Imaging Techniques and Artifacts

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Review of Gradient Echo

- Advantages
  - Fast Imaging Applications
  - Flexible contrast (T_1 or T_2*)
- Disadvantages
  - Off-resonance sensitivity
  - T_2^*-weighted rather than T_2-weighted

Principal GRE Advantages

- Fast Imaging Applications
  - **Why?** *Can use a shorter TE/TR than spin echo*
  - **When?** Breath-held, realtime, & 3D volume imaging
- Flexible image contrast
  - **Why?** Adjusting TE/TR/FA controls the signal
  - **When?** Characterize a tissue for diagnosis
- Bright blood signal
  - **Why?** Inflowing spins haven't "seen" numerous RF pulses
  - **When?** Cardiovascular & angiographic applications

Principal GRE Advantages

- Low SAR
  - **Why?** Imaging flip angles are (typically) small
  - **When?** When heating risks are a concern
- Quantitative
  - **Why?** Multi-echo acquisition are practical.
  - **When?** Flow quantification & Fat/Water mapping
- Susceptibility Weighted Imaging
  - **Why?** No refocusing pulse.
  - **When?** T_2^*-weighted (hemorrhage) imaging
- More...

Principal GRE Disadvantages

- Off-resonance sensitivity
  - **Why?** No refocusing pulse
    - Field inhomogeneity, Susceptibility, & Chemical shift
- T_2^*-weighted rather than T_2-weighted
  - **Why?** No re-focusing pulse
    - Spin-spin dephasing is not reversible with GRE
- Larger metal artifacts than SE
  - Why? No refocusing pulse.
    - Large field inhomogeneities aren't corrected with GRE

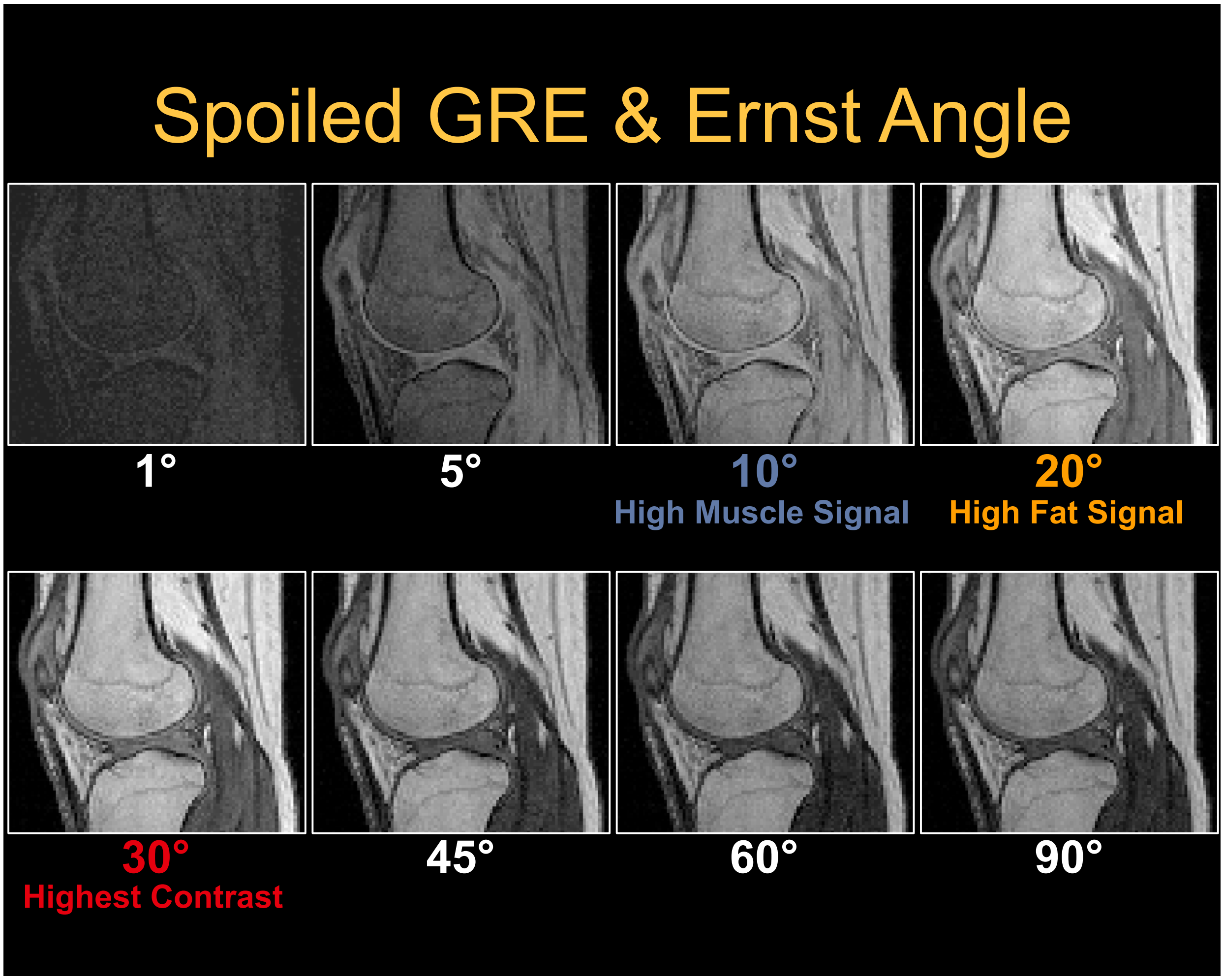
Gradient vs Spin Echo Contrast

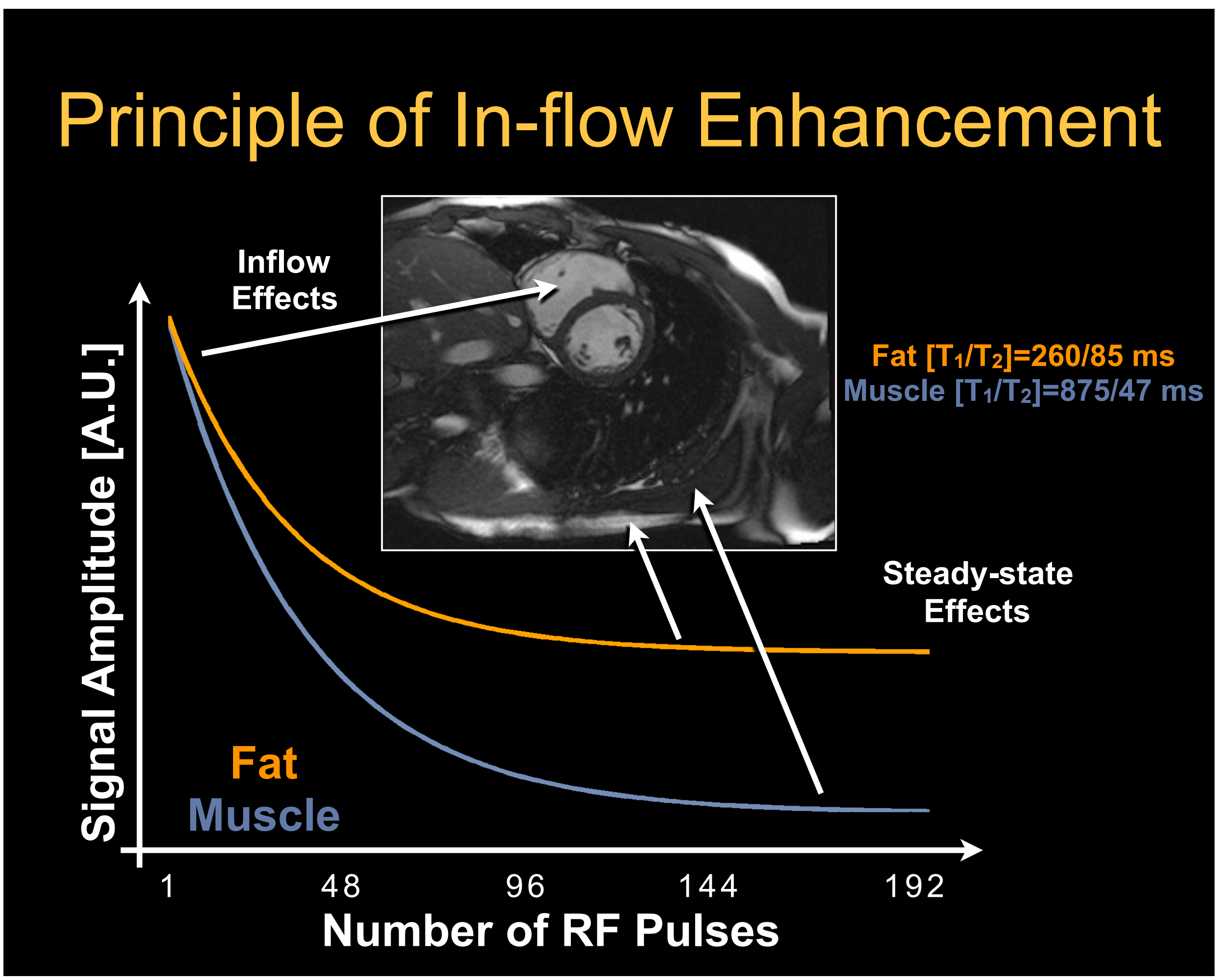
Gradient Echo Parameters

Type of Contrast	TE	TR	Flip Angle
Spin Density	<5ms	>100ms	<10°
T_1-Weighted	<5ms	<50ms	>30°
T_2^*-Weighted	>20ms	>100ms	<10°

Spin Echo Parameters

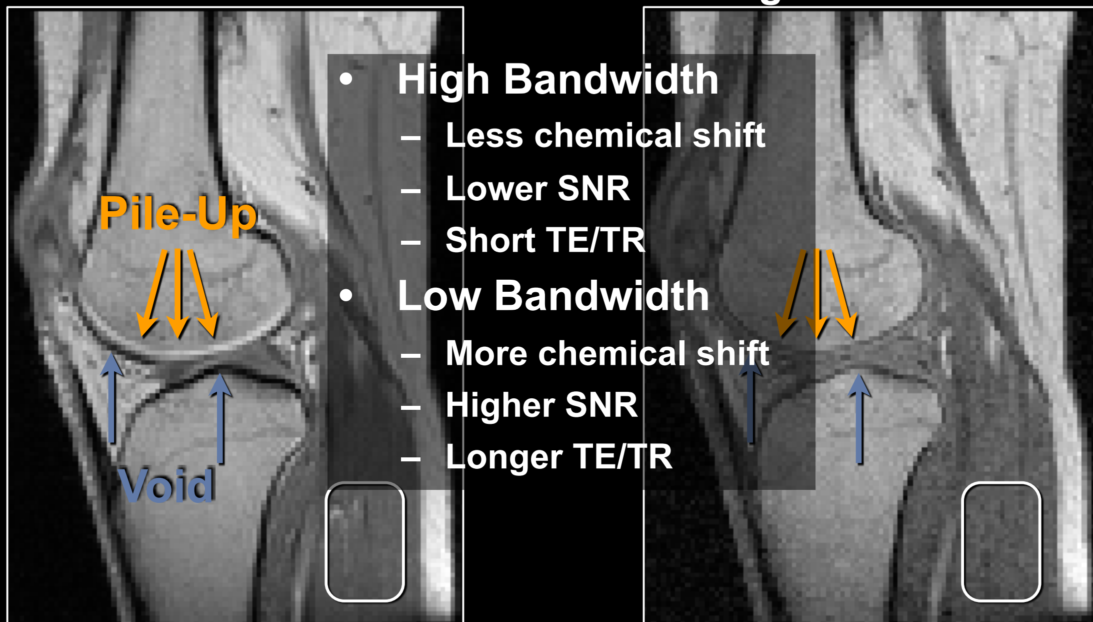
Type of Contrast	TE	TR	Flip Angle
Spin Density	10-30ms	>2000ms	90+180
T_1-Weighted	10-30ms	450-850ms	90+180
T_2-Weighted	>60ms	>2000ms	90+180


Spoiled GRE & Ernst Angle
1°
5°
10°
High Muscle Signal
20°
High Fat Signal
30°
Highest Contrast
45°
60°
90°


Principle of In-flow Enhancement
Inflow Effects
Fat [T1/T2]=260/85 ms
Muscle [T1/T2]=875/47 ms
Steady-state Effects
Signal Amplitude [A.U.]
Fat
Muscle
1
48
96
144
192
Number of RF Pulses

GRE, Fat/Water & Bandwidth

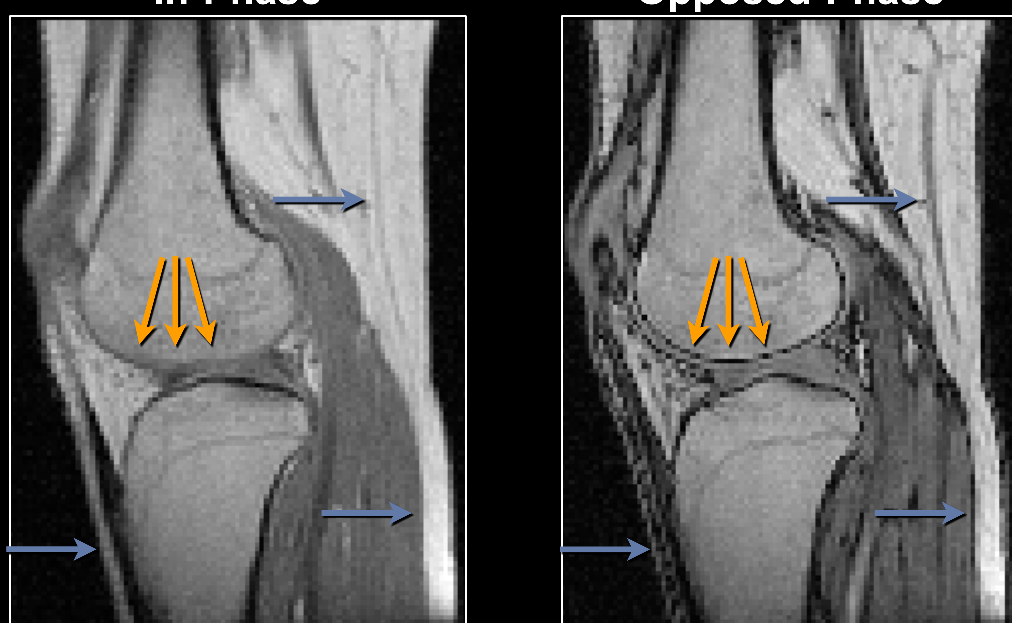
Low Bandwidth **High Bandwidth**



Acquisition ***bandwidth*** is related to the ***speed*** with which an echo is acquired. If the ***bandwidth*** (speed) is high, then there is less time for chemical shift, less time for signal acquisition (lower SNR), and a shorter TE/TR.

GRE and Fat/Water Phase

In-Phase **Opposed-Phase**



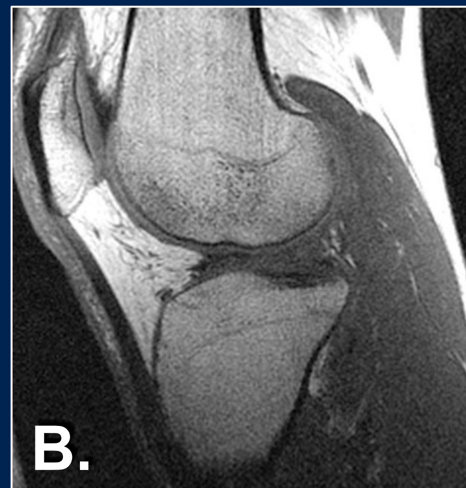
MRI Acronyms

	Siemens	GE	Phillips	Toshiba	Hitachi
Spoiled Gradient Echo	FLASH	SPGR	T1-FFE	T1-GGE	RSSG
Balanced Steady-State Free Precession	TrueFISP	FIESTA	Balanced FFE	True SSFP	BASG

MRI Acronyms

	Siemens	GE	Phillips	Toshiba	Hitachi
Turbo spin echo/ Fast spin echo	TSE	FSE	TSE	FSE	FSE
Single-shot TSE	HASTE	Single-shot FSE	Single-shot FSE	FASE	Single-shot FSE
3D TSE with variable flip angle	SPACE	CUBE	VISTA	mVox	

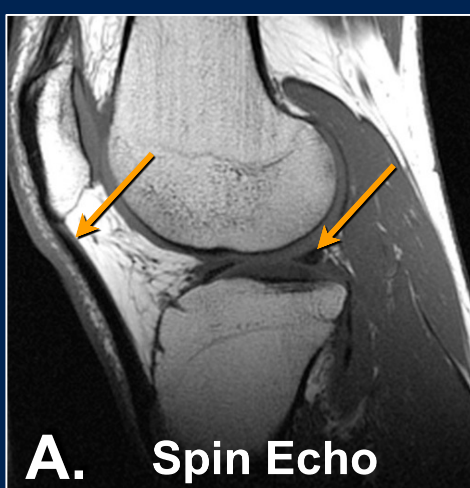
Gradient vs. Spin Echo

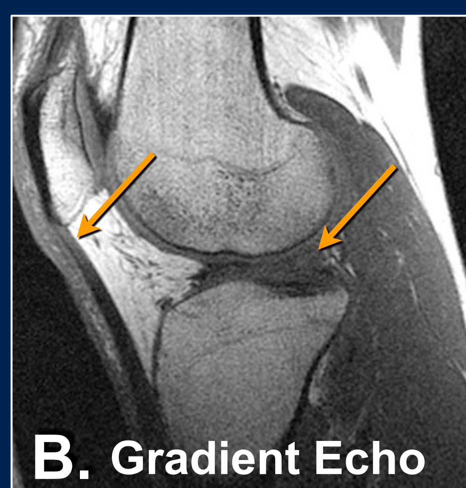


Which image is a gradient echo image?

Images Courtesy of Brian Hargreaves

Gradient vs. Spin Echo





Both are T1-weighted

Spin Echo has higher SNR (longer TR)

GRE has shorter TE (meniscus/tendon is brighter)

Images Courtesy of Brian Hargreaves

Gradient Echo Imaging...

Gradient echo imaging is great for everything except:

A. T_2*-weighted imaging.

B. T_2-weighted imaging.

C. True 3D imaging.

D. Real time imaging.

Gradient Echo Imaging...

Gradient echo imaging is great for everything except:

A. T_2*-weighted imaging
Yes. GRE can be a T_2*-weighted sequence.

B. **T_2-weighted imaging**
No. GRE can not be T_2-weighted

C. True 3D imaging
Yes! GRE is a fast sequence

D. Real time imaging
Yes! GRE is a fast sequence

Gradient Echo Imaging...

A. ...is great for T_2 imaging

B. ...works well for imaging near metal implants

C. ...is a fast acquisition technique

D. ...is insensitive to off-resonance effects

Gradient Echo Imaging...

A. ...is great for T_2 imaging
   GRE is sensitive to T_2*, whereas SE is sensitive to T_2

B. ...works well for imaging near metal implants
   Metal causes large distortions for which SE is useful

C. ...is a fast acquisition technique
   Yes! The TE/TR are typically quite short compared to SE

D. ...is insensitive to off-resonance effects.
   GRE is sensitive to B_0 inhomogeneity, chemical shift and susceptibility shifts

Gradient Echoes - True or False?

1. GRE sequences have longer TRs than SE sequences.
2. GRE is great for fast T1-weighted imaging.
3. Metal artifacts on GRE are typically small.
4. GRE is great for T2 contrast.

In Gradient Echo Imaging Always...

A. Use the highest available flip angle.

B. Calculate and use the Ernst angle.

C. Use a flip angle for maximum contrast.

In Gradient Echo Imaging Always...

A. Use the highest available flip angle.

B. Calculate and use the Ernst angle.

C. Use a flip angle for maximum contrast.

Gradient Echoes - True or False?

1. GRE and SE can both provide T2* contrast.
2. GRE and SE use the same TE and TR to produce a T1-weighted image.
3. SE is better for visualizing tissues with a very short T2 because of the refocusing pulses.
4. In GRE higher flip angles always produce brighter images.

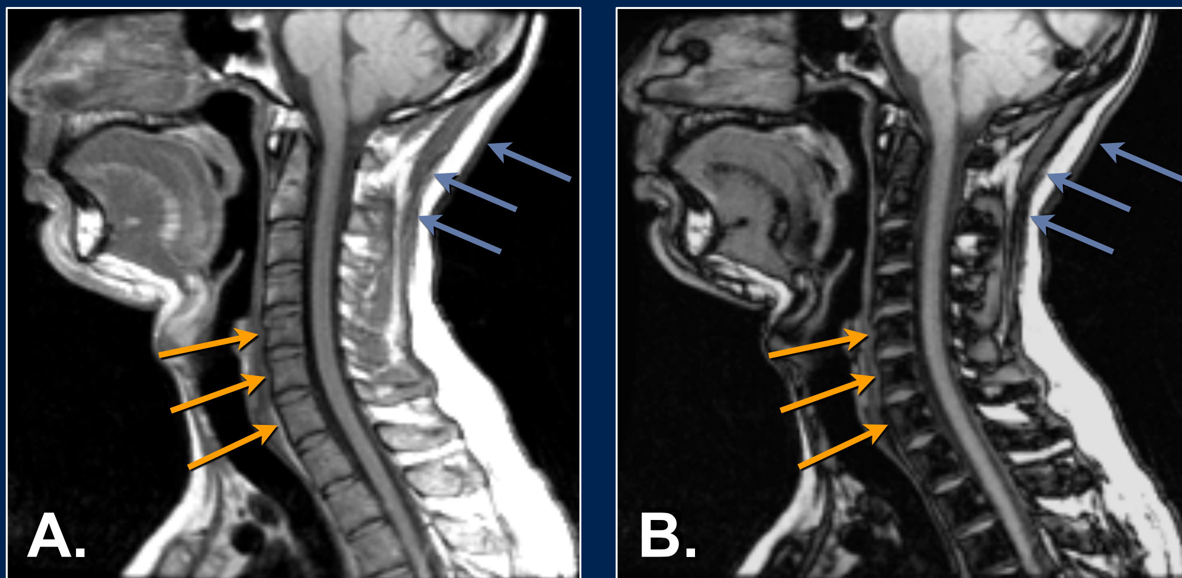
Gradient Echoes - True or False?

1. GRE is less sensitive to off-resonance than spin echo imaging.
2. GRE uses a refocusing pulse to form an echo.
3. Gradient and RF spoiling enable faster imaging.

Which image is the in-phase image?

Images Courtesy of Scott Reeder

Which image is the in-phase image?



In-Phase **Opposed-Phase**

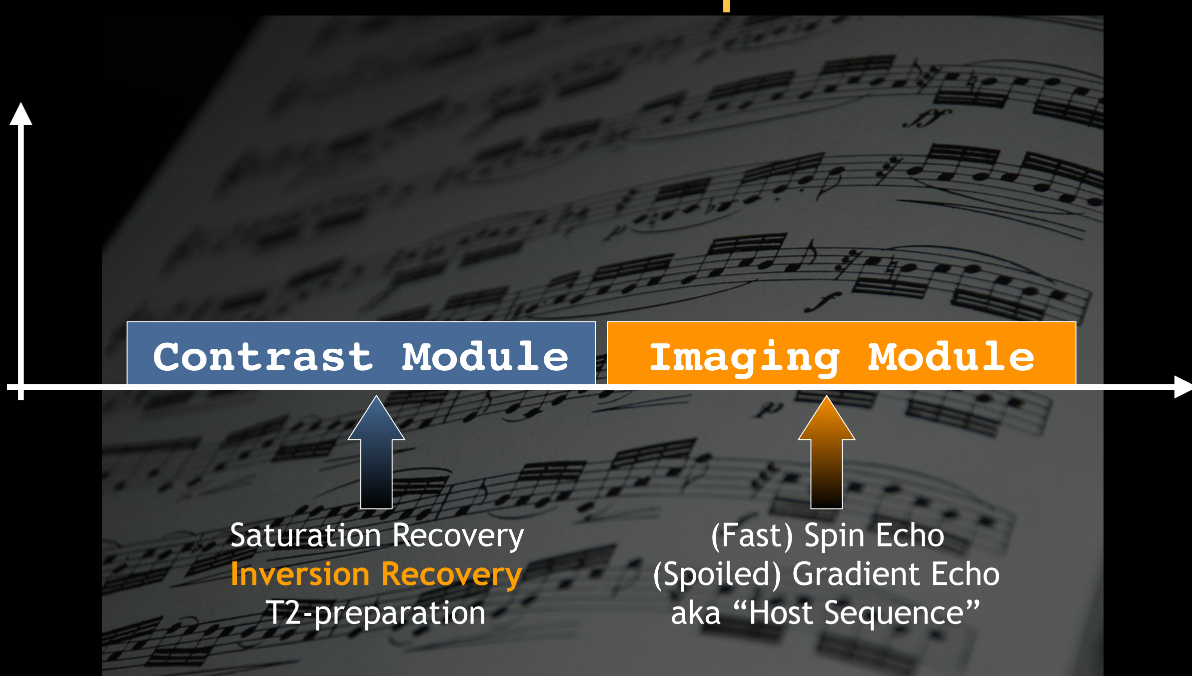
Images Courtesy of Scott Reeder

Gradient Echoes - True or False?

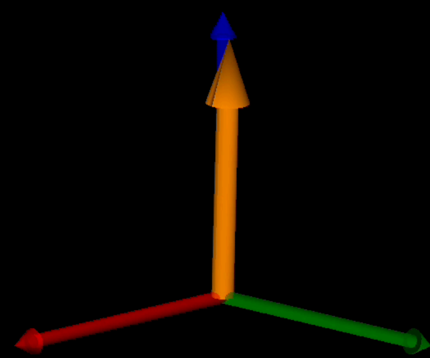
1. Fat and water precess at frequencies that are >1000Hz different.
2. Fat and water are always out of phase.
3. Fat and water destructively interfere when they are in phase.
4. In-flowing spins are bright because they “see” hundreds of excitation pulses.

Inversion Recovery Spin Echo MRI

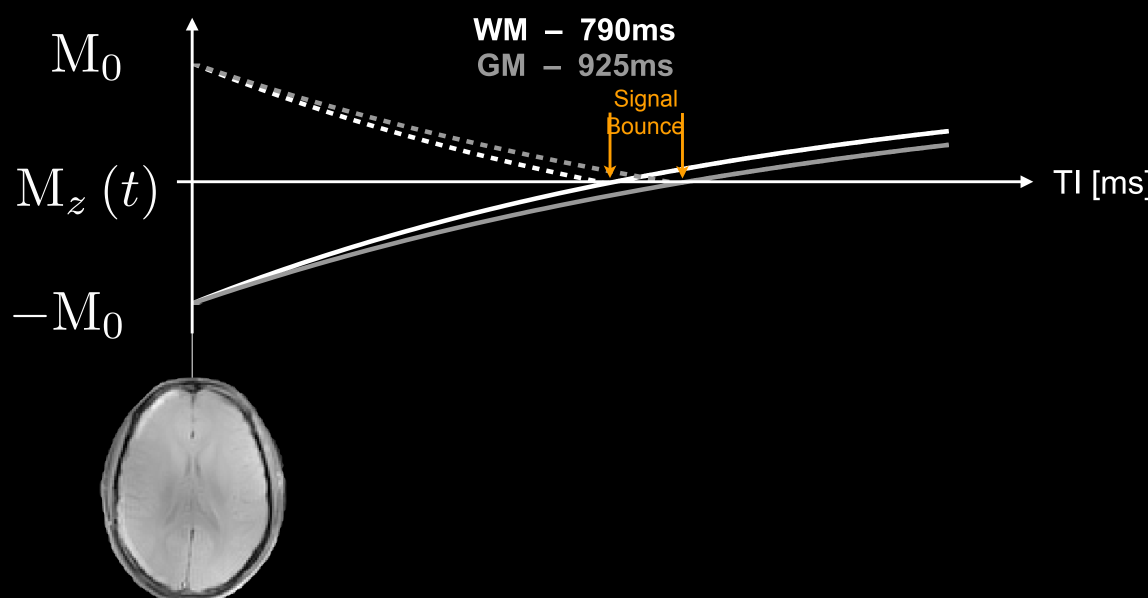
MRI Pulse Sequences



What is an inversion



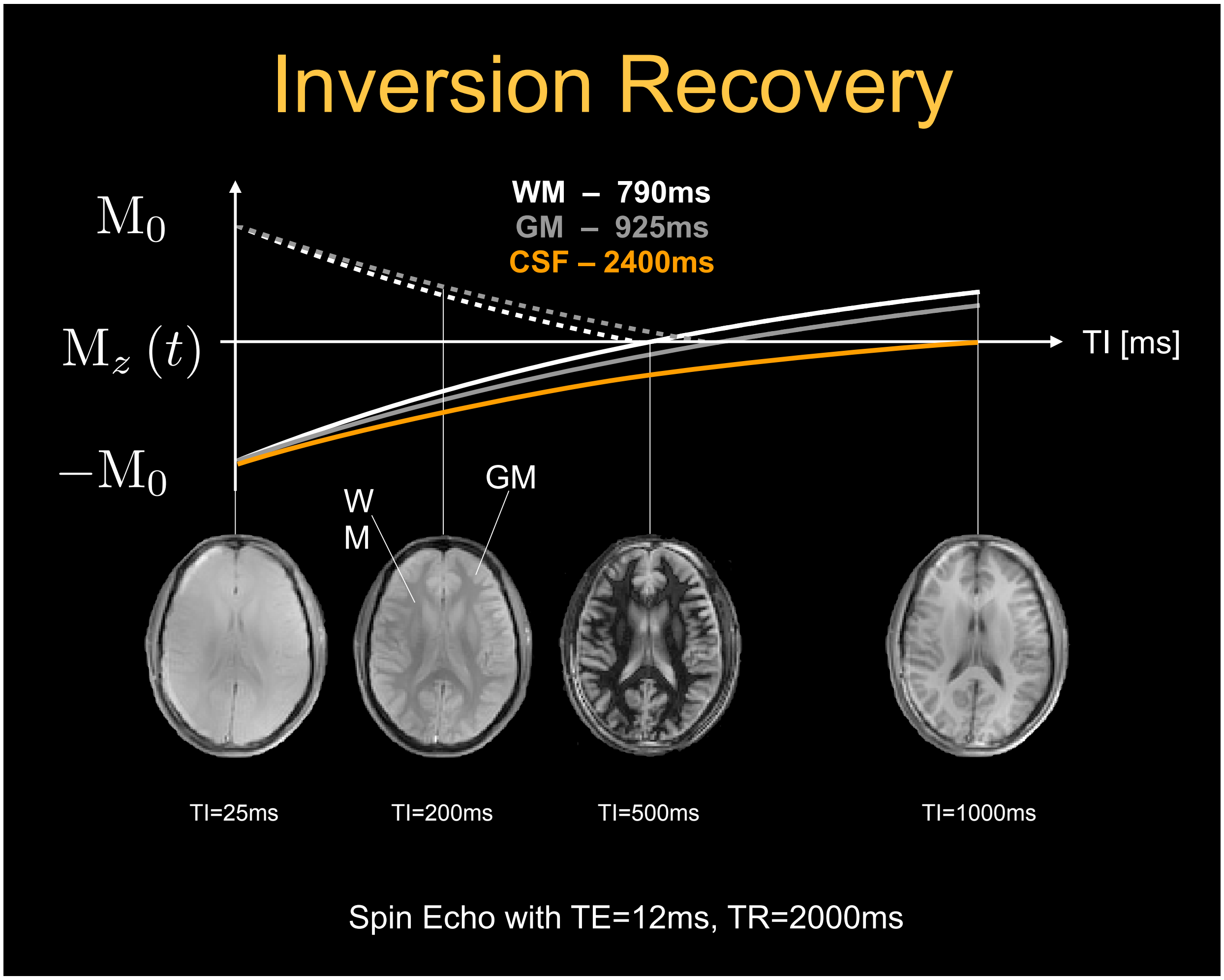
Inversion Recovery

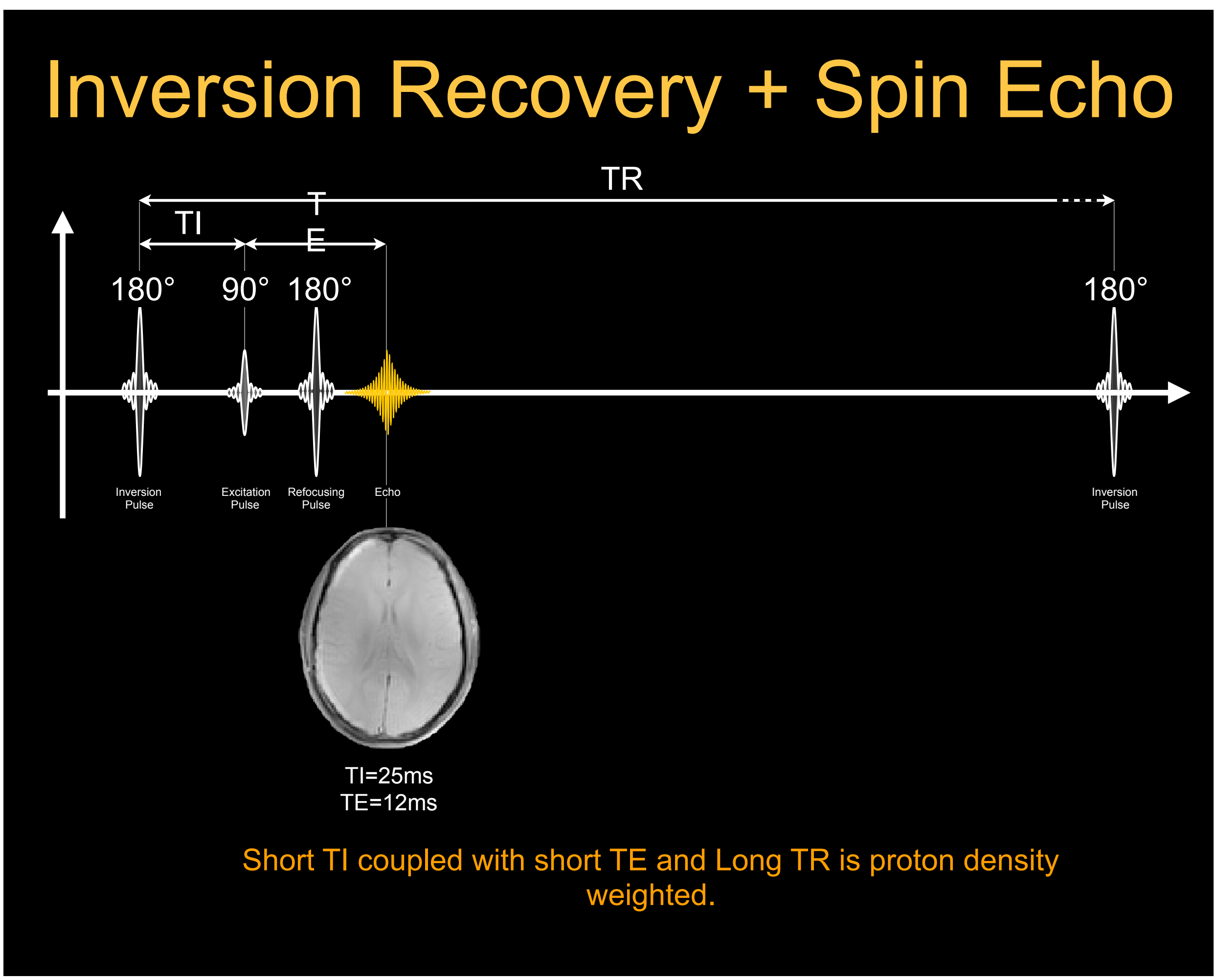


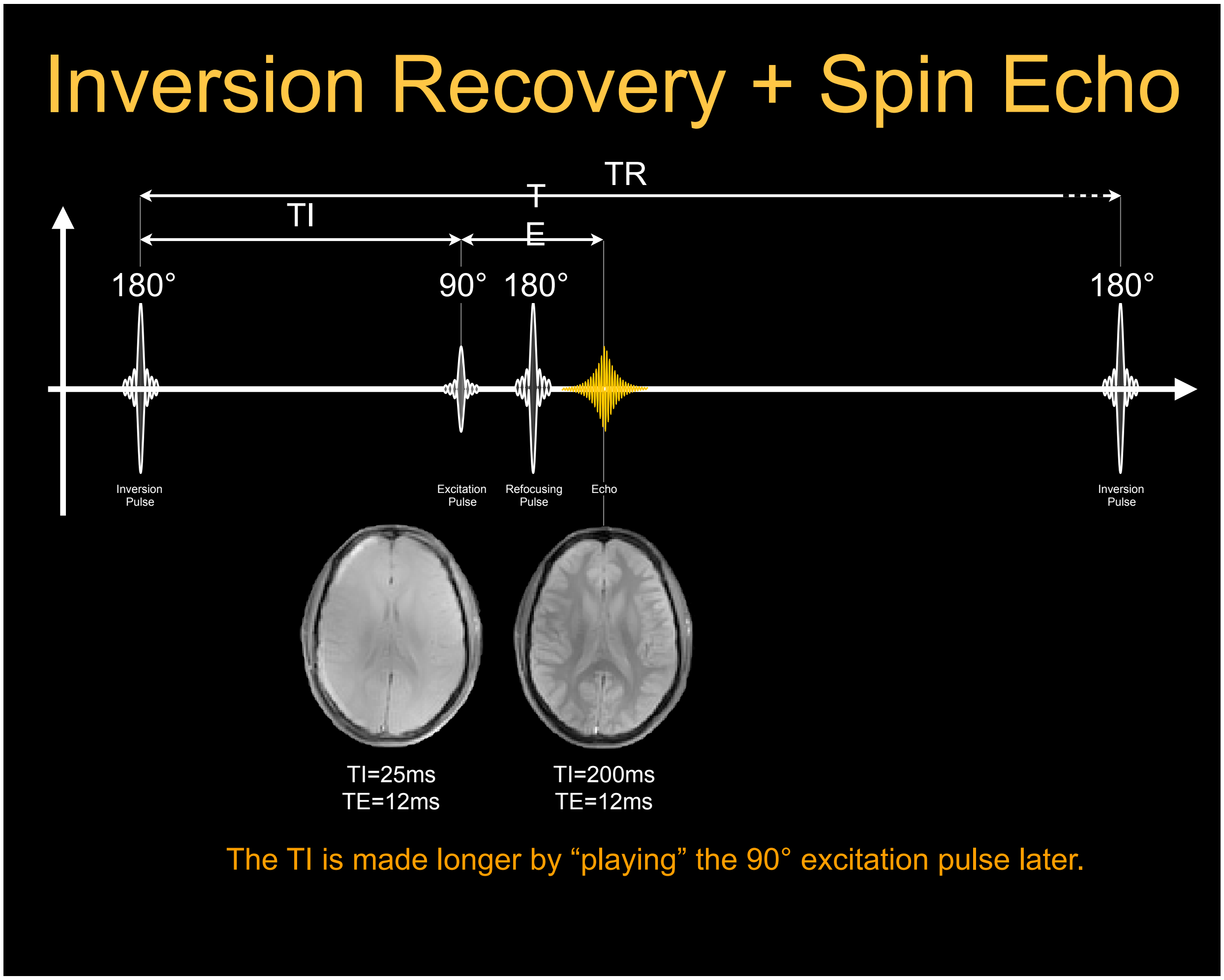
TI=25ms

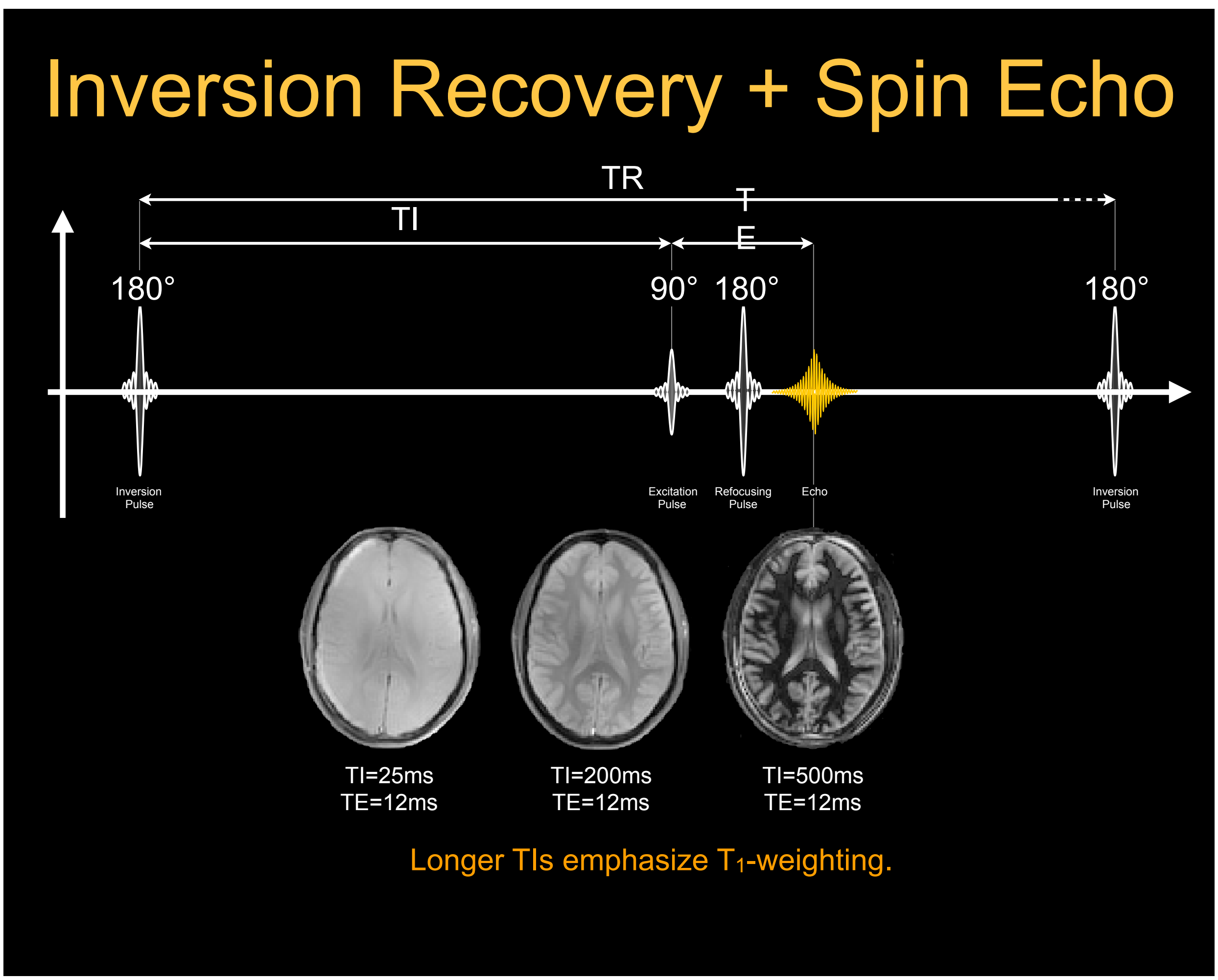
MRI images are typically ***magnitude*** (absolute value) images.

Spin Echo with TE=12ms, TR=2000ms

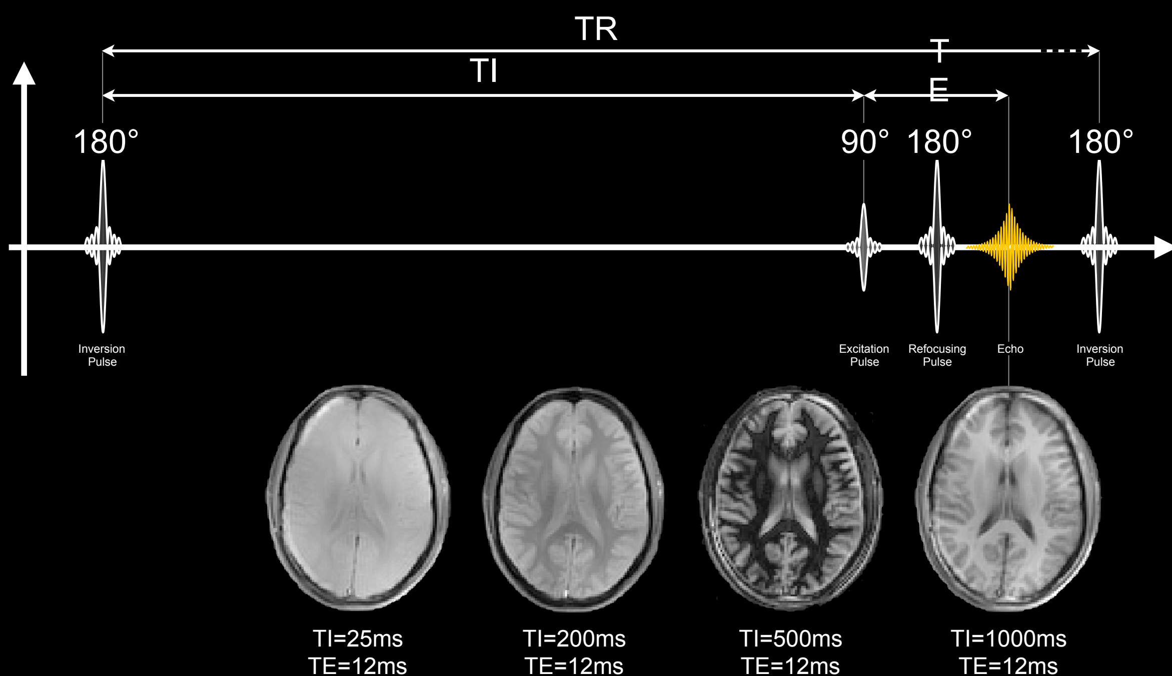

Inversion Recovery
WM – 790ms
GM – 925ms
CSF – 2400ms
M_0
$M_z(t)$
$-M_0$
TI [ms]
W
M
GM
TI=25ms
TI=200ms
TI=500ms
TI=1000ms
Spin Echo with TE=12ms, TR=2000ms


Inversion Recovery + Spin Echo
TR
TI
T
E
180°
90°
180°
180°
Inversion Pulse
Excitation Pulse
Refocusing Pulse
Echo
Inversion Pulse
TI=25ms
TE=12ms
Short TI coupled with short TE and Long TR is proton density weighted.


Inversion Recovery + Spin Echo
TR
TI
TE
180°
90°
180°
180°
Inversion Pulse
Excitation Pulse
Refocusing Pulse
Echo
Inversion Pulse
TI=25ms
TE=12ms
TI=200ms
TE=12ms
The TI is made longer by “playing” the 90° excitation pulse later.

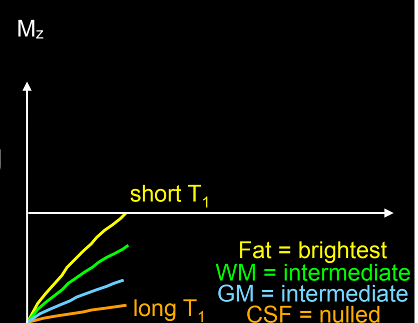

Inversion Recovery + Spin Echo
TR
TI
TE
180°
90°
180°
180°
Inversion Pulse
Excitation Pulse
Refocusing Pulse
Echo
Inversion Pulse
TI=25ms
TE=12ms
TI=200ms
TE=12ms
TI=500ms
TE=12ms
Longer TIs emphasize T_1-weighting.

Inversion Recovery + Spin Echo



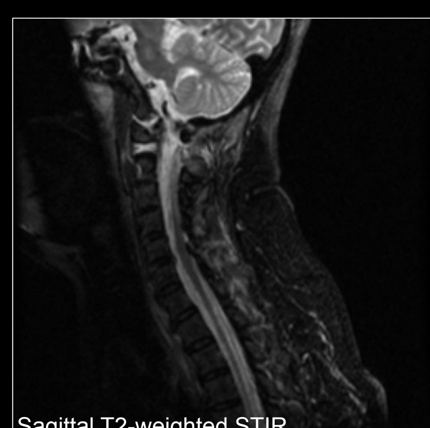
Really long TIs can null CSF (FLAIR).

Short Tau Inversion Recovery (STIR)



- **T1 (or T2-weighted) with nulled fat**
  - **Intermediate TR (2,000ms) adds T1-weighting**
  - **Short TE (60ms) limits T2-weighting**
  - **Long TI (120 to 170ms) nulls fat**
- **Applications**: edema, fat sat, MSK,…

Sagittal T2-weighted Spin Echo



Sagittal T2-weighted STIR

Images Courtesy of Frank Korosec & radiopaedia.org

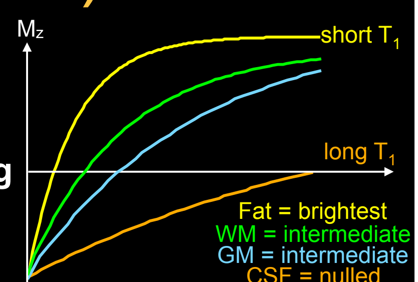
STIR vs. T2-weighted Fast Spin Echo

(A) Coronal **STIR** of the knee. **High-signal marrow edema** is identified in the middle of the tibial plateau and medial femoral condyle. Fraying of the lateral meniscus free edge represents a degenerative radial tear. (B) Coronal **T2-weighted FSE** at the same position. The **edema is largely obscured** by the high-signal-intensity marrow.

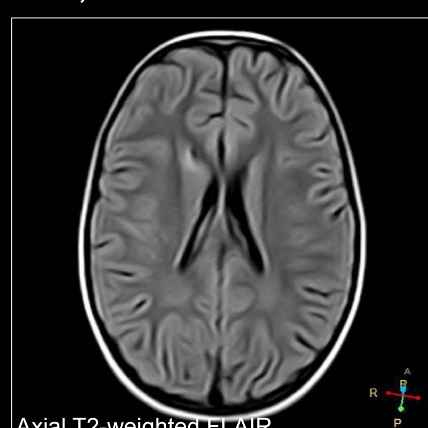
Duke Review of MRI Principles, p. 88.

FLuid Attenuated Inversion Recovery (FLAIR)

- **T2-weighted image with nulled CSF**
  - **Long TR (11,000ms) limits T1-weighting**
  - **Long TE (145ms) emphasizes T2-weighting**
  - **Long TI (2200ms) nulls CSF**
- **Applications**: stroke, MS, cancer,…



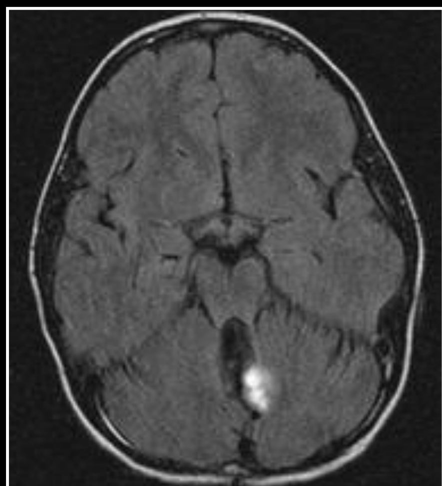
Axial T2-weighted Spin Echo



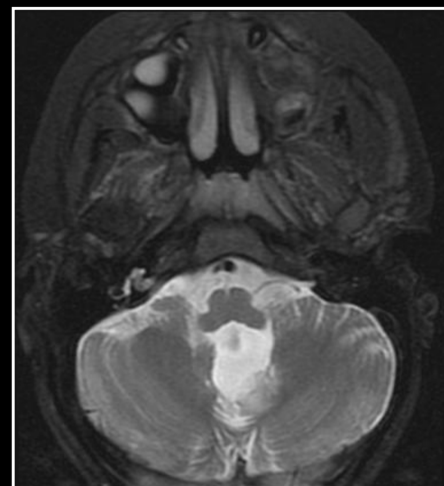
Axial T2-weighted FLAIR

FLAIR attenuates CSF and improves lesion conspicuity.

FLAIR vs. T2-weighted Fast Spin Echo



T2 Flair (TR = 8000 ms, TE = 127 ms)



Fast Spin Echo

FLAIR attenuates CSF and improves lesion conspicuity.

Images Courtesy of Frank Korosec

Spatial Localization

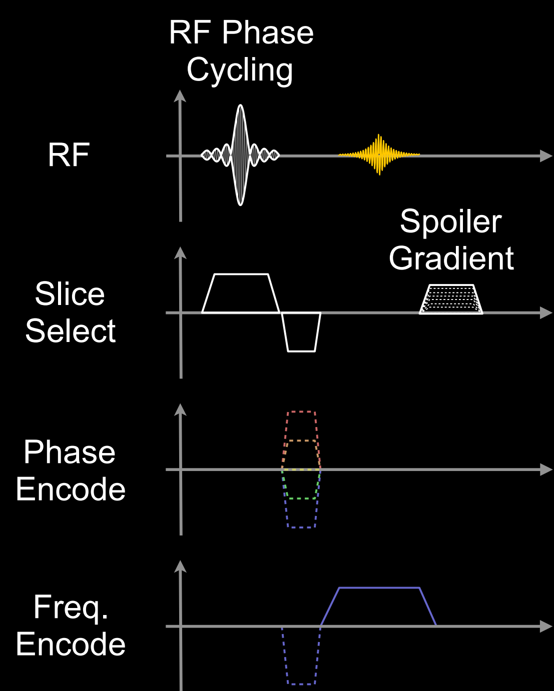
Spatial Encoding

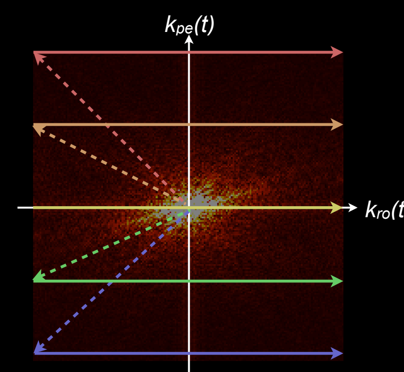
- Three key steps:
  - Slice selection
    - You have to pick slice!
  - Phase Encoding
    - You have to encode 1 of 2 dimensions within the slice.
  - Frequency Encoding (aka *readout*)
    - You have to encode the other dimension within the slice.

What is *k*-space?

- *k*-space is the raw data collected by the scanner.
  - A point in k-space tells us about the presence/absence of a spatial frequency (pattern) in the acquired image.
  - Each echo measures *many* of the spatial frequencies that comprise the object.
- Gradients move us around in k-space
- A line of *k*-space is filled by an echo

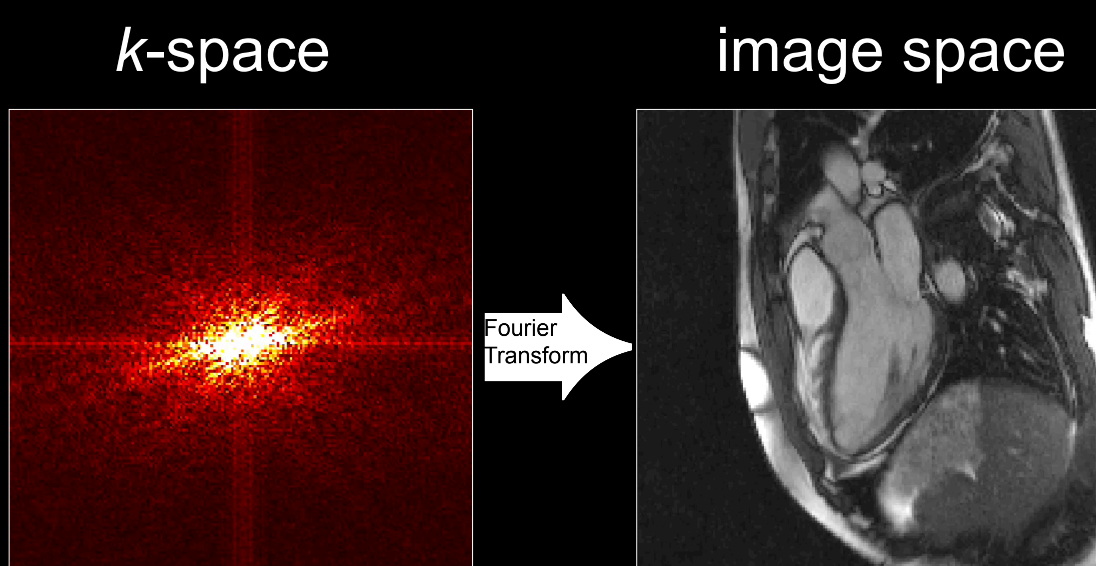
Where am I in *k*-space?





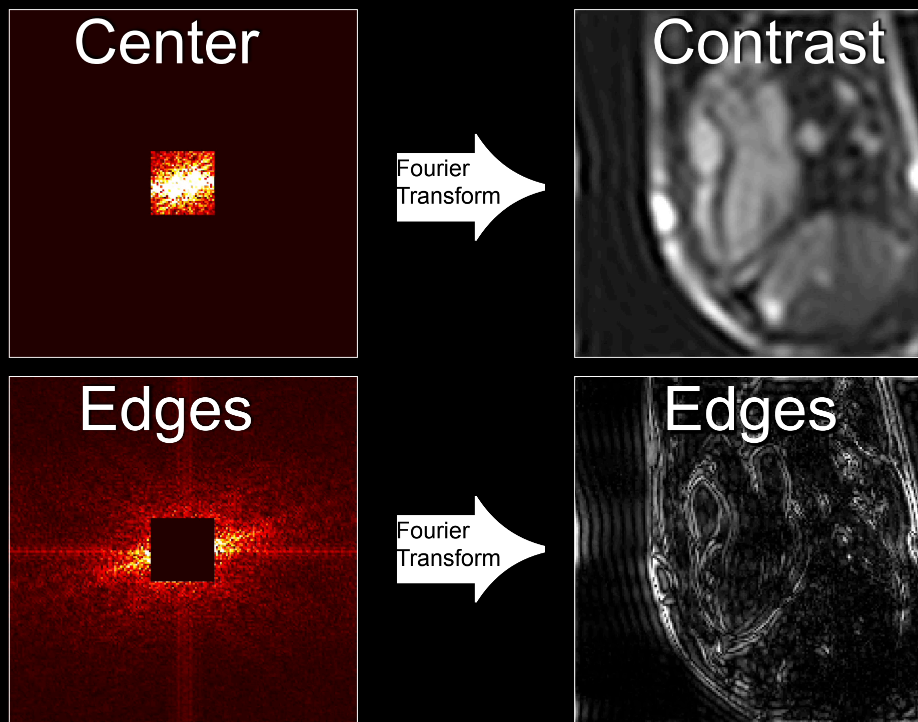
Gradients move the acquisition through *k*-space.

What is *k*-space?

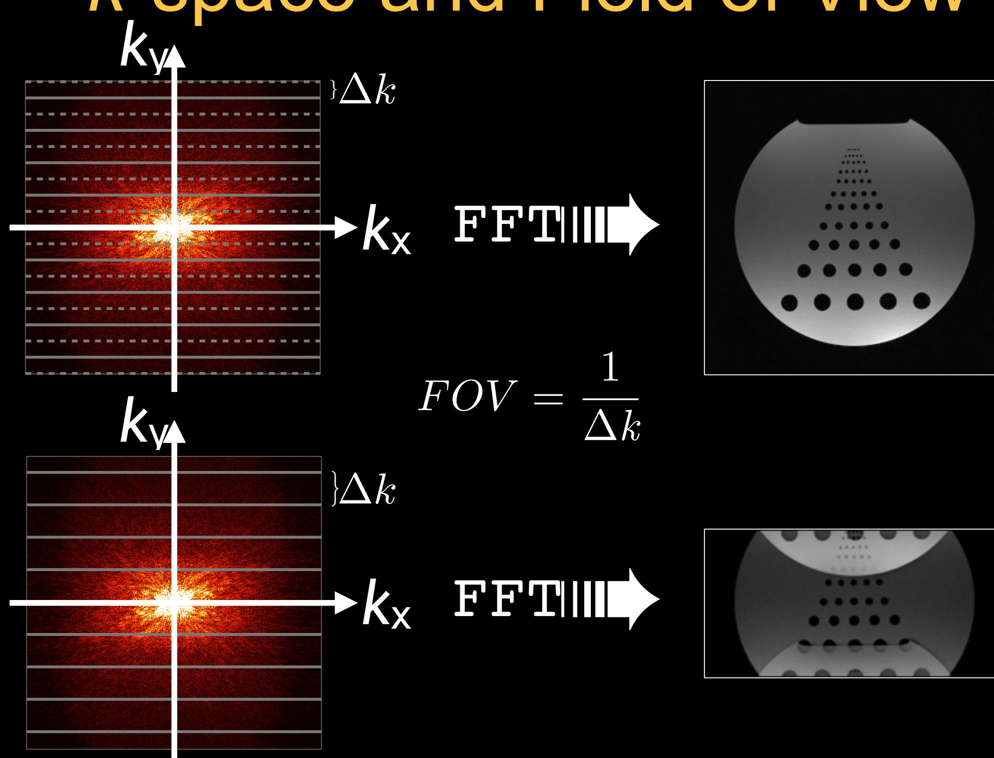


_k_-space is the raw data collected by the scanner.

What is *k*-space?

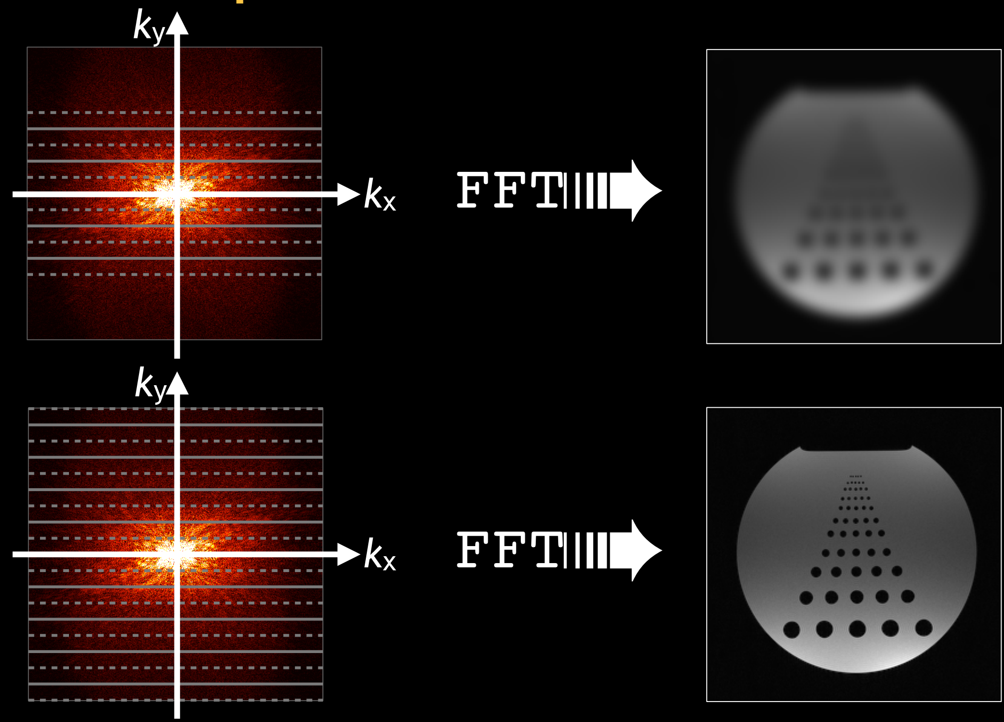


k-space and Field of View



Uniformly skipping lines in *k*-space causes ***aliasing***.

k-space and Resolution



Acquiring more high phase encodes increases resolution.

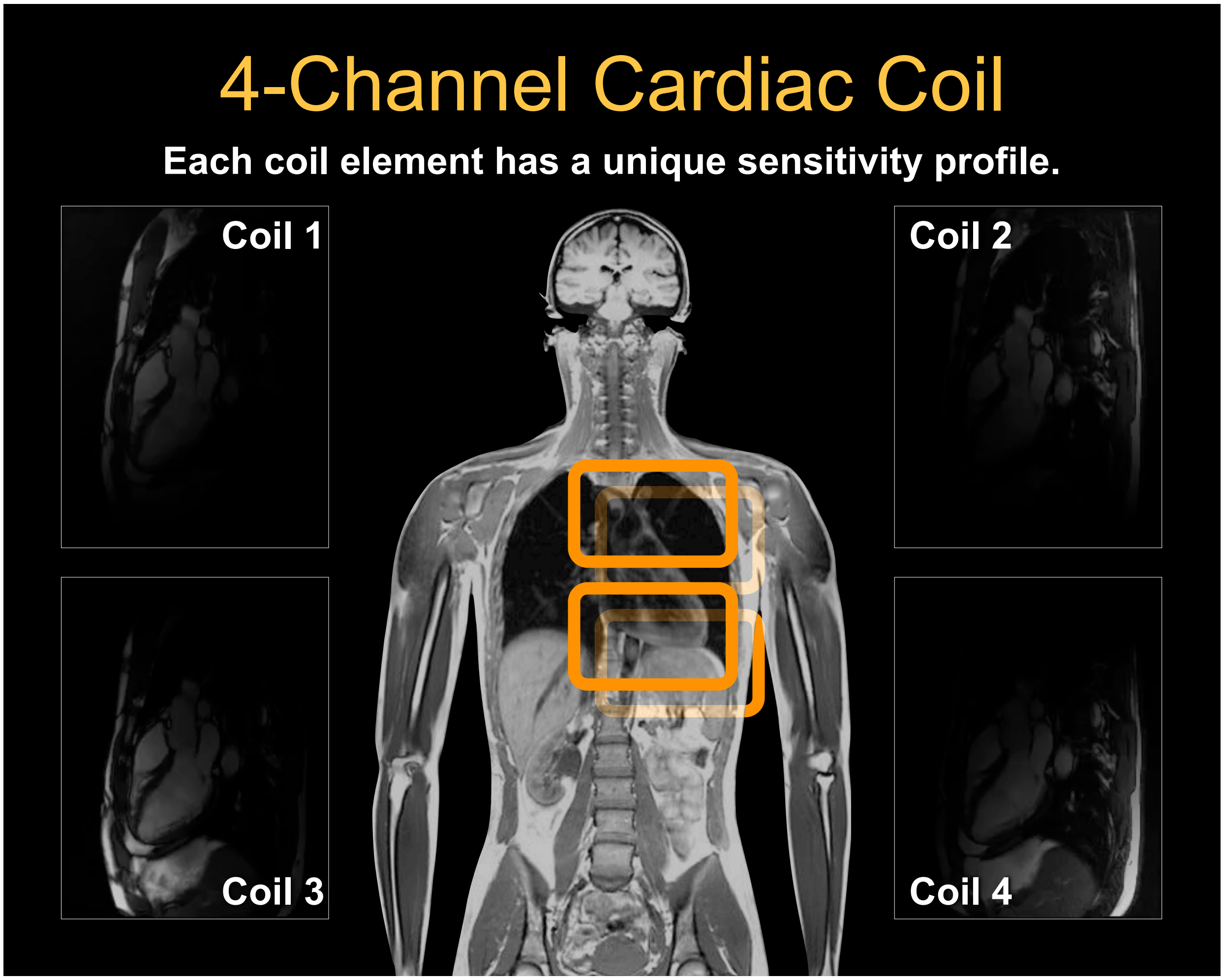
k-space - True or False?

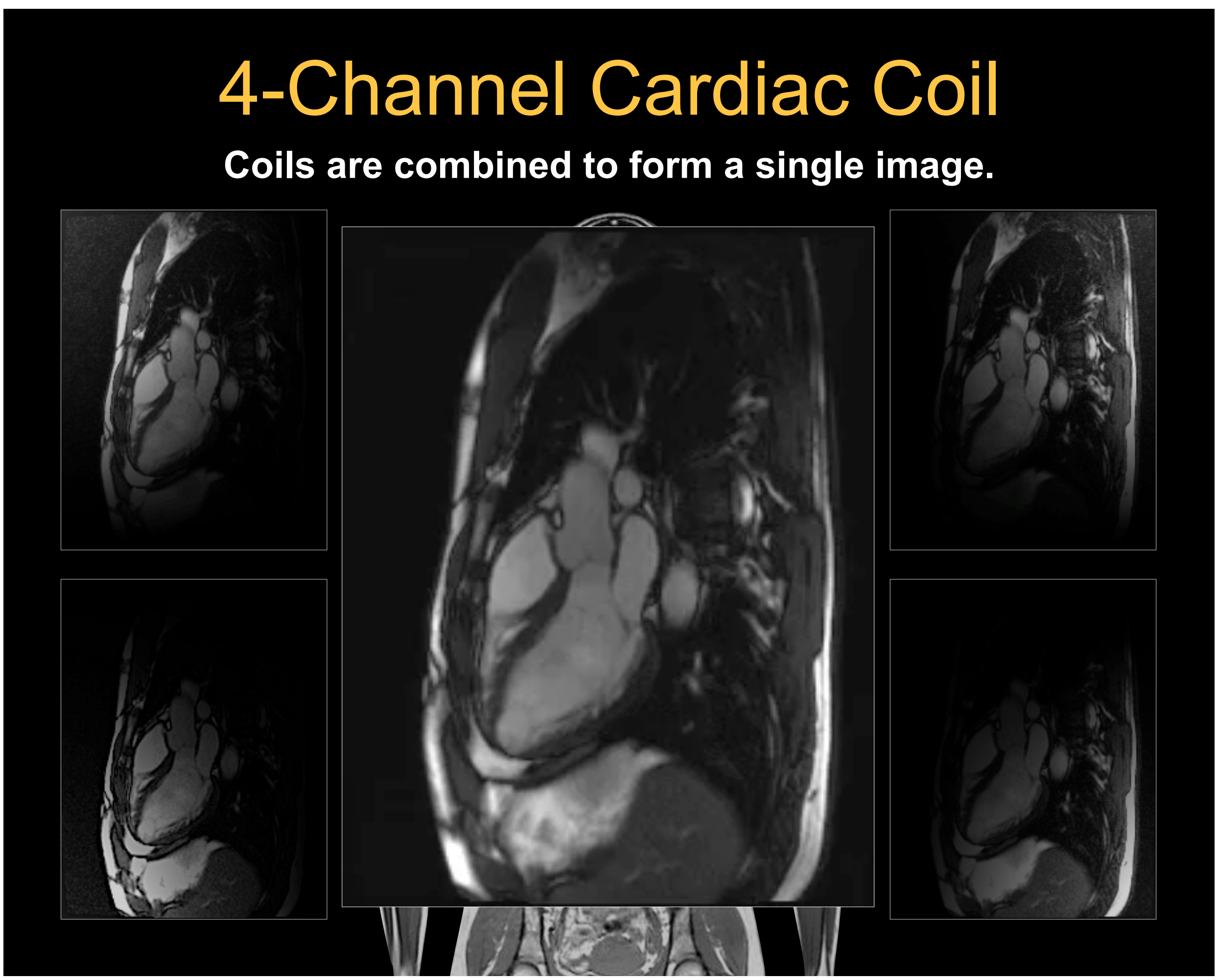
1. *k*-space is the raw data collected by the scanner.
2. A point in *k*-space represents one pixel's intensity in the image.
3. An echo corresponds to a single point in *k*-space.
4. The edges of *k*-space relate to image contrast.
5. High resolution imaging takes longer because we need to acquire more of *k*-space.

Parallel Imaging

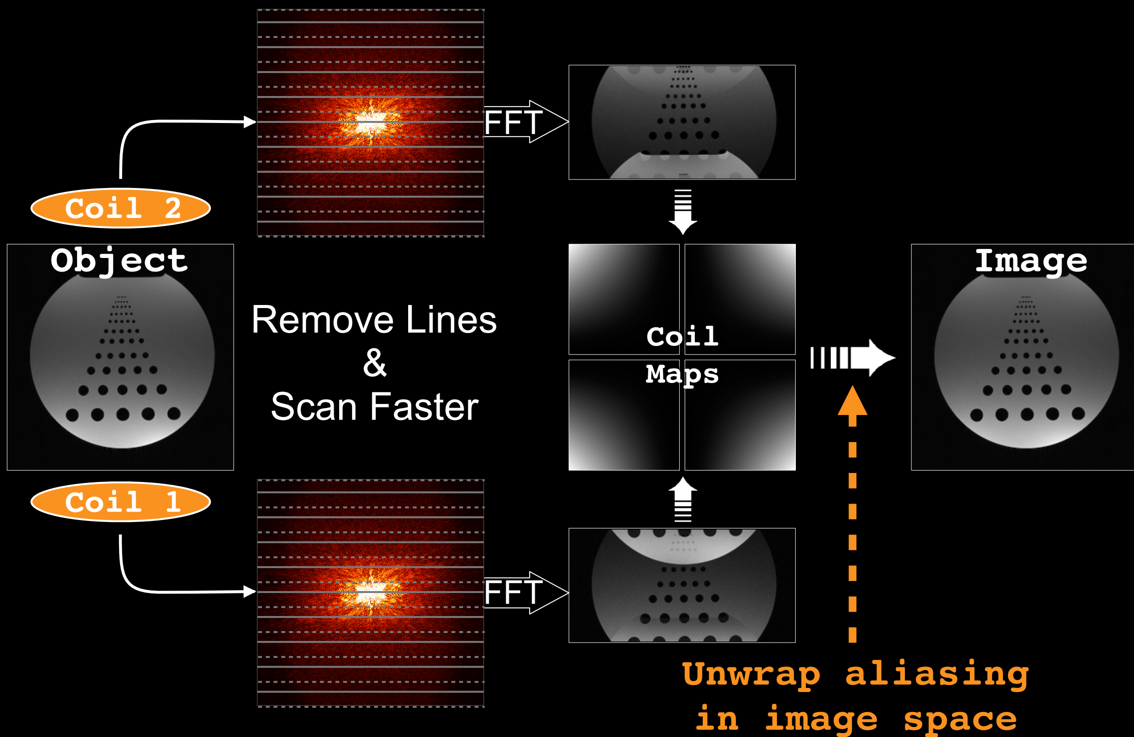
Parallel Imaging

- Applications
  - 2x-3x acceleration used routinely
- Advantages
  - Accelerate image acquisition
    - Shorter breath holds, quicker or more thorough exams.
  - Improve spatial or temporal resolution
    - Without increasing scan time.
- Disadvantages
  - Faster scanning is noisier scanning.
  - Noisier than other acceleration methods.
  - Accelerations >2-3x for 2D imaging are too noisy.
  - Accelerations >3-4x for 3D imaging are too noisy.


4-Channel Cardiac Coil
Each coil element has a unique sensitivity profile.
Coil 1
Coil 2
Coil 3
Coil 4

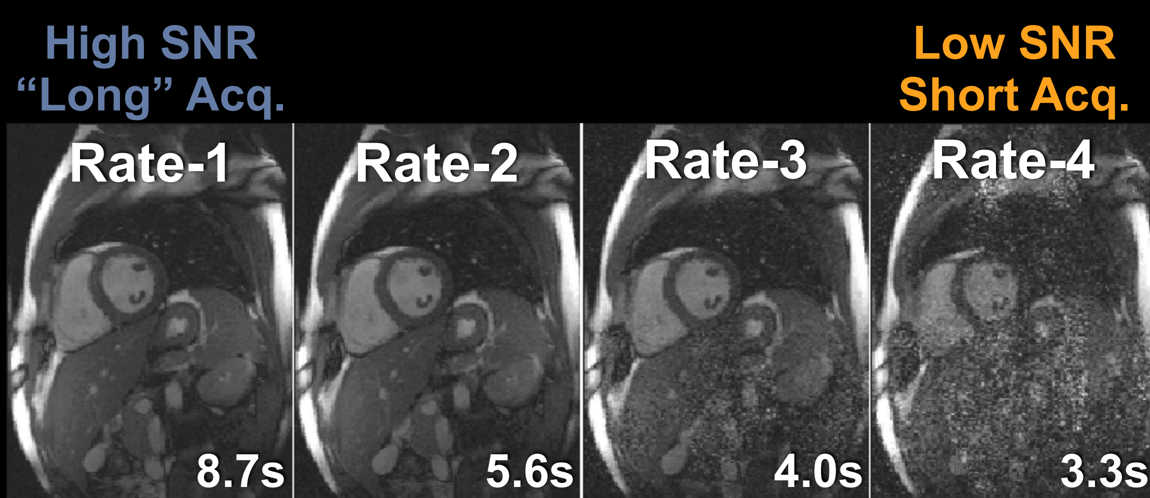

4-Channel Cardiac Coil
Coils are combined to form a single image.

Parallel Imaging (SENSE)



Pruessmann KP. *Magn Reson Med*. 1999;42(5):952-962.

Impact of Acceleration



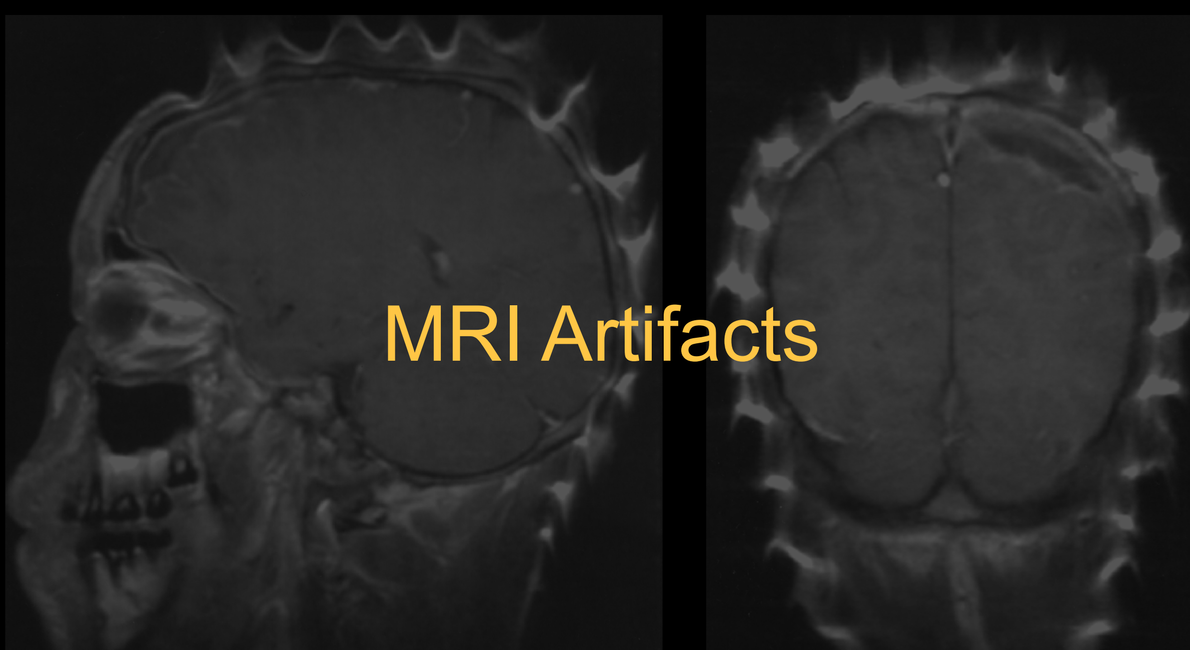
P. Kellman (NIH)

High acceleration rates lead to local noise amplification.

Parallel Imaging - True or False?

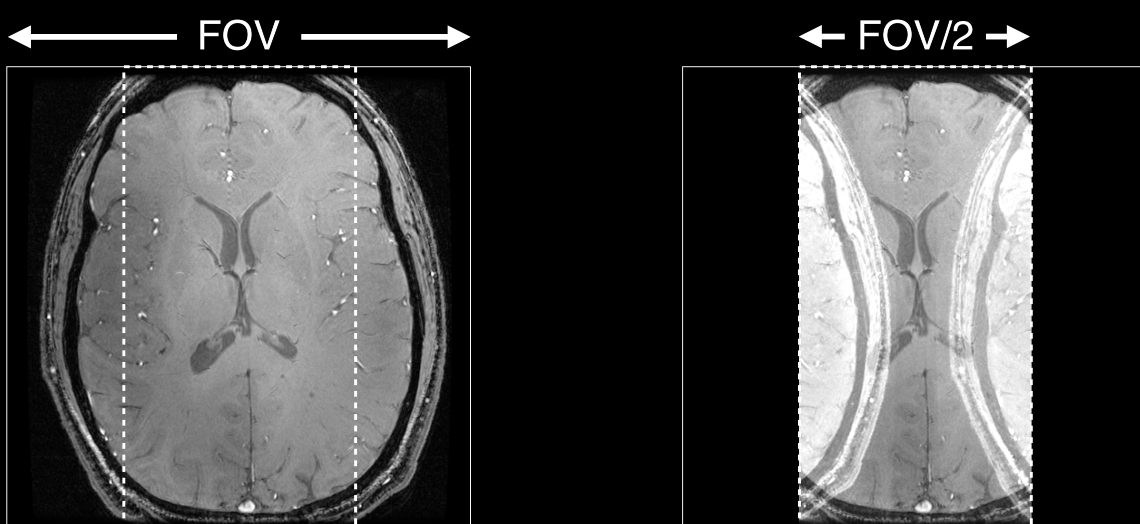
1. Parallel imaging comes for free (no SNR penalty).
2. Parallel imaging can be used with single channel coils.
3. Parallel imaging accelerations of 20-30x are typical.

MRI Artifacts



Phase Encode Artifacts

Aliasing Artifact

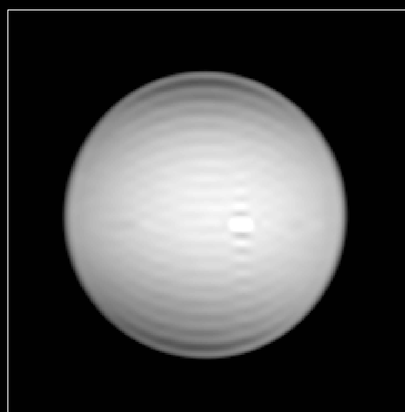


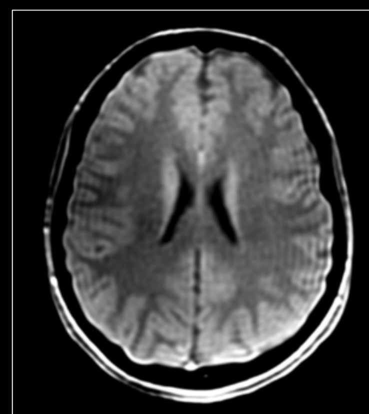
- Occurs when FOV is too small. Why?
  - Gradients are active across FOV and beyond.
  - Spins outside the specified FOV still see the gradients.
  - These spins are misinterpreted as coming from areas within the specified FOV.

Solution: Larger FOVs reduce/eliminate aliasing (wrap around) artifacts.

Gibb's Ringing

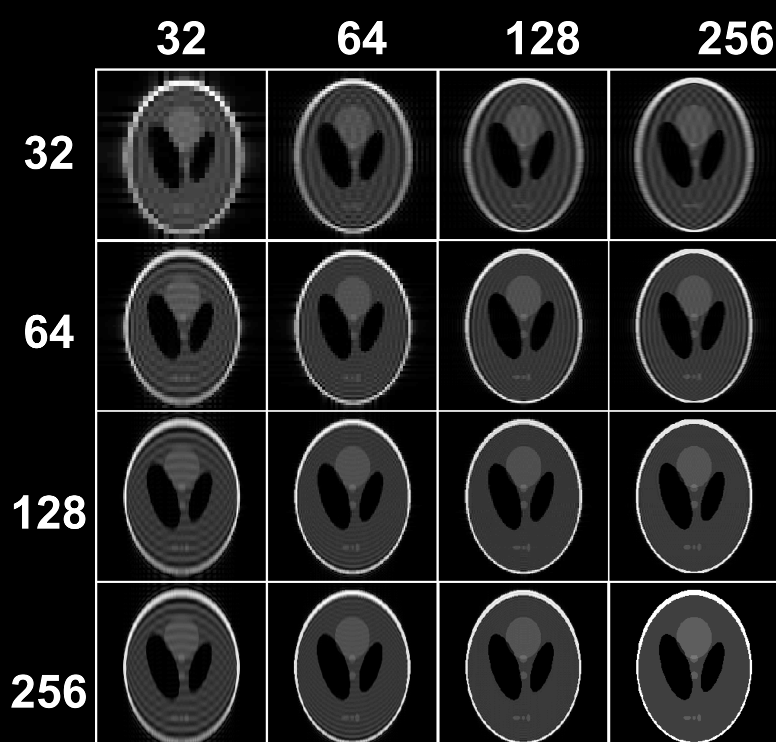
- Spurious ringing around sharp & high-contrast edges
  - More common in low resolution, high contrast images.
    - Phase encode direction is commonly lower resolution.
- Can reduce by:
  - Acquiring higher resolution images
  - Filtering *k*-space data, reducing oscillations in the image





Solution: Higher resolution imaging and filters reduce Gibbs's ringing.

Effects of Resolution



Increasing resolution reduces Gibb's ringing.

Frequency Encoding Artifacts

Chemical Shift Artifact

- “First Kind”
  - Displacement/mis-registration of fatty tissues
  - Worse with lower receiver bandwidth
    - Frequency encoding artifact
- “Second Kind”
  - Signal cancellation due to in-phase and out-of-phase fat and water within a pixel
  - Seen in GRE (not spin echo)
  - “India ink artifact”
  - *Not* specifically a frequency encoding artifact

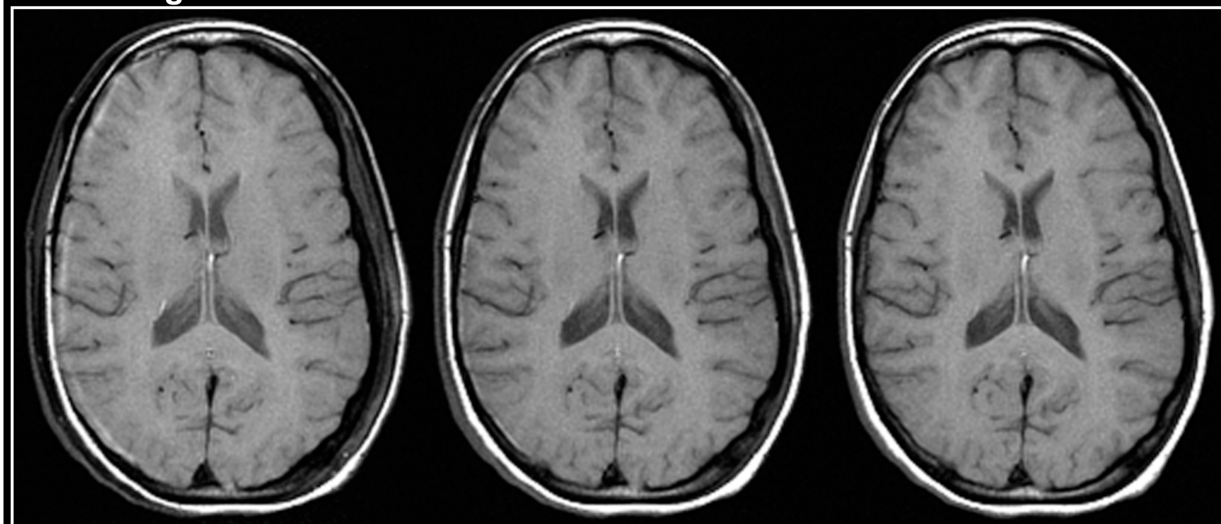
http://www.xrayphysics.com/chem_sh.html

Chemical Shift Artifact - Type 1

Low Bandwidth
Large Fat-Water Shift
High SNR

← Readout

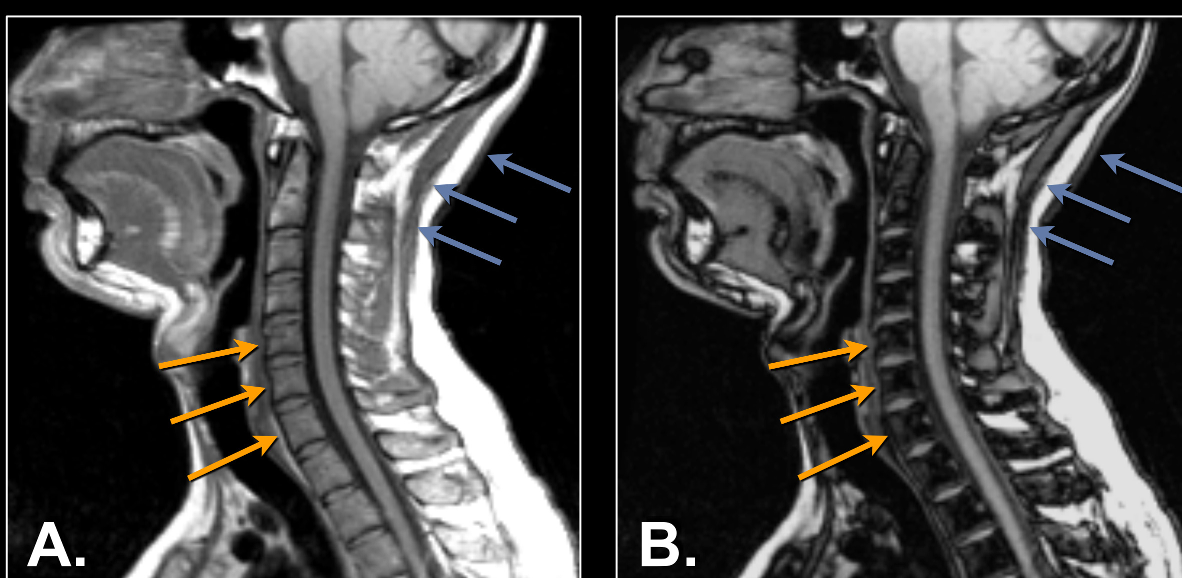
High Bandwidth
Small Fat-Water Shift
Low SNR



BW = ± 4kHz   BW = ± 8kHz   BW = ± 16kHz

Solution: Higher bandwidth imaging reduces chemical shift Type-1.

Chemical Shift Artifact - Type 2

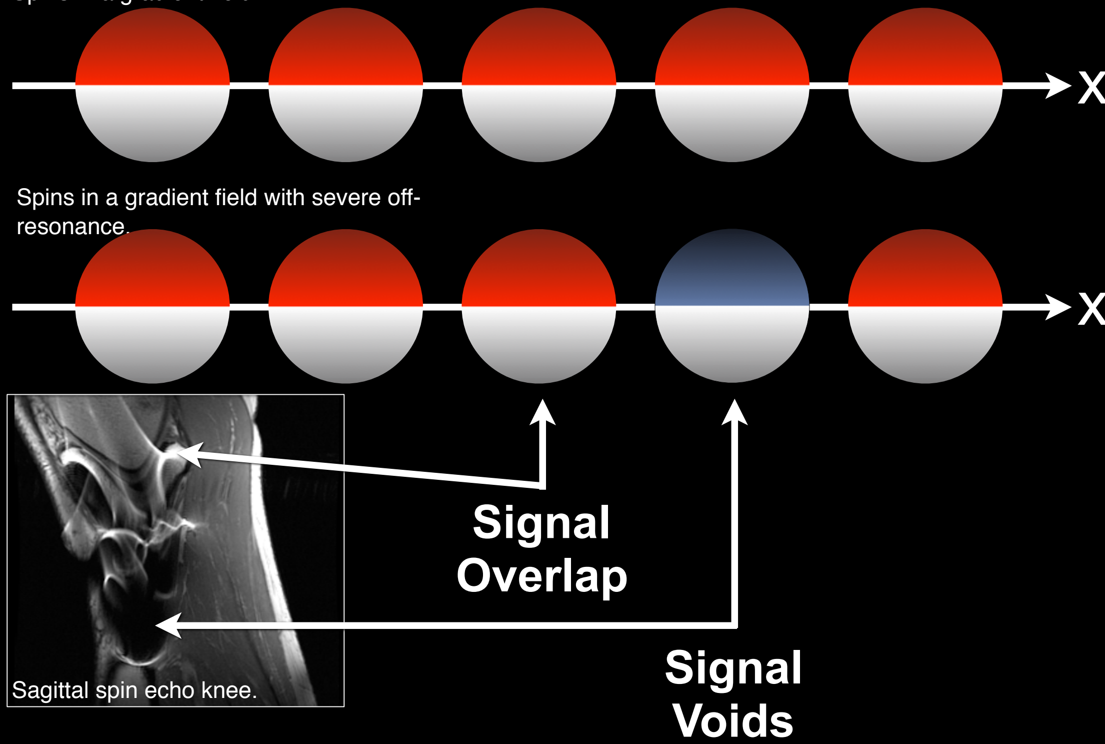


In-Phase   **Opposed-Phase**

Solution: In-phase TE with GRE reduces chemical shift Type-2. Not seen on spin echo.

Metal Implant Artifacts

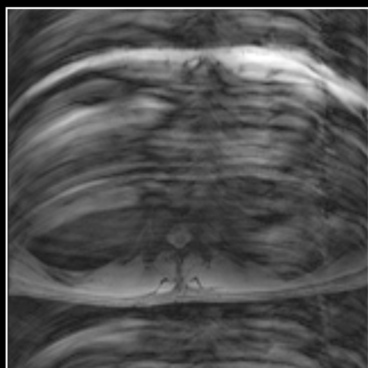
Spins in a gradient field.



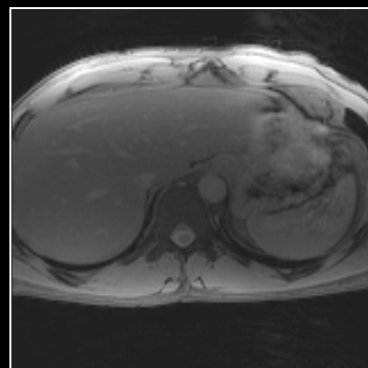
Solution: High bandwidth imaging with spin echoes.

Flow and Motion Artifacts

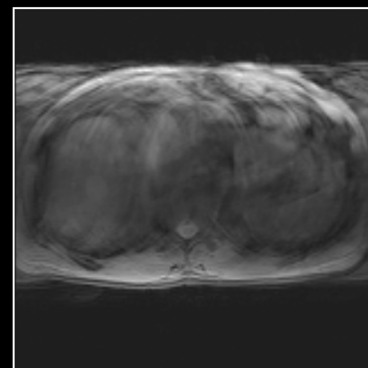
Breathing (Motion) Artifacts



Free Breathing



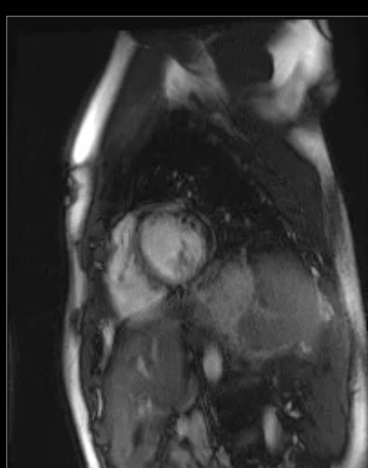
Breath held



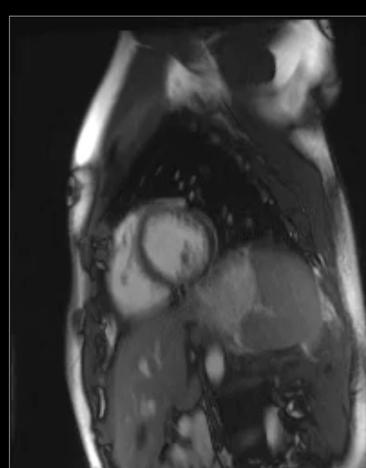
Free Breathing

Motion artifacts appear in the phase encode direction.

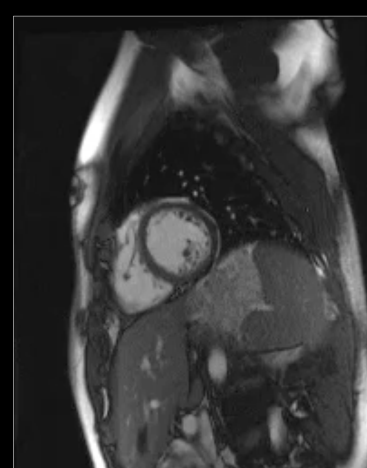
Breathing (Motion) Artifacts



Free Breathing
~15s



Four Averages
~60s



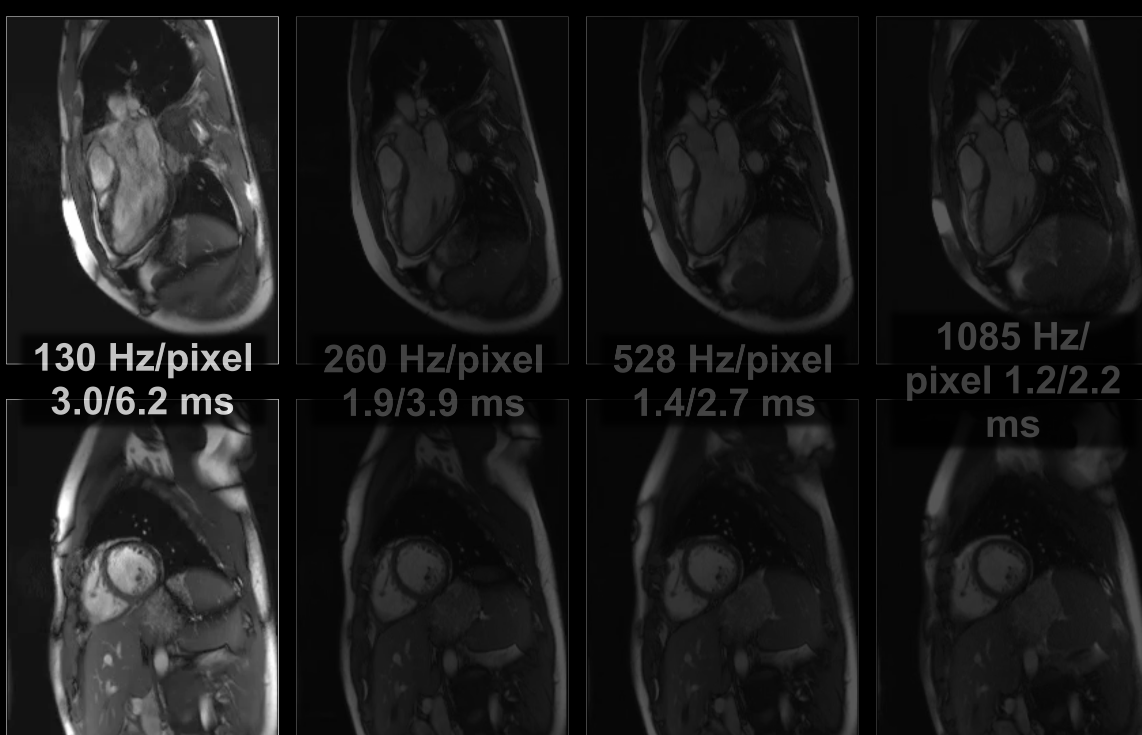
Breath Held
~15s

Averaging and breath holding can reduce respiratory artifacts.

Respiratory Motion Artifact Reduction

- Communicate
  - Increase awareness & alertness
- Decrease breath hold time
  - ⬇ spatial and/or temporal resolution
- Back-up Plan
  - Averaging
  - Respiratory bellows gating
- Advanced methods
  - Navigator or bellows gated imaging
  - Realtime MRI

bSSFP - Blood Flow Artifacts



Solution: For bSSFP use the highest available bandwidth to limit flow artifacts.

CSF Flow Artifacts

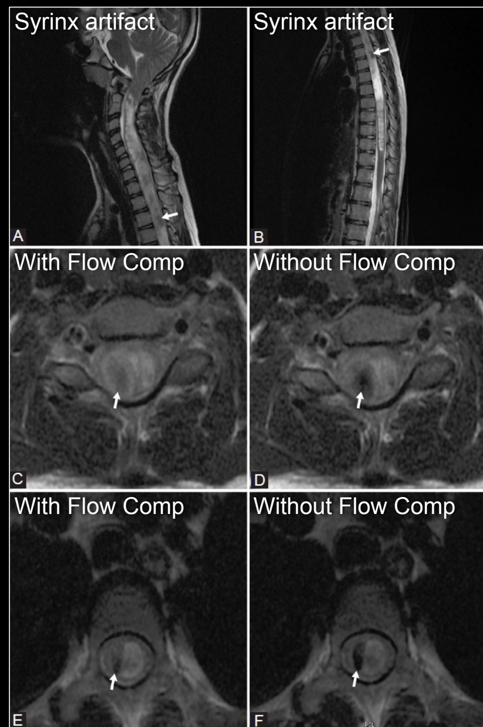


Figure 1 (A-F): Sagittal T2-weighted images showing syrinx in cervical (A) and thoracic (B) cord; faint flow voids (arrows) are seen within the syrinx. (C, D): Axial T2-weighted images of cervical cord with (c) and without (d) flow compensation; flow voids (arrows) are more obvious in D (without flow compensation). (E, F): Axial T2-weighted images of thoracic cord with (E) and without (f) flow compensation; flow voids (arrows) are more obvious in F (without flow compensation).

Solution: For gradient echo imaging use flow compensation (longer TE/TR).

http://www.ijri.org/viewimage.asp?img=IndianJRadiolImaging_2013_23_1_97_113626_f1.jpg

More Artifacts!

Gradient Non-linearity

- Basic *assumption* in MRI is that the z-component of the B-field created by the gradient coils varies linearly with x, y, or z over the FOV.
- Higher gradient amplitudes and slewrates can be achieved by compromising on spatial linearity.
- Gradient non-linearity causes geometric and intensity distortions.

Gradient Non-linearity

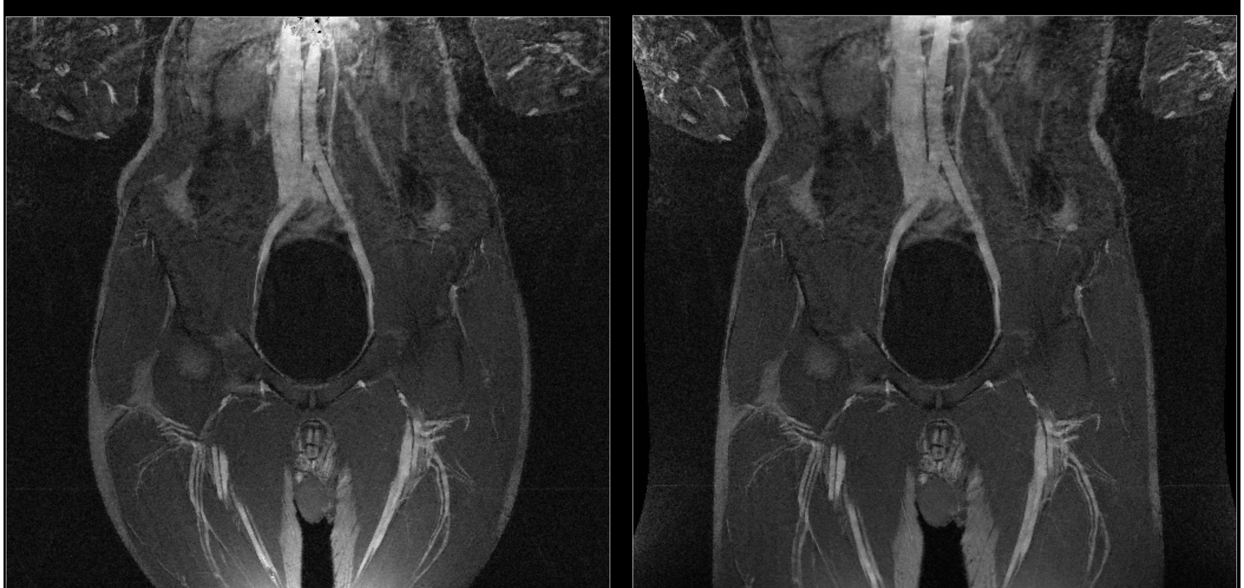
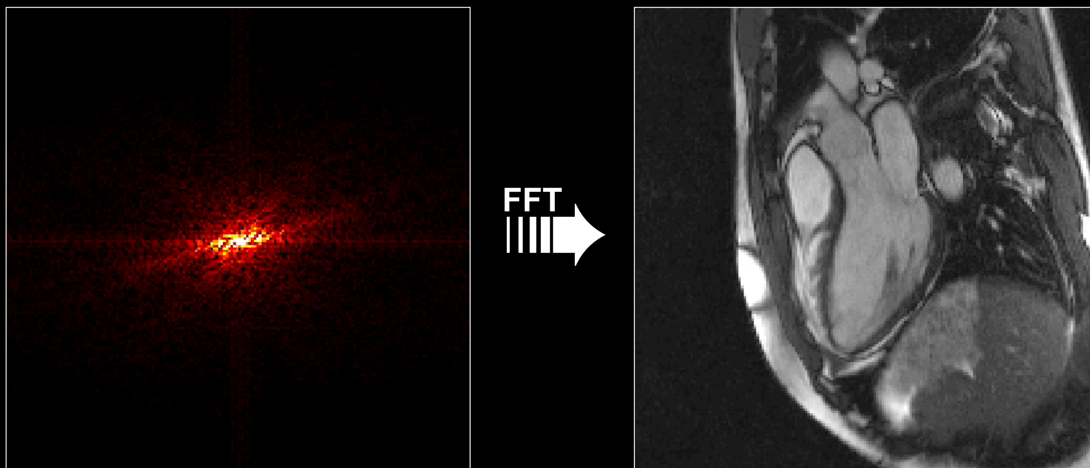


Image warping parameters that are system specific and applied to all images.

Image Courtesy of M.T. Alley & B.A. Hargeaves

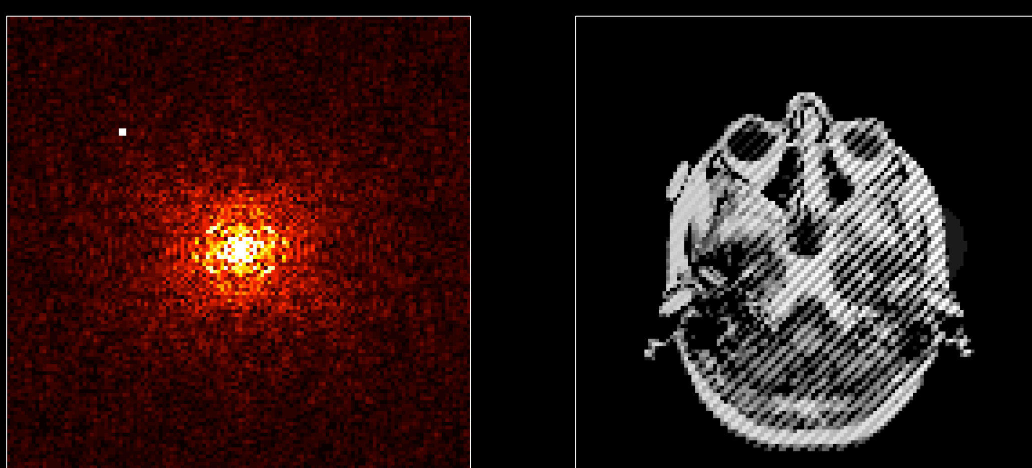
k-space spikes

k-space   image space



A *k*-space spike creates a banding artifact.

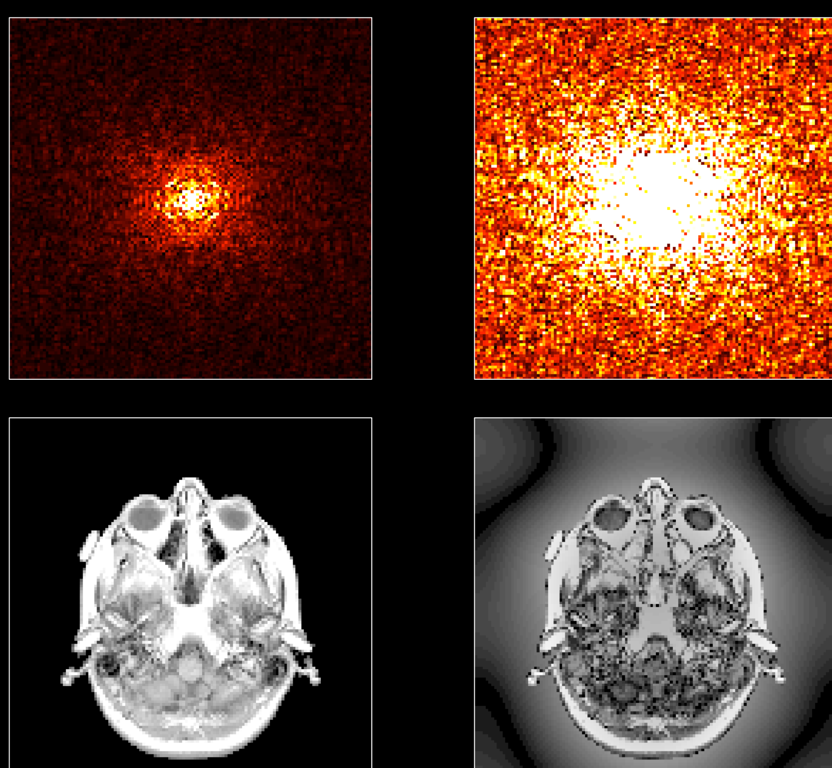
Noisy Spike Artifacts



Data Clipping

- Received signal saturates the receiver
- Peak signal usually in the middle of *k*-space, therefore loose low spatial frequency information
  - Contrast
  - Intensity
- Pre-scan procedure usually avoids data clipping by adjusting receiver gains

Data Clipping



B_1 Inhomogeneity Artifact

- Poor B_1 penetration due to copper foil.

Images Courtesy of http://chickscope.beckman.uiuc.edu/roosts/carl/artifacts.html

Susceptibility Artifact

- Arises from B_0 perturbations caused by a mismatch in magnetic susceptibility.
- Common near metal/tissue and air/tissue boundaries.

Coin Placed Near Phantom

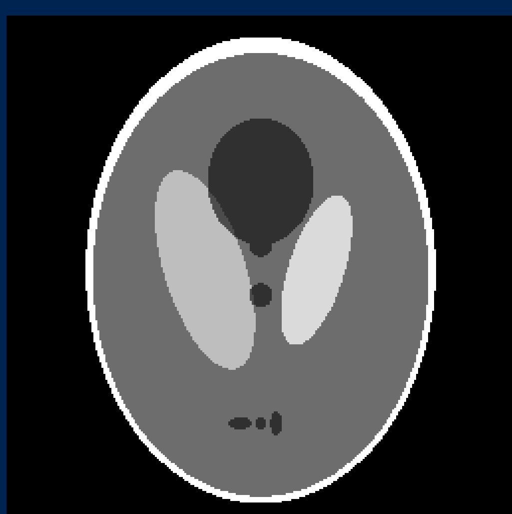
Images Courtesy of http://chickscope.beckman.uiuc.edu/roosts/carl/artifacts.html

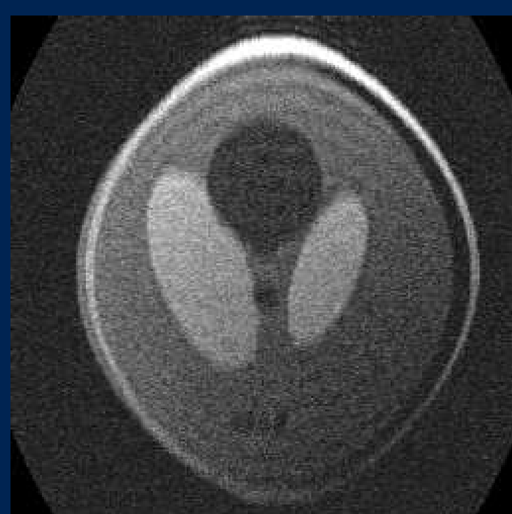
Radiofrequency Interference

- Caused by RF leak
  - Scanner Door is Open
  - Wires running in/out of scan room
  - Faulty Room Shielding

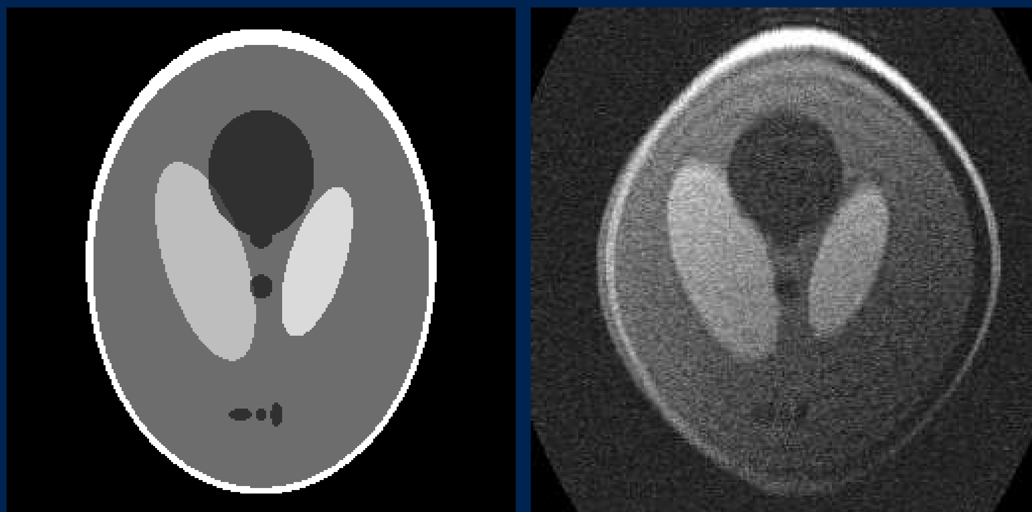
Images Courtesy of http://chickscope.beckman.uiuc.edu/roosts/carl/artifacts.html

How many artifacts can you see?





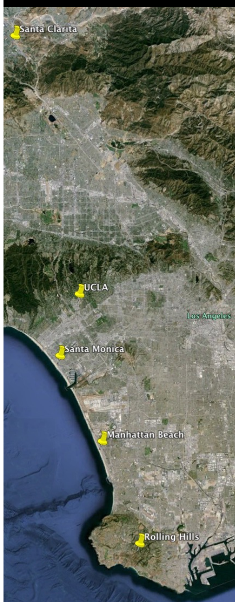
How many artifacts can you see?



Noise
Gradient Distortion
Gibb’s Ringing
Chemical Shift
Coil shading

Summary

UCLA Radiology - MRI Scanners



Westwood - RRMC

3T Trio | 1.5T Avanto | 1.5T Aera

MP100

1.5T Sonata

MP200

Biograpgh mMR

MP300 (Clinical Research)

3T Prisma | 3T Skya | 1.5T Avanto | 3T Vida | 1.5 Aera

TRIC (Research Only)

3T Prisma

Santa Monica - Hospital

3T Skya | 1.5T Avanto

Outpatient WIC

1.5T Avanto | 3T Skya

1919 BIC

3T Skya | 3T Skya

Manhattan Beach

3T Skya

Santa Clarita

3T Skya | 3T Skya

>70T

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MRRL: Mission Statement

Our goal is the development, validation, standardization, and clinical deployment of quantitative MRI techniques for basic science understanding, early diagnosis, treatment guidance, therapeutic response assessment, and prediction of critical biological features for clinical neurology, cardiology, and oncology.

UCLA
Magnetic Resonance Research Labs

2016 MRRL Annual Retreat
@Santa Barbara

MR Innovations and New Directions

Quantitative Imaging

Integrated Diagnostics

MRI, histopathology, molecular, genetic, clinical

Artificial Intelligence

Support / inform clinical decision making


Intra-Departmental Collaborators
DCVI
Paul Finn
Abdominal Imaging Section
David Lu
Steven Raman
Ely Felker
Breast Imaging Section
Anne Hoyt
Melissa Joines
Stephanie Lee-Felker
Pediatric Imaging Section
Shahnaz Ghahremani
Medical Imaging Informatics
Alex Bui
William Hsu
Corey Arnold
Center for Computer Vision and Imaging Biomarkers (CVIB)
Matt Brown


Inter-Departmental Collaborators
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Jason Cong
Mechanical Engineering
Tsu-Chin Tsao
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Sherin Devaskar
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Obstetrics and Gynecology
Carla Janzen
Mathematics
Stanley Osher
Electrical Engineering
Robert Candler
Pathology
Anthony Sisk
Urology
Robert Reiter
Leonard Marks
UCLA Jonsson Comprehensive Cancer Center
UCLA Cardiac Arrhythmia Center
UCLA ENGINEERING Bioengineering
DMD
ipam
Center for Domain Specific Computing
UCLA Graduate Programs in Bioscience

Thanks

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Images/Slides Courtesy of

Daniel Ennis, Ph.D.