.wikipedia.org/wiki/Diffusion_tensor_imaging

MRI Environment

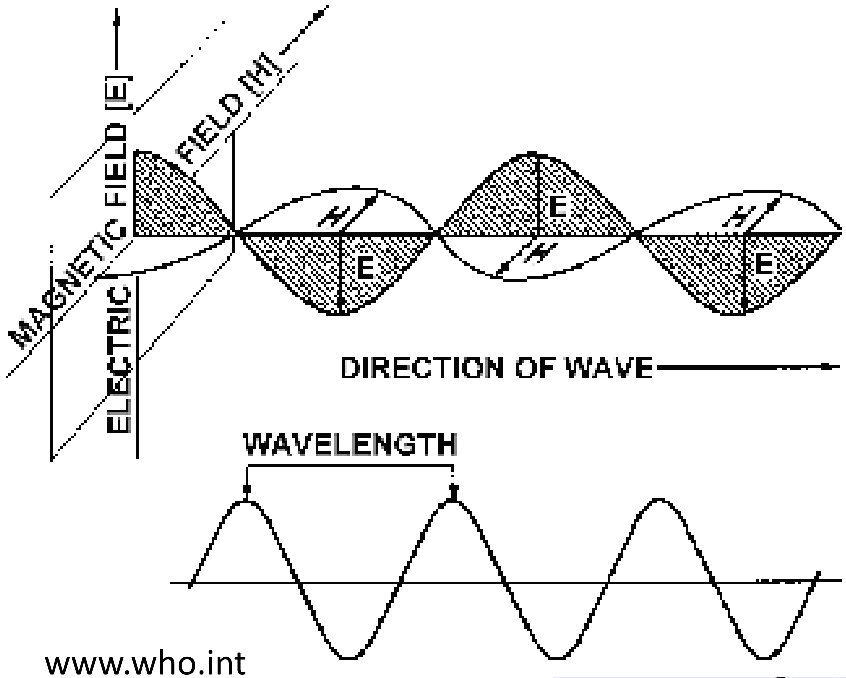
- Large magnetic field located within the bore of the magnet

How it works / Basic Principles

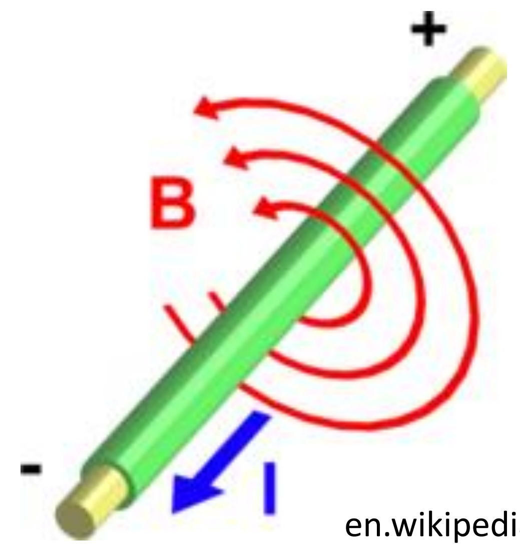
Basic Concepts of MRI

1. **Magnetism, nuclear spin and precession**
2. RF pulse
3. Free induction decay
4. T1, T2, T2*
5. Image contrast

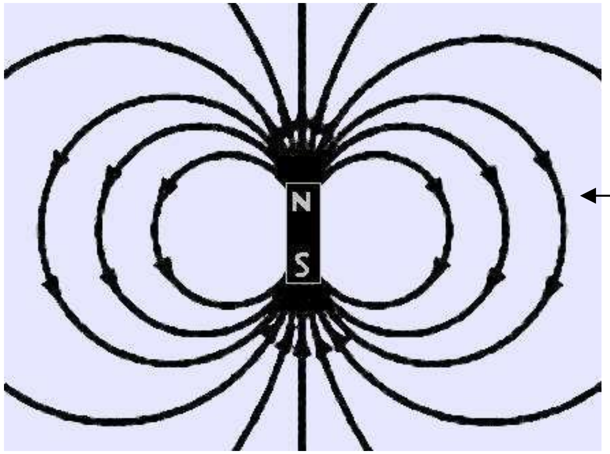
Electricity & Magnetism



www.who.int



en.wikipedia.org

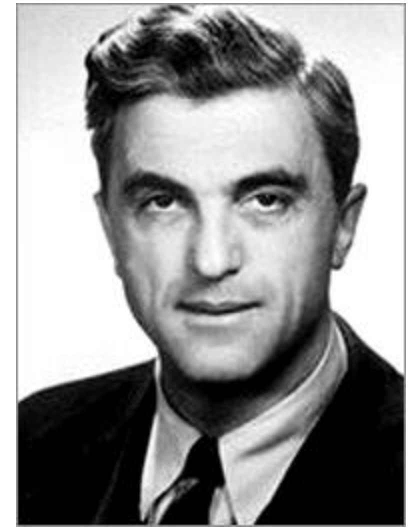


www.wondermagnet.com

-closed loops

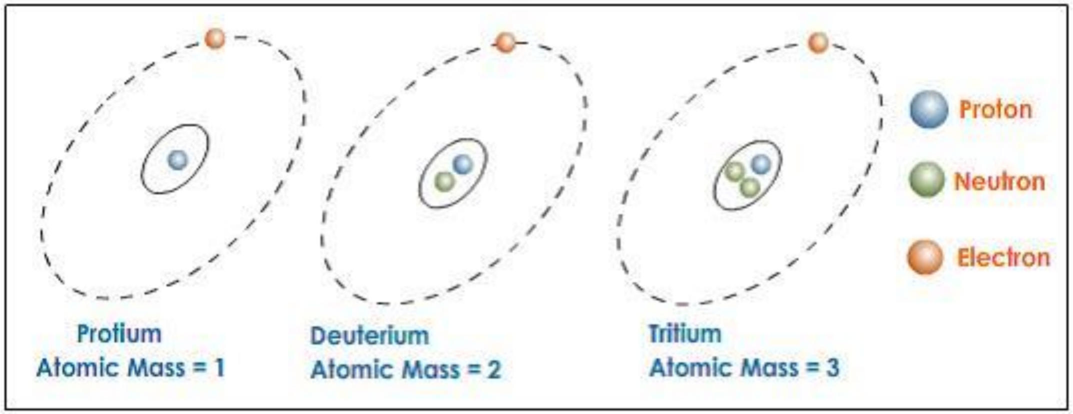
bar magnet, but also for earth, loop of wire

Nuclear Magnetism



- Felix Bloch, 1952 Nobel Prize
- All nuclei with an *odd atomic weight* have a property called "spin"
- In MR, we are generally interested in the hydrogen nucleus (H) or proton (no neutron)
- These protons have angular momentum, **P**, and magnetic moment, $\boldsymbol{\mu}$
- P is dependent on number of protons and neutrons in the nucleus (it is discrete or quantized)

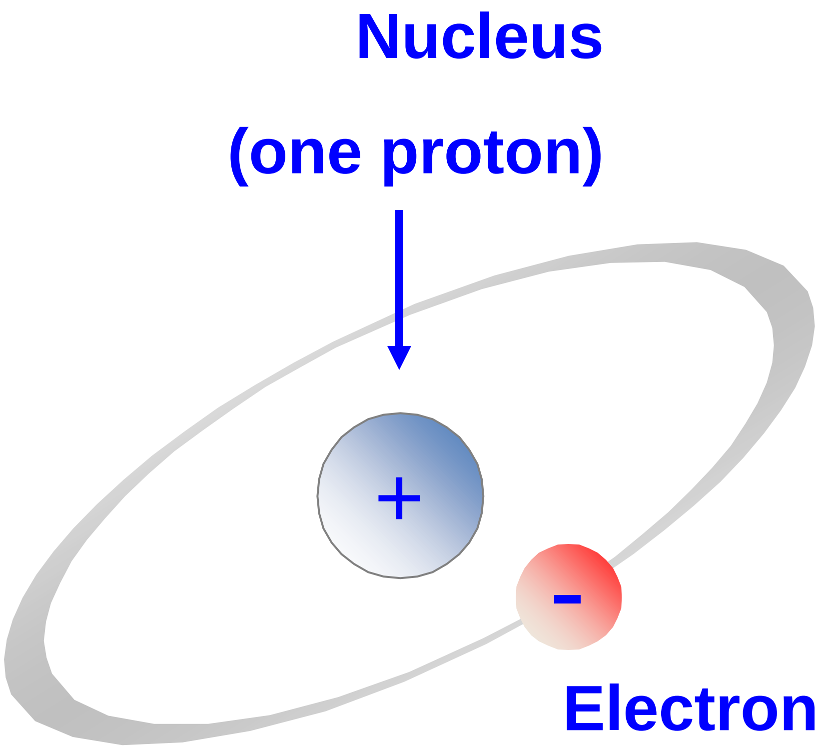
Hydrogen Atom



- Protium is the ^{1}**H** (atomic mass 1.00782504(7)
- Most common hydrogen isotope with an abundance of more than 99.98%
- Nucleus of this isotope consists of only a single proton
- Cation of Protium is called a proton (H+)

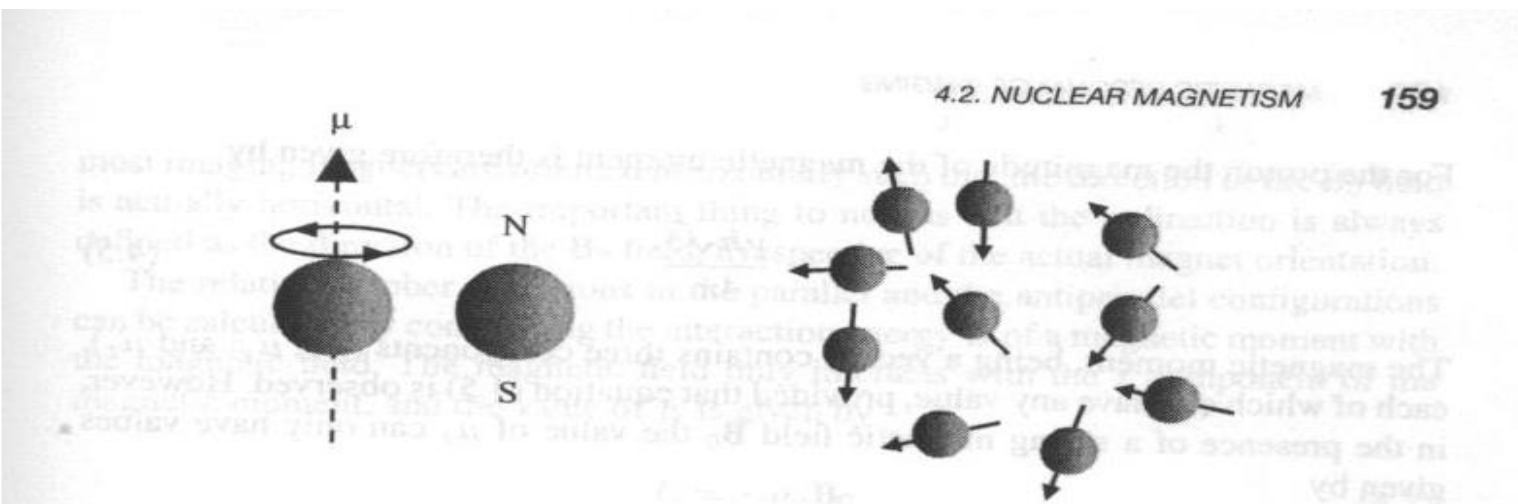
Protons

- **Large amount of fat and water in the human body made up of hydrogen atoms**
- **These hydrogen nuclei have an NMR signal and act like tiny tops that wobble as they spin**
- **They are oriented randomly**



Hydrogen Atom

Hydrogen (Proton)

- Like a small magnet
- Absence of external field, orientation of magnetic moment is random, net field is zero
- 

Now, let's add an external magnetic field -

- B_0 = the constant, strong, external field
- Measured in Tesla
- 1 Tesla = 10,000 Gauss
- 1/2 Gauss = magnetic field at earth's surface

Magnetism

- **Magnetic strength is measured in Tesla and gauss**
-
- **1 Tesla (1.0T) = 10,000 gauss**

- **Did you know…**
  - **Earth's magnetic field = .5 gauss**
  - **Refrigerator magnet = 50 gauss**
  - **3.0T scanner = 30,000 gauss**
  - **We have a 7 Tesla scanner at the University of Pittsburgh**

Magnet Facts

- **The magnet is the most expensive part of the MR scanning system**

- **MRI system uses 3 fields**
  - **Static, referred to as B0**
    - **Permanent - heavy, weighing 100 tons or more**
    - **Resistive - needs electricity to generate it's own field; low field strength**
    - **Superconductive - several miles of wire kept cooled by liquid helium and chilled water**
  - **Radio-frequency, referred to as RF or B1**
  - **Gradient magnetic field - needed for imaging**

- **Two important features:**

  homogeneity - a uniform field

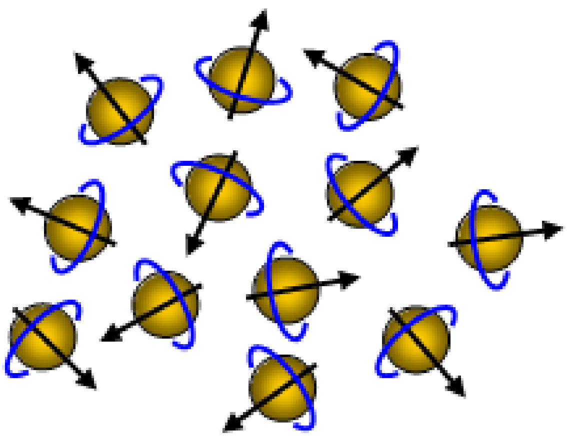
  stability - steady signal over time

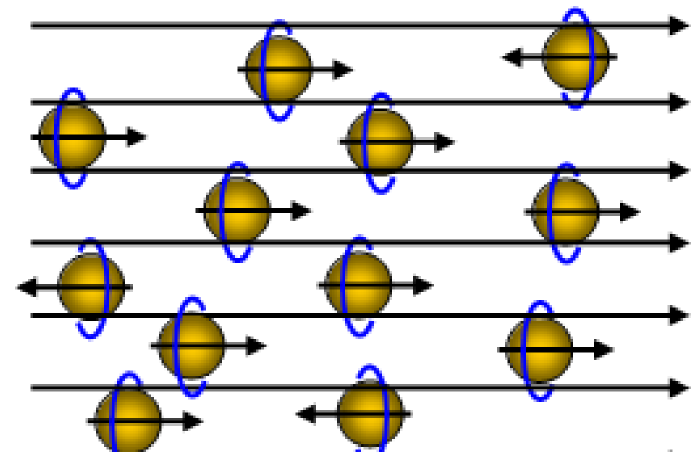
Magnetic Susceptibility of Substances (Reaction to External Field)

- Diamagnetic = no unpaired orbital electrons, oxyhemoglobin, water, most substances in nature (weakly affected by external field)
- Paramagnetic = unpaired orbital electrons, deoxyhemoglobin (become magnetized by external field, but do not retain magnetization in absence of field)
- Ferromagnetic = permanently magnetized by external field (Fe, Co, Ni)

Back to Hydrogen....

Add a magnetic field, and the protons align to it

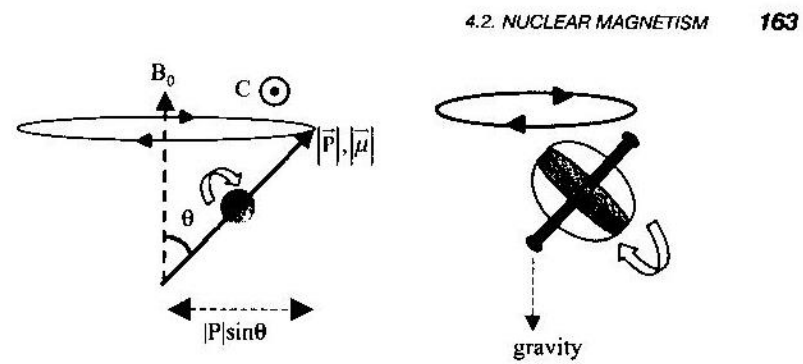




Spin Precession (Classical)

- Now we know, H+ is spinning away in the B_0 field, either parallel or anti-parallel in orientation at an angle (54.7°)
- Because it is trying to align with $B_{0,}$ a torque is creating, which is similar to the motion of a gyroscope
- The frequency of precession is called the resonant frequency or Larmor frequency (ω)

$$\omega_0 = \gamma B_0$$



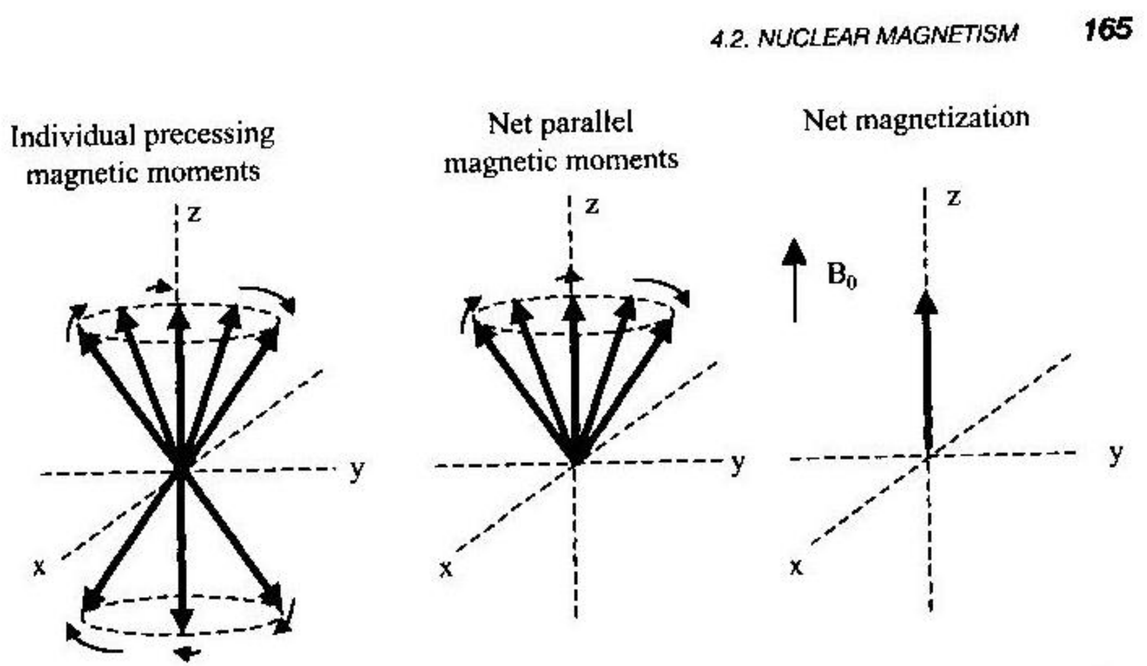
γ = gyromagnetic ratio (different for different nuclei)

γ = 42.6 MHz/T for H

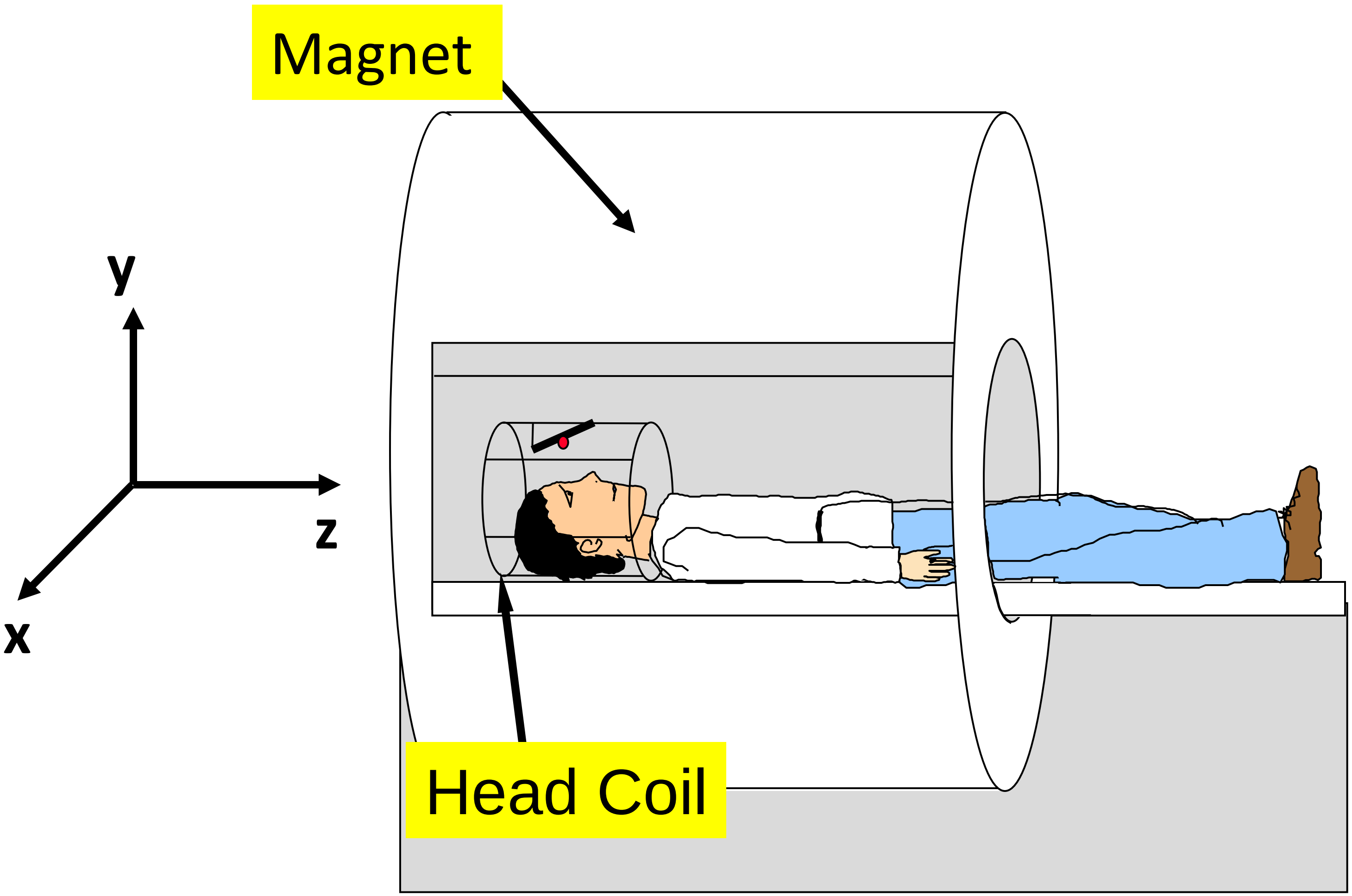
Net Magnetization

- Can think of the effect of all protons as a "net magnetization" such that:

$$M_z = M_0, M_x = 0, M_y = 0$$



Coordinate System in Reference to Equipment



Courtesy of Dr. Bea Luna

Basic Concepts of MRI

1. Magnetism, nuclear spin and precession
2. **RF pulse**
3. Free induction decay
4. T1, T2, T2*
5. Image contrast

Add Radiofrequency Pulse

(RF) Radio frequency part of the electromagnetic spectrum in which electromagnetic waves can be generated by alternating current fed to an antenna.

The RF pulses used in MRI are commonly in the 1-100 megahertz range, and can be a source of potential heating of tissues and foreign bodies, such as metallic implants, mainly at the surface.

This is a principal area of concern for MRI safety limits caused by absorption (see specific absorption rate) of the applied pulses of RF energy.

Radio Frequency (RF) Pulse

- Electromagnetic energy applied to protons at their **resonant frequency** (ω)

  (NOTE: Think of a child on a swing)

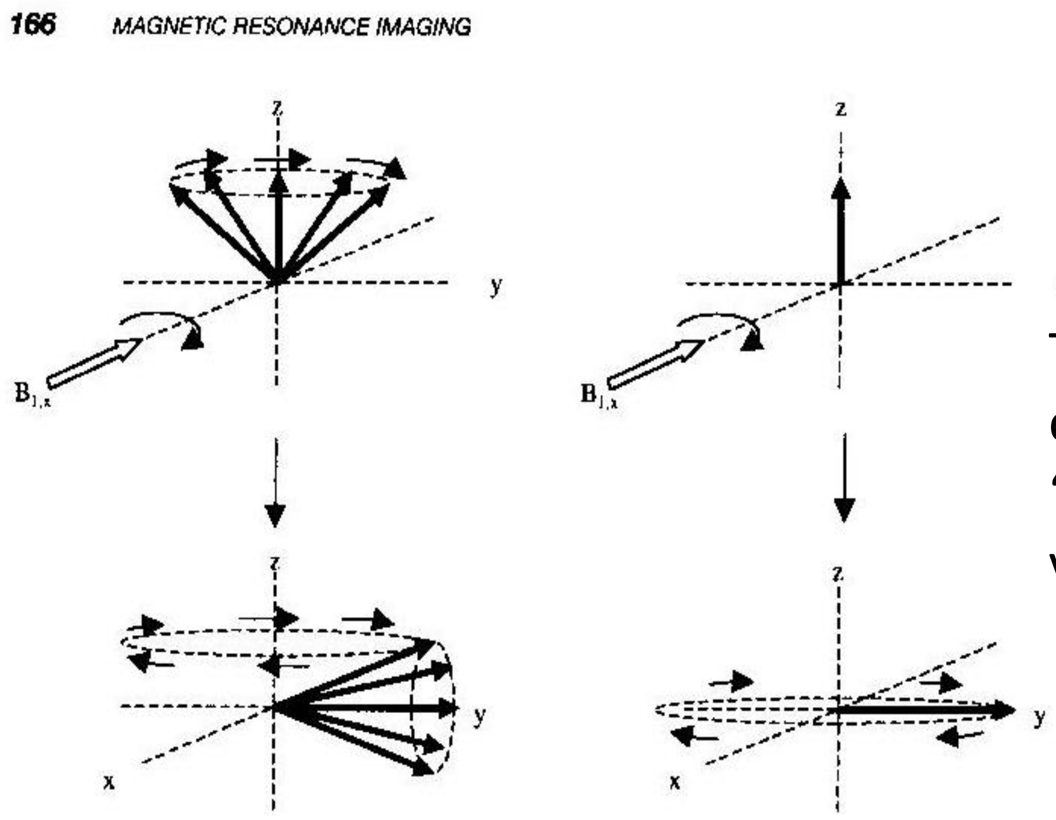
  In MRI, RF pulse = 3-100MHz

- "Tips" net magnetization from z to x direction

- Tip angle depends on strength of applied RF field and the amount of time its applied

RF Pulse Illustration

This is the concept with "individual spins"



This is the concept with "magnetic vectors"

Knocking them down into the transverse plane!!

After the RF Pulse

1. Protons immediately begin to align back to their lowest energy state along the B_0 field (T1 longitudinal relaxation)
   - As they do so, they emit energy
   - Specifically, as the magnetic flux (ϕ) changes in an enclosed loop, a current is produced and measured by the RF coil

$$E \alpha -d\phi/dt$$

2. Loss of phase coherence in the transverse plane (T2, transverse relaxation)

Basic Concepts of MRI

1. Magnetism, nuclear spin and precession
2. RF pulse
3. **Free induction decay**
4. T1, T2, T2*
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Free Induction Decay (FID)

- Energy signal that is measured as protons return to their energy state
- Oscillating exponential decay

Received Free Induction Decay Signal

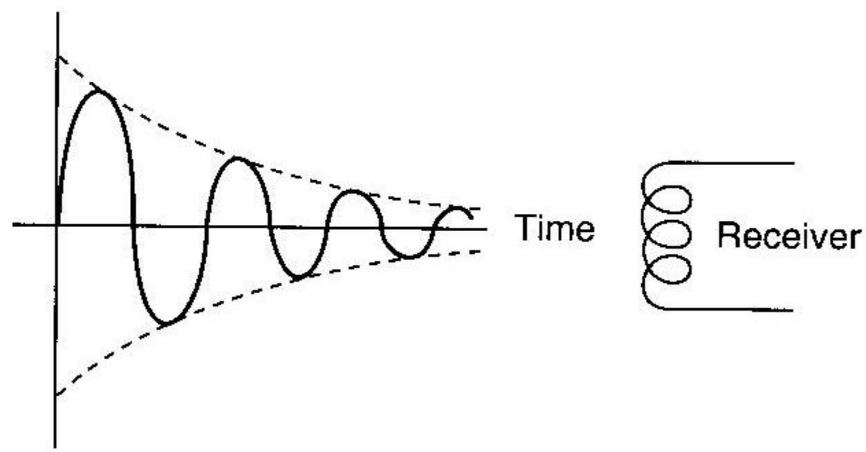


Figure 4-12. The decaying sinusoidal waveform of the received signal (the FID).

From MRI: The Basics, by Hashemi, R.H., and Bradley, W.G., Jr.: Lippincott Williams & Williams (1997), pg. 47

Basic Concepts of MRI

1. Magnetism, nuclear spin and precession
2. RF pulse
3. Free induction decay
4. **T1, T2, T2***
5. Image contrast

Longitudinal Relaxation Time (T1)

- Also called spin lattice relaxation
- Measures return rate of protons to their alignment the B_0 axis
- A tissue dependent property

168 MAGNETIC RESONANCE IMAGING

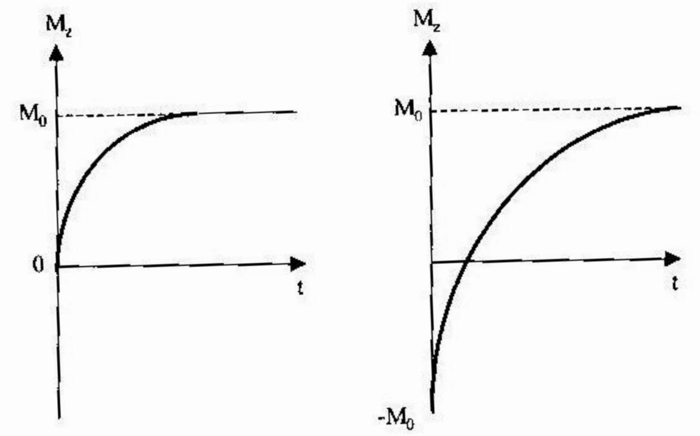
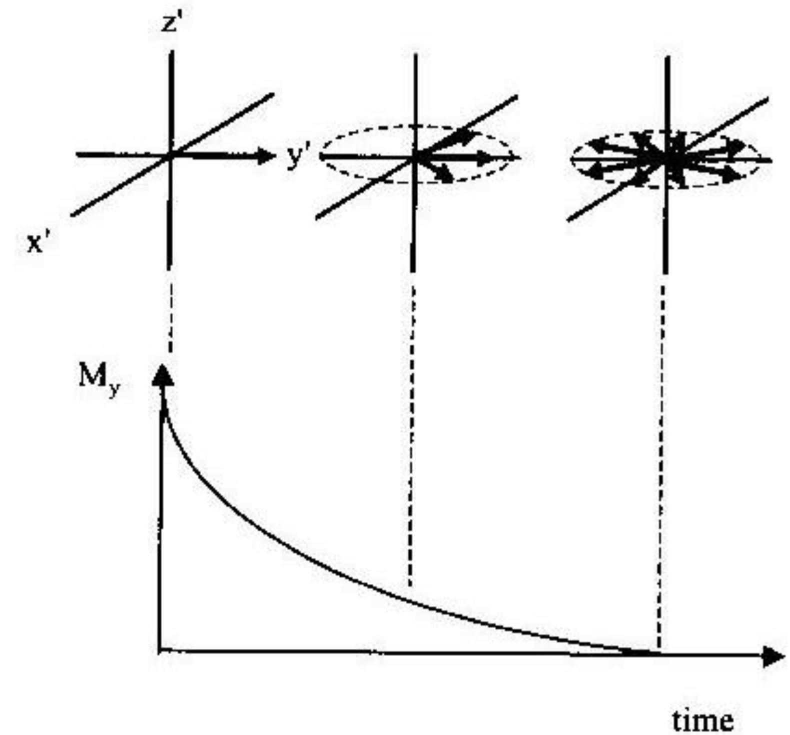


FIGURE 4.8. *Plots of M_z versus time after (left) a 90° pulse and (right) a 180° pulse.*

Transverse Relaxation (T2)

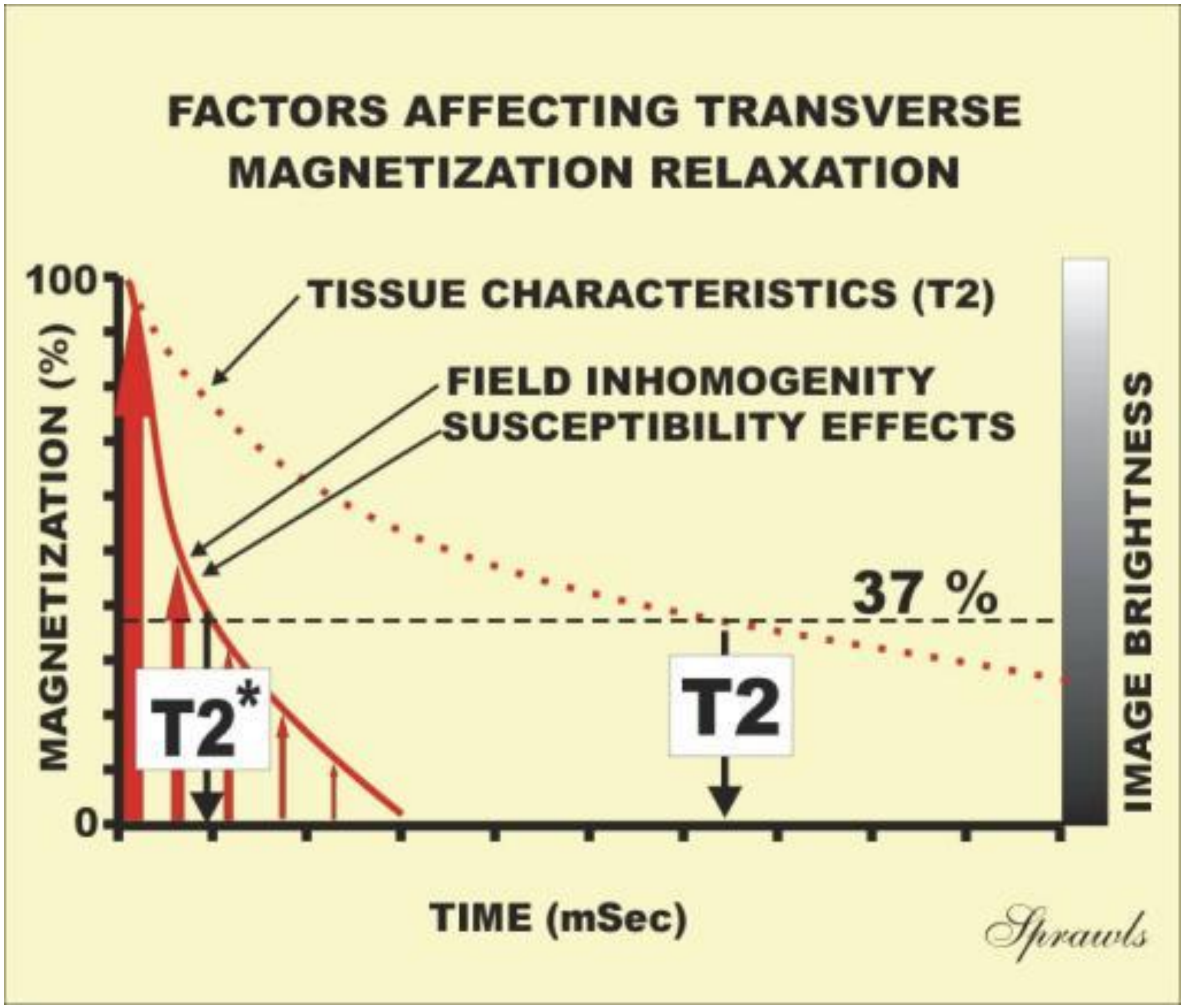
- Also called spin-spin relaxation
- Loss of "phase coherence" between protons precessing in the transverse plane
- Characterizes rate of decay of M_{xy}
- Decrease in net magnetization over time, due to:
  - Interactions between protons (T2)
  - Inhomogeneous magnetic field ($T2^*$)
- Tissue dependent property



T2 and T2*

- T2 is the transverse relaxation in a perfect magnetic field
- But, the field is not perfect
- T2* is the loss in phase coherence due to the inhomogeneous magnetic field
- T2 = T2’ + T2*
- T2* causes faster decay in the signal
- T2* is useful for Functional MRI

T2* Effects



http://www.sprawls.org/mripmt/MRI04/index.html

T1 and T2 for Different Tissues

- T2, in solids, the molecules are closer, the spin-spin interactions result in faster dephasing
- T1, depends on physical state of tissues, specifically the way that the protons can give off or absorb energy from their surrounding lattice structure (more viscous materials have a shorter T1)

TABLE 4.2. Tissue Relaxation Times at 1.5 T

Tissue	T_1 (ms)	T_2 (ms)
Fat	260	80
Muscle	870	45
Brain (gray matter)	900	100
Brain (white matter)	780	90
Liver	500	40
Cerebrospinal fluid	2400	160

Basic Concepts of MRI

1. Magnetism, nuclear spin and precession
2. RF pulse
3. Free induction decay
4. T1, T2, T2*
5. **Image contrast**

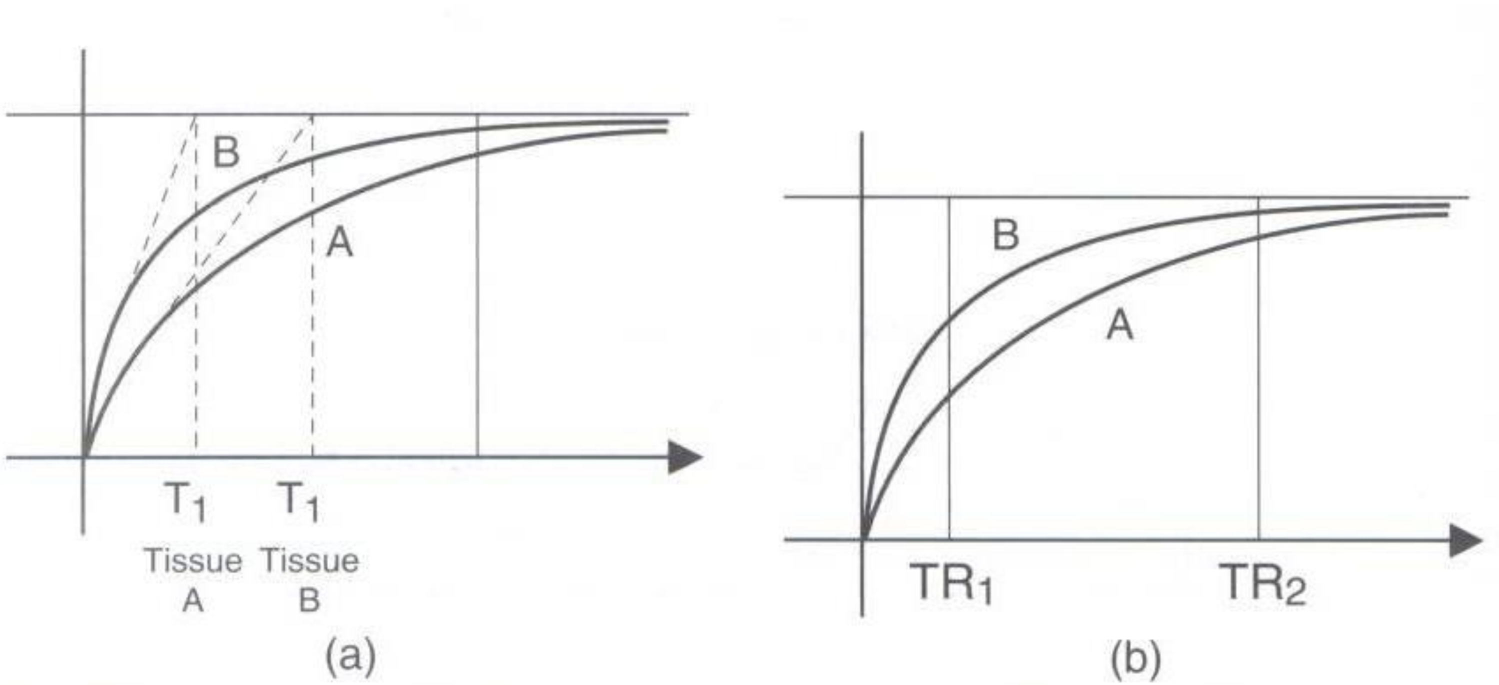
Image Contrast

- Can change the times between RF pulses (TR) and/or the time when the FID is measured (TE) to see contrast between tissues

- TR = time of repetition (between 2 RF pulses or flip angles)

- TE = echo time (waiting time to allow dephasing in transverse plane before sampling)

Contrast Effects of T1

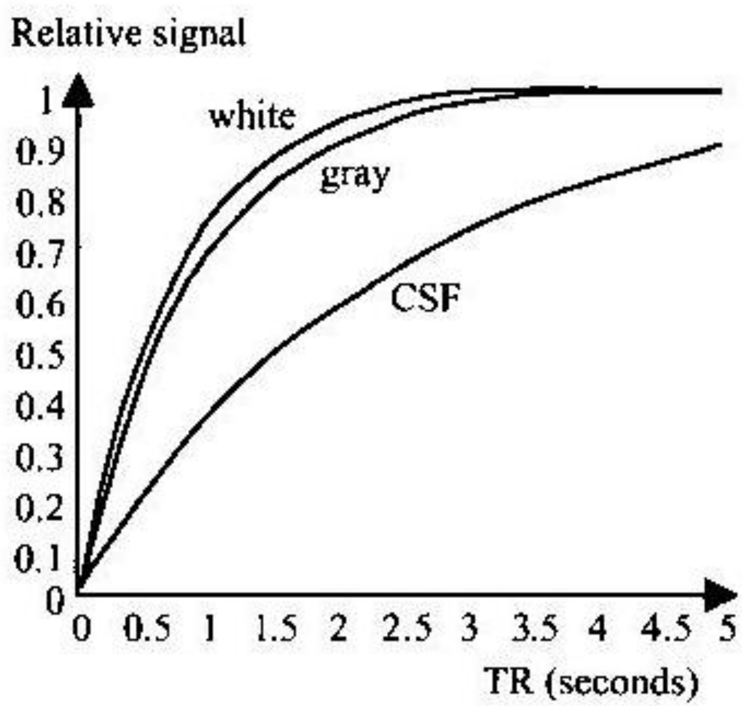


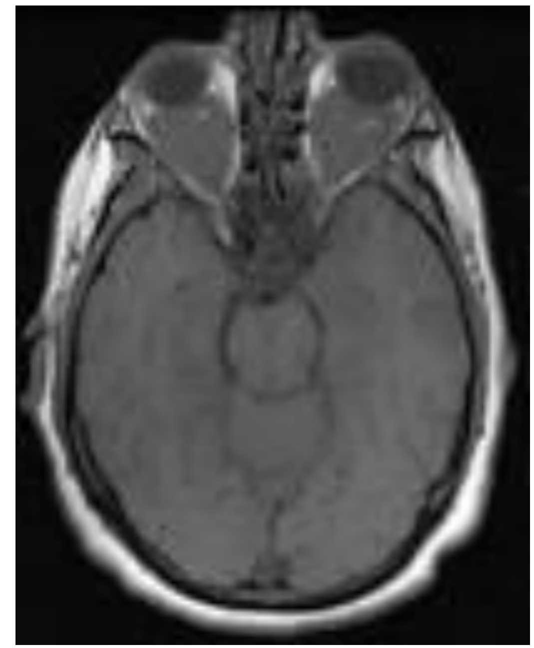
Question 1: Which tissue in (a) has a longer T1?

Question 2: Which TR in (b) will give better contrast between tissues?

From <u>MRI: The Basics</u>, by Hashemi, R.H., and Bradley, W.G., Jr.: Lippincott Williams & Williams (1997), pg. 54.

T1 Contrast



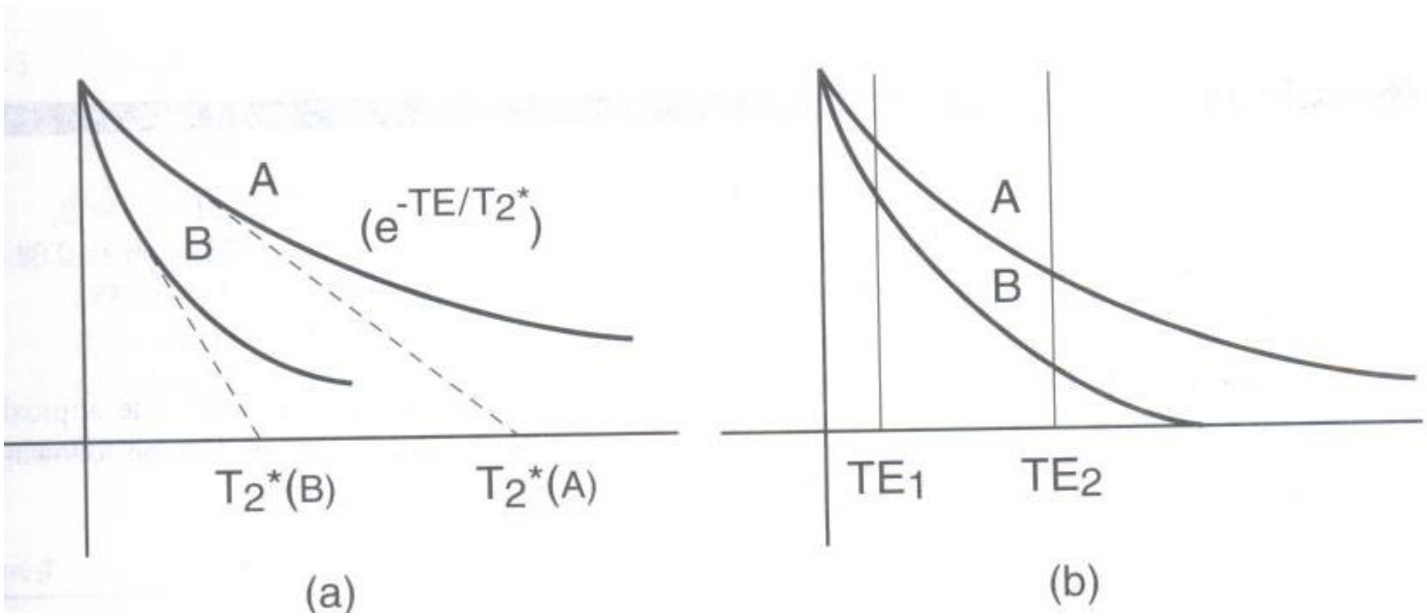


www.med.harvard.edu

Short TR - enhances T1 effect,

Short (or minimal) TE - reduces T2* effect

Contrast Effects of T2

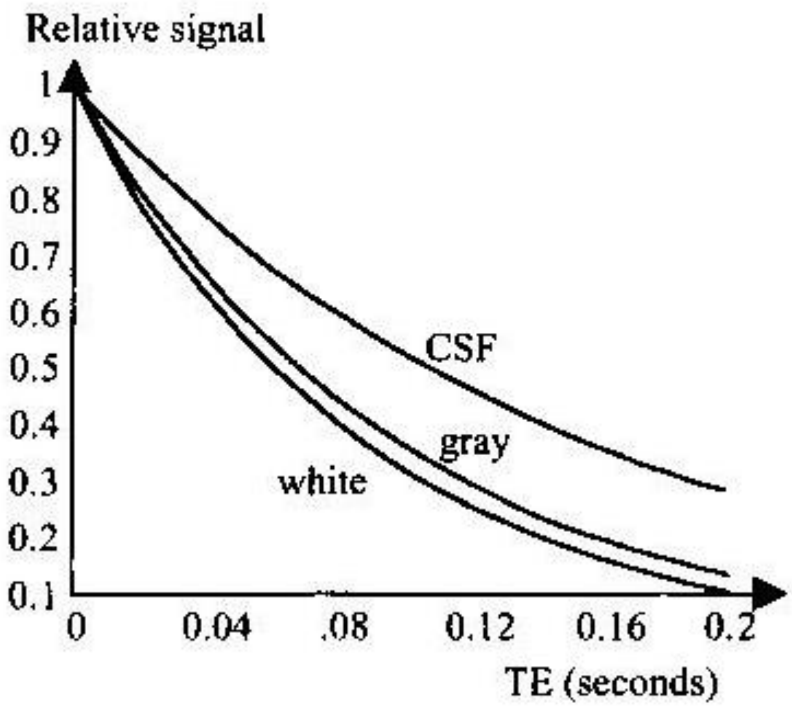


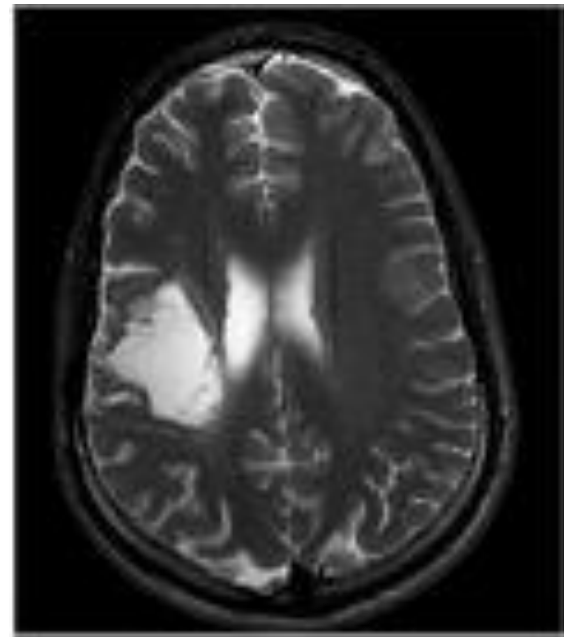
Question 1: Which tissue in (a) has a longer T2?

Question 2: Which TE in (b) will give better contrast between tissues?

From MRI: The Basics, by Hashemi, R.H., and Bradley, W.G., Jr.: Lippincott Williams & Williams (1997), pg. 55.

T2 Contrast





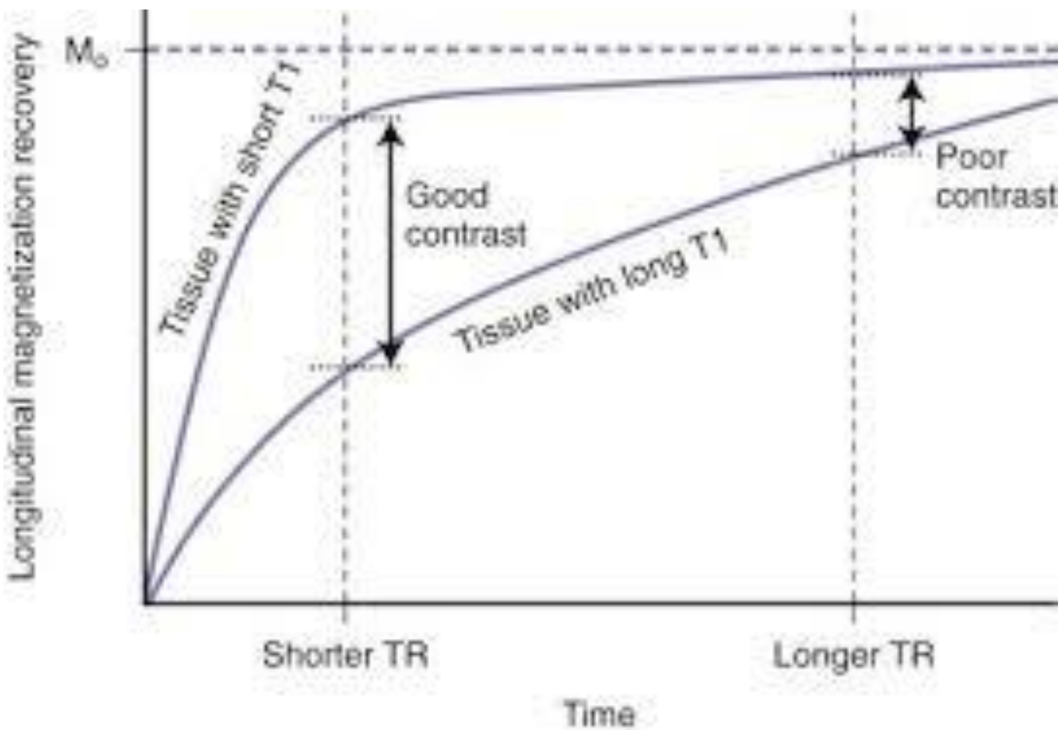
www.medicalphilips.com

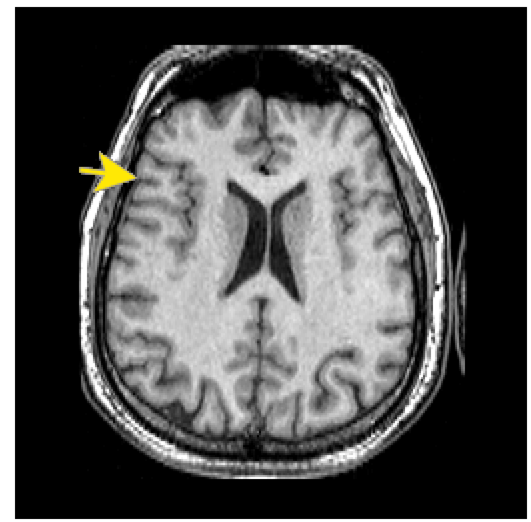
Long TR – reduces T1 effect

Long TE – enhances T2 (and T2*) effect

Example of T1 Weighting

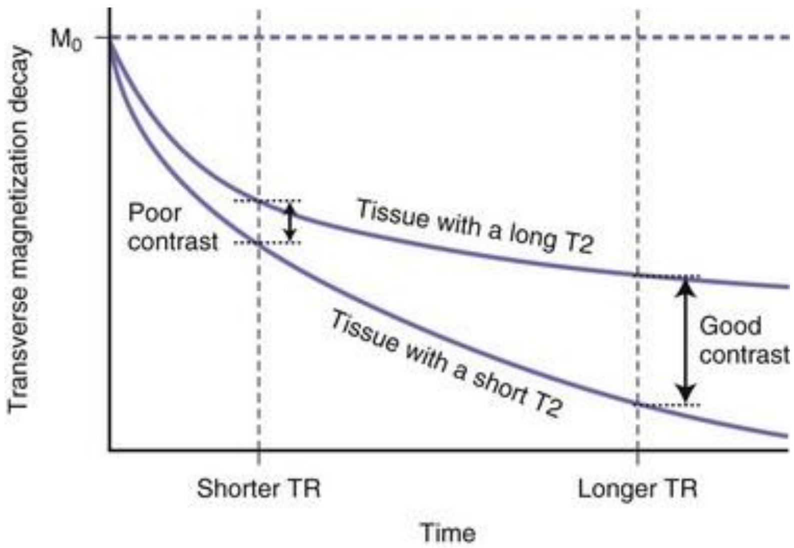
Assume all tissues have same proton density (not really true) – dashed axis represents TE, solid axis represents TR

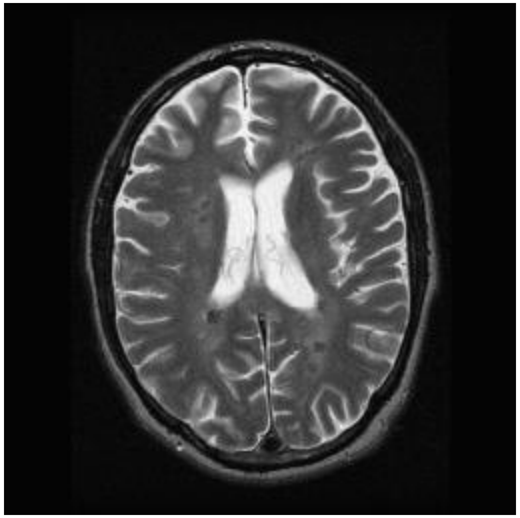




From <u>MRI: The Basics</u>, by Hashemi, R.H., and Bradley, W.G., Jr.: Lippincott Williams & Williams (1997), pg. 61.

Example of T2 Weighting



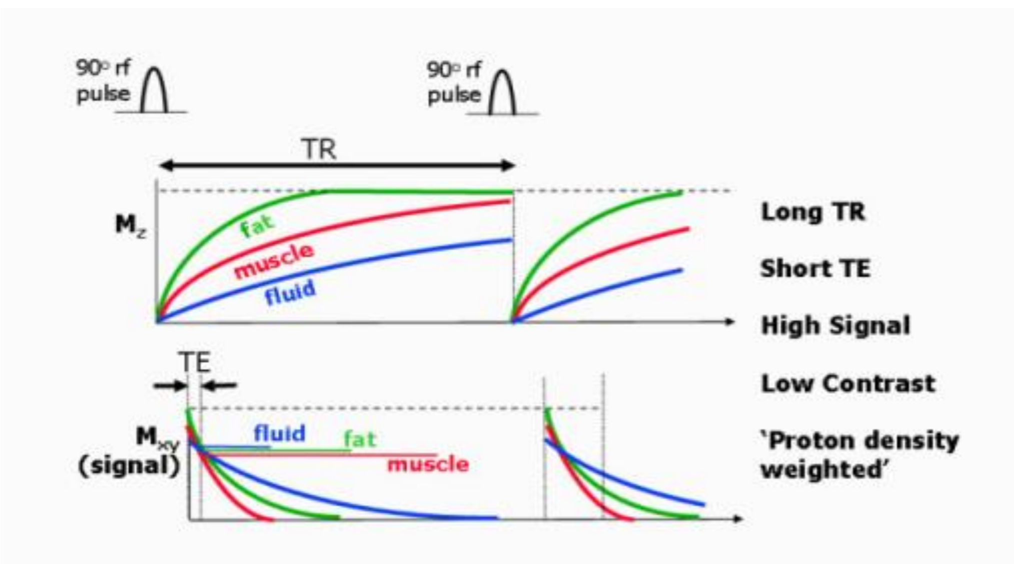


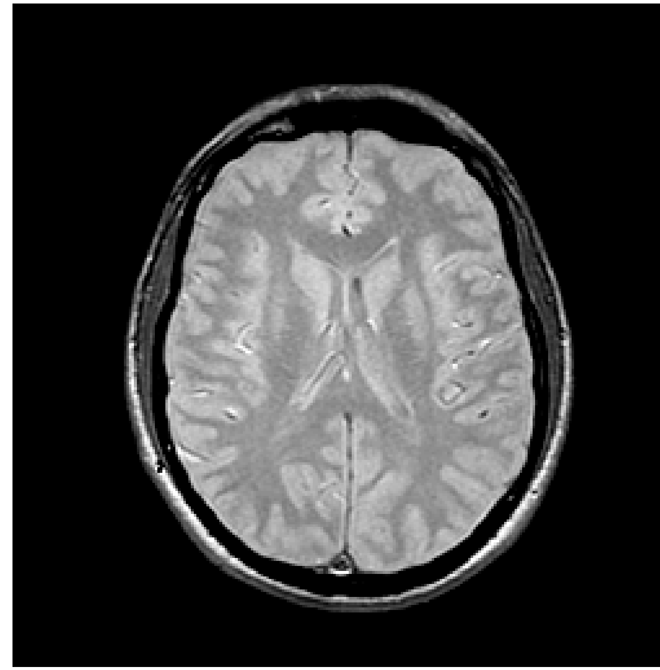
www.hull.ac.uk

From MRI: The Basics, by Hashemi, R.H., and Bradley, W.G., Jr.: Lippincott Williams & Williams (1997), pg. 61.

Proton Density Weighted

- Long TR
- Short TE
- Contrast mainly due to differences in number of protons in tissues





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Next Topics

1. Spin echo pulse sequence
2. Distinguishing spatial information
   a. Slice selection
   b. Phase encoding
   c. Frequency encoding
3. Other pulse sequences
4. Recording the signal
5. Instrumentation

Spin Echo Pulse Sequence

- A **pulse sequence** is a set of RF pulses applied to produce a specific results
- Spin echo is the most common pulse sequence
- Spin echo involves "refocusing" the proton spins while they are decaying in the xy plane to get a peak signal
- Used to eliminate dephasing caused by magnetic field inhomogeneities (gets rid of T2* effects)
- Can use this to measure T_2 of tissues (since $T_2^* = T_2$ in a perfect field)

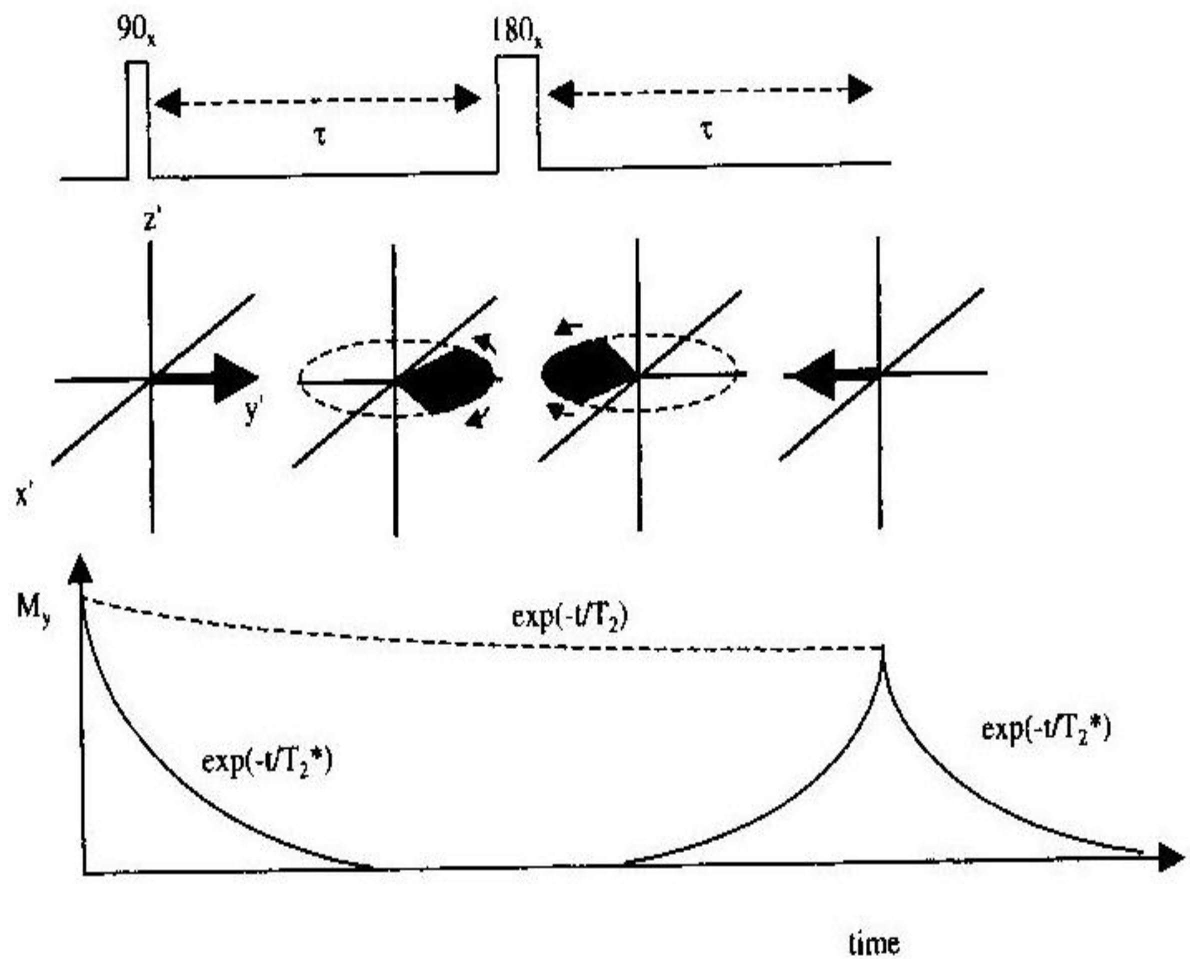
How Spin Echo Works

1. Apply 90° RF pulse

2. T2* effects lead to rapid "dephasing" of the spinning protons

3. Apply an 180° RF pulse (at time τ)

4. The phases now converge to create a maximum peak magnetization (at time 2τ)



The Spin Echo "Runner Analogy"

1. Runners start at same point (like protons after 90° pulse)

2. They run at different speeds (like T2* effects lead to "dephasing")

3. They all turn 180° (apply an 180° RF pulse)

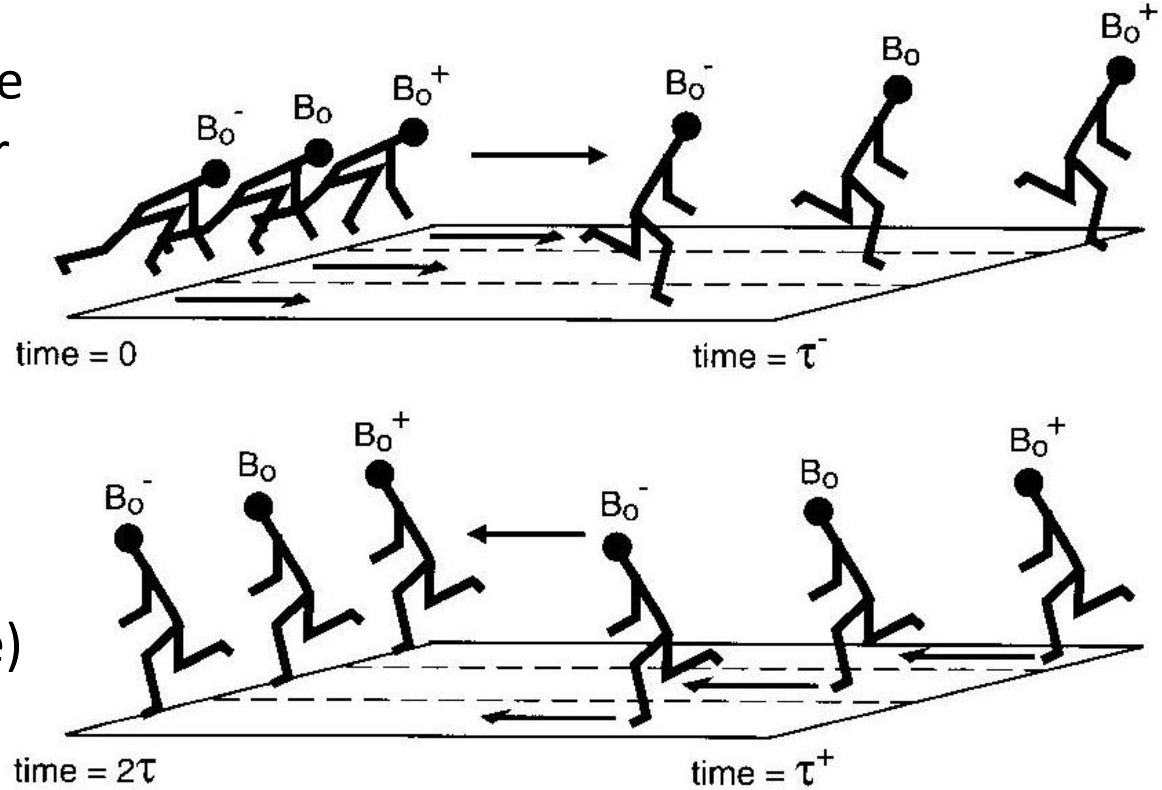


Figure 8-2. Analogy of three runners on a track. At time τ they are made to turn around and run back towards the starting point. Because the slowest runner is now in the lead, they will all reach the starting point at exactly the same time (at time 2τ).

4. They all reach starting point at same time <u>as long as they continue at their same speeds</u> (phases converge to create a maximum signal)

From <u>MRI: The Basics</u>, by Hashemi, R.H., and Bradley, W.G., Jr.: Lippincott Williams & Williams (1997), pg. 78.

Spin Echo Video

- https://www.youtube.com/watch?v=yKmEbCPV4Cg

Next Topics

1. Spin echo pulse sequence
2. **Distinguishing spatial information**
    a. **Slice selection**
    b. **Phase encoding**
    c. **Frequency encoding**
3. Other pulse sequences
4. Recording the signal
5. Instrumentation

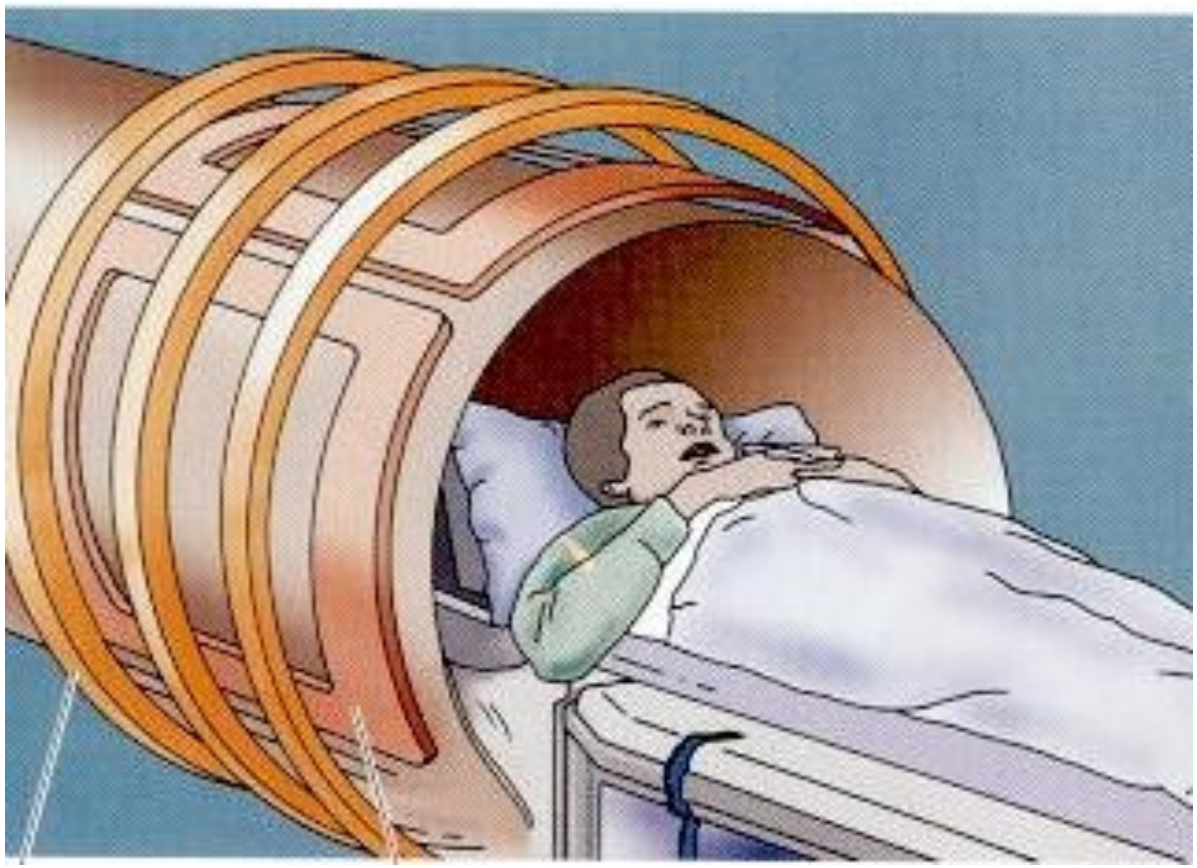
How Do We Get Spatial Information??

- So far, the signal we've discussed is just sum of individual signals from each individual proton
- Remember that: $\omega = \gamma B$
  - Where B is the magnetic field strength, γ is a constant and ω is the resonant frequency at which the protons are "tipped"
- By slightly changing B, we can alter the resonant frequency or amount of energy needed to "tip" the protons

Gradient Fields

- **In a given area of tissue, each region experiences its own magnetic field**
- **Gradients, or “the variation of the field with respect to position” allow us to image each position**
- **Three coils located within the magnet**
- **They are turned off and on and used for spatial localization**

Gradient Fields are needed for imaging

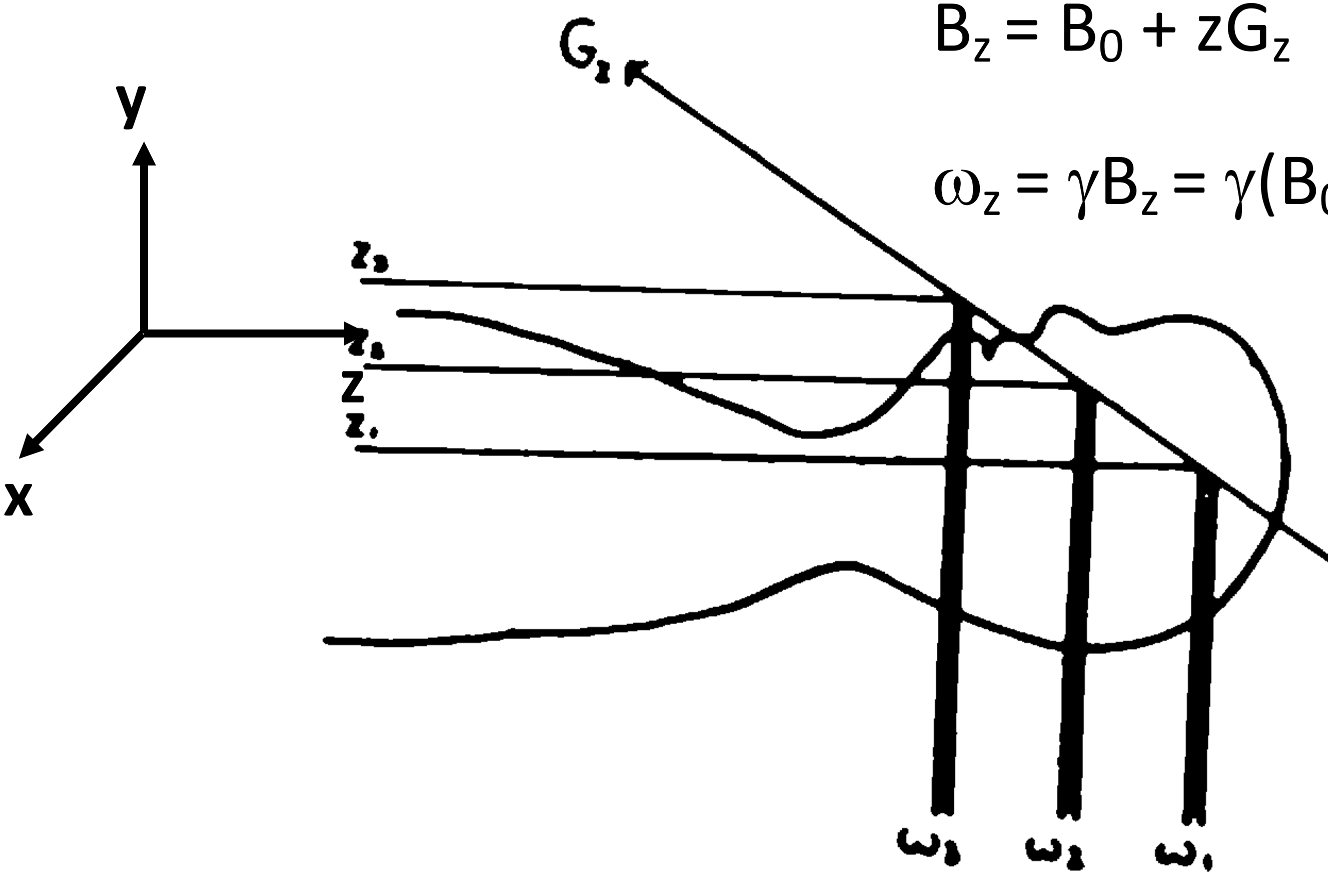


Slice Selection (4.3.1)

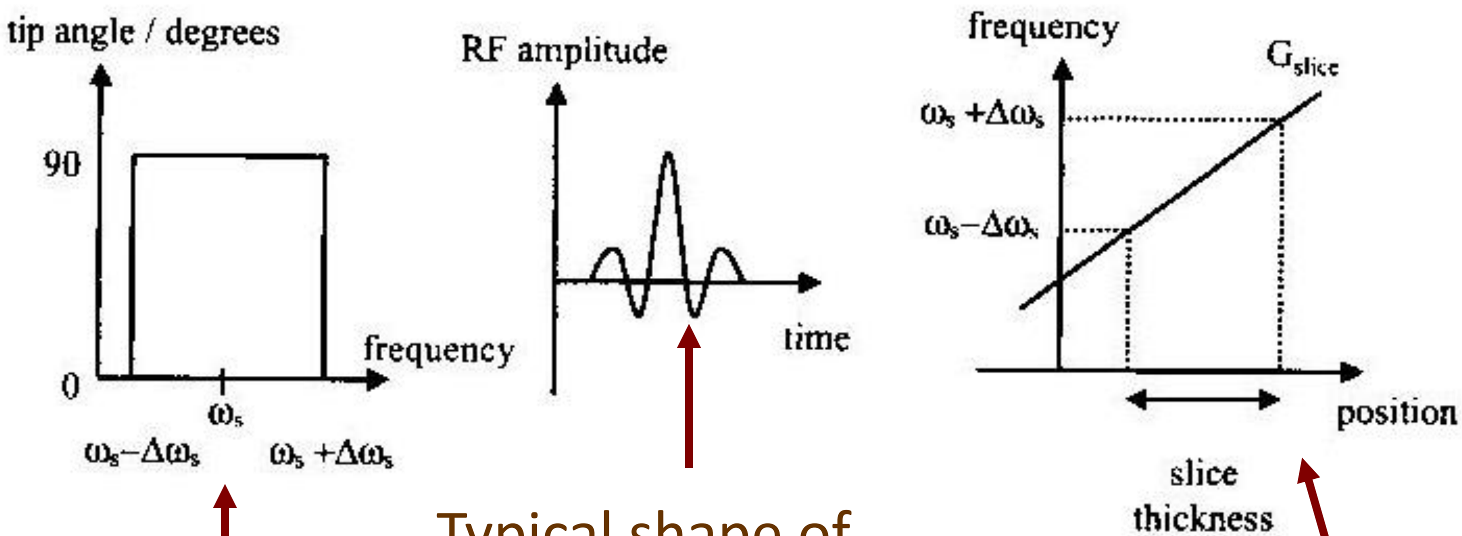
Add a linear magnetic gradient (G_z) along the z-axis (or B_0 field direction) so that

$$B_z = B_0 + zG_z$$

$$\omega_z = \gamma B_z = \gamma(B_0 + zG_z)$$



Slice Selection (continued)

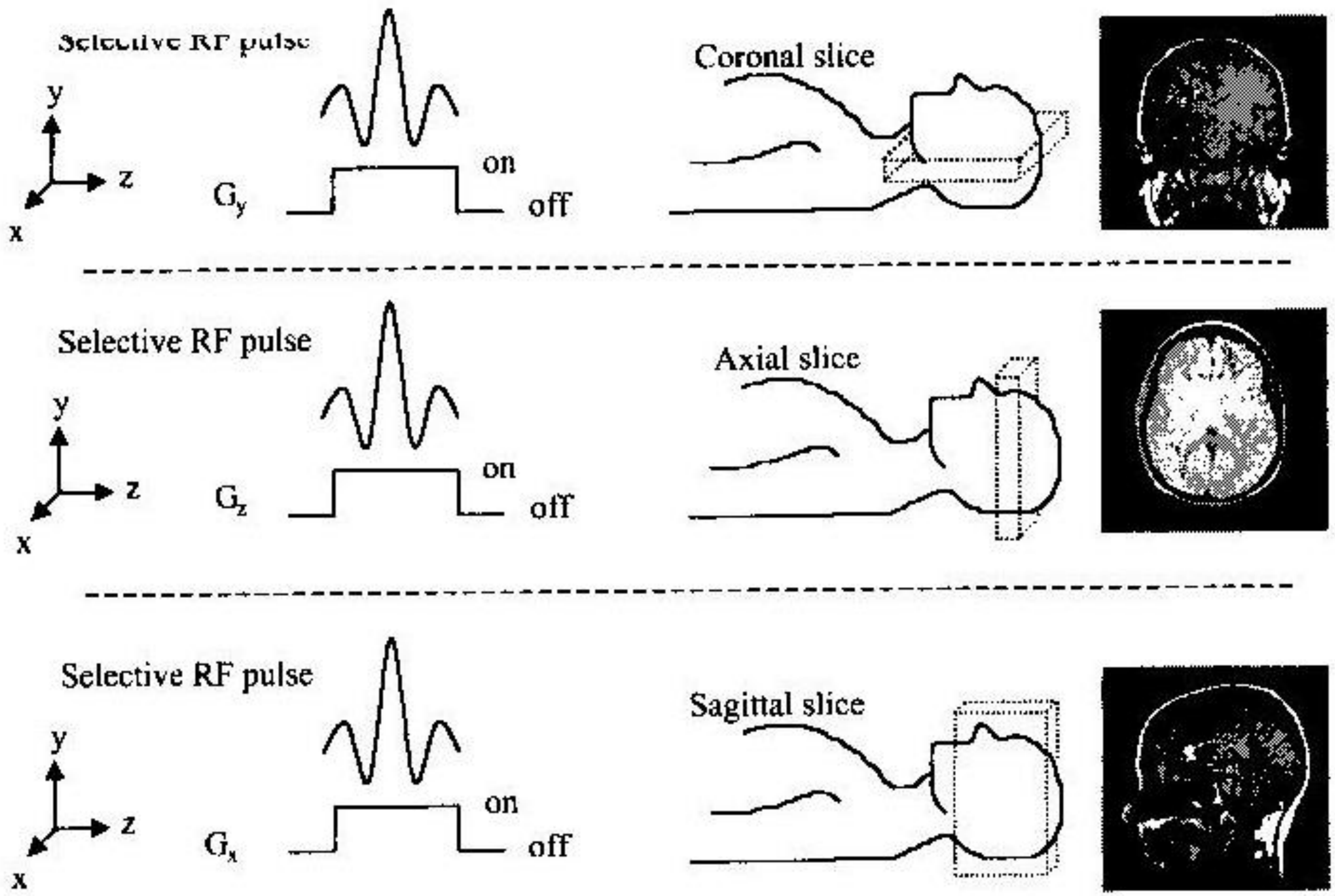


Typical shape of
slice selection pulse
(time domain sinc function to
approximate square frequency band)

Apply RF Pulse at frequency ω_s
with bandwidth $2\Delta\omega_s$

Only protons in this
area will be affected
by the RF pulse

Slice Planes



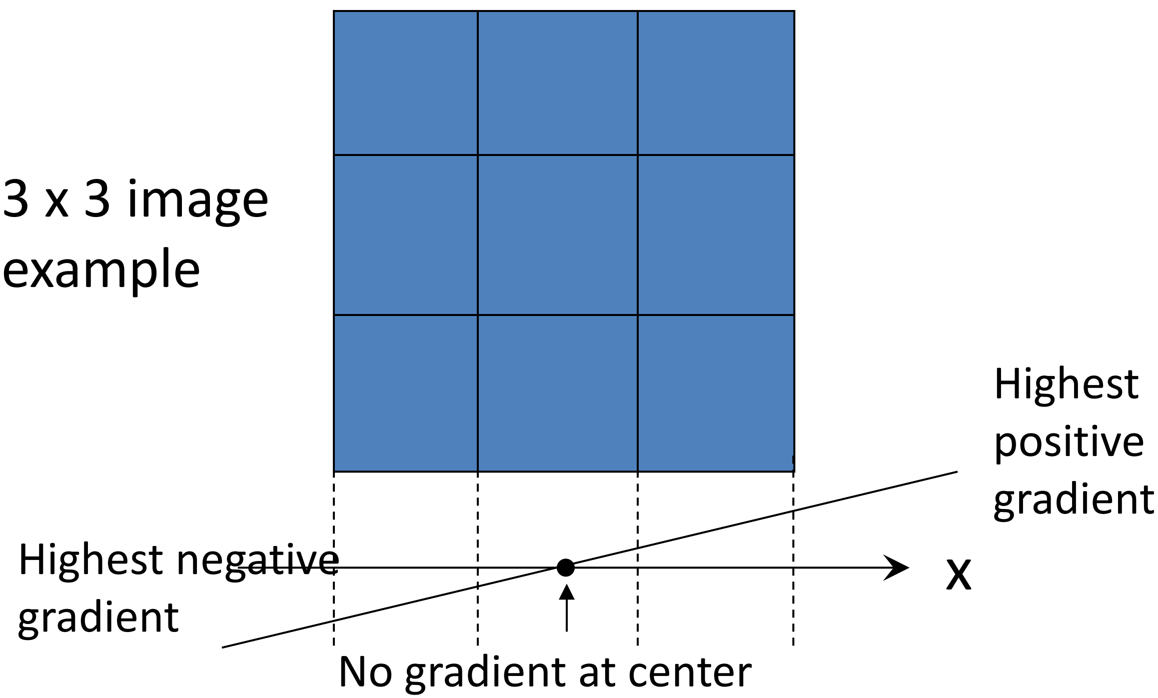
Encoding the xy Directions

- Need to also vary information in the xy plane to determine the spatial location of the recorded signal
- In the x-direction, we apply a spatially dependent precessional frequency gradient, Gx, to the protons
- In the y-direction, we apply a spatially dependent phase gradient, Gy, to the protons

Frequency Encoding

- x-direction (or read-out direction)
- **During data acquisition**, apply a magnetic gradient (G_x) to make the nuclei precess at slightly different frequencies

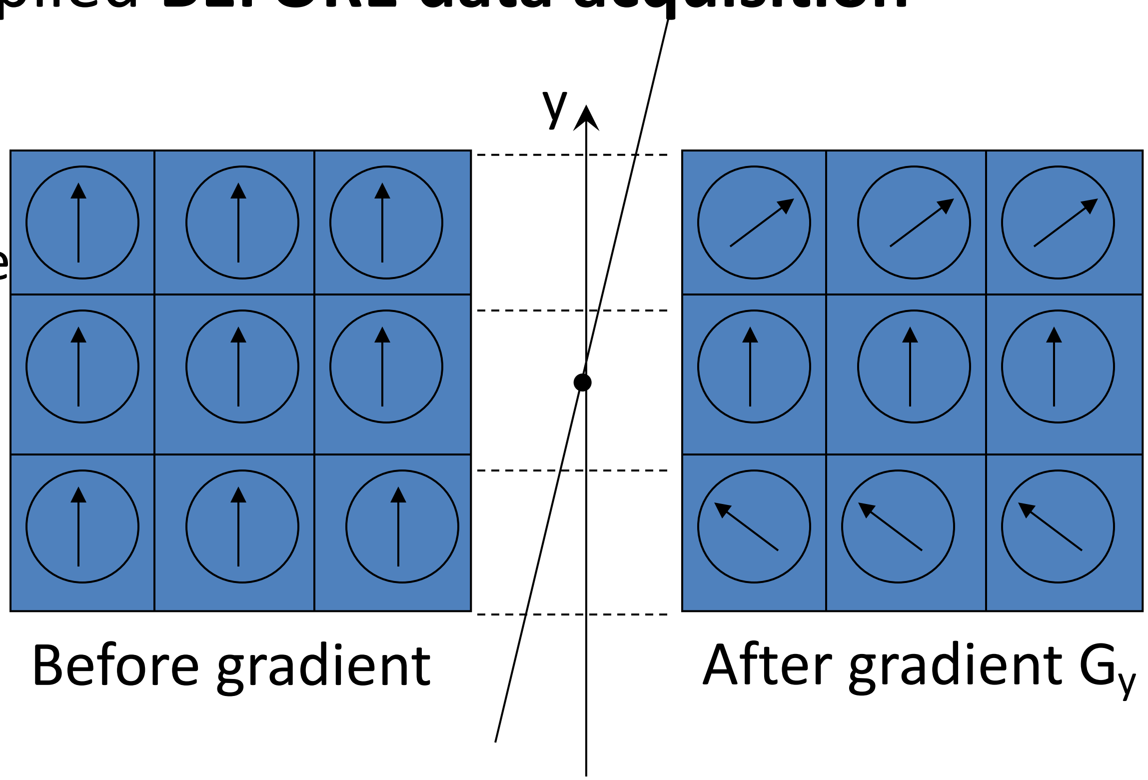
3 x 3 image example



Phase Encoding

- y direction (or phase encoding direction)
- Resolves spatial features by using the phase information of the proton spins
- Applied **BEFORE data acquisition**

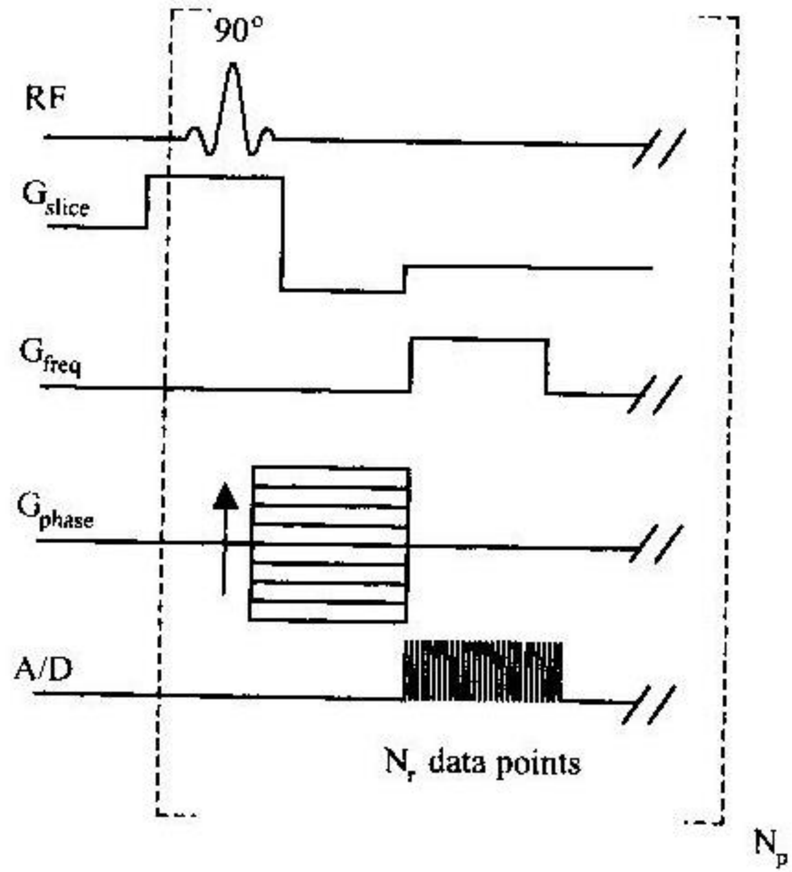
3 x 3 image example



Example of Spatial Encoding Gradients

Collecting N_p by N_r sized image

- Apply slice gradient ($G_z = G_{slice}$) and RF pulse
- Turn on phase encoding gradient ($G_y = G_{phase}$), implemented N_p times
- Turn on frequency encoding gradient ($G_x = G_{freq}$) during data acquisition (collecting N_r times)



Next Topics

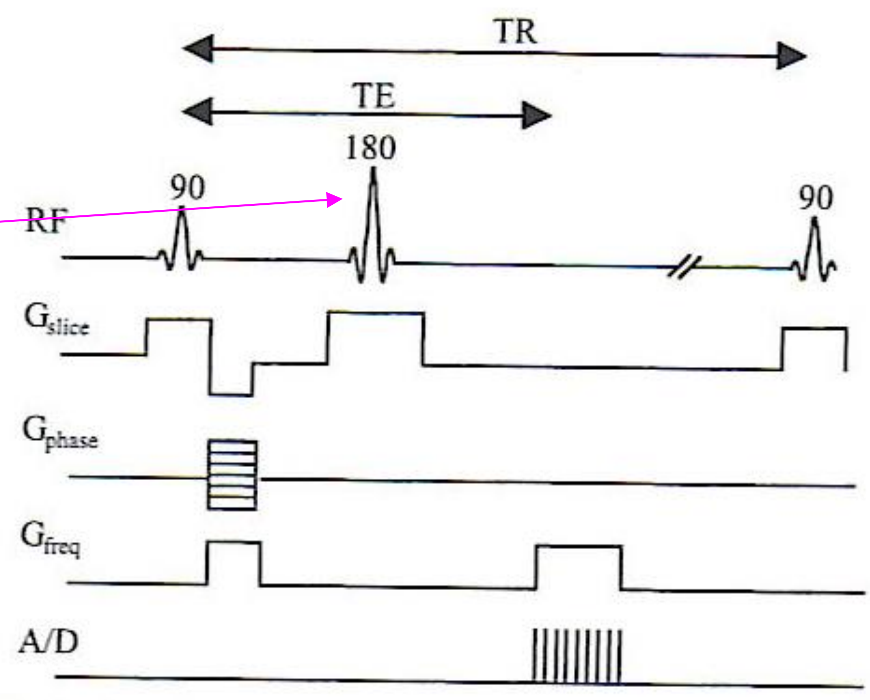
1. Spin echo pulse sequence
2. Distinguishing spatial information
    a. Slice selection
    b. Phase encoding
    c. Frequency encoding
3. **Other pulse sequences**
4. Recording the signal
5. Instrumentation

Pulse Sequences (4.5)

- **Spin Echo** (again) – recall it is used to refocus T2[+] effects from inhomogeneous magnetic fields so we can obtain the true T2 image

Now, in terms of a complete pulse sequence diagram:

Apply a refocusing gradient to rephase the spins in the slice-select direction



Remember, by adjusting TE and TR we can obtain the image contrast that we desire

Pulse Sequences

- Spin-echo has high SNR
- BUT, a spin-echo image takes a long time to collect
- Example, suppose TR = 2 sec, N_p = 256
- Total time = TR x N_p x NEX

  (NEX = number of excitations or proton flips)

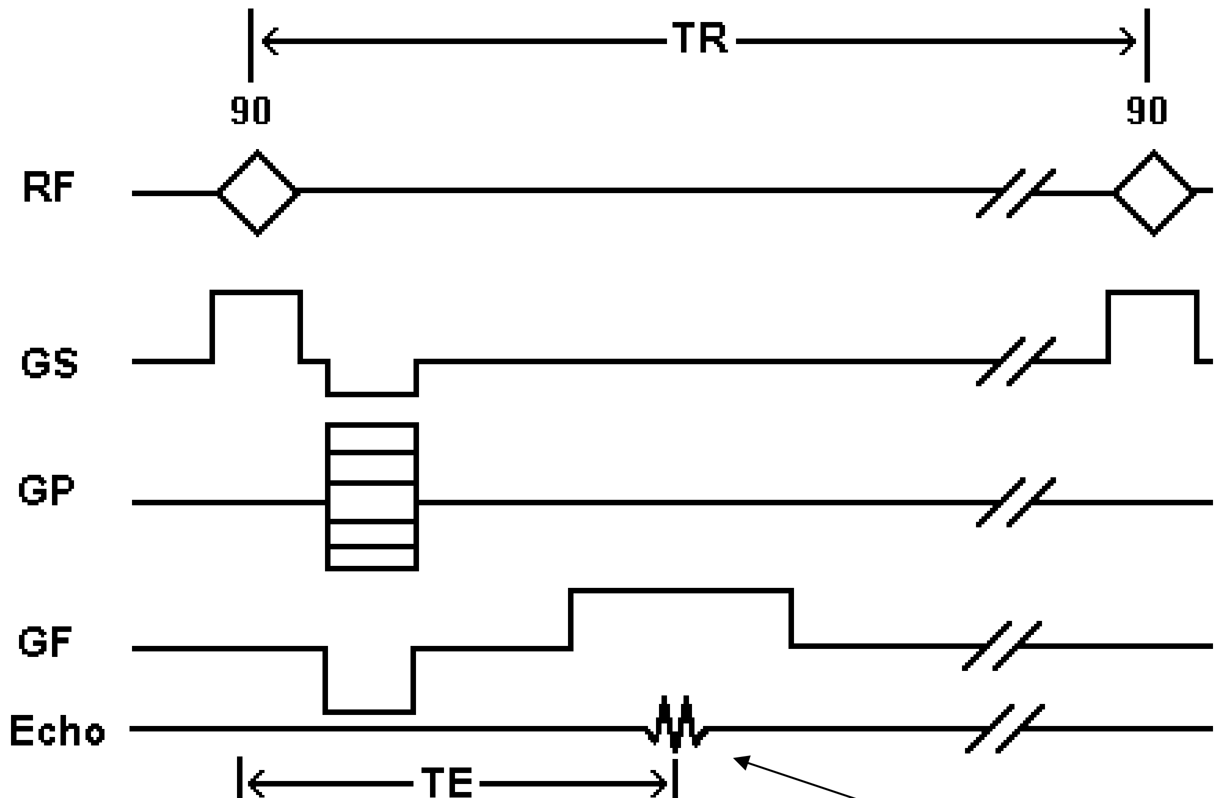
  = 2sec x 256 x 1 = 512sec x (1min/60s) = **8.53 min**

  (note: collecting all of x direction for each RF pulse)
- This is the time to collect one slice!!
- We need something faster for Functional MRI

Gradient Echo Pulse Sequences

- Does not apply 180° refocusing pulse
- Faster data collection
- Instead of measuring signal at the peak of rephasing, measure “echo” of signal decay
- Since T2* decay is faster than T2 decay, TE and TR should be shorter
- Can also reduce our flip angle from 90° to increase imaging speed

Gradient Echo Example



Slice selection

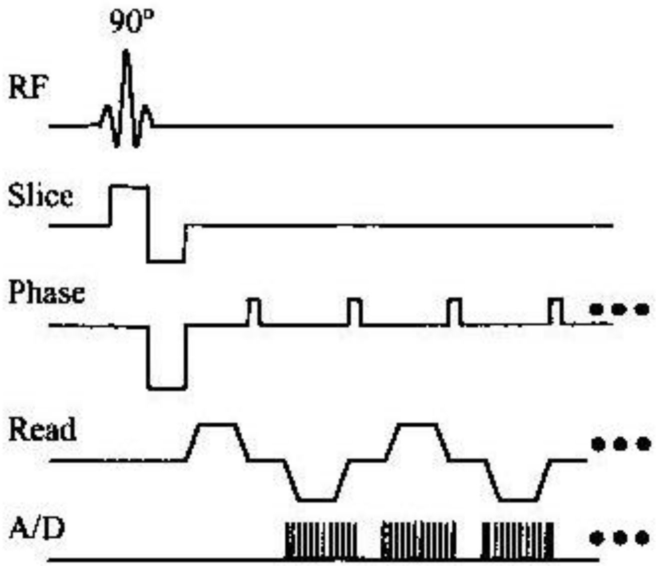
Phase Encoding

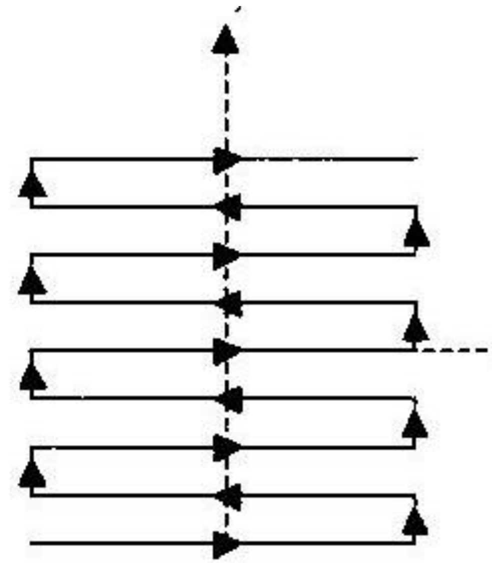
Frequency encoding through the data collection period

Recording the signal

http://www.mritutor.org

Echo-Planar Imaging (EPI)





Back and forth collection trajectory for a single slice

-Very rapid, used to collect entire slice in a single "echo train" (only one RF pulse per slice)

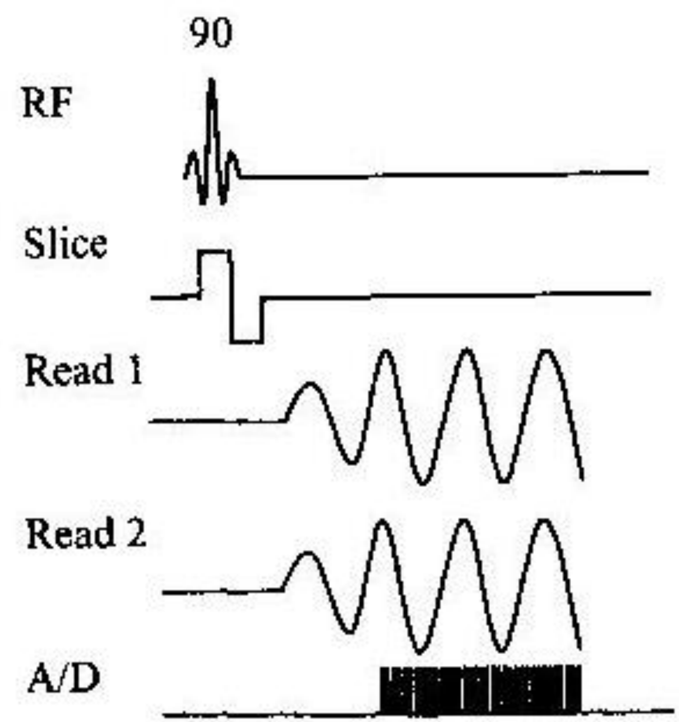
-Can collect entire slice in 100ms

Adjusting the xy gradients is sort of like a Labyrinth Game

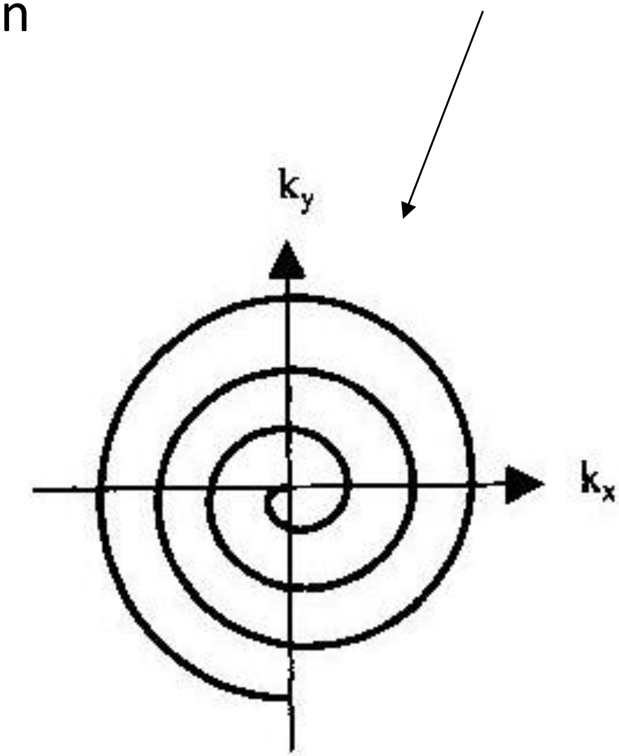
Need to turn the x and y gradients (like the knobs on the labyrinth game) to get the correct spatial information (or to get the ball to the correct location)

Spiral Imaging

-Non-rectangular, very rapid
-Entire slice for 1 RF pulse
-Not as hard on the gradients of the machine (smoother, don't have to turn sharp corners)



Spiral collection trajectory



Next Topics

1. Spin echo pulse sequence
2. Distinguishing spatial information
   a. Slice selection
   b. Phase encoding
   c. Frequency encoding
3. Other pulse sequences
4. **Recording the signal**
5. Instrumentation

Recording the FID Signal

1. **Preamplification**

   - Voltage induced from FID signal is first amplified

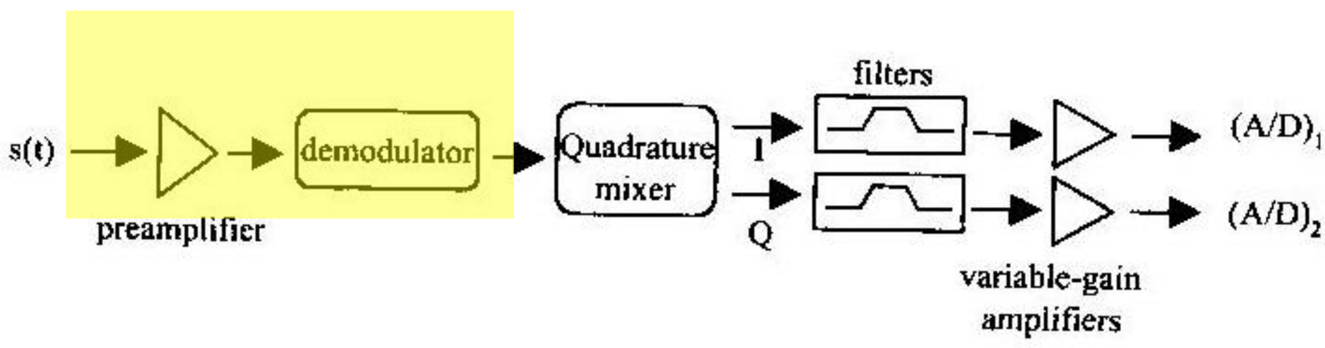
2. **Demodulation**

   - Since FID signal has a high frequency

     $\omega_0 = \gamma B_0 = (42.6\ Mz/T)(1.5T) = 63.9Mz$,

     it is difficult to digitize at this frequency

   -Demodulate to a lower frequency (ω_{if}) prior to collection



Recording the FID Signal

3. **Quadrature Mixer –** Splits signal into two equal-magnitude components

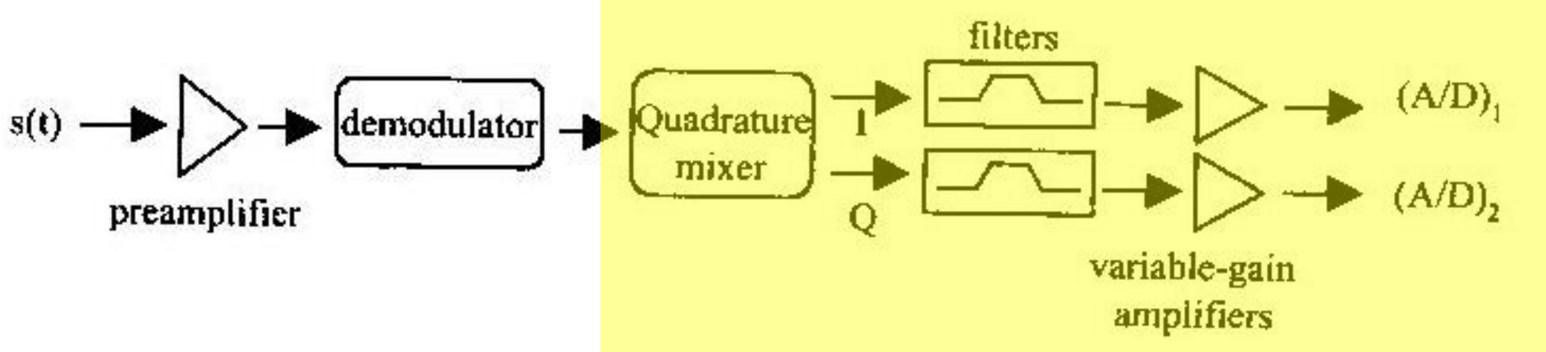
   - Mixes real signal with $\cos(\omega_{if}t)$ and

     imaginary signal with $\sin(\omega_{if}t)$

4. **Low pass filter**

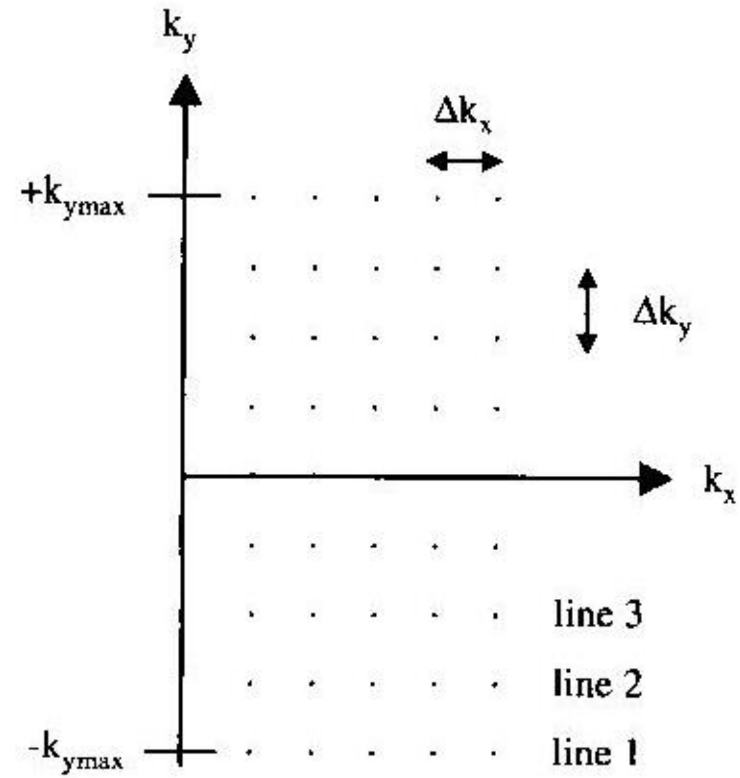
5. **Amplification**

6. Digitization



FID Signal (4.3.4)

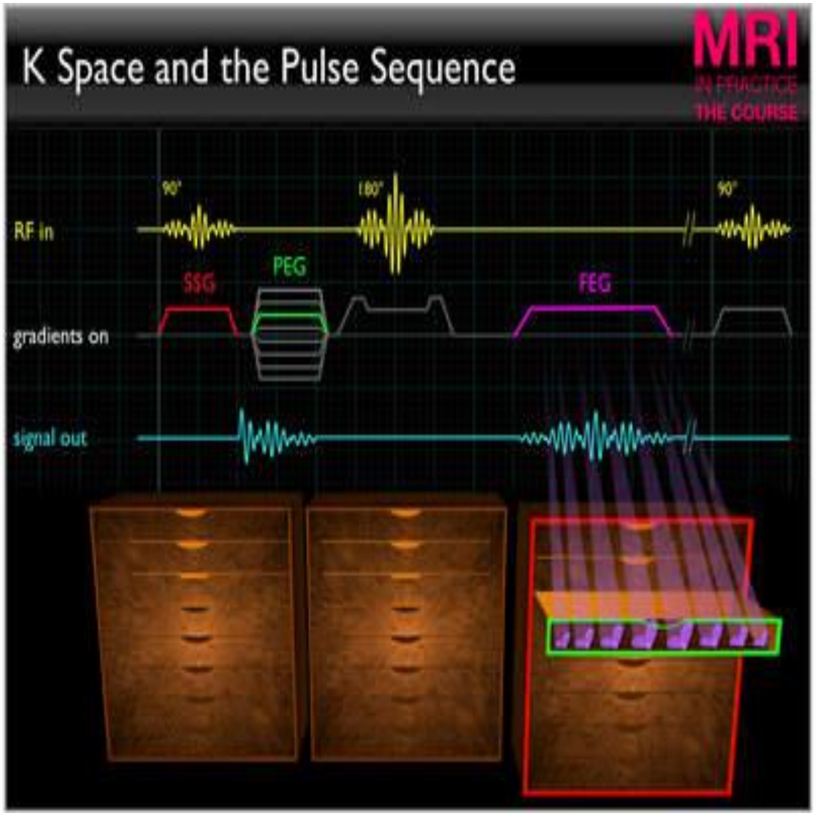
- The recorded signal is a measure of frequencies
- This frequency space is called ***k-space***
- x-direction represents information from frequency encoding
- y-direction represents information from phase encoding
- Space between points is set by the Field of View (FOV)



Collecting Data in K-space

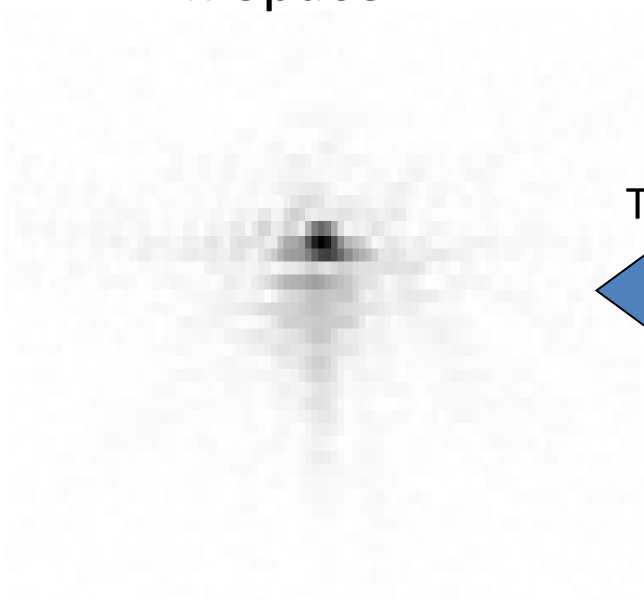
- K-space is a frequency space for 2 dimensional spatial frequencies

- To create an image, use the 2D Fourier Transform



k-space

k-Space



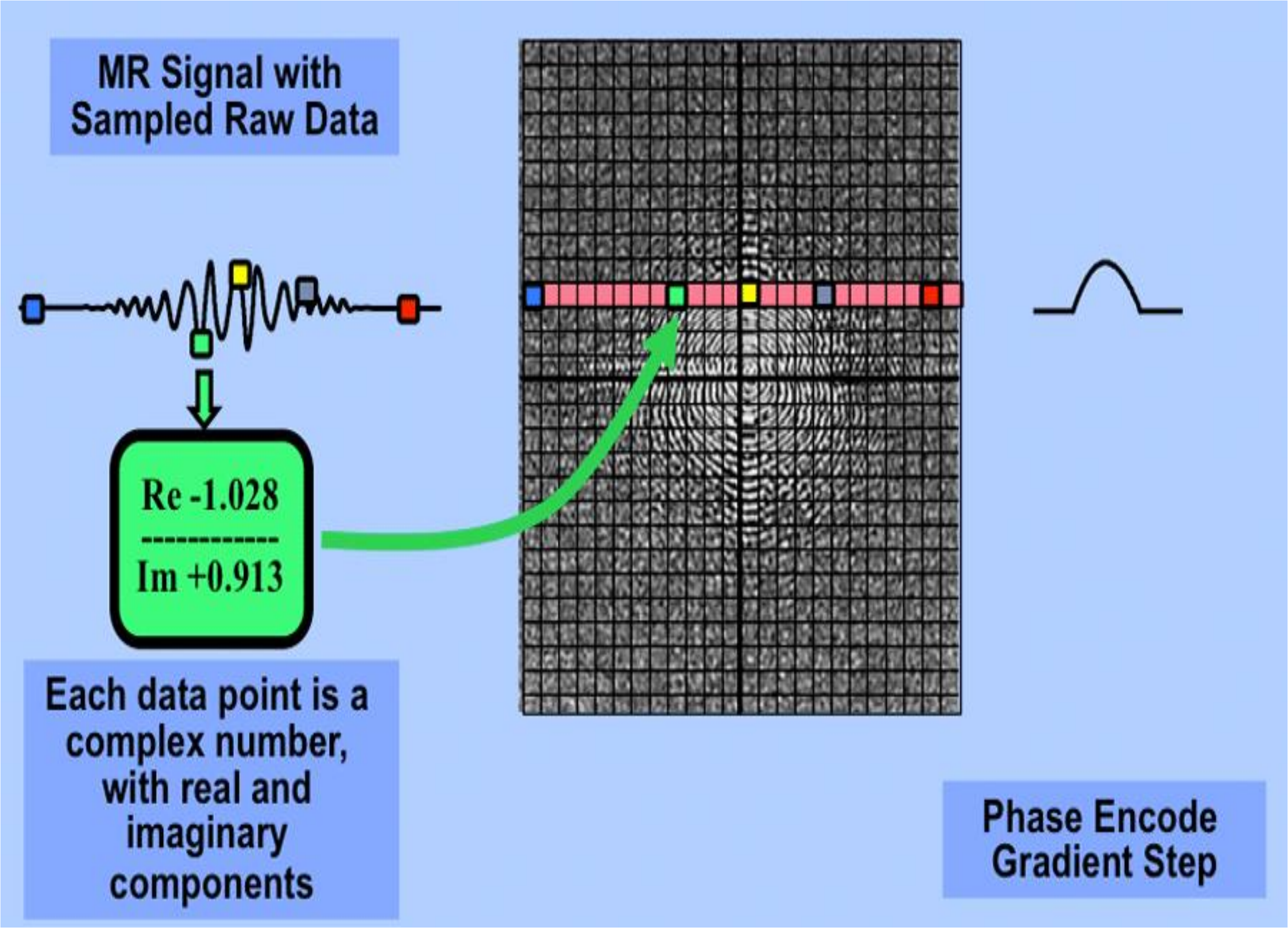
Fourier
Transform

Image Space

-Center of k-space represents lowest frequencies (low frequencies contain “bulk” information of the image)

-Frequencies increase as you move from center (high frequencies contain details of image)

K-space – 2D Spatial Frequencies

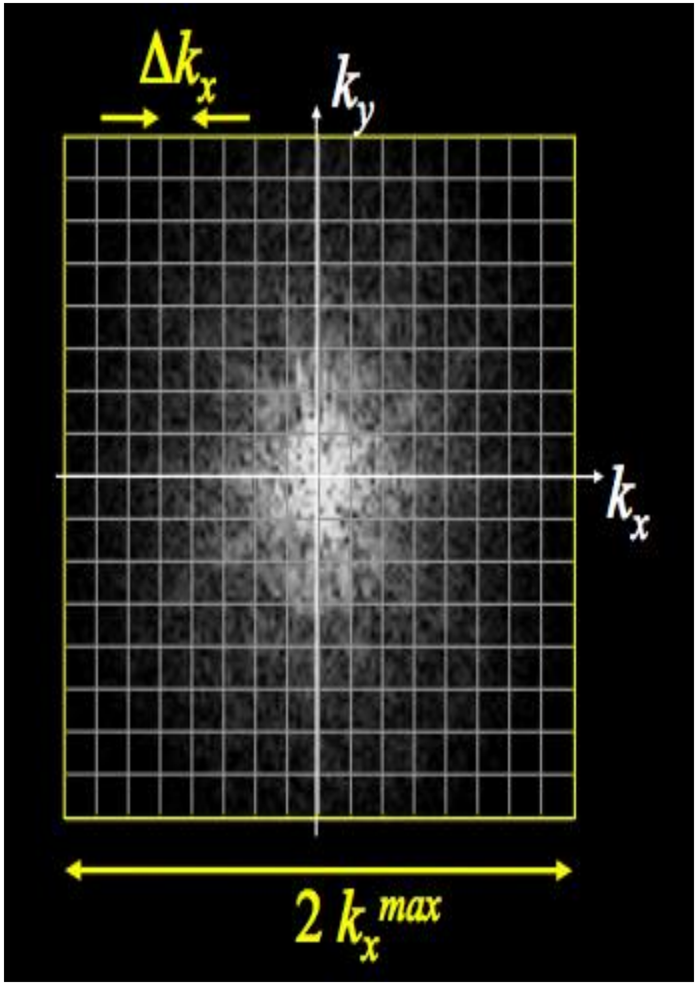


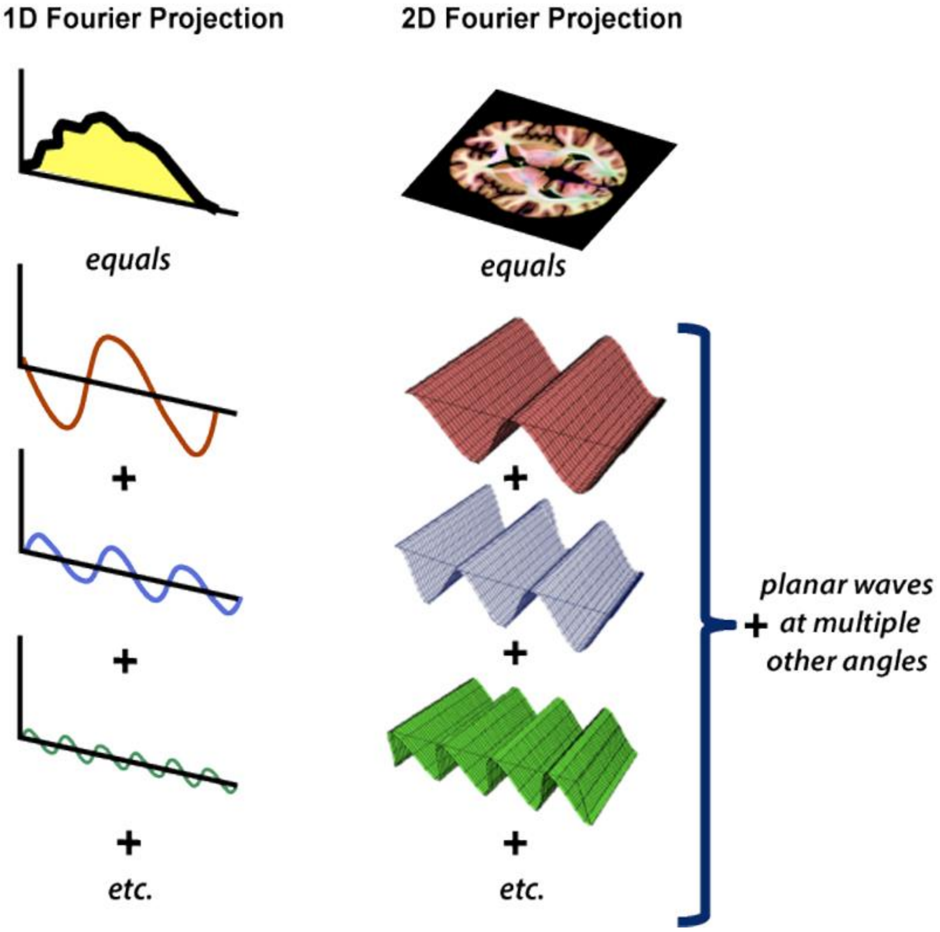
To Create the Image:
2D Spatial Fourier Transform

$$F(x,y) = \sum_{m=0}^{M-1}\sum_{n=0}^{N-1} f(m,n)e^{-j2\pi(x\frac{m}{M}+y\frac{n}{N})}$$

$$f(m,n) = \frac{1}{MN}\sum_{m=0}^{M-1}\sum_{n=0}^{N-1} F(x,y)e^{j2\pi(x\frac{m}{M}+y\frac{n}{N})}$$

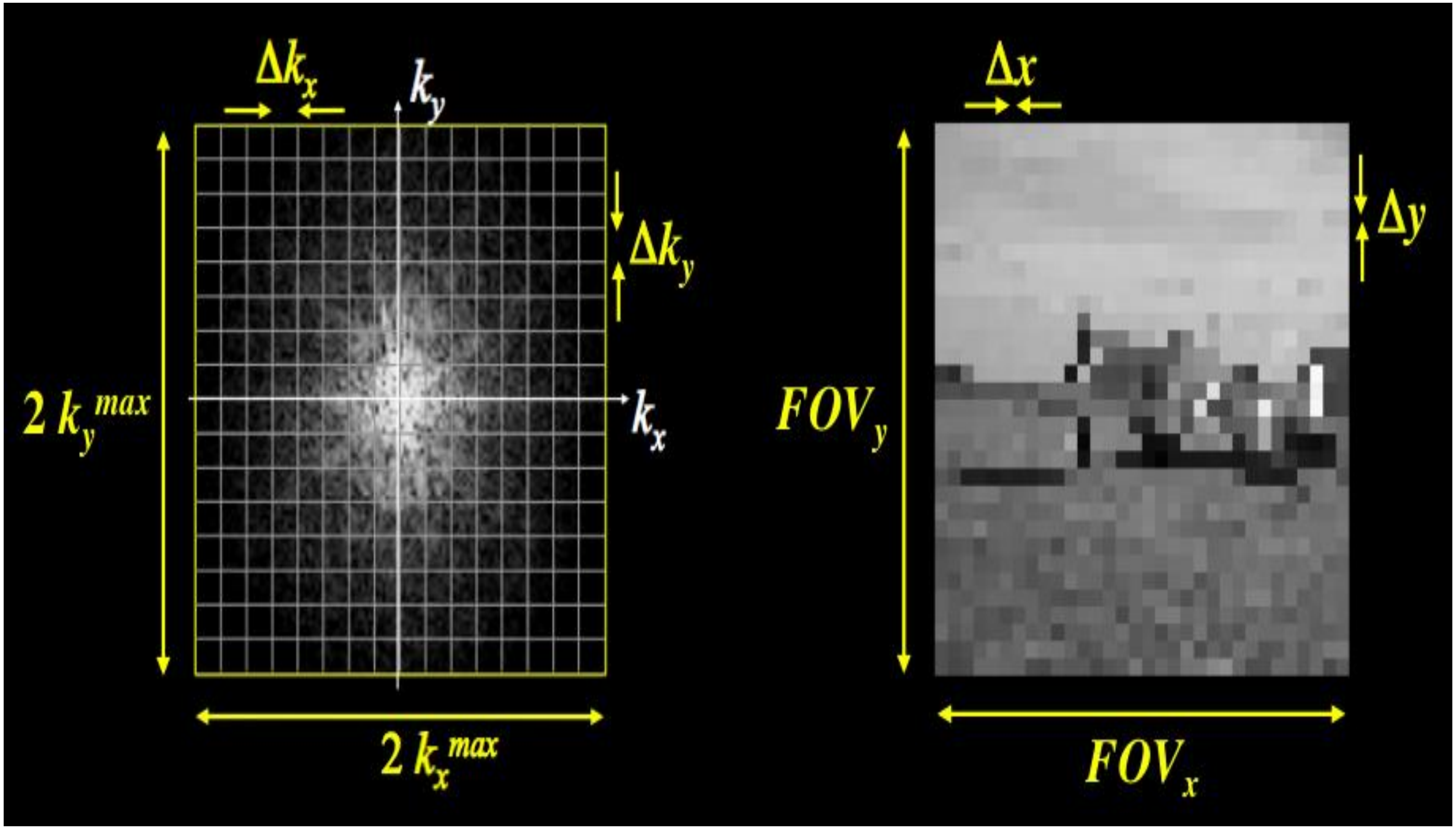
K-Space – raw data



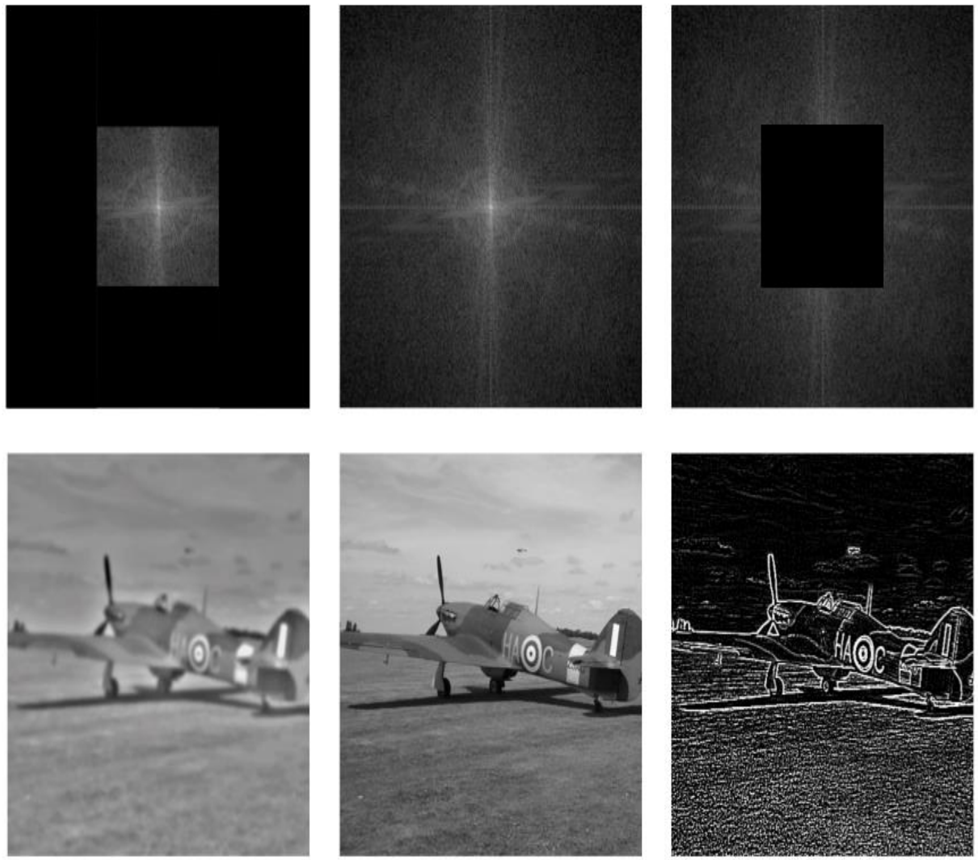


http://mriquestions.com/what-are-2d---3d-fts.html

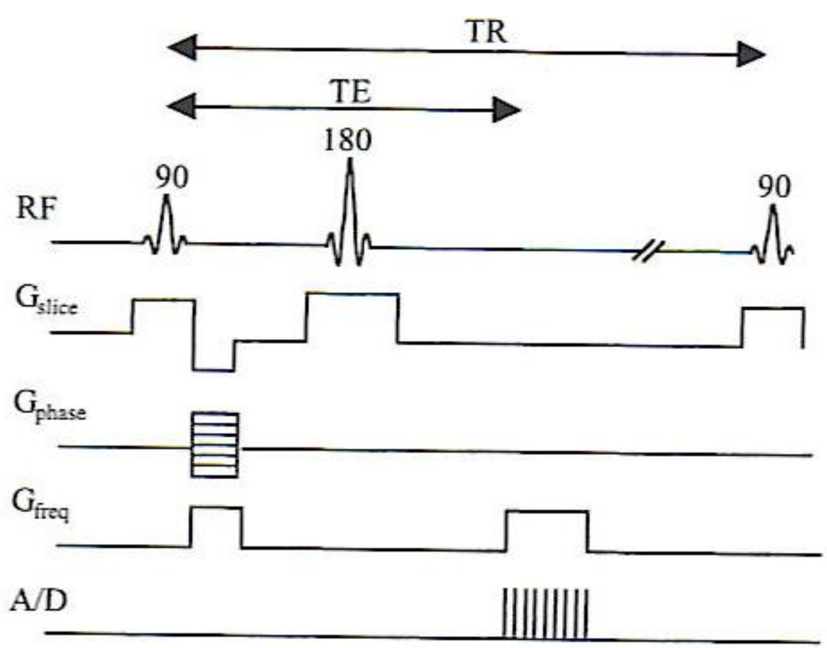
K-space to Image Space

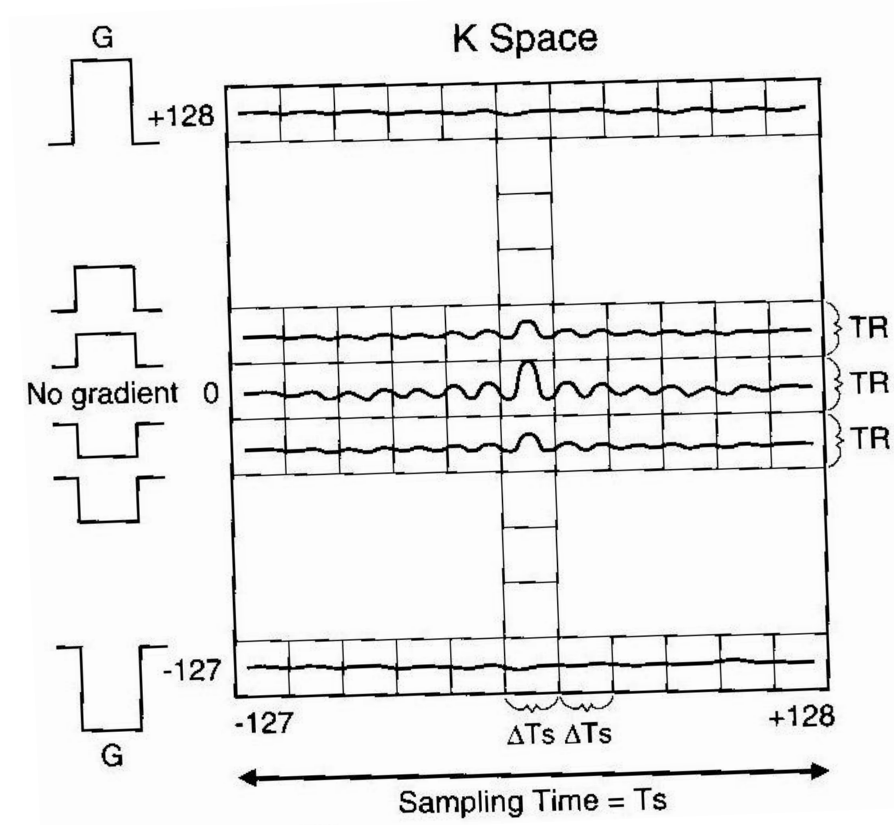


K-Space: Low Frequency vs High Frequency



Pulse Sequence Diagram and k-space





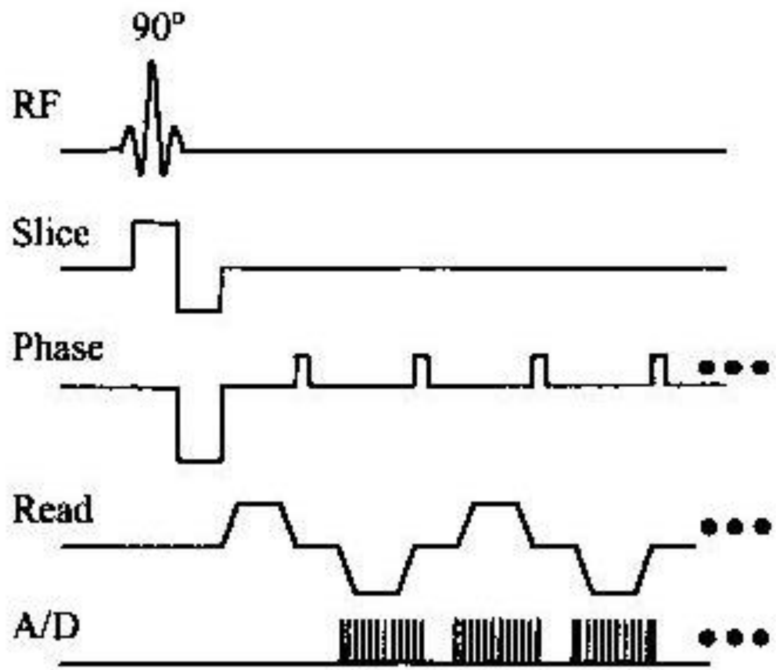
-Spin echo pulse sequence

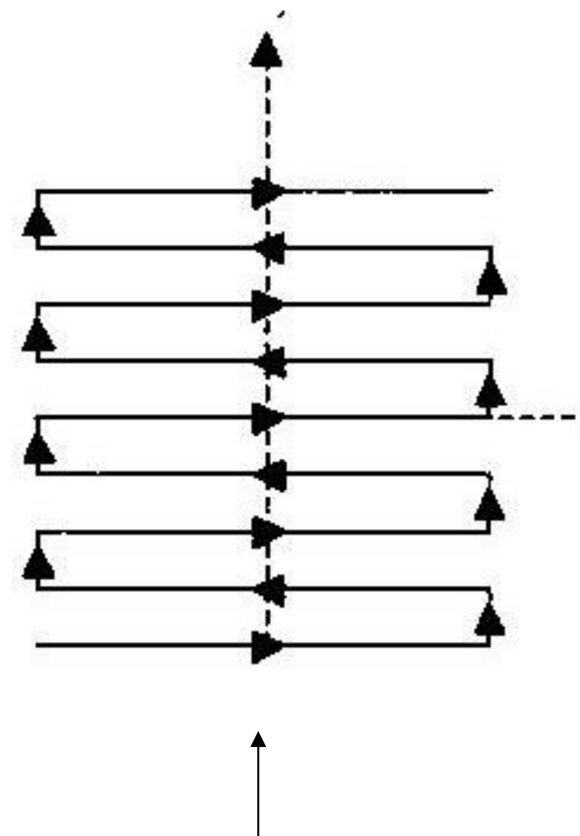
-Apply phase encoding (ky direction) prior to collection of each line

-Collecting all x-direction (or kx) for RF pulse

From MRI: The Basics, by Hashemi, R.H., and Bradley, W.G., Jr.: Lippincott Williams & Williams (1997), pg. 137.

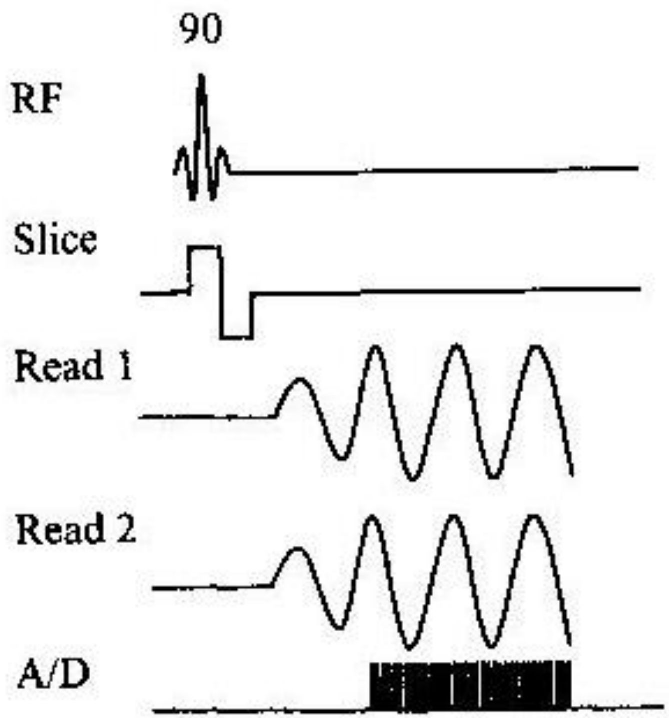
Let's look at EPI again....

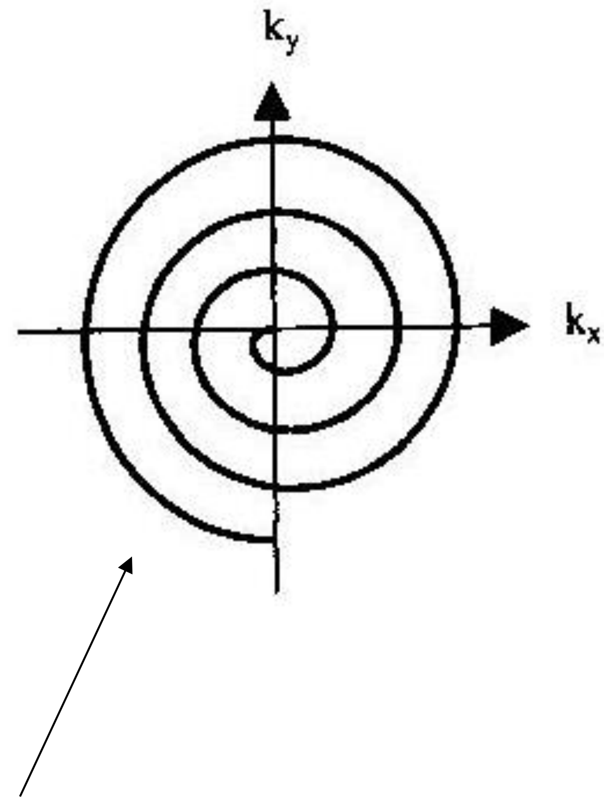




Collecting all of k-space at once

Spiral Again…





-Collecting low frequencies of k-space first

-Depending on shape of spiral, can sample the low frequencies more densely

Next Topics

1. Spin echo pulse sequence
2. Distinguishing spatial information
    a. Slice selection
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    c. Frequency encoding
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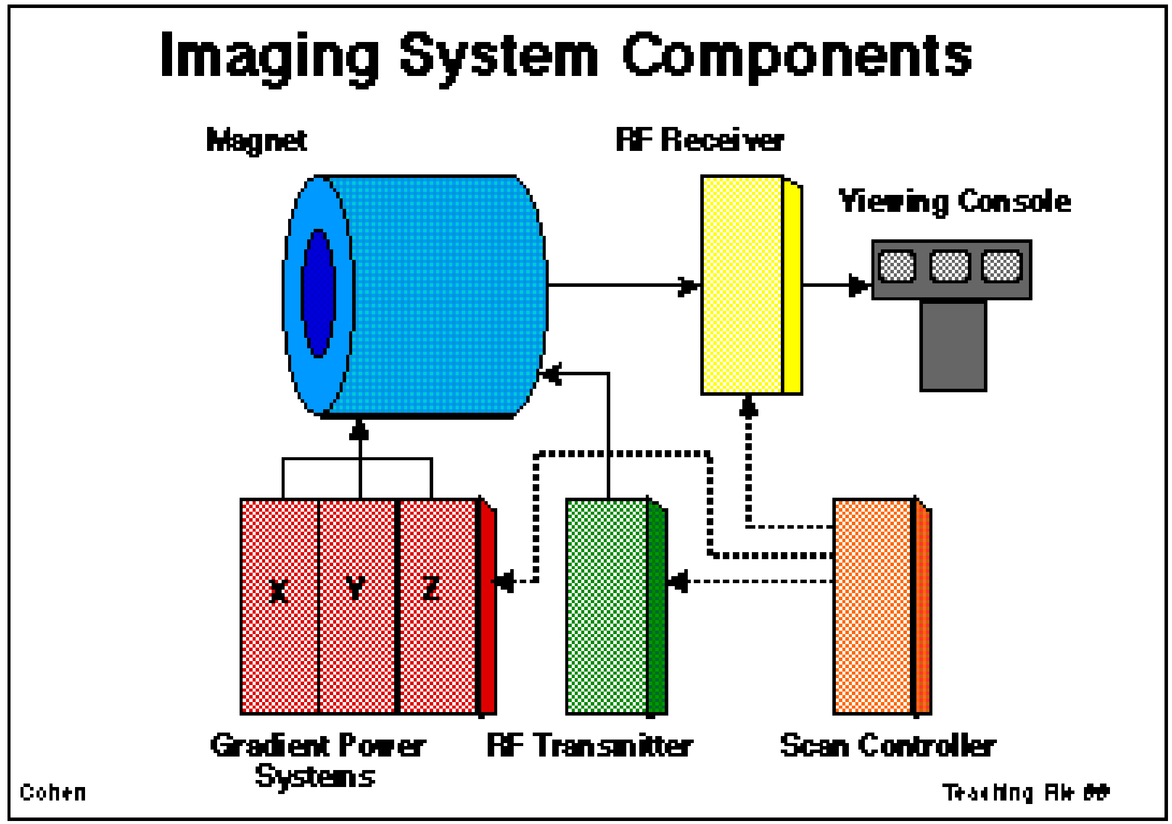
5. **Instrumentation**

Instrumentation (4.4)

<u>3 Main Components</u>

1. The main magnet
2. Three magnetic field gradient coils
3. The RF Coil



The Magnet

-Magnetic field should strong and as homogeneous as possible

-Center is called the ‘bore’ (where the subject lies)

www.jastec.org/

Three types:

1. Permanent – made out of permanently magnetized material, for example, cobalt-samarium; these are very heavy
2. Resistive magnets – created by passage of a constant current through a conductor, for example, copper; limited by the generated heat
3. Superconducting magnets - for field strengths over 0.35T

Superconducting Magnet

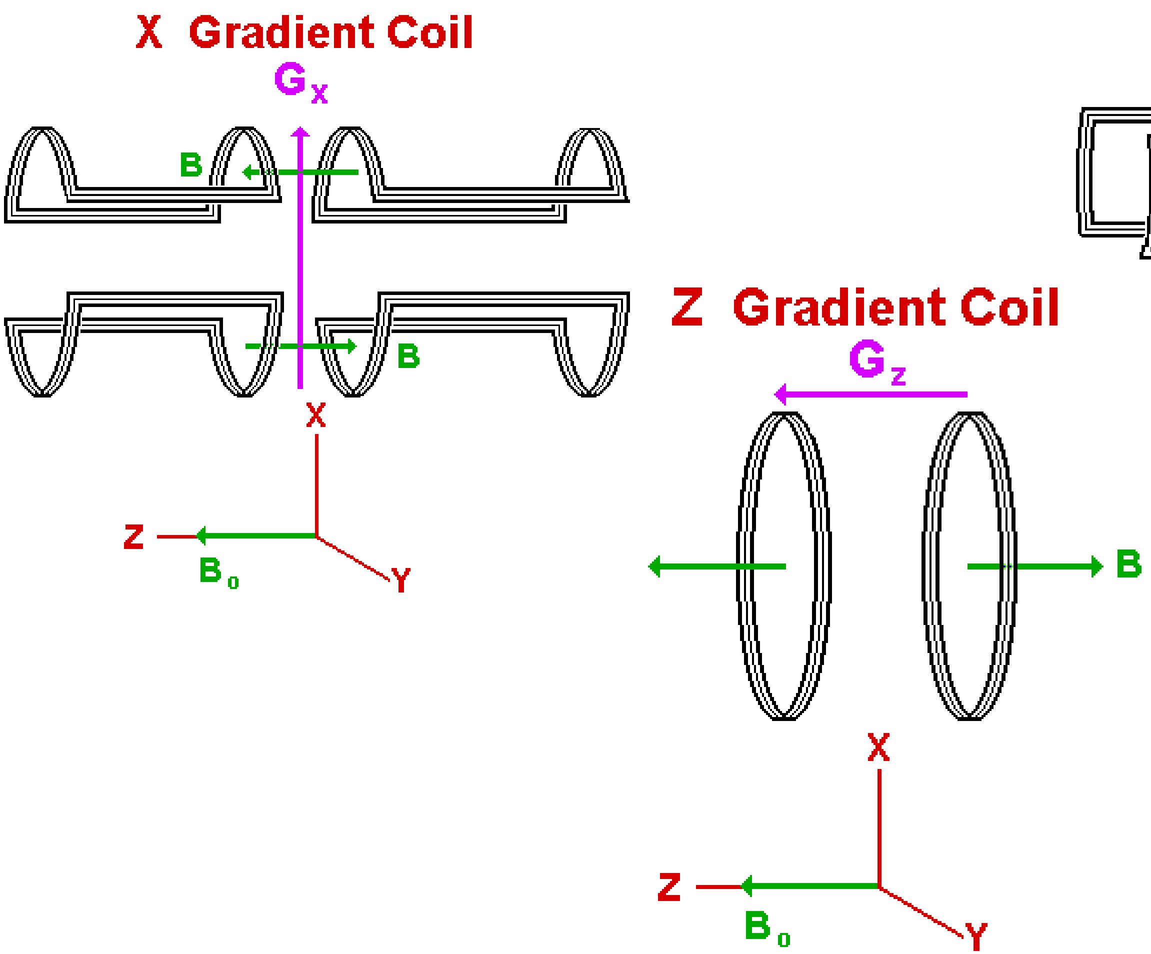
- Reduce (or eliminate) resistance in conductive material to minimize over-heating problem
- Uses wire made of special alloy (niobium-titanium)
- Keep at VERY LOW TEMPERATURE (9 Kelvin)
- Achieve low temperature by surrounding with a layer of liquid helium, then a layer of liquid nitrogen
- Constant current leads to a permanent magnetic field (cannot turn the magnetic field off and on)

The Gradient Coils

- To encode spatial information
- Gradients of about 4 Gauss/cm, therefore can use copper cooled with chilled water
- These must be switched on and off rapidly during data collection
- Switching speeds limit data collection rate
- The noise you hear during an MRI is from the gradients switching

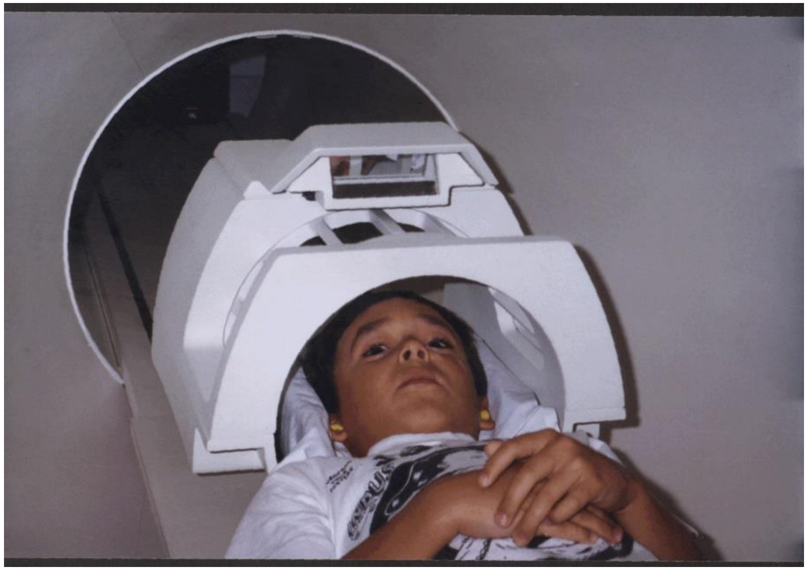
http://www.dotynmr.com/mri/images/MRI3axesgrad.jpg

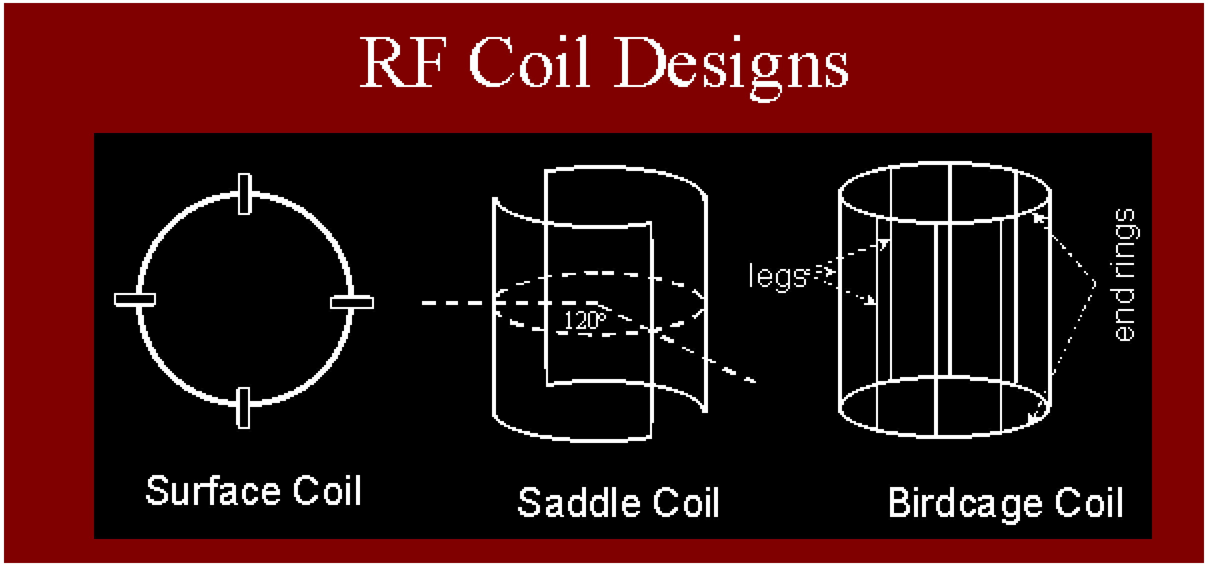
Gradient Coil Configuration



RF Coil

- Sends RF pulse and detects signal (transceiver)
- Generally placed in close proximity to imaged tissue
- Different geometries to image different body parts





http://www.fmrib.ox.ac.uk/

Shielding the Magnetic Field

- With superconducting magnets, the field is always on
- Strong fields can affect computers, other equipment as well as posing safety issues (no pacemakers, etc.)
- Generally surround the room with a “shielding material”, copper, nickel
- Have safety lines around the room to represent drops in the field (for example, the 5-Gauss line)

http://www.imedco-shielding.com

Next Topics

I. Finish MRI with -

1. **Contrast Agents**
2. Image Characteristics
   - -SNR, CNR
   - -Sources of Artifacts

II. MR Spectroscopy

III. MR Angiography

MRI Contrast Agents

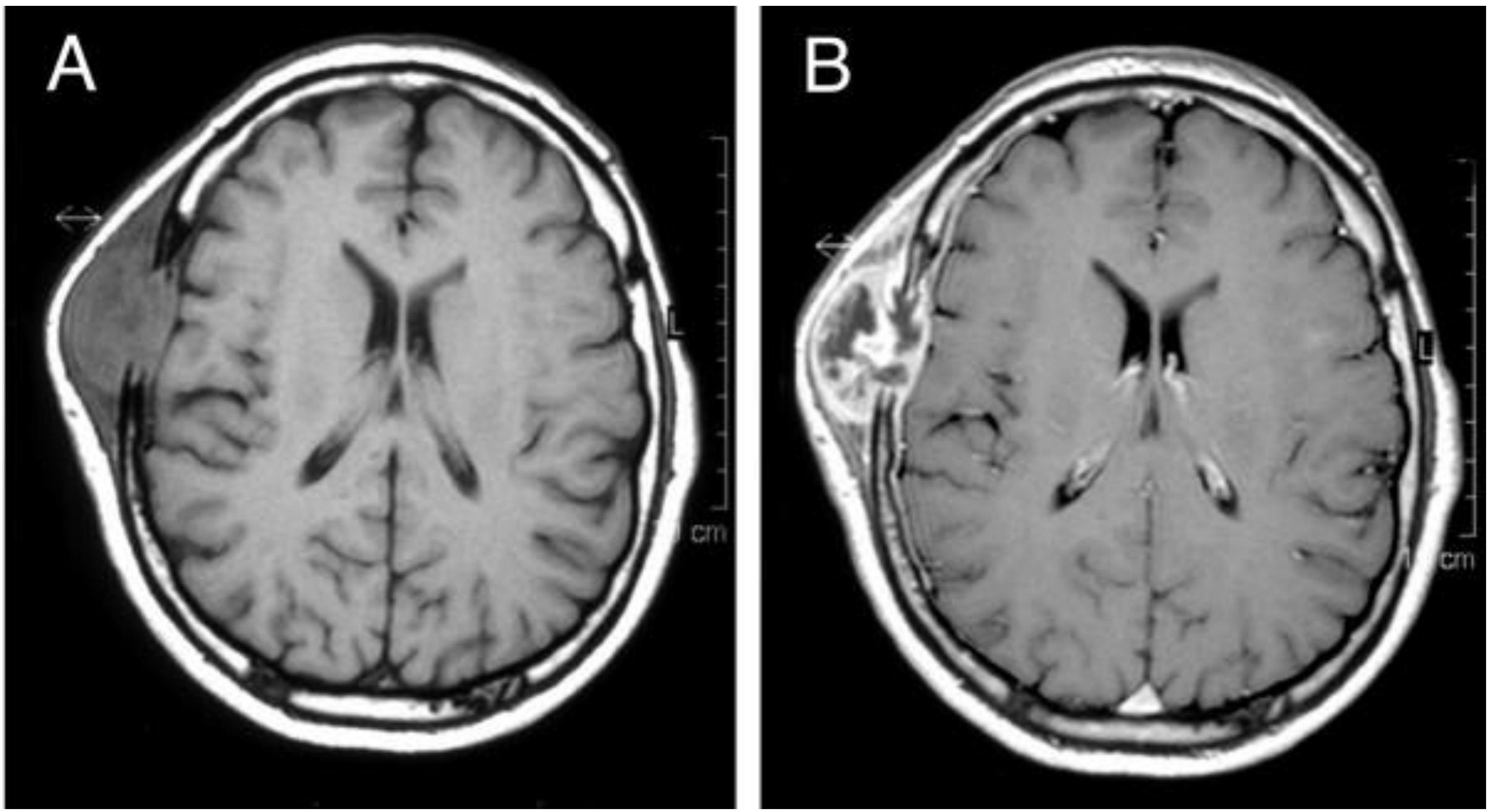
- Usually have enough contrast with T1, T2 weighting
- Use contrast agents when looking for very small pathologies or in other special cases
- Two types:
  1. Paramagnetic agents
  2. Superparamagnetic agents

Paramagnetic Agents

- Metal ions with large number of unpaired electrons (gadolinium, manganese, etc)
- These metals are toxic, so must be contained in a “chemical cage” or chelate
- These agents shorten the T1 and T2 of protons attached to neighboring water molecules
- Most used to detect brain disorders

Example – Gadolinium Contrast

Metastatic deposit involving the right frontal bone with large extracranial soft tissue component and meningeal invasion



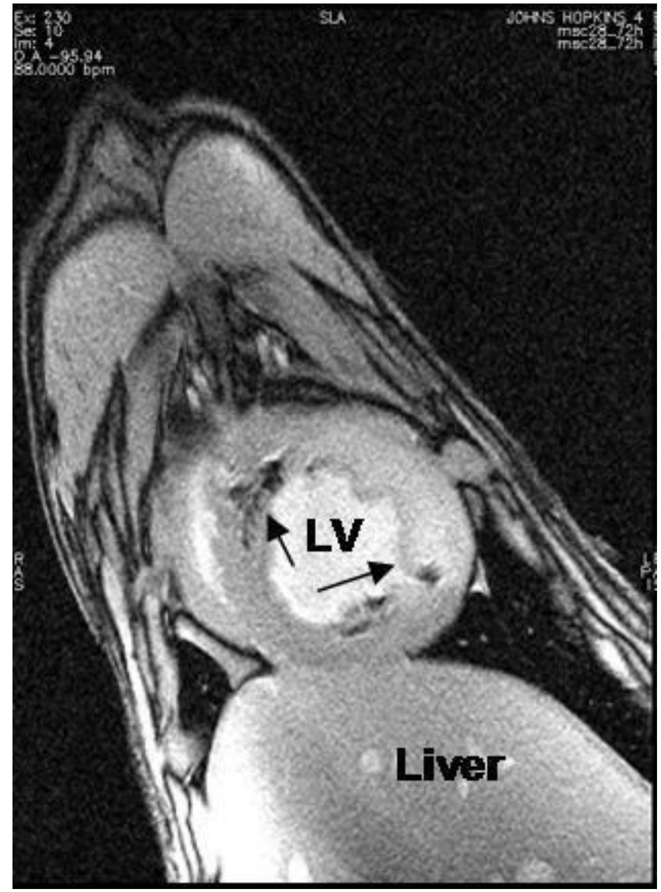
BEFORE CONTRAST

AFTER CONTRAST

www.biomedcentral.com

Superparamagnetic Agents

- Small magnetic particles (30 nm or less in diameter) containing iron
- Cause inhomogeneities in the magnetic field
- Negative contrast agents (cause a reduction in tissue intensity in accumulation points)



Arrows on MRI pictures of a dog's heart point to dark areas where mesenchymal stem cells, labeled with iron-oxide particles, can be targeted to repair muscle damaged by heart attack.

http://www.hopkinsmedicine.org/

Next Topics

I. Finish MRI with -

1. Contrast Agents
2. **Image Characteristics**
   - **-SNR, CNR**
   - **-Sources of Artifacts**

II. MR Spectroscopy

III. MR Angiography

Signal to Noise Ratio (SNR)

1. Better at higher field strengths (B_0)
2. Dependent on tissue and parameters (T1, T2, TE, TR)
3. Proportional to the sensitivity of the RF Coil
4. Better with more signal averaging
5. Dependent on the field of view (FOV) and number of phase and frequency encoding steps --
   better with more dense sampling of k-space (smaller FOV or more encoding steps)
6. Better with increased slice thickness

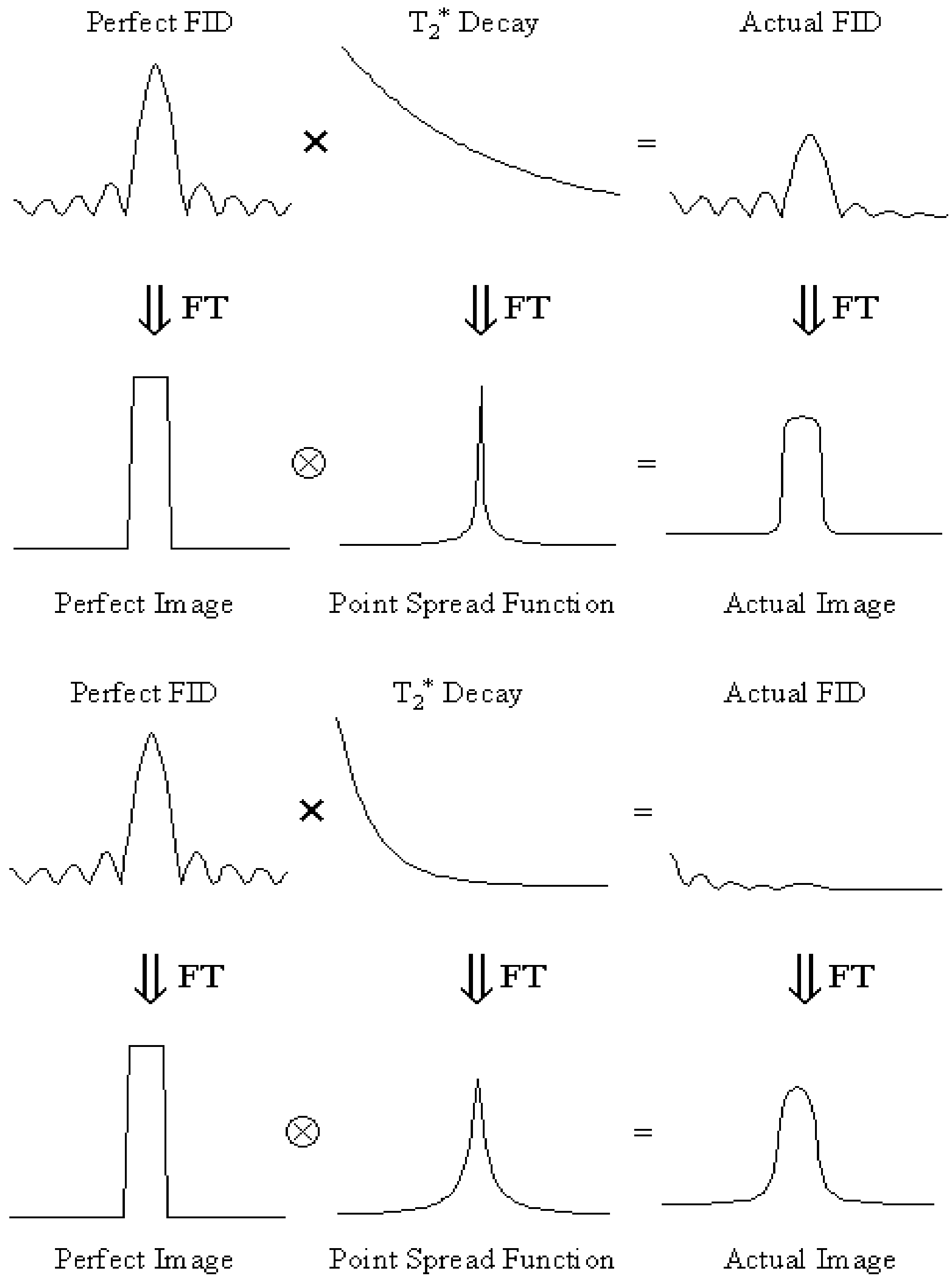
Spatial Resolution

Point Spread Function (PSF) – dependent on the pulse sequence and is affected by:

1. Digital resolution – further the FOV in k-space, the better the resolution (more high frequencies)
2. Width of the sinc function (because of square gradient pulses) is inversely proportional to number of phase and frequency encoding steps
3. Degree of T2* relaxation

$$FWHM = PSF_{Lorentz} = 1/\pi T2^{*} G_{freq}$$

Example of **the effect of T2* decay on the sharpness of a line through an image. The smaller the value of T2*, the wider the point spread function, and the more smoothed (less sharp) the profile becomes.**



http://www.fmrib.ox.ac.uk/~stuart/thesis/chapter_5/chapter5.html

Contrast-to-Noise Ratio

- Mainly affected by T1, T2, TR, TE
- T1 contrast is better at lower field strength (slower relaxation into B_0)
- Also affected by same factors which affect SNR
  - Field strength, RF Coil Sensitivity, averaging, FOV, number of encoding steps, etc.

Sources of Artifact

- Undersampling or aliasing
- Gibbs ringing or trucation artifact
- Patient related (motion)
- Susceptibility artifacts
- RF-related
- Inhomogenious magnetic field
- Gradient related artifacts

Aliasing Artifact / Wrap Around

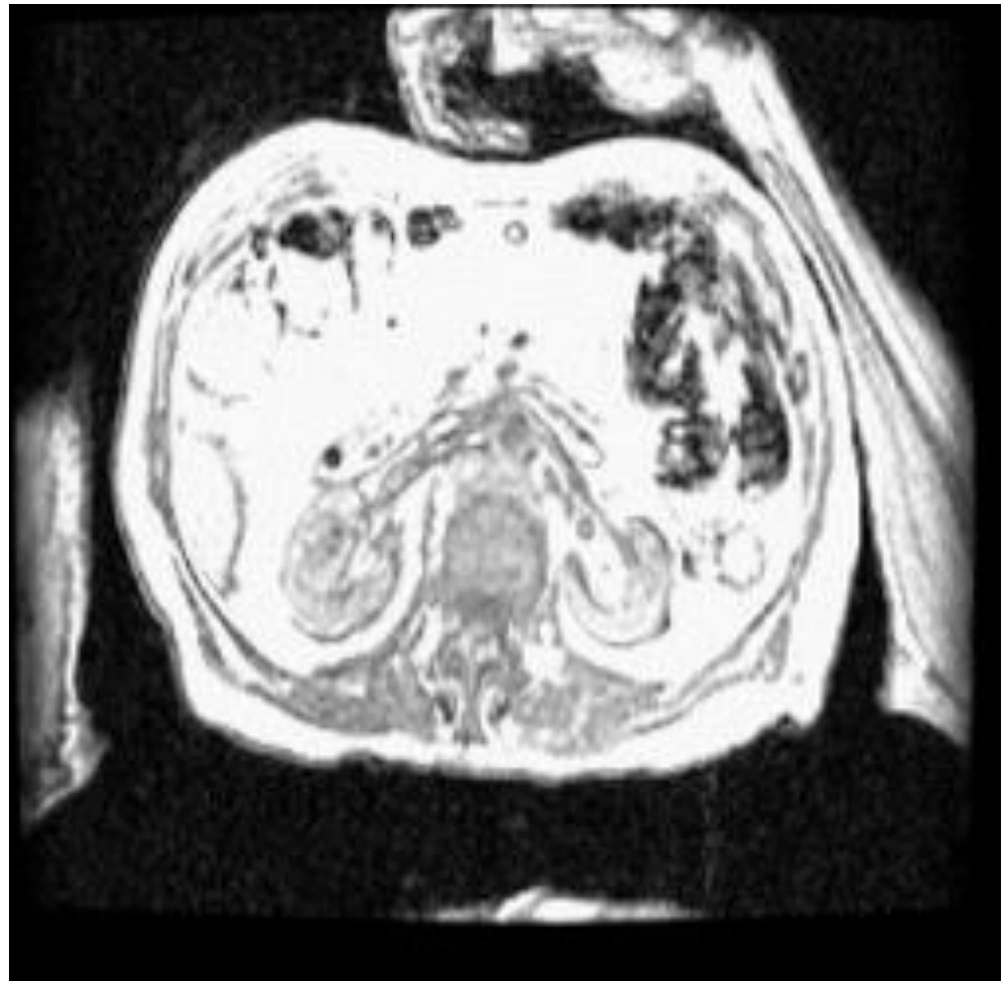
-Wrap-around due to incorrect FOV

-Object is outside of FOV but is within the sensitive volume of the coil

-Usually in phase-encode direction

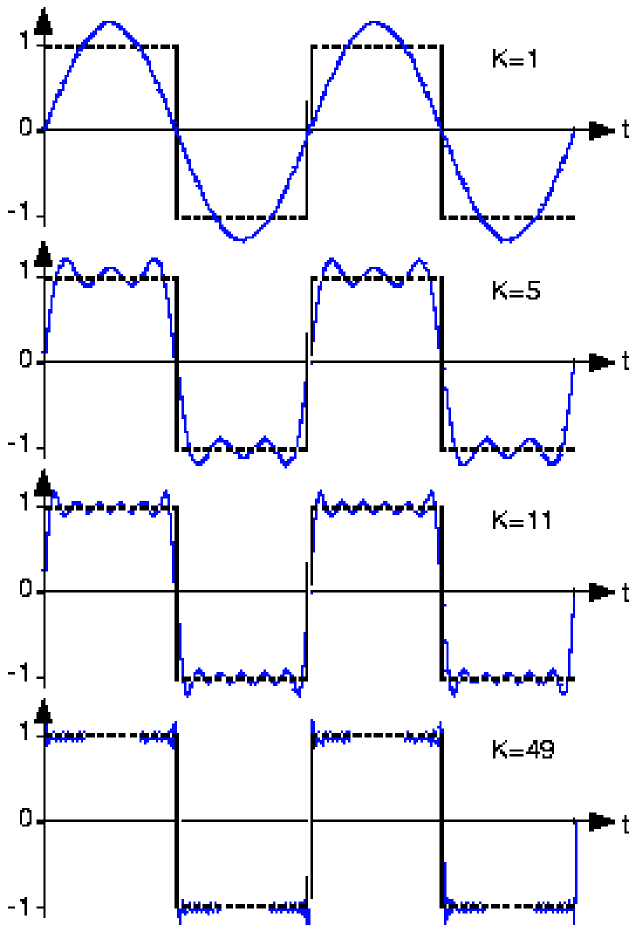
-More specifically, sampling rate is less than the range of frequencies in the FID signal

-Should increase FOV by sampling higher frequencies

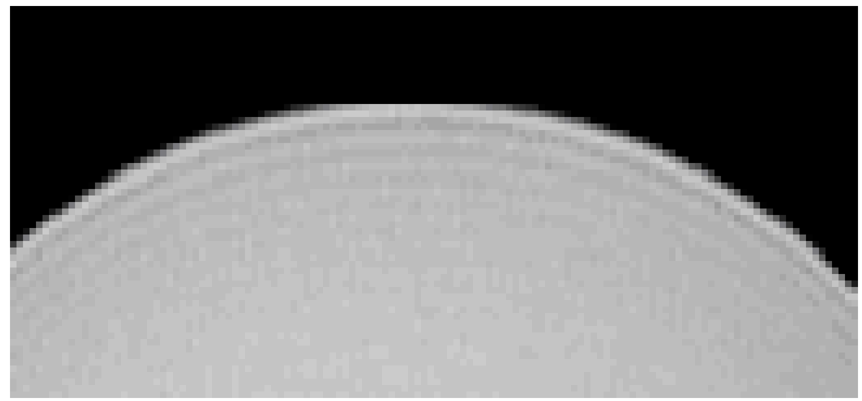


Ringing Artifact

- Due to Gibbs Phenomenon of trying to model a square function with sinusoids



http://cnx.org/content/m10092/latest/



www.hull.ac.uk/mri/lectures/gpl_page.html

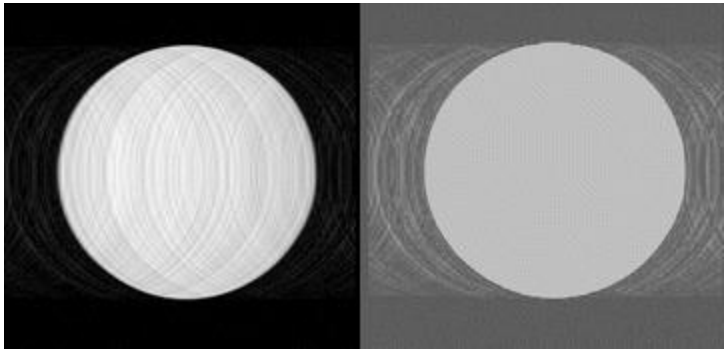
-Occurs at interface between high and low signal boundaries

-Cannot capture corners because of finite sampling (limited number of Fourier points or frequencies)

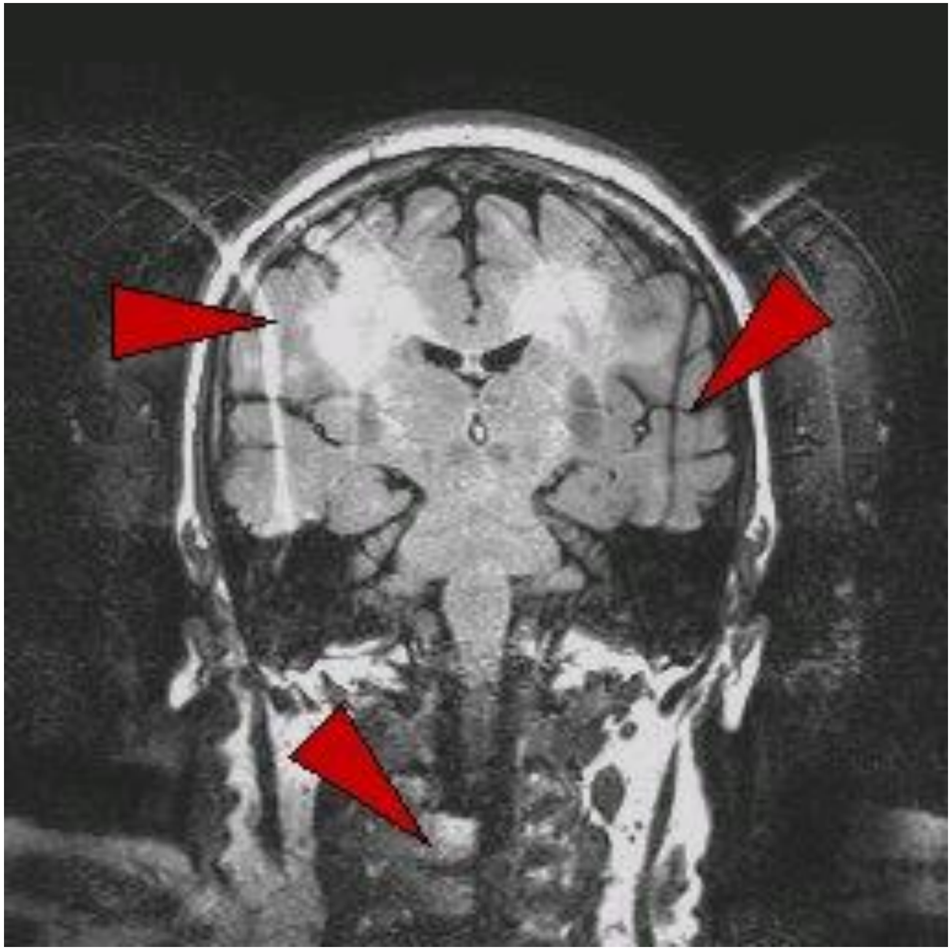
Patient Motion

-Leads to unclear boundaries or appearance of "ghosts" in the image

-Heart beat, breathing

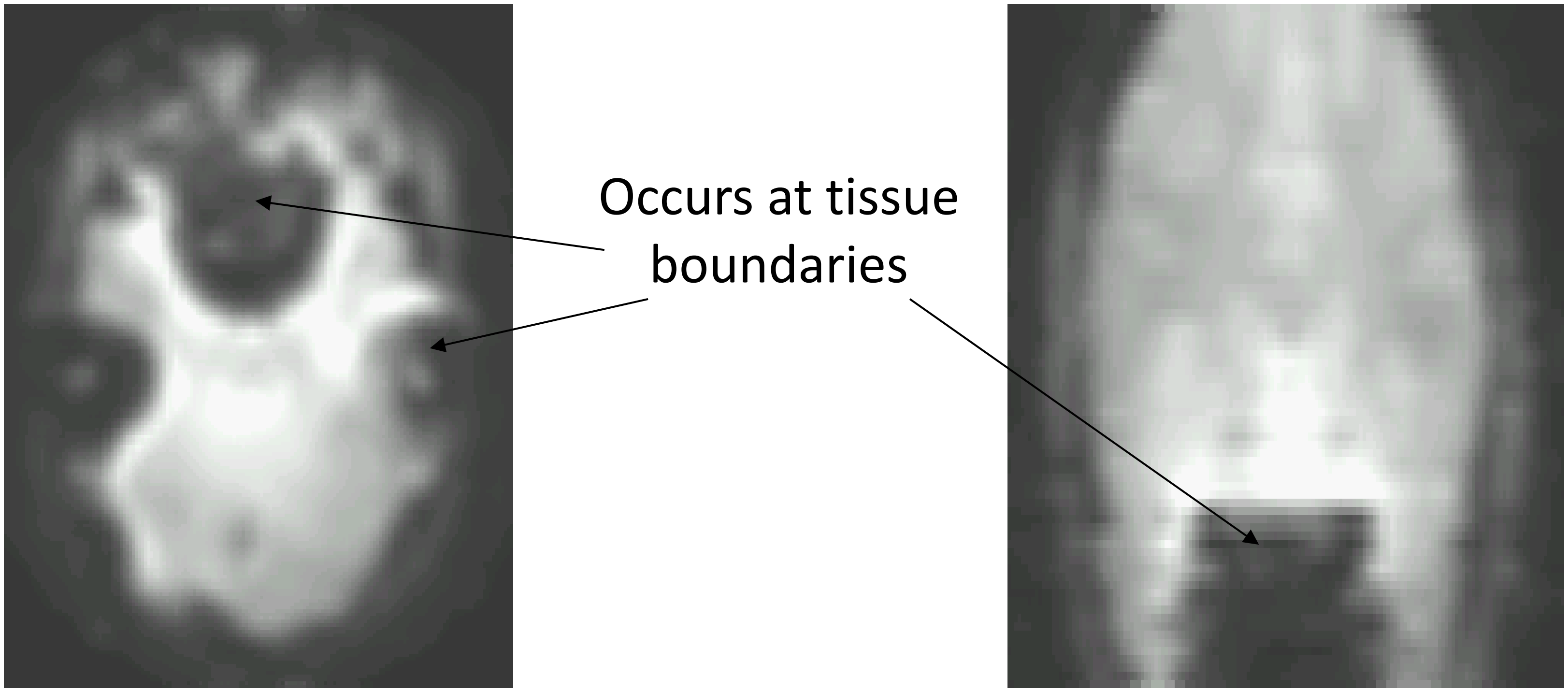


www.hull.ac.uk/mri/lecture**s**



http://www.mr-tip.com/

Susceptibility Artifacts



-Caused by variations in the response of different tissues to the external magnetic field.

-Non-linear changes in resonant frequency at tissue boundaries

Susceptibility Artifact

Another example –

Patient with permanent metal in their mouth

Next Topics

Finish MRI with -

1. Contrast Agents
2. Image Characteristics
   - -SNR, CNR
   - -Sources of Artifacts
3. **Safety**

MR Spectroscopy

MR Lecture 3

I. Finish MRI with -

1. Contrast Agents
2. Image Characteristics
    - -SNR, CNR
    - -Sources of Artifacts

II. MR Spectroscopy

III. MR Angiography

MR Spectroscopy (MRS)

- NMR is typically used to measure the structure and chemical content of substances in a tube
- MRI Spectroscopy is *in vivo* localized NMR

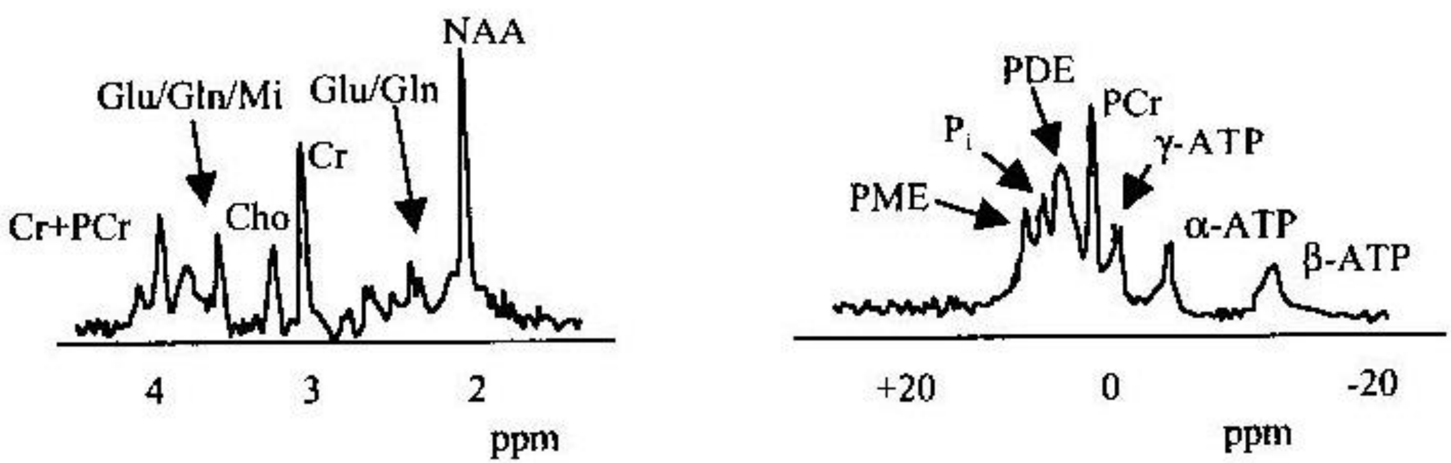


FIGURE 4.40. *(left) A localized proton spectrum obtained from the brain at 3 T. The peaks correspond to Cr (creatine), Glu (glutamate), Gln (glutamine), Cho (choline), Mi (myo-inositol), and NAA (n-acetylaspartate). (Right) A corresponding localized phosphorus spectrum from the brain. The peaks shown are PME (phosphomonoester), P_i (inorganic phosphate), PDE (phosphodiester),*

Difference Between NMR and MRI

from: http://theboard.byu.edu/

Q Dear 100 Hour Board,

What is the difference between NMR and MRI?

- Downfield Resonance

A Dear Downfield Resonance,

Your name implies that you know the difference and are just testing the board. But maybe you are truly ignorant of the answer. The difference is the letter "N" vs. the letter "I". For real. NMR stands for nuclear magnetic resonance, while MRI stands for magnetic resonance imaging. MRI is the term in medical circles because people are scared of all things nuclear. Would you like to have all your nuclei magnetically resonated? Of course not. But to be magnetically resonance imaged, why that's no concern at all. Just change that "N" to an "I," and all your concerns magically vanish. But it's all the same thing.

How NMR Works

- Same concept as MRI
  - Nuclei align in magnetic field
  - Send an RF pulse at a frequency to resonate the ***nuclei of interest***
  - Measure the FID signal for a particular piece of volume (or volume in the tube)
  - Fourier Transform to get an NMR Spectrum

- Now no spatial information, no spatial gradients; just getting NMR spectrum from a piece of tissue

Nuclei of Interest

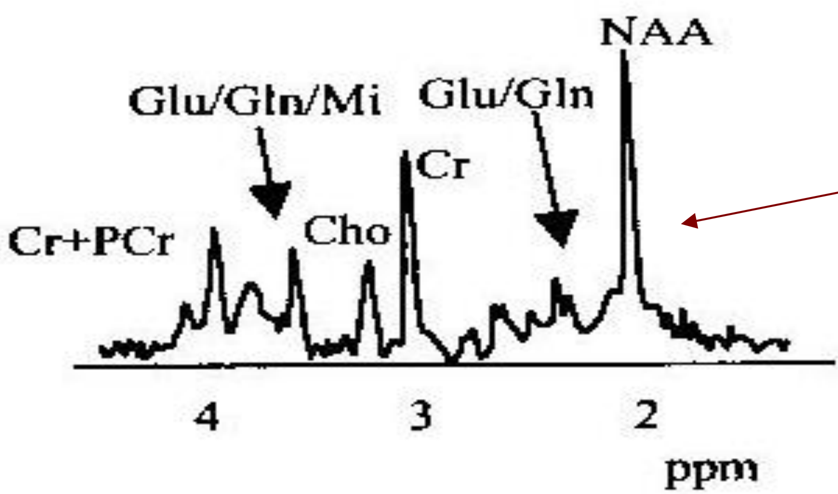
TABLE 4.1. Properties of Nuclei Found at High Abudance in the Body

Nucleus	Atomic Number	Atomic Mass	I	$\gamma/2\pi$ (MHz/T)	MRI Signal
Proton	1	1	1/2	42.58	Yes
Phosphorus	15	31	1/2	17.24	Yes
Carbon	6	12	0	–	No
Oxygen	8	16	0	–	No
Sodium	11	23	3/2	11.26	Yes

*As in MRI, can only perform MRI Spectroscopy on elements with odd atomic mass and/or odd atomic number, as these possess SPIN

Observed Spectrum

- The **number of peaks** tells you the number of different environments the hydrogen atoms are in.
- The **ratio of the areas under the peaks** tells you the ratio of the numbers of hydrogen atoms in each of these environments.
- The **chemical shifts** give you important information about the sort of environment the hydrogen atoms are in.



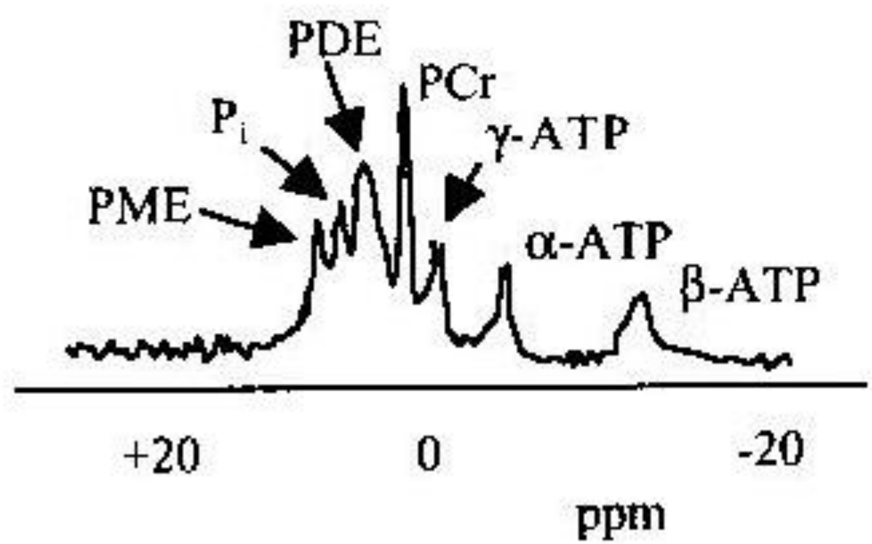
Broad peaks in vivo due to tissue inhomogeneities

MR Spectroscopy

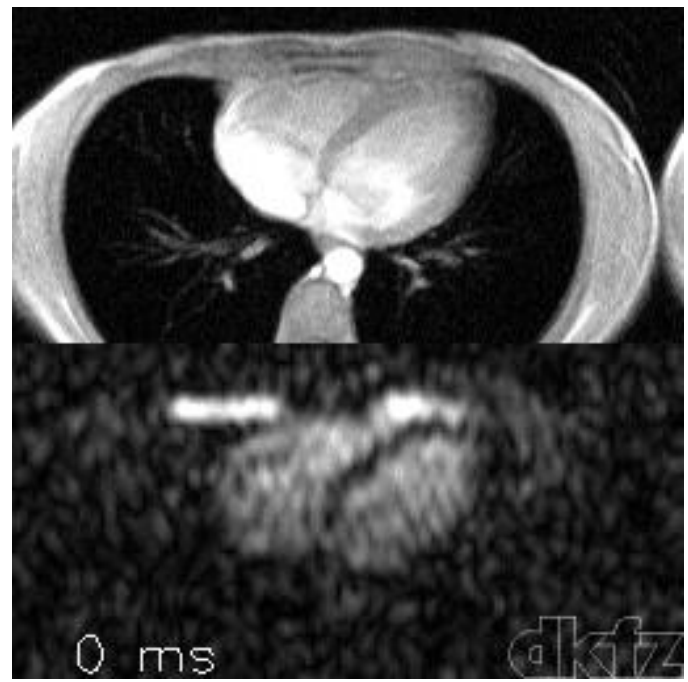
- Major peaks in **proton** spectroscopy are from lipids and water
  - *Must suppress these to see signals from more dilute metabolites using **frequency selective irradiation techniques***
- Units are in PPM (parts per million)
  - *Dimensionless so that the strength of the magnetic field and the applied resonant frequency do not need to be specified (remember that* $\omega = \gamma B$)

Other Elements

Phosphorus Spectrum



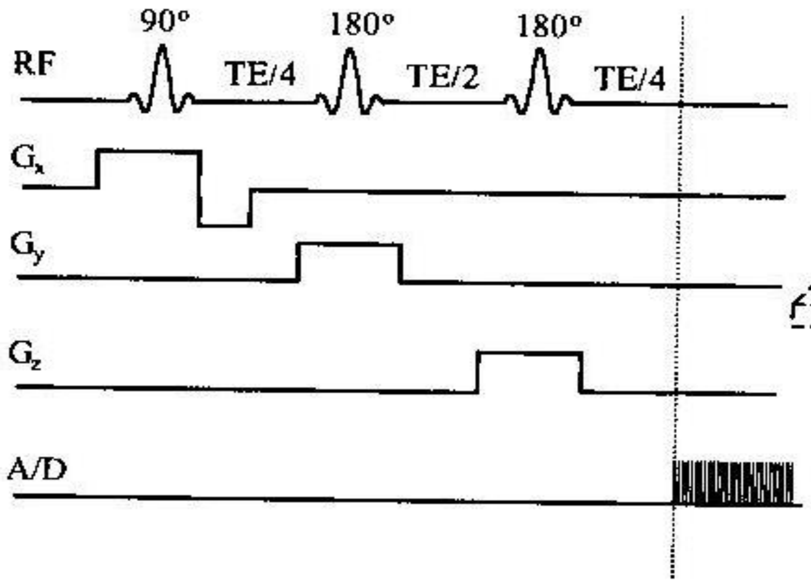
Sodium Image of the Heart
ottom image)

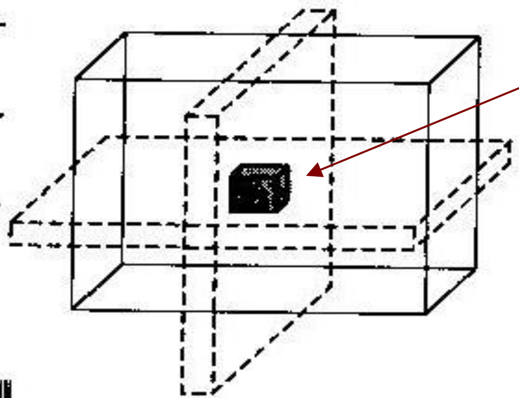


www.dkfz-heidelberg.de/mrphys/sodium/cw_herz.gif

Common MRS Pulse Sequences

- PRESS = point resolved spectroscopy





Resulting spectra comes only from this voxel

FIGURE 4.41. *(Left) A PRESS pulse sequence used to acquire an NMR spectrum from a single voxel. (Right) the voxel (shaded) is defined by the intersection of the three slices in the sequence. Only nuclei within this voxel will experience all three RF pulses and therefore be refocused to give an NMR signal. In practice, extra RF pulses and gradients are used for water suppression.*

Common MRS Pulse Sequences

- Chemical Shift Imaging (CSI)
- 1, 2, or 3 dimension ***phase-encoding*** of the FID to produce separate spectra from multiple voxels

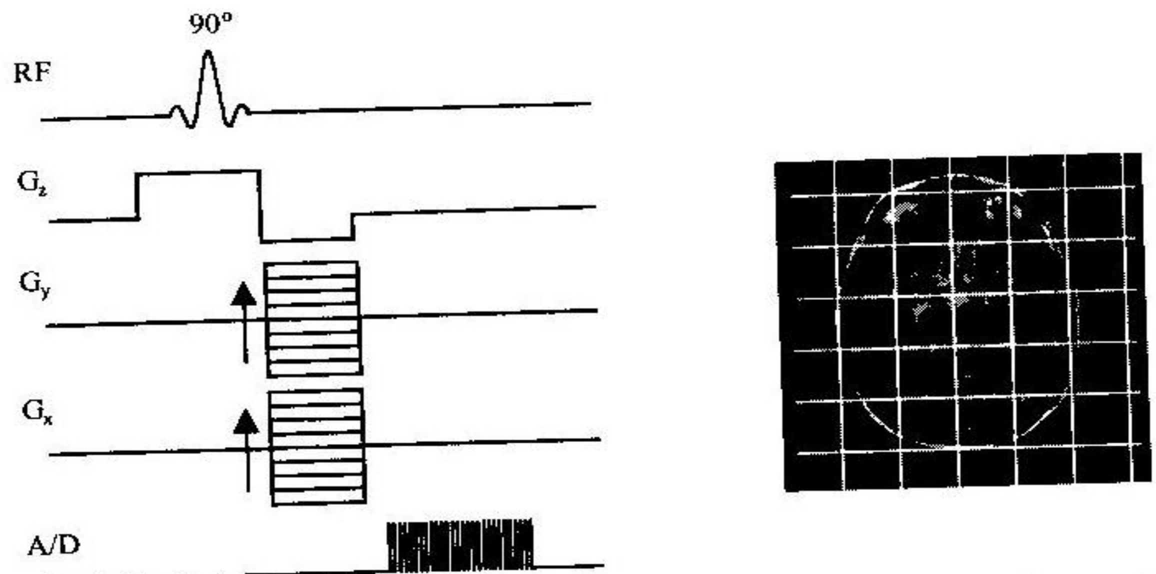


FIGURE 4.42. *(Left) A two-dimensional CSI sequence that produces NMR spectra from a range of voxels in the xy plane (right). The voxels are often overlaid on the axial image for correlating the anatomical structure with the biochemical information.*

Applications of MRS

- Oncology
- Liver diseases
- Neurology
- Brain development
- Organ transplantation
- Muscular metabolism
- Nutrition
- Pharmacology

(From: The BBI Newsletter, August, 1996)

Applications of MRS

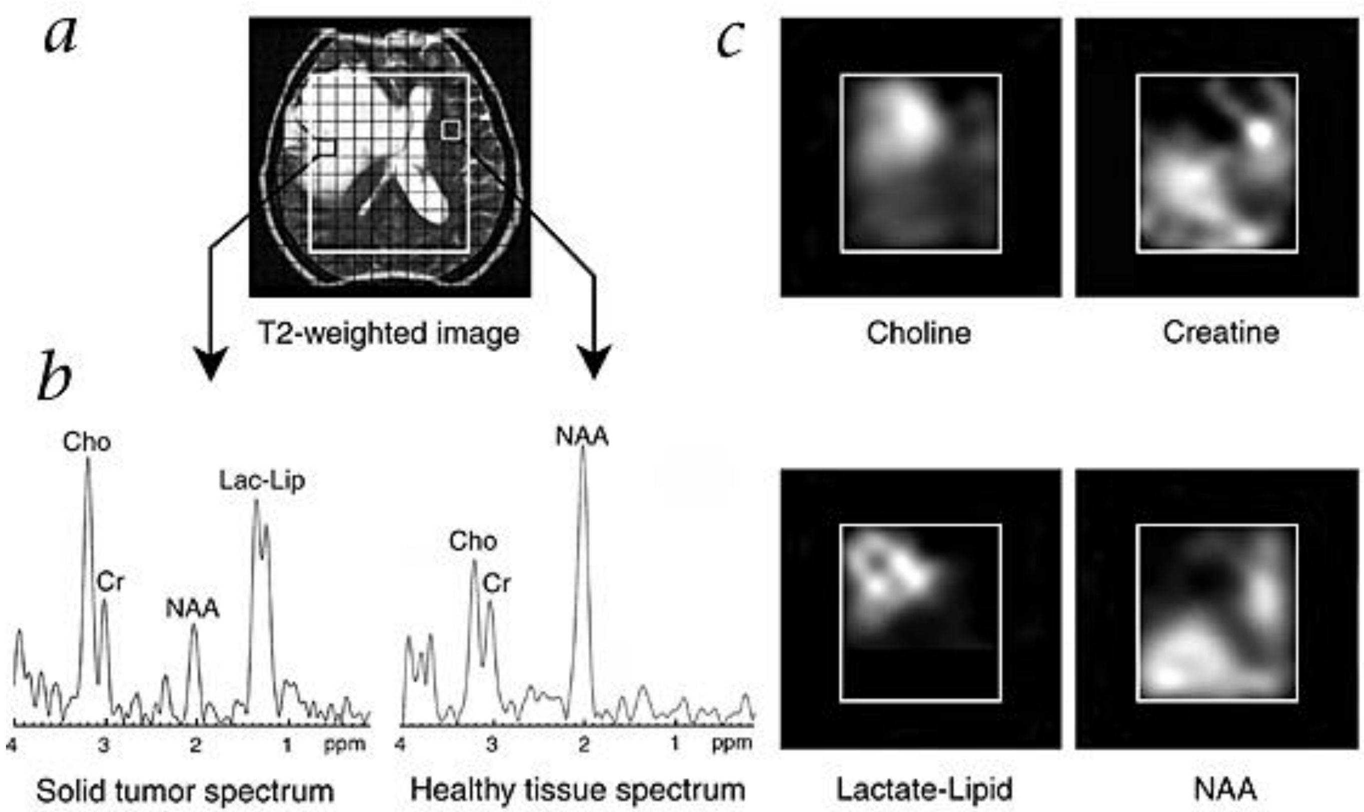
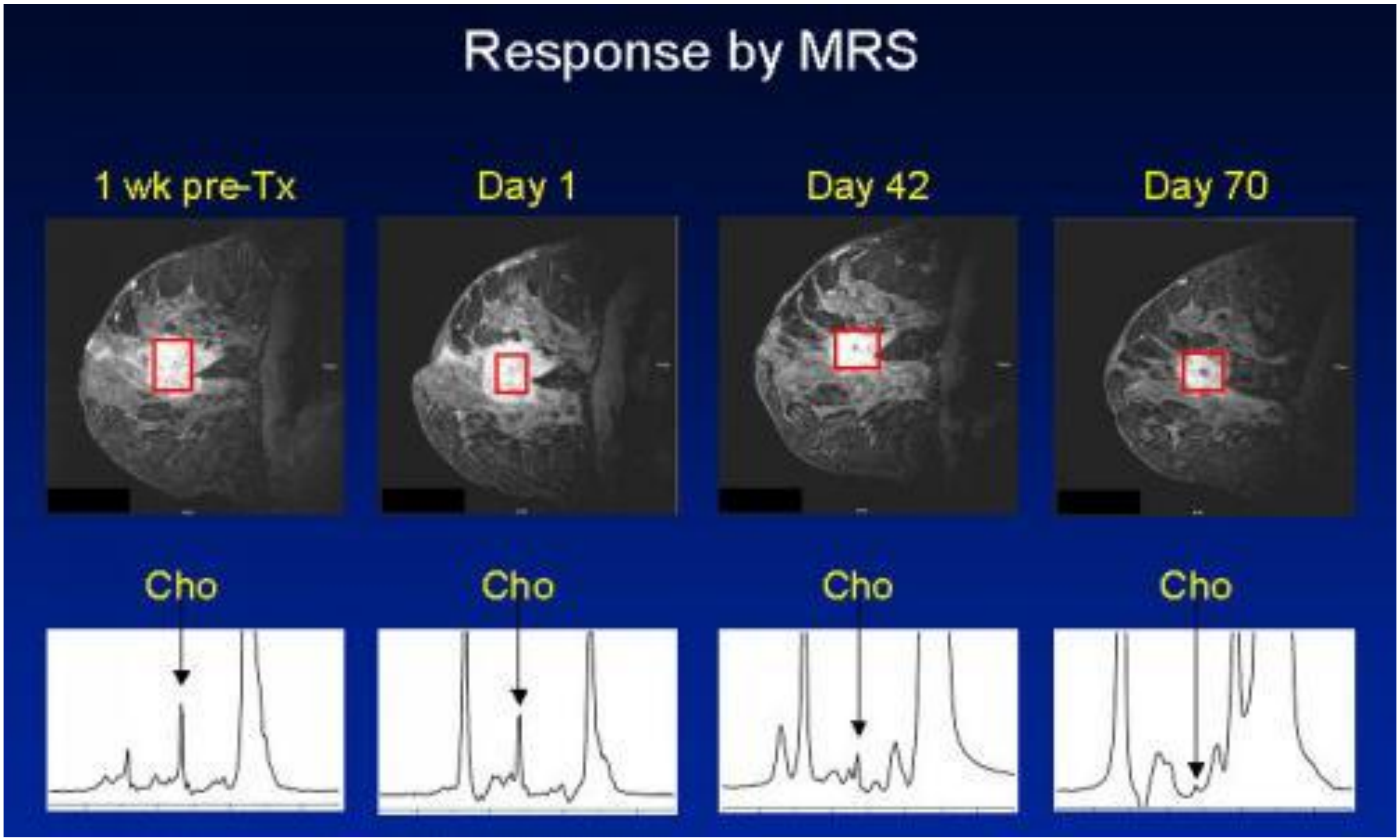


Figure 1: *Nature Medicine* **6**, 1287 - 1289 (2000)

Applications of MRS



http://www.cmrr.umn.edu/research/breast/TxResponseBoth_500.jpg

MR Lecture 3

I. Finish MRI with -

1. Contrast Agents
2. Image Characteristics
   - -SNR, CNR
   - -Sources of Artifacts
3. Safety

II. MR Spectroscopy

III. MR Angiography

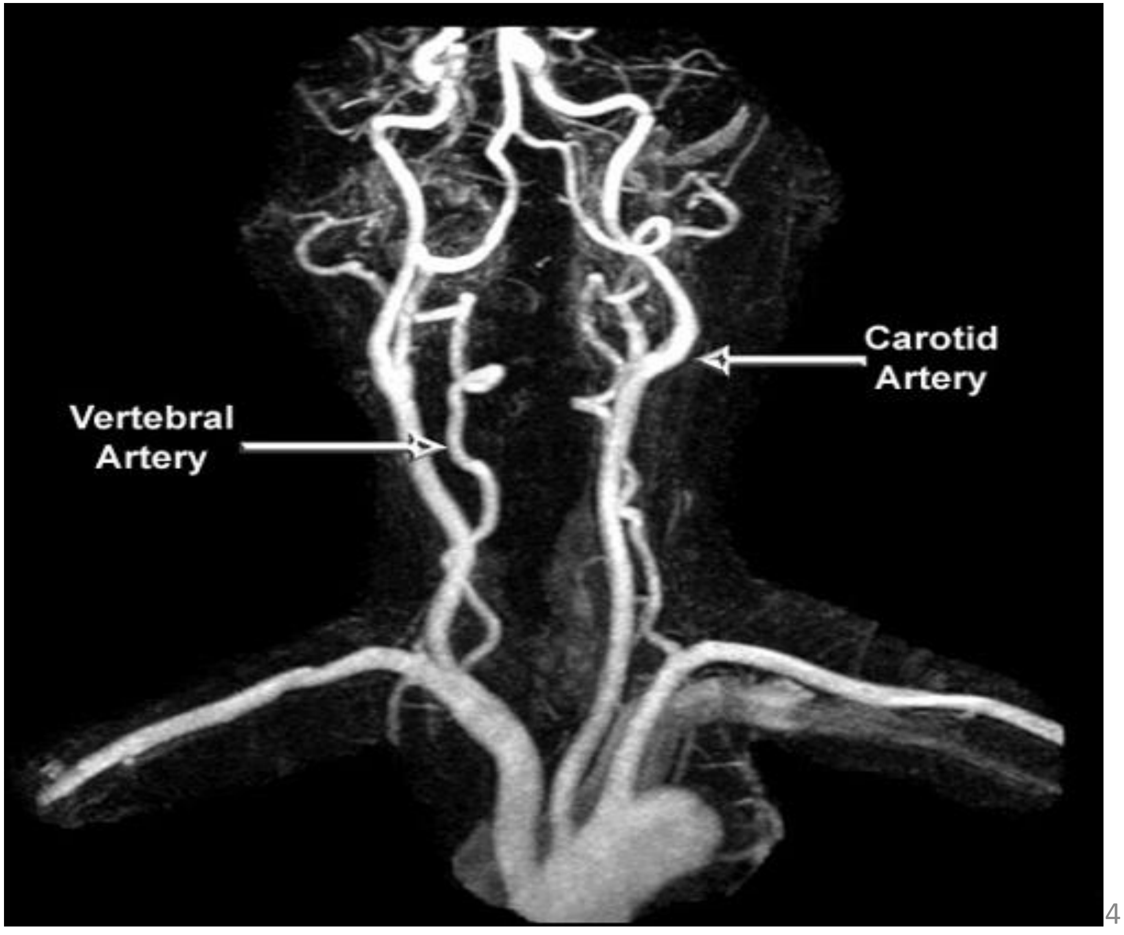
- Time of Flight Methods

- Phase-Contrast Methods

MRI Angiography (MRA)

- No injected contrast agent (usually)

Neck vessels



www.lahey.org/

Time-of-Flight (TOF) Methods

- Shorten the T1 of blood (to $T1_{eff}$) as it flows through the imaging volume during data acquisition
- T1 is shortened because blood flowing into the slice has not undergone the RF pulse and thereby enters with full magnetization ($M_z = M_0$)

$$(1/T1_{eff}) = (1/T1) + (\nu/S_{th})$$

where ν = blood velocity, S_{th} = slice thickness

TOF Considerations

- Use a large tip angle (or flip angle from RF pulse) to cause heavy T1 weighting
- Signal intensity from tissue is small, signal intensity from flowing blood is larger due to $T1_{eff}$

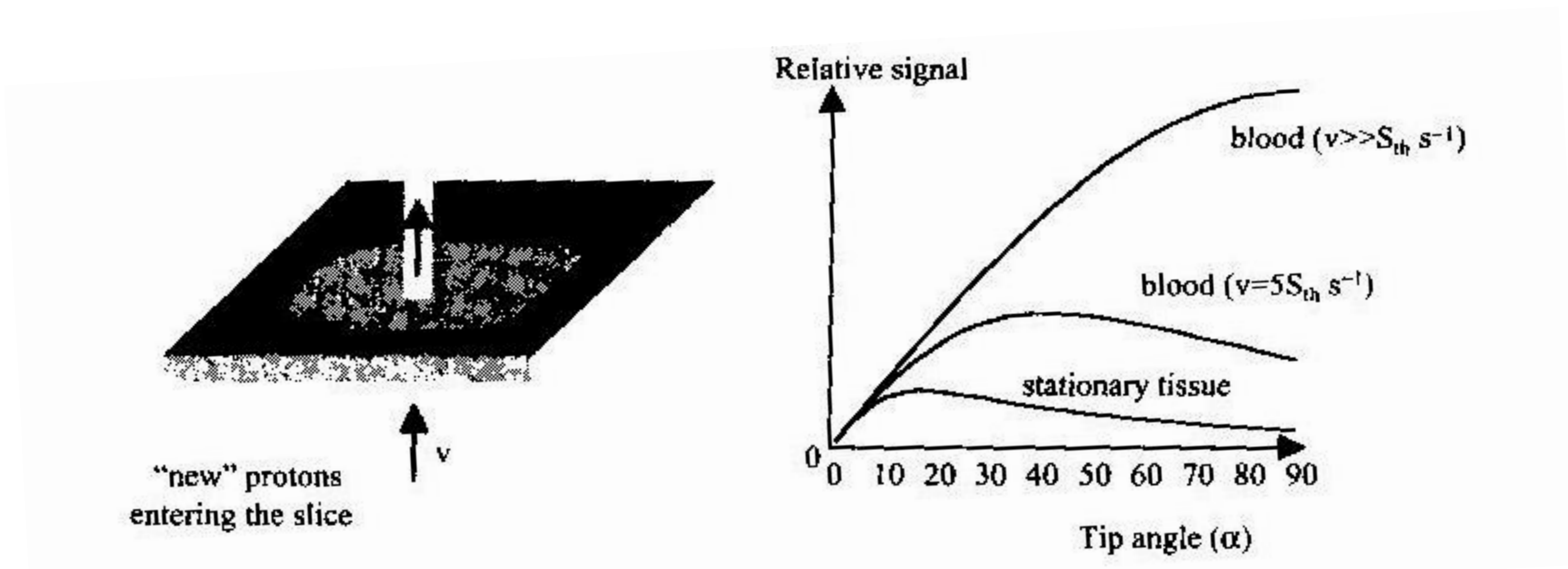
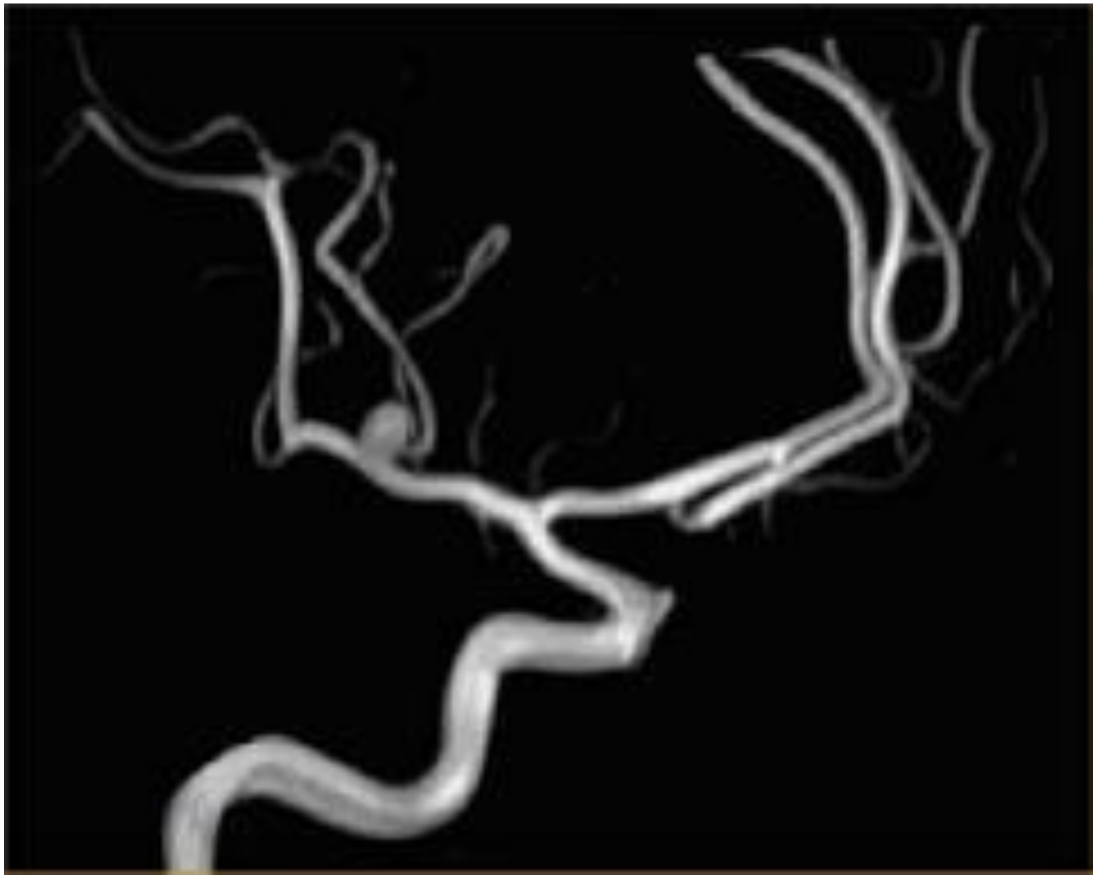


FIGURE 4.36. (Left) A schematic of blood

TOF Example



http://www.shef.ac.uk/

Phase-Contrast Methods

- Induce a phase shift in the precessing magnetization of flowing blood with a flow-sensitive "bipolar" gradient pulse
- Insert into gradient-echo or spin-echo pulse sequence

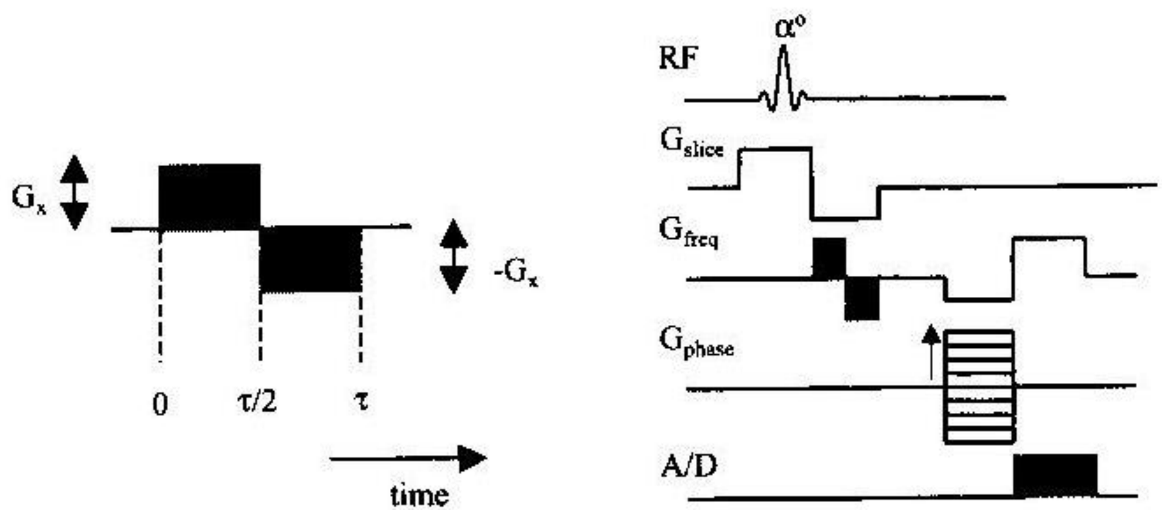


FIGURE 4.38. Inclusion of a bipolar gradient module (left) into a two-dimensional imaging sequence (right) can be used to produce phase contrast angiograms.

Phase-Contrast (cont.)

- By applying this G_x gradient, a velocity dependent phase is introduced into the signal

$$\phi = \int_{t=0}^{\tau/2} \gamma G_x x(t)\, dt + \int_{t=\tau/2}^{\tau} \gamma(-G_x)x(t)\, dt \qquad (4.62)$$

where ϕ = phase, γ = gyromagnetic ratio

- For stationary protons, $\phi = 0$

- For protons in blood flowing at a constant velocity, υ_x, in the x-direction

$\phi = \gamma \upsilon_x \tau^2 G_x$ (τ = time of Gx application)

More Examples

www.roseradiology.com/