6.1 MR Image Formation

Matrix, Gradients & Signals
Image formation & k-pace

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Outline

- Imaging Matrix
- Gradients & Signals
- Phase, Frequency and Amplitude
- Slice selection
- Phase encoding
- Frequency encoding

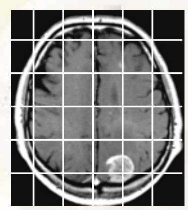
Objectives

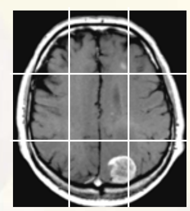
Upon completion of this course, the attendee should…

1. Learn about the matrix.
2. Understand the MR signals and how they are affected by gradients
3. Learn the concept phase, frequency & amplitude.
4. Understand image formation, slice selection, phase encoding, frequency encoding
5. Understand the concept of k-space.

Imaging Matrix

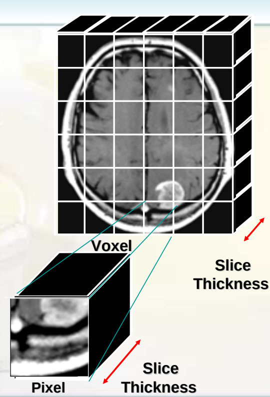
- Digital images are created with a matrix
- Smallest unit of the digital image is a pixel


6 x 6


3 x 3

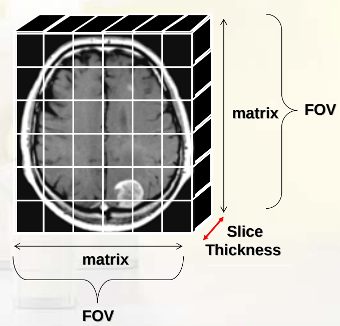
Pixel , Voxel

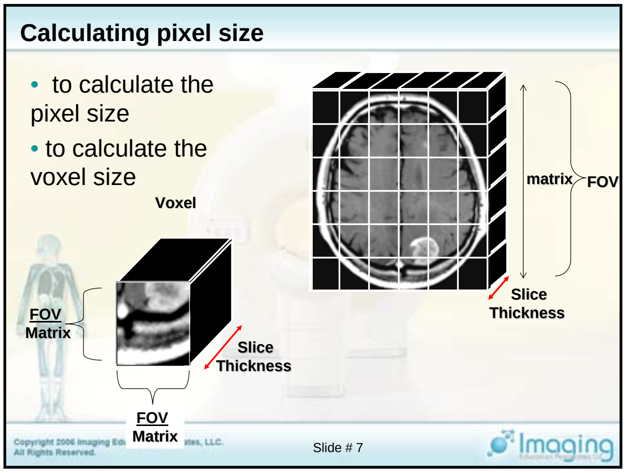
- In MRI slices are acquired
- The voxel is a 3d volume element
- The face of the voxel is the pixel



What makes up a digital image?

- The size of the area imaged in MRI is the field of view (FOV)
- The number of pixels (rows x columns) is the matrix
- The depth is the slice thickness




Calculating pixel size
• to calculate the pixel size
• to calculate the voxel size
Voxel
FOV
Matrix
Slice
Thickness
FOV
Matrix
matrix
FOV
Slice
Thickness
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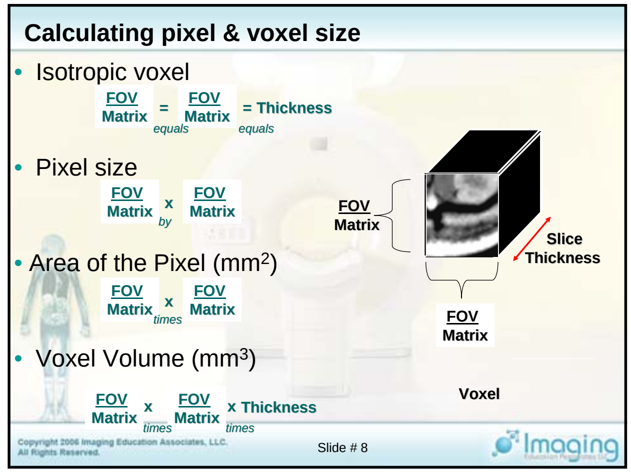
Slide # 7
Imaging


Calculating pixel & voxel size
• Isotropic voxel
FOV/Matrix = FOV/Matrix = Thickness
equals equals
• Pixel size
FOV/Matrix x FOV/Matrix
by
• Area of the Pixel (mm2)
FOV/Matrix x FOV/Matrix
times
• Voxel Volume (mm3)
FOV/Matrix x FOV/Matrix x Thickness
times times
FOV
Matrix
Slice
Thickness
FOV
Matrix
Voxel
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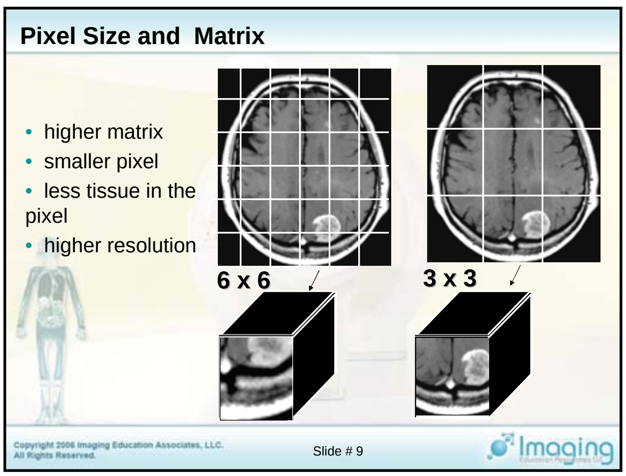
Slide # 8
Imaging


Pixel Size and Matrix
• higher matrix
• smaller pixel
• less tissue in the pixel
• higher resolution
6 x 6
3 x 3
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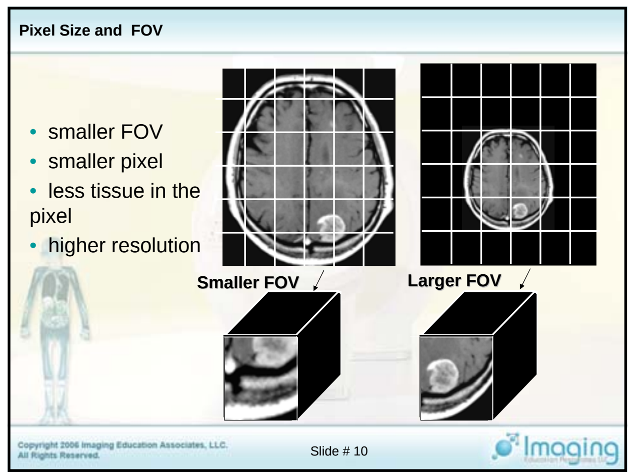
Slide # 9
Imaging


Pixel Size and FOV
• smaller FOV
• smaller pixel
• less tissue in the pixel
• higher resolution
Smaller FOV
Larger FOV
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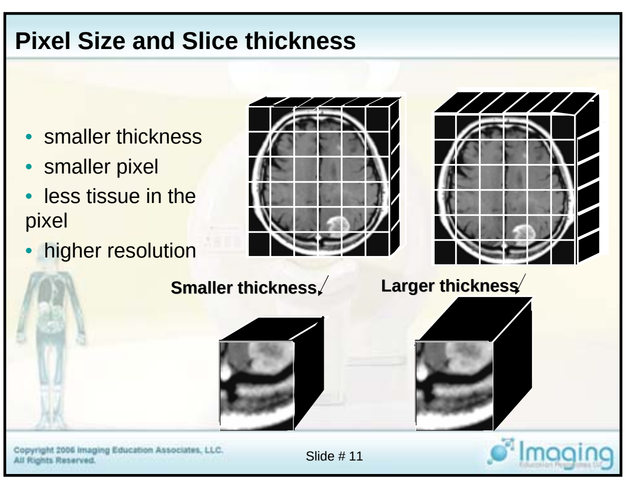
Slide # 10
Imaging


Pixel Size and Slice thickness
• smaller thickness
• smaller pixel
• less tissue in the pixel
• higher resolution
Smaller thickness
Larger thickness
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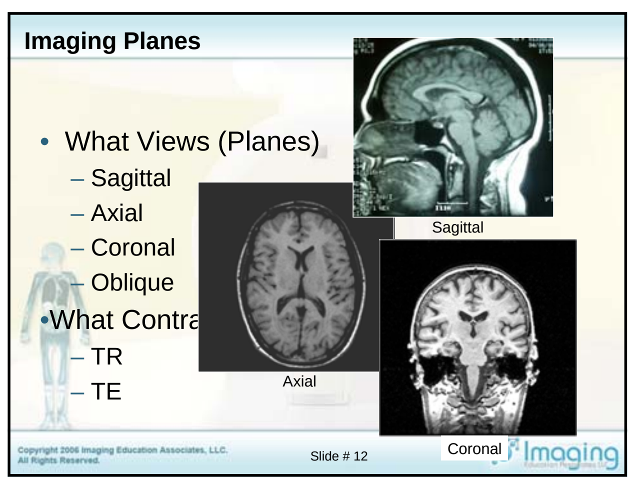
Slide # 11
Imaging


Imaging Planes
• What Views (Planes)
– Sagittal
– Axial
– Coronal
– Oblique
•What Contra
– TR
– TE
Sagittal
Axial
Coronal
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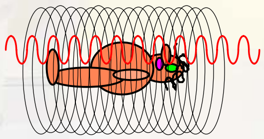
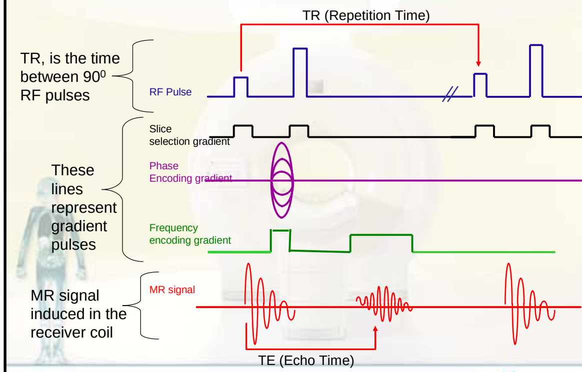
Slide # 12
Imaging

To Create MR Images

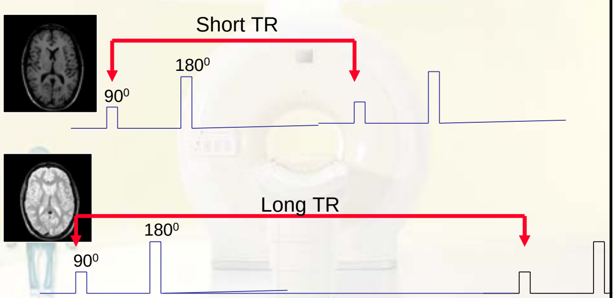
- The patient is placed in the magnetic field
  - to align the spins
- The RF pulse is applied
  - to excite the spins
  - at the Larmor Frequency



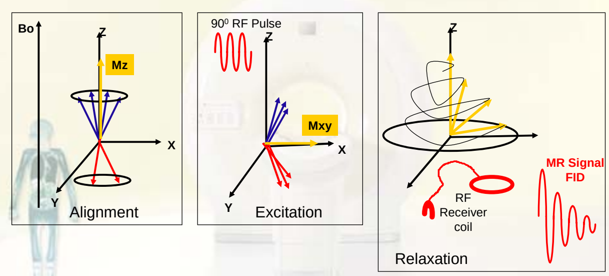
Timing Diagrams – RF & Gradient Pulses



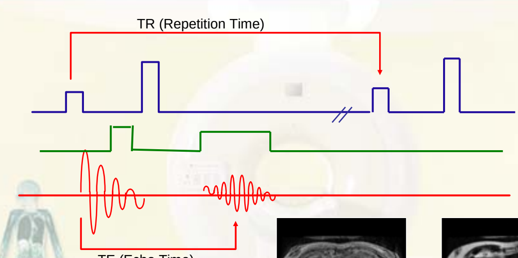
Short & Long TR Imaging



MR Excitation Relaxation



Timing Diagram



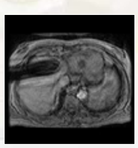
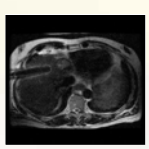
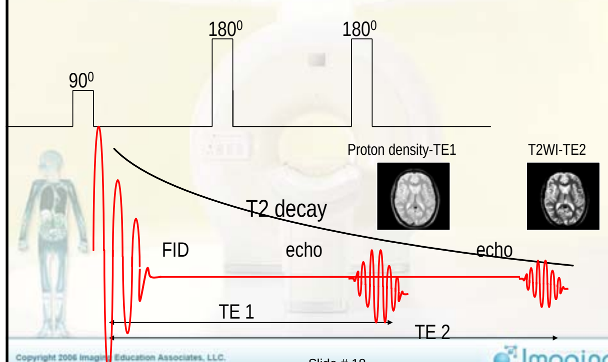


Image with artifact



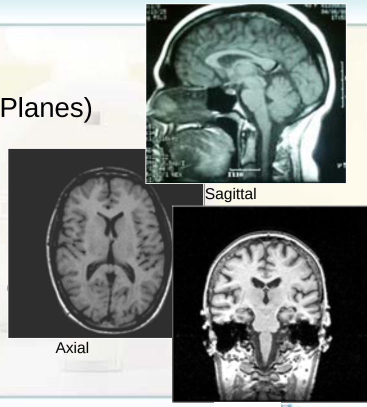
Cleaned up the "SIC"

Timing Diagram -TE

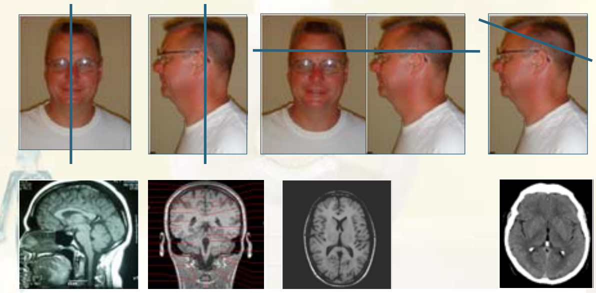


Imaging Planes

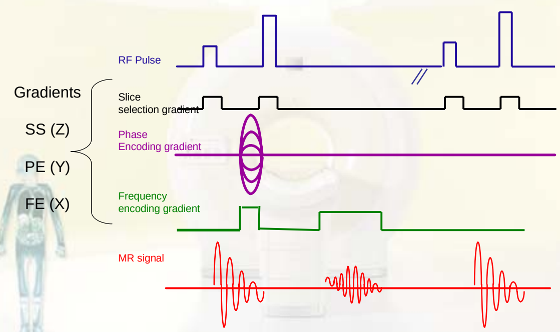
- What Views (Planes)
  - Sagittal
  - Axial
  - Coronal
  - Oblique
- What Contrast
  - TR
  - TE



Imaging Planes

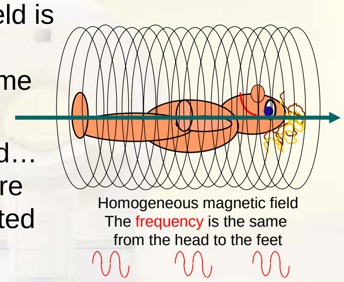


Timing Diagram – Gradients- logical coordinate system



Slice Selection

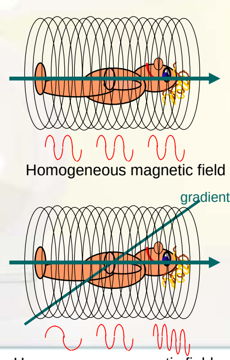
- If the magnetic field is homogeneous, the frequency is the same … head to feet
- If the RF is applied… in this case the entire body would be excited



Homogeneous magnetic field
The frequency is the same from the head to the feet

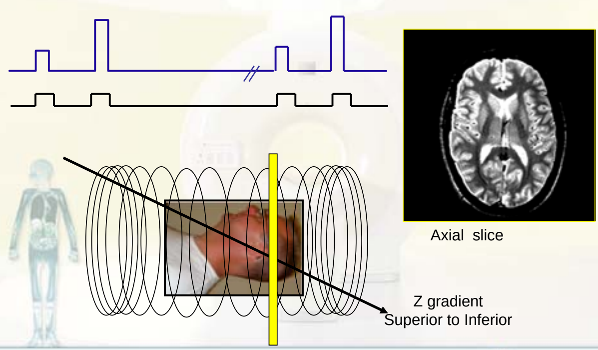
Selective Excitation

- To excite a location within the imager, within the body..
- A magnetic field gradient is applied
- The RF pulse is applied that matches a location

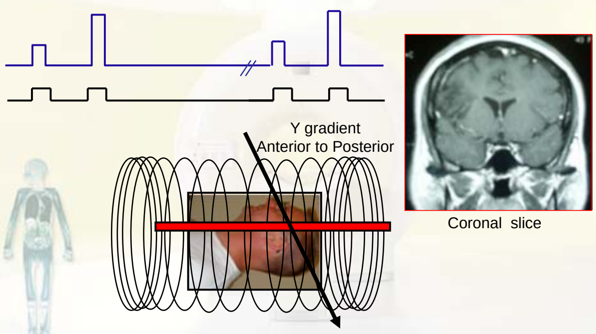


Homogeneous magnetic field
With a linear gradient field applied

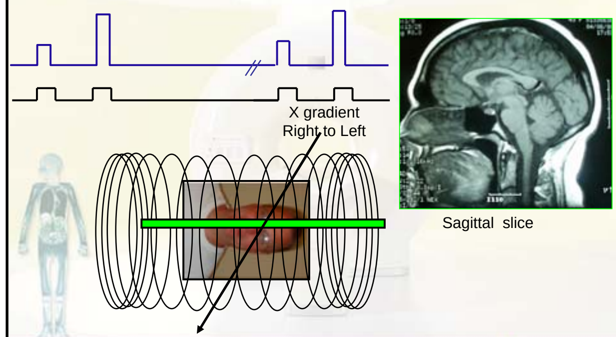
Selecting an Axial Slice – Physical Coordinate System



Selecting a Coronal Slice - Physical Coordinate System

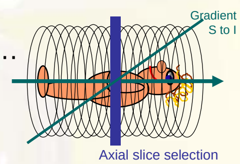


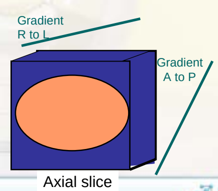
Selecting a Sagittal Slice - Physical Coordinate System



Phase & Frequency Encoding

- Once the slice is selected…
- Encoding along the other axes,
  - –With gradients
    - •R to L
    - •A to P
  - –For encoding
    - •Phase encoding
    - •Frequency encoding



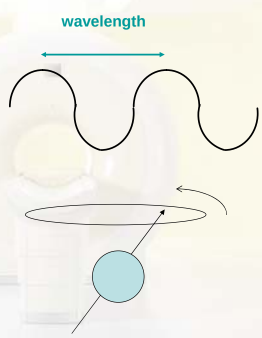


Outline

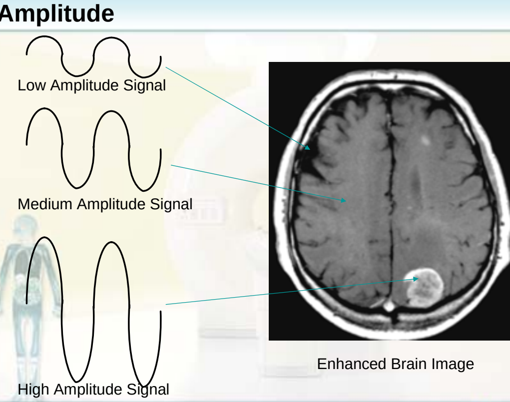
- Imaging Matrix
- Gradients & Signals
- Phase, Frequency and Amplitude
- Slice selection
- Phase encoding
- Frequency encoding

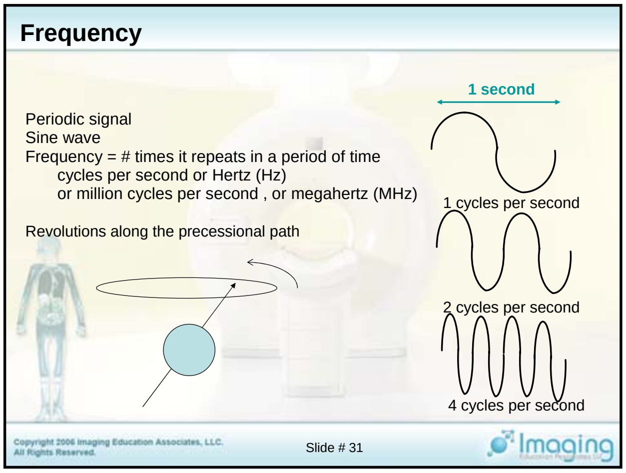
Periodic signals

Phase
Frequency
Amplitude
Wavelength



Amplitude




Frequency
Periodic signal
Sine wave
Frequency = # times it repeats in a period of time
cycles per second or Hertz (Hz)
or million cycles per second , or megahertz (MHz)
Revolutions along the precessional path
1 second
1 cycles per second
2 cycles per second
4 cycles per second
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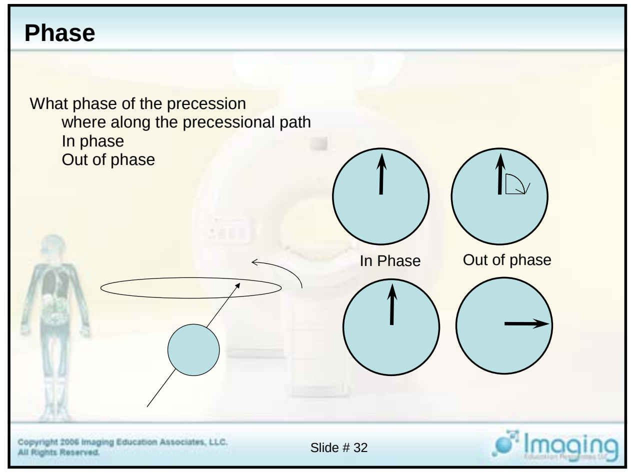
Slide # 31
Imaging


Phase
What phase of the precession
where along the precessional path
In phase
Out of phase
In Phase
Out of phase
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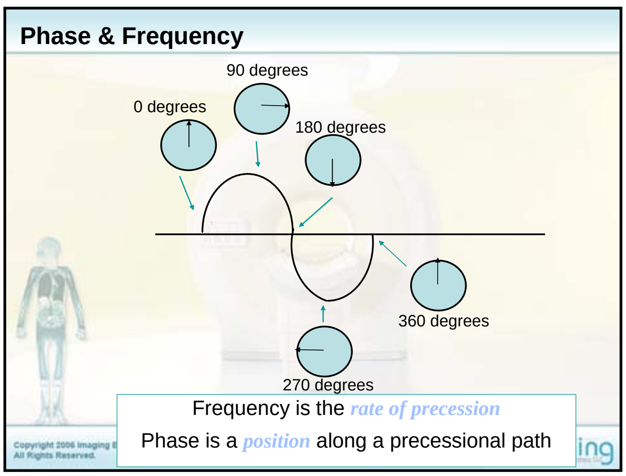
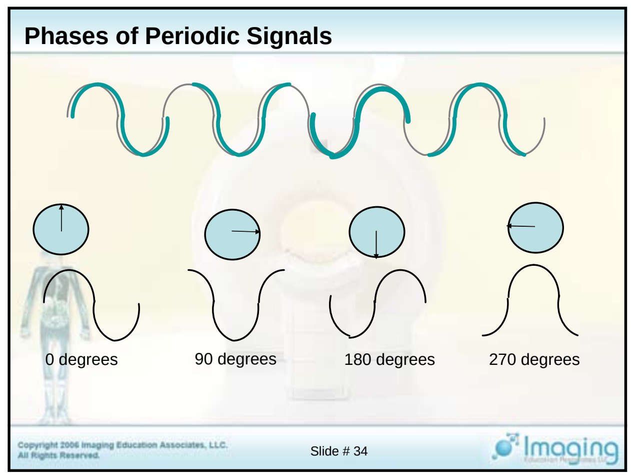
Slide # 32
Imaging


Phase & Frequency
90 degrees
0 degrees
180 degrees
360 degrees
270 degrees
Frequency is the rate of precession
Phase is a position along a precessional path


Phases of Periodic Signals
0 degrees
90 degrees
180 degrees
270 degrees
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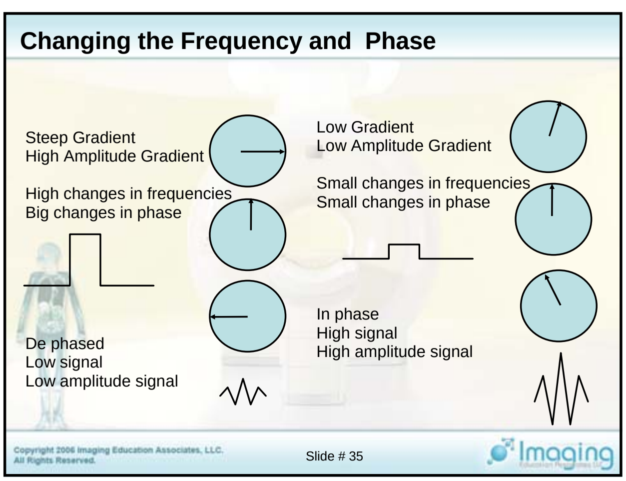
Slide # 34
Imaging


Changing the Frequency and Phase
Steep Gradient
High Amplitude Gradient
High changes in frequencies
Big changes in phase
De phased
Low signal
Low amplitude signal
Low Gradient
Low Amplitude Gradient
Small changes in frequencies
Small changes in phase
In phase
High signal
High amplitude signal
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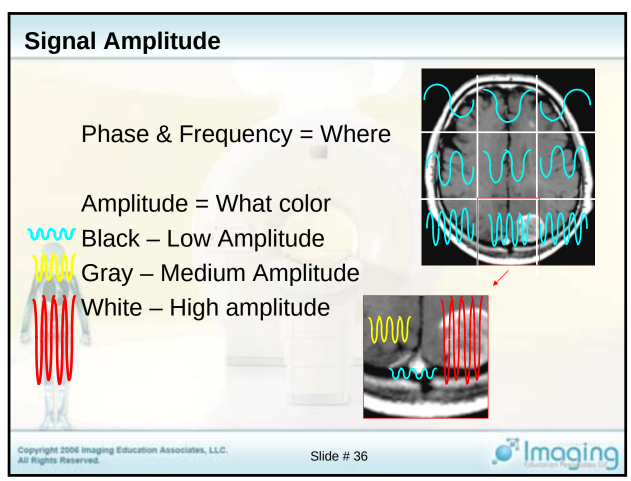
Slide # 35
Imaging


Signal Amplitude
Phase & Frequency = Where
Amplitude = What color
Black – Low Amplitude
Gray – Medium Amplitude
White – High amplitude
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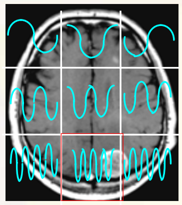
Slide # 36
Imaging

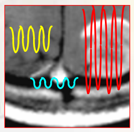
Phase & Frequency

Phase & Frequency = Where
Same frequency – different phase

Same phase different frequency

Same phase and frequency, different ampltude

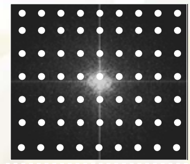




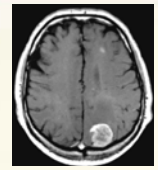
K-Space & MR Imaging

Amplitude = What color
- Black, low
- Gray, med
- White, high amplitude signal

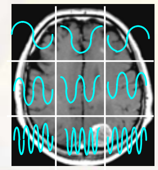
Phase & Frequency = Where
- Phase lines in k-space
- Freqency – points along each line



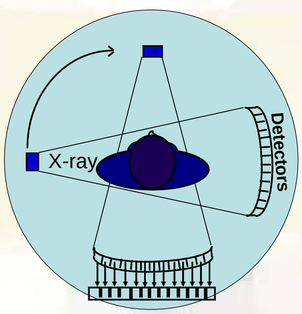
K-space (raw signal data)



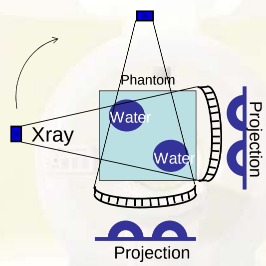
MR Image)



CT Image Acquisition

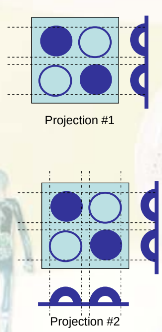


Back Projection

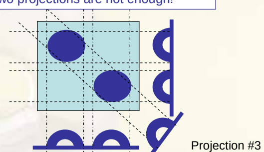


In CT, the xray tube rotates around the "phantom"
In this case the x-ray beam is attenuated by the water in the phantom, and therfore "projects" a "shadow" within the detectors…

Back Projection - Reconstruction



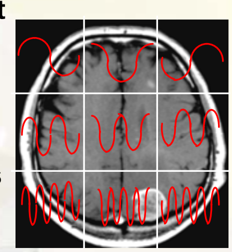
Where the lines intersect, there could be water in the phantom
Two projections are not enough!



He third projection allowed for the image!

MR Image Formation

- **In order to define a point in space, we need three coordintes X, Y & Z**
- **To define these three coordinates, we do 3 jobs**
  - **- slice selection**
  - **- phase encoding**
  - **- frequency encoding**



3 x 3 Matrix

Outline

- Imaging Matrix
- Gradients & Signals
- Phase, Frequency and Amplitude
- Slice selection
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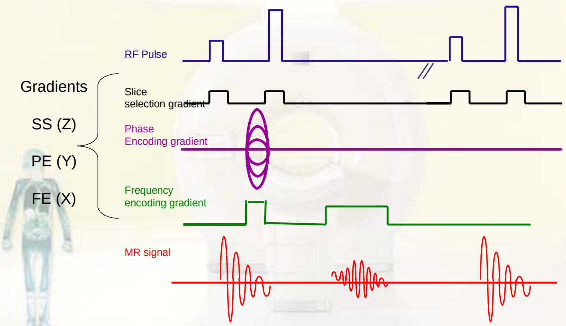
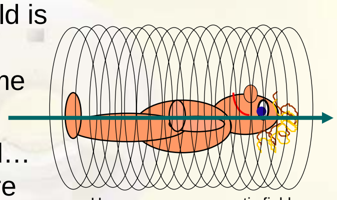
- Frequency encoding

Timing Diagram - Logical Coordinate System



Slice Selection

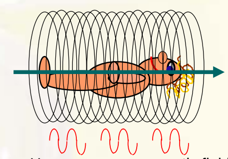
- If the magnetic field is homogeneous, the frequency is the same … head to feet
- If the RF is applied… in this case the entire body would be excited



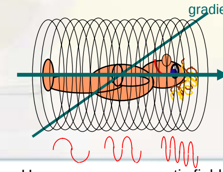
Homogeneous magnetic field
The frequency is the same
from the head to the feet

Selective Excitation

- To excite a location within the imager, within the body..
- A magnetic field gradient is applied
- The RF pulse is applied that matches a location



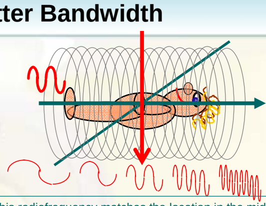
Homogeneous magnetic field



Homogeneous magnetic field
With a linear gradient field applied

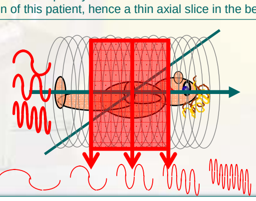
Slice Thickness & Transmitter Bandwidth

- If only one frequency is "sent in" or transmitted for excitation, we get a slice as thin as tissue paper.



This radiofrequency matches the location in the mid section of this patient, hence a thin axial slice in the belly

- For a thicker slice a range of frequencies is "transmitted" known as the Transmit Bandwidth

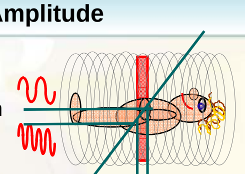


FYI… This is not the bandwidth that we typically "set" during image acquisition. That is the receiver bandwidth. Receive bandwidth will be discussed later in this section

This range of radiofrequencies (or Bandwidth) matches the location in the mid section of this patient, hence a thin axial slice in the belly

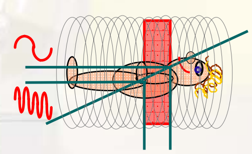
Slice Thickness & Gradient Amplitude

- Steep Gradients (high amplitude) slice selection gradient, produce thin slices.



With a given BW, a steep gradient produces a thinner slice

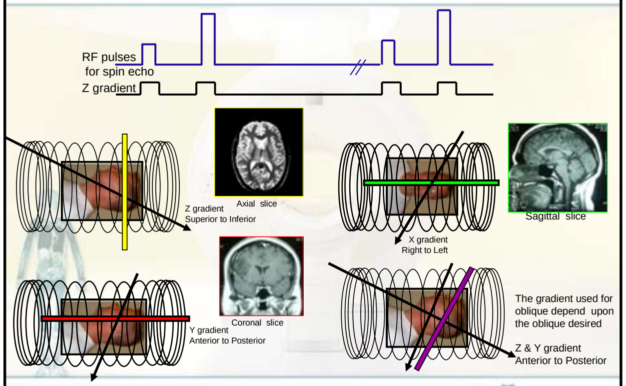
- Flatter Gradients (low amplitude) slice selection gradient, produce thicker slices.



With a given BW, a flatter gradient produces a thicker slice

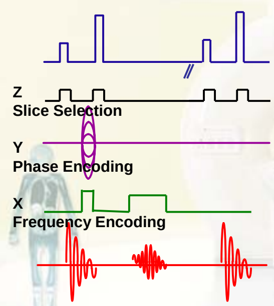
- "Steep things make skinny things!"

Imaging Planes & Slice Selection Gradients



Physical vs Logical Gradients

Logical Gradients

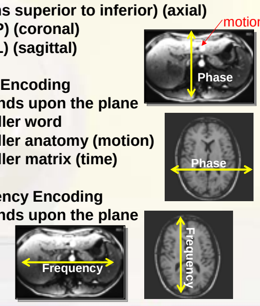


Physical Gradients

•Slice Selection
Z (runs superior to inferior) (axial)
Y (A-P) (coronal)
X (R-L) (sagittal)

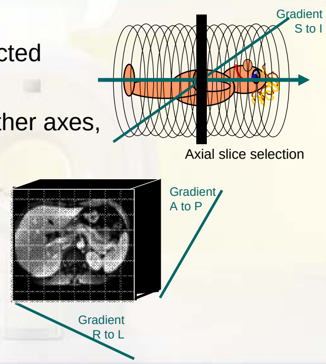
•Phase Encoding
-Depends upon the plane
smaller word
smaller anatomy (motion)
smaller matrix (time)

•Frequency Encoding
-Depends upon the plane

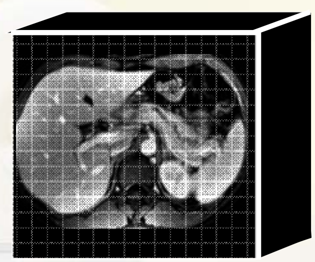


Spatial Encoding within the Slice

- Once the slice is selected
- Encoding along the other axes,
  - With gradients
    - R to L
    - A to P
  - For encoding
    - Phase encoding
    - Frequency encoding

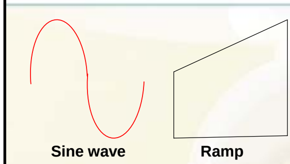


Spatial Encoding within the Slice



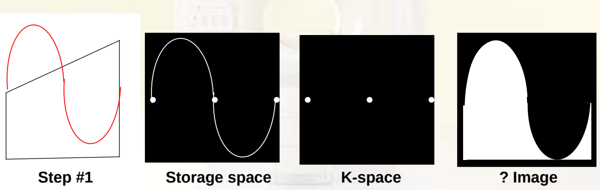
Fourier states that any "shape" can be reconstructed by periodic signals

Fourier Transformation – Step #1

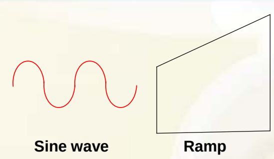


Step #1
•Let's take one sine wave and
•Try to produce a "ramp"

•Not Even close…

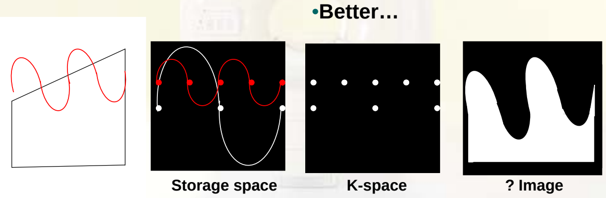


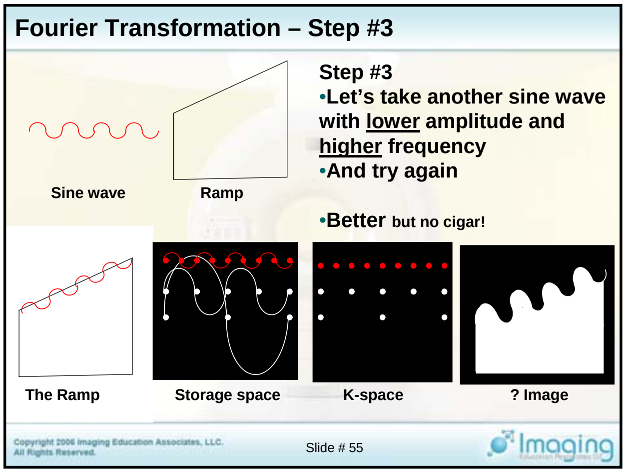
Fourier Transformation – Step #2



Step #2
•Let's take another sine wave with lower amplitude and higher frequency
•And try again

•Better…




Fourier Transformation – Step #3
Step #3
•Let's take another sine wave with lower amplitude and higher frequency
•And try again
•Better but no cigar!
Sine wave
Ramp
The Ramp
Storage space
K-space
? Image
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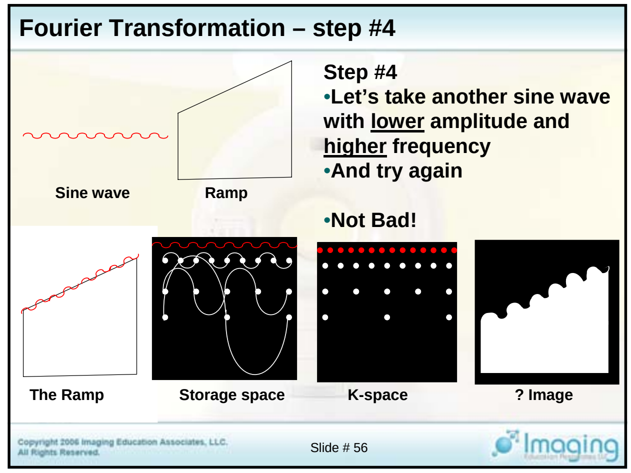
Slide # 55
Imaging


Fourier Transformation – step #4
Step #4
•Let's take another sine wave with lower amplitude and higher frequency
•And try again
•Not Bad!
Sine wave
Ramp
The Ramp
Storage space
K-space
? Image
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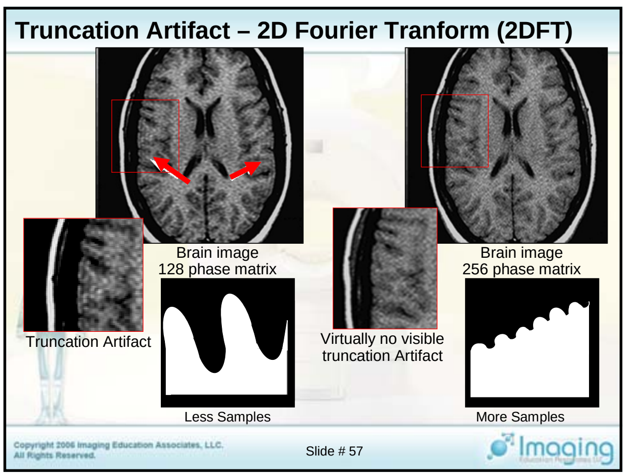
Slide # 56
Imaging


Truncation Artifact – 2D Fourier Tranform (2DFT)
Brain image
128 phase matrix
Truncation Artifact
Less Samples
Brain image
256 phase matrix
Virtually no visible truncation Artifact
More Samples
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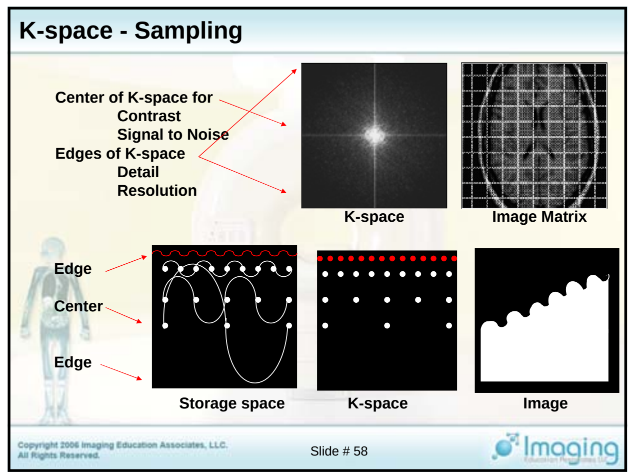
Slide # 57
Imaging


K-space - Sampling
Center of K-space for
Contrast
Signal to Noise
Edges of K-space
Detail
Resolution
K-space
Image Matrix
Edge
Center
Edge
Storage space
K-space
Image
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Slide # 58
Imaging

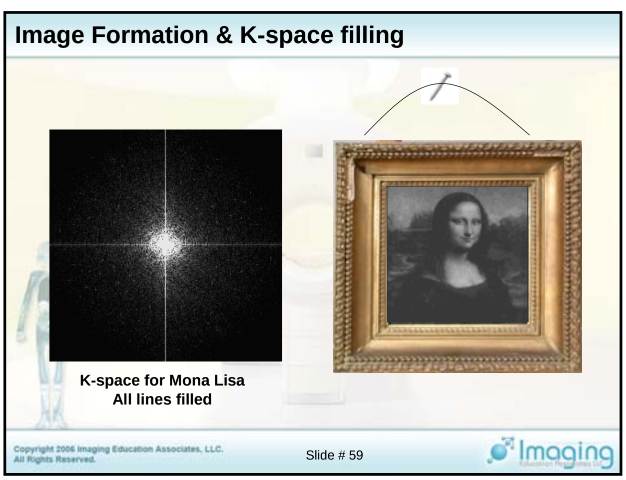
Image Formation & K-space filling
K-space for Mona Lisa
All lines filled
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Slide # 59
Imaging

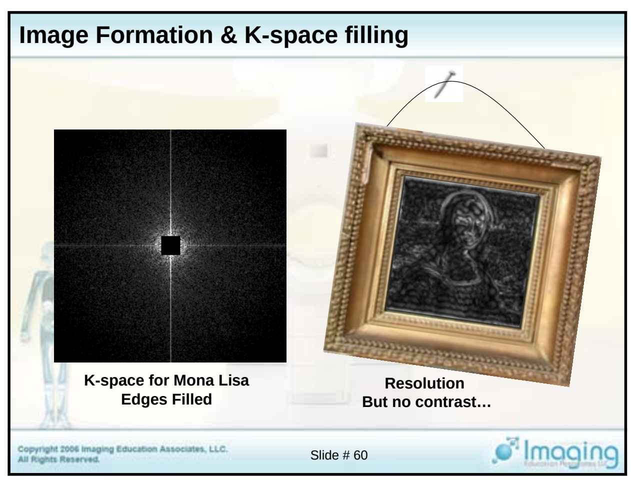
Image Formation & K-space filling
K-space for Mona Lisa
Edges Filled
Resolution
But no contrast…
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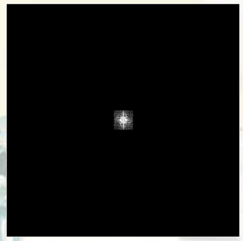
Slide # 60
Imaging

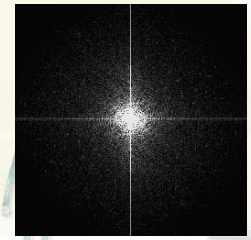
Image Formation & K-space filling



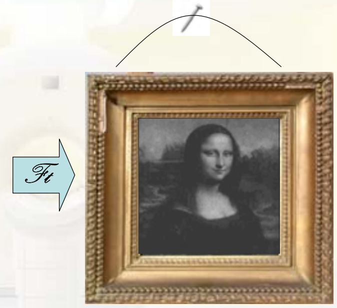
K-space for Mona Lisa
Center lines filled

Contrast but
No resolution…

Fourier Transformation



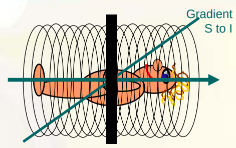
K-space for Mona Lisa
All lines filled



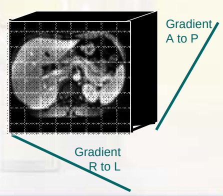
Fourier transformer will do FT, one at a time
Array processor will to an "array" of FT's

Let's Make an MR Image…

- Select a slice
- Encode along the other axes,
  - With gradients
    - R to L
    - A to P
  - Encoding Steps
    - Phase encoding
    - Frequency encoding



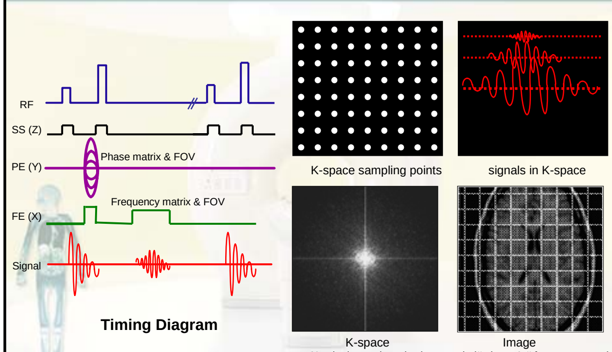
Axial slice selection



Outline

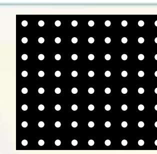
- Imaging Matrix
- Gradients & Signals
- Phase, Frequency and Amplitude
- Slice selection
- Phase encoding
- Frequency encoding

Image Acquisition & Image Formation

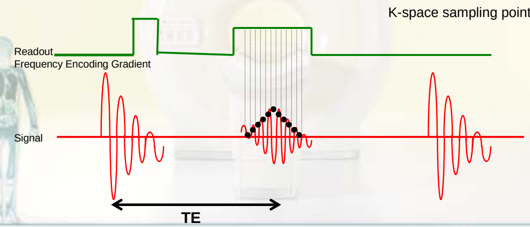


Sampling MR Signal

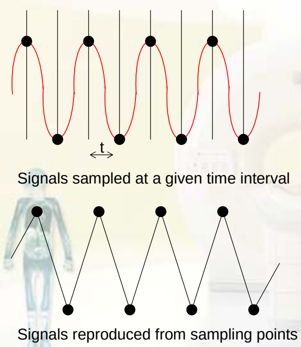
- Signals are created by a 90⁰ and a 180⁰ pulse
- Signals are sampled during "readout" at TE
- Points are "stored" in k-space for until enough points are sampled to create an MR Image



K-space sampling points



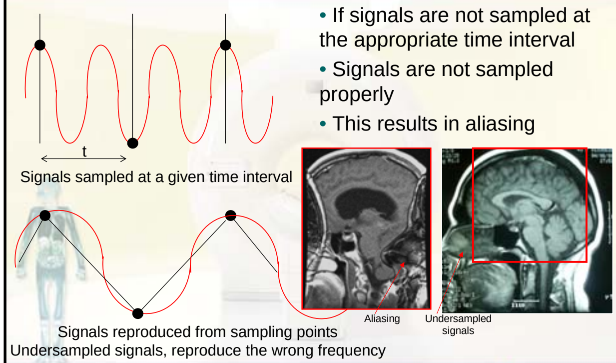
Nyquist Therum



- Signals must be samples at least twice per cycle
- This means that they must be sampled at the highest frequency
- Sampling is performed at a given time interval (t) based on the frequency

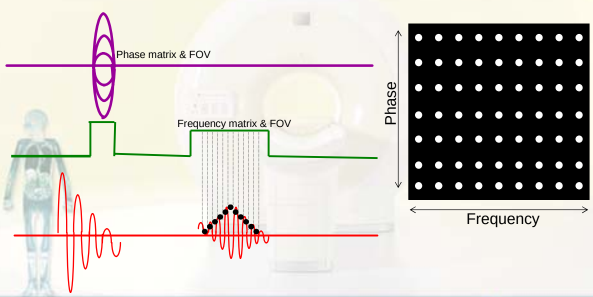
Aliasing

- If signals are not sampled at the appropriate time interval
- Signals are not sampled properly
- This results in aliasing



K-Space

- K-space has lines, # Phase encoding steps
- And points along each line, # Frequency steps



K-Space

- Steep (-) phase encoding gradient
- Sample the echo
- "Store" in k-space

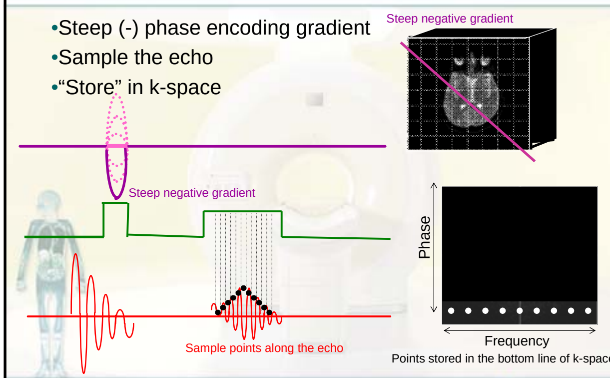
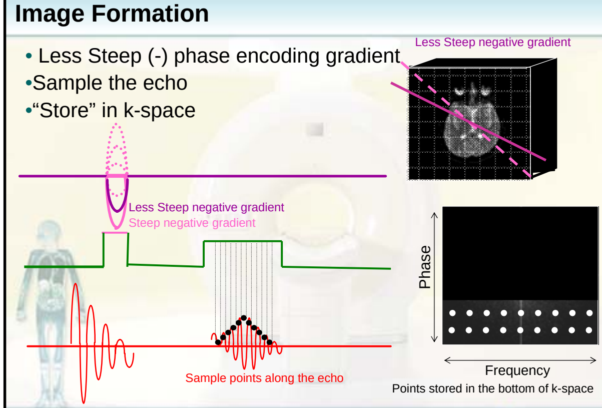
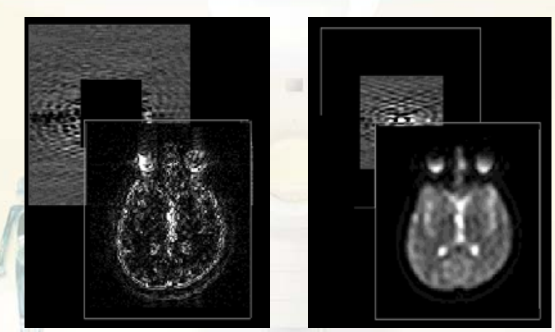


Image Formation

- Less Steep (-) phase encoding gradient
- Sample the echo
- "Store" in k-space



K-Space



Edges only **Center only**

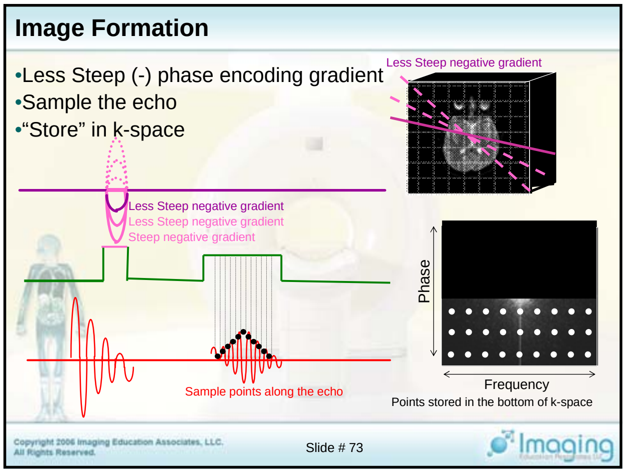


Image Formation
•Less Steep (-) phase encoding gradient
•Sample the echo
•"Store" in k-space
Less Steep negative gradient
Less Steep negative gradient
Less Steep negative gradient
Steep negative gradient
Phase
Frequency
Sample points along the echo
Points stored in the bottom of k-space
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Slide # 73
Imaging

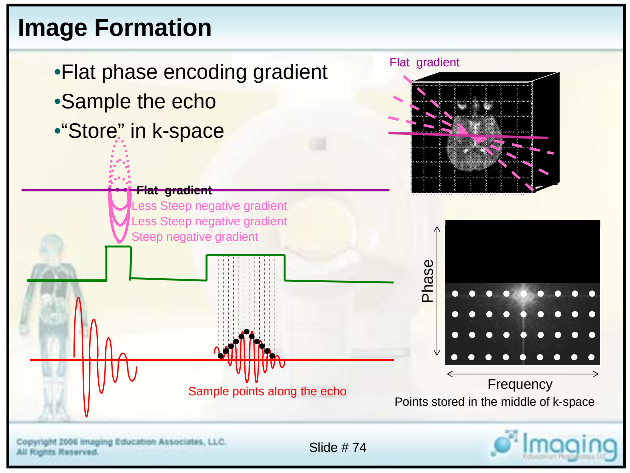
Image Formation
•Flat phase encoding gradient
•Sample the echo
•"Store" in k-space
Flat gradient
Flat gradient
Less Steep negative gradient
Less Steep negative gradient
Steep negative gradient
Phase
Frequency
Sample points along the echo
Points stored in the middle of k-space
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Slide # 74
Imaging

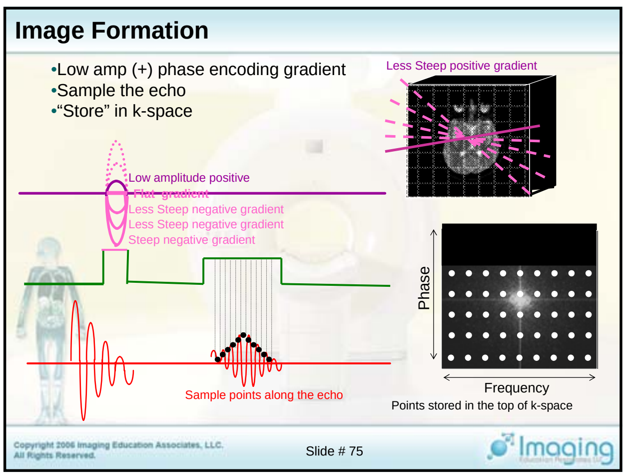
Image Formation
•Low amp (+) phase encoding gradient
•Sample the echo
•"Store" in k-space
Less Steep positive gradient
Low amplitude positive
Flat gradient
Less Steep negative gradient
Less Steep negative gradient
Steep negative gradient
Phase
Frequency
Sample points along the echo
Points stored in the top of k-space
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Slide # 75
Imaging

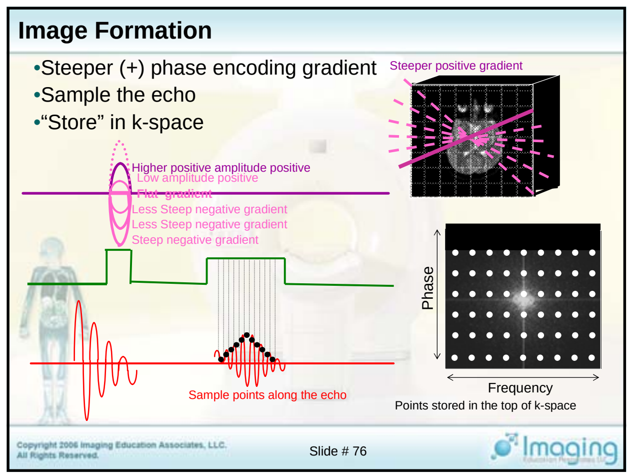
Image Formation
•Steeper (+) phase encoding gradient
•Sample the echo
•"Store" in k-space
Steeper positive gradient
Higher positive amplitude positive
Low amplitude positive
Flat gradient
Less Steep negative gradient
Less Steep negative gradient
Steep negative gradient
Phase
Frequency
Sample points along the echo
Points stored in the top of k-space
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Slide # 76
Imaging

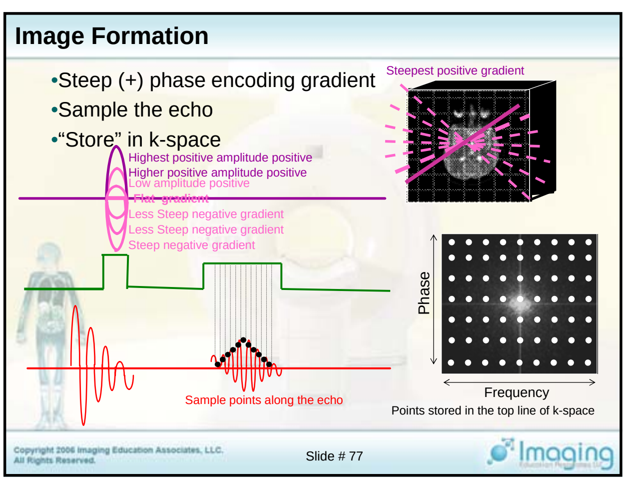
Image Formation
•Steep (+) phase encoding gradient
•Sample the echo
•"Store" in k-space
Steepest positive gradient
Highest positive amplitude positive
Higher positive amplitude positive
Low amplitude positive
Flat gradient
Less Steep negative gradient
Less Steep negative gradient
Steep negative gradient
Phase
Frequency
Sample points along the echo
Points stored in the top line of k-space
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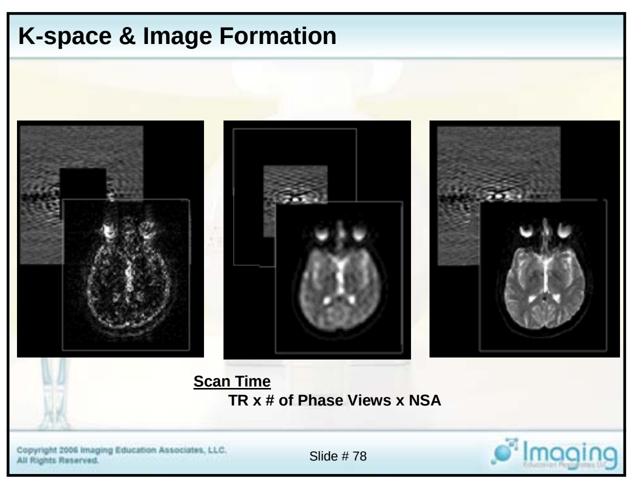
Slide # 77
Imaging


K-space & Image Formation
Scan Time
TR x # of Phase Views x NSA
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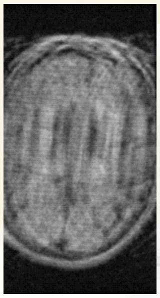
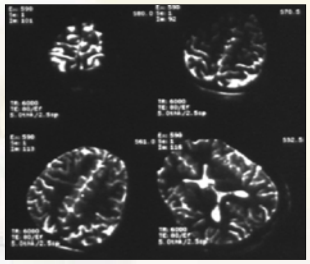
Slide # 78
Imaging

Motion Artifact





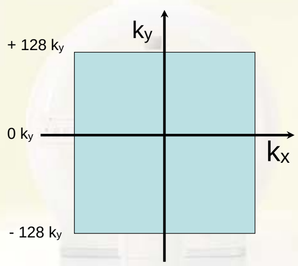
Outline

- Imaging Matrix
- Gradients & Signals
- Phase, Frequency and Amplitude
- Slice selection
- Phase encoding
- Frequency encoding
- k-space manipulation

Filling k-space

*Assume 256 phase matrix for this entire module

Remember:
The amplitude of the phase encoding gradient applied during the FID "encodes" the sampled echo for a particular phase "line" or "profile" in k-space

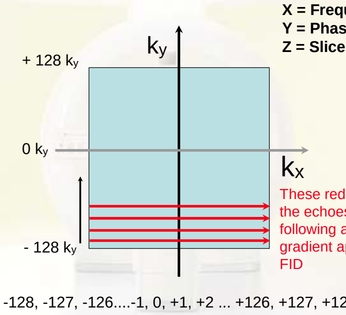


If we desire a final image with 256 pixel resolution in the phase direction of our FOV, then we will need to acquire 256 distinctive lines of acquisition filling the data points in k-space

Linear Filling

Fills from "bottom" up

Remember:
X = Frequency
Y = Phase
Z = Slice



These red arrows represent the echoes sampled following a given phase gradient applied during the FID

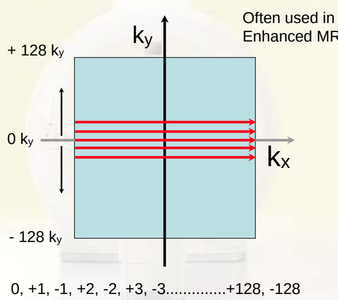
-128, -127, -126....-1, 0, +1, +2 ... +126, +127, +128

Centric Filling

Fills from "Middle" out

This technique acquires high signal data "lines" first

Often used in Contrast Enhanced MRA studies



0, +1, -1, +2, -2, +3, -3.............+128, -128

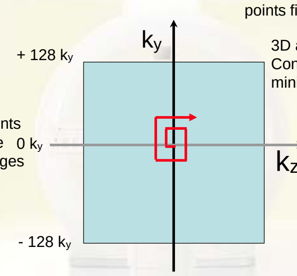
Elliptic Filling

Fills from "Center" out

This technique acquires the most "central" data points first

3D acquisition used for Contrast Enhanced MRA to minimize venous filling

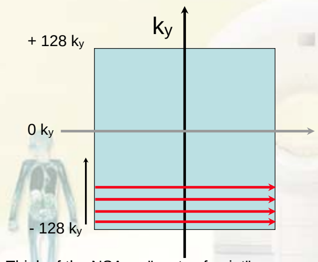
*The center data points in k-space contribute most to the final images signal (contrast)

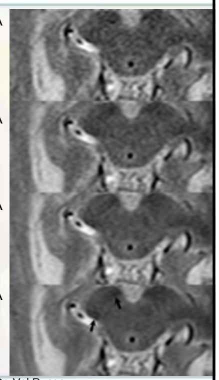


These techniques fill k-space in either a "symmetrical" fashion as shown here, or in a random pattern from the center data points outward

Number of Signals Averaged (NSA)

Scan Time = TR x N_y x NSA





Think of the NSA as "coats of paint"
It's the number of times each "line" or "phase view" of k-space is sampled

Image courtesy Dr. Val Runge

Reducing NSA

Scan Time = TR x N_y x NSA

Reducing NSA

- Reduces scan time
- DOES NOT reduce spatial resolution
- Increases noise (reduces SNR)
- Increased flow/motion artifacts

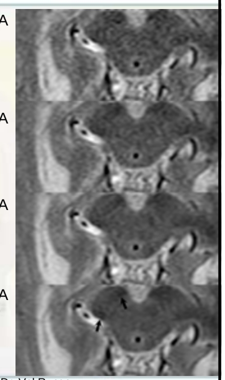
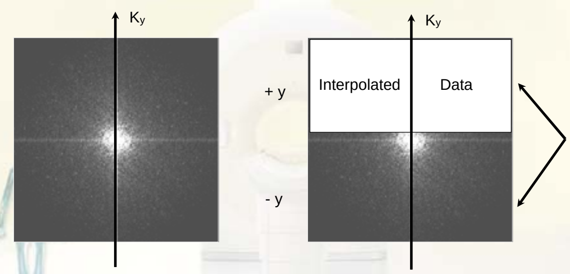


Image courtesy Dr. Val Runge

Partial Fourier

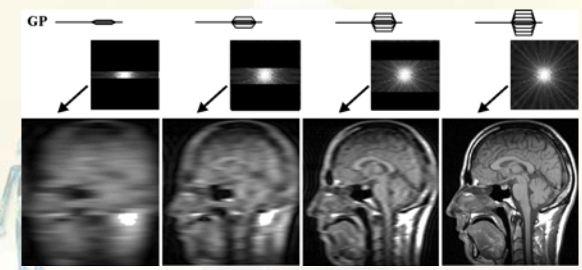
Scan Time = TR x N_y x NSA



Partial Fourier reduces scan time at the cost of increased noise (reduced SNR)
Spatial Resolution is Unaffected

Reducing Phase Matrix

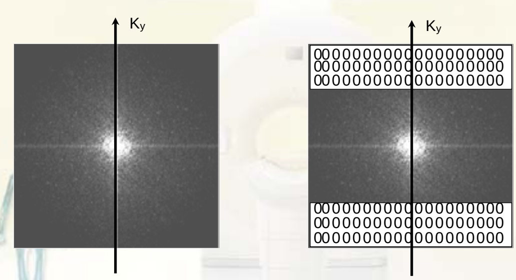
Scan Time = TR x N_y x NSA



"Physics of Clinical MR Taught Through Images"
V. Runge, Thieme Medical Publishers, 2005

Zero Fill

Scan Time = TR x N_y x NSA



Zero Fill

Scan Time = TR x N_y x NSA

Reducing N_y

- Reduces Scan Time
- Reduces Spatial Resolution
- Increased SNR
- Increases Truncation Artifact

* Note: the number of phase encodings may be selected by scan percentage

256_x 128_y 256_x 256_y

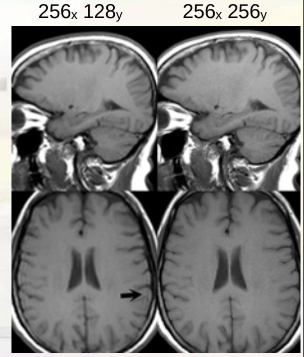
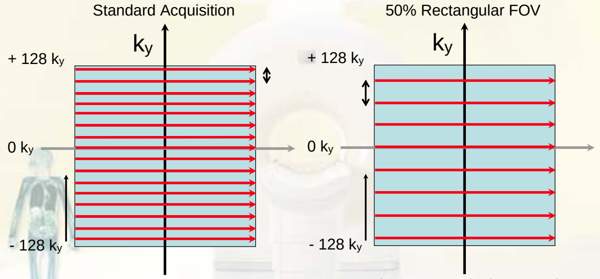


Image courtesy Dr. Val Runge

Rectangular FOV

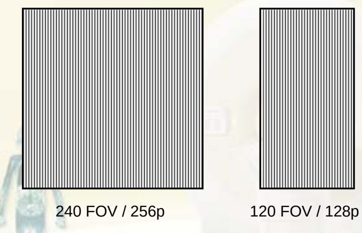
Scan Time = TR x $\underline{N_y}$ x NSA

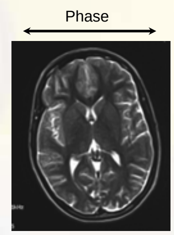


Reduces N_y - reducing scan time
Increasing "step" between phase views reduces $_p$FOV

Rectangular FOV

Scan Time = TR x $\underline{N_y}$ x NSA



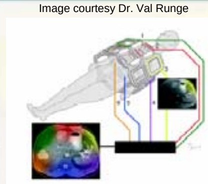


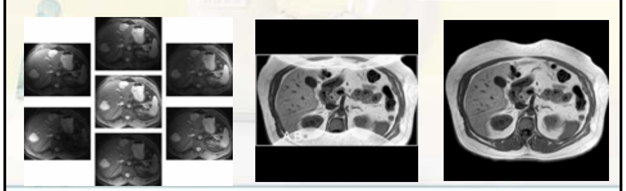
rFOV reduces scan time at the cost of increased noise (reduced SNR)

Parallel Imaging

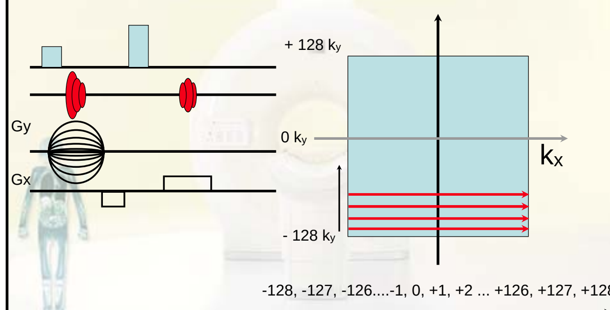
- Scan time is reduced by using a rectangular FOV (therefore spatial resolution is maintained)
- Data from multi-channel / phased-array coils is used the image reconstruction process
- Some techniques require a "reference" or "calibration" scan prior to the actual scan
- Image is reconstructed with the prescribed FOV

Image courtesy Dr. Val Runge

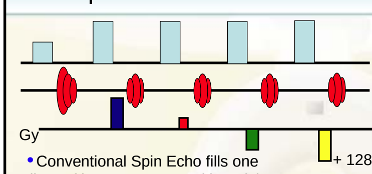




Conventional Spin Echo

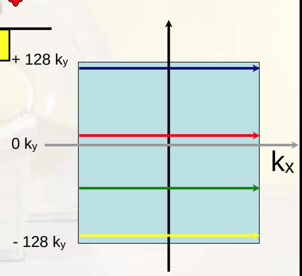


Fast Spin Echo



4 ETL Example

- Conventional Spin Echo fills one "line" of k-space per repetition of the pulse sequence
- Fast Spin Echo fills multiple lines of k-space per repetition of the pulse sequence
- The number of lines filled per repetition period is determined by the Echo Train Length (ETL)
- The TE most effecting image contrast is placed in the more central "lines" (effective TE)



Scan Time

Conventional Spin Echo

TR x N_y x NSA

128 phase
160 phase
192 phase
256 phase

Scan time increases with increasing spatial resolution (phase)

Scan time shortens with reduction in spatial resolution (phase)

Fast Spin Echo

$$\frac{\textbf{TR x } N_y \textbf{ x NSA}}{\textbf{ETL}}$$

10 ETL
14 ETL
17 ETL
25 ETL

Scan time shortens with increasing ETL

Image "blurring" can increase with increasing ETL

Image Courtesy Siemens Medical Systems

Benefits of Fast Spin Echo

Sample Scan Time

TR x N_y x NSA

3000 TR x 256 phase x 2 NSA = 25.6 minutes !

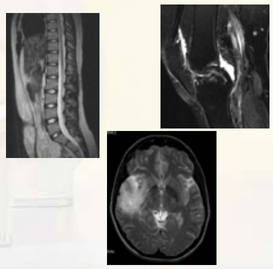
Same scan with FSE and ETL of 16 = 1.6 minutes !!

500 TR
1500 TR
3000 TR
5000 TR

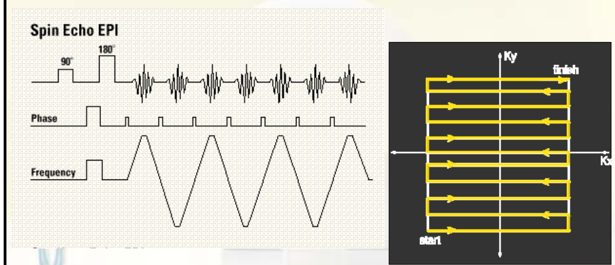
Images with bright fluid often show pathology best due to presence of water

The long T1-relaxation time of water requires longer TR times to obtain images with bright fluid

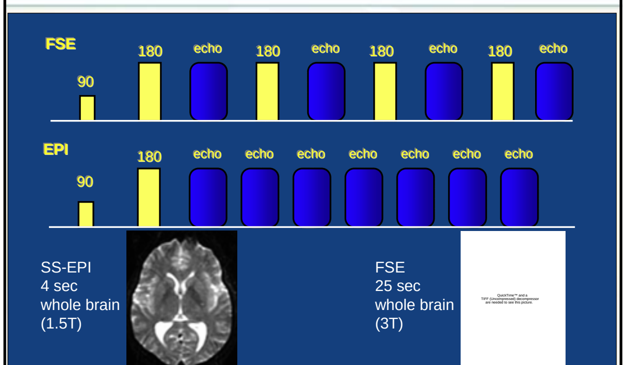
Scan time increases with increasing TR



Echo Planar Imaging (EPI)



EPI Speed Compared to FSE



Summary

Scan Time = TR x N_y x NSA

How many lines of acquisition?

Zero-fill

Reduced NSA

Partial Fourier

Rectangular FOV
(Parallel Imaging)

Reducing scan time by altering the way k-space is filled typically reduces either spatial resolution or SNR

Since reduced spatial resolution is almost always undesirable, therefore, most advanced imaging techniques are SNR starved

Outline

- Imaging Matrix
- Gradients & Signals
- Phase, Frequency and Amplitude
- Slice selection
- Phase encoding
- Frequency encoding

6.1 MR Image Formation

Matrix, Gradients & Signals
Image formation & k-space

Thank you for your attention!

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