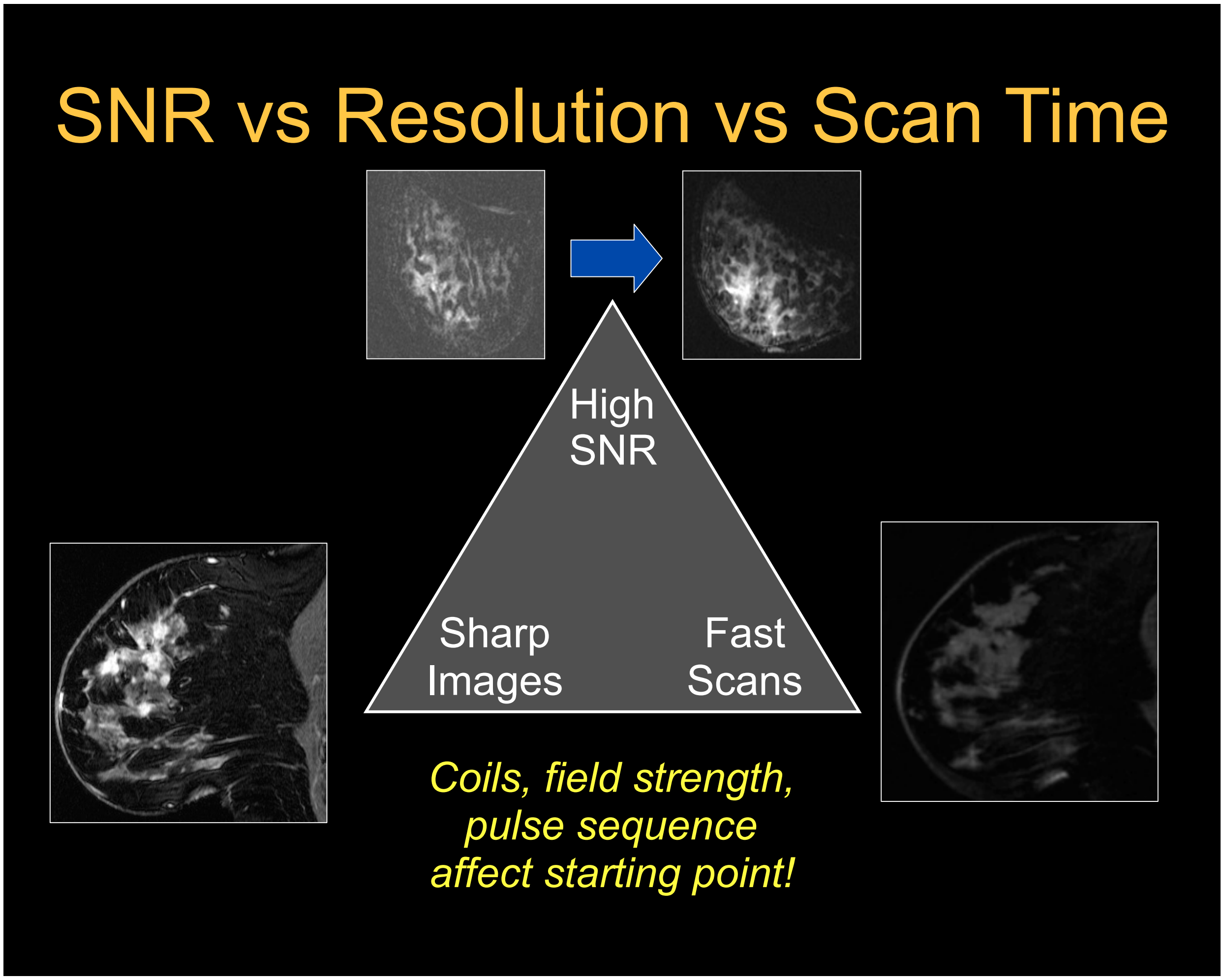
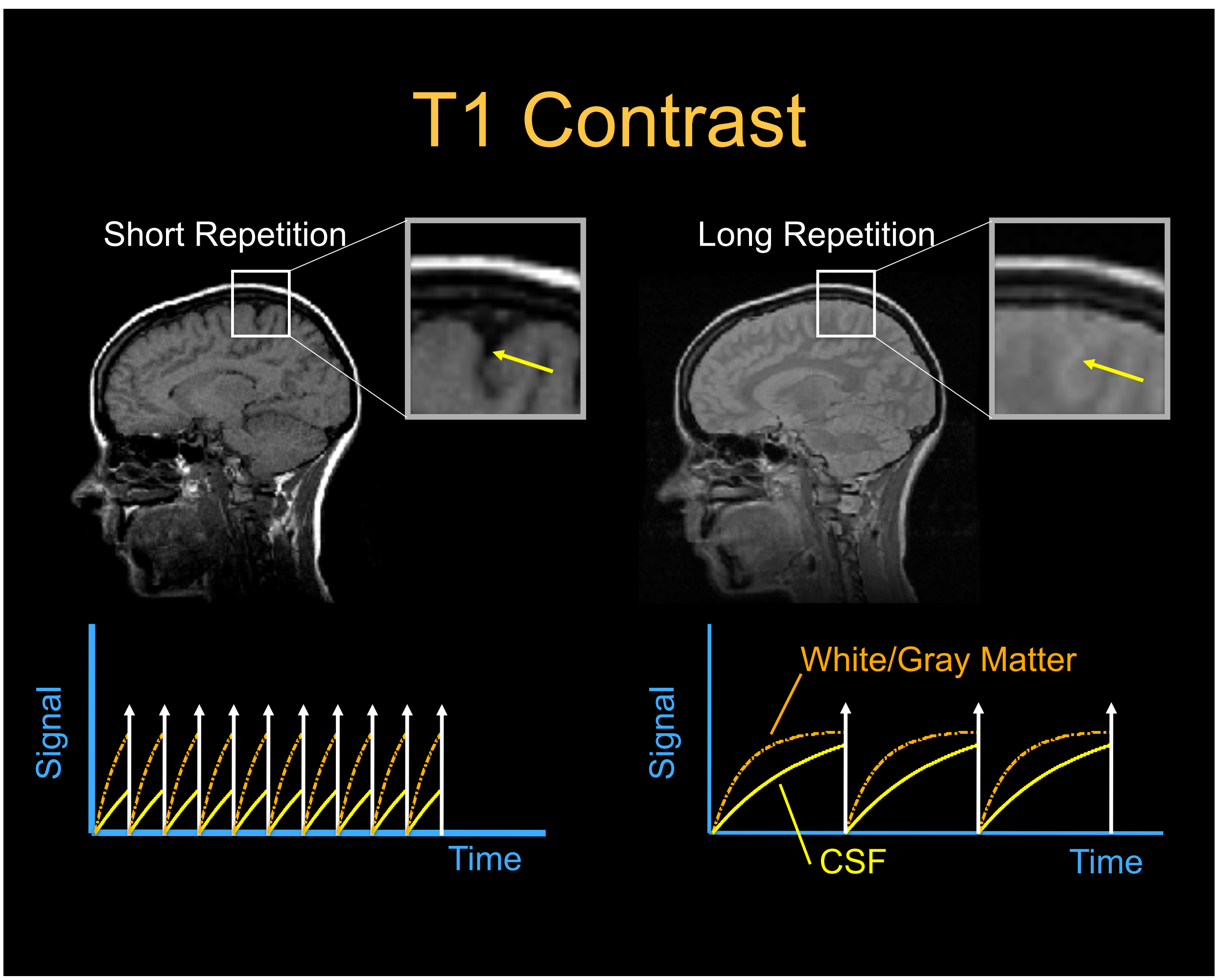
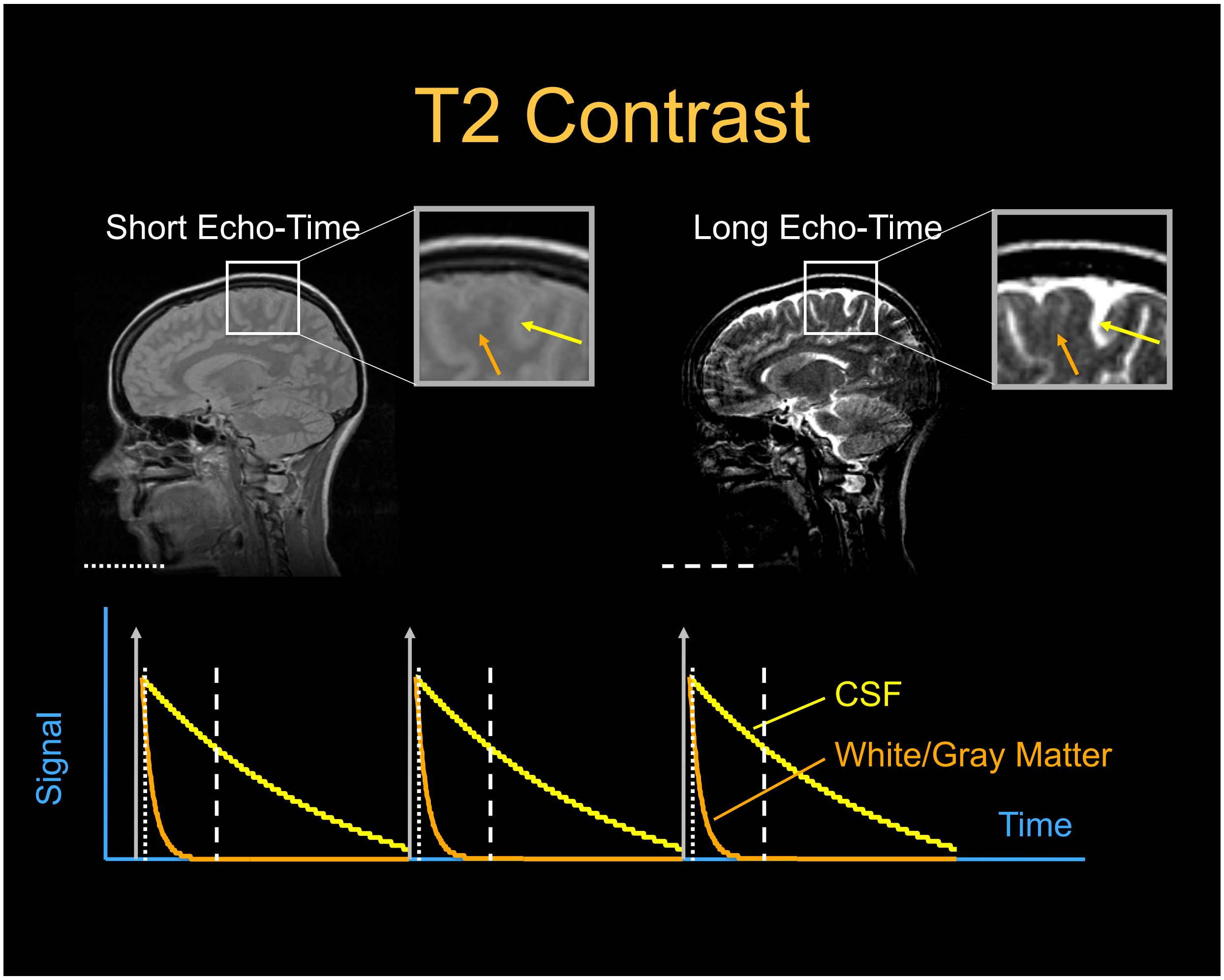
Gradient Echo MRI

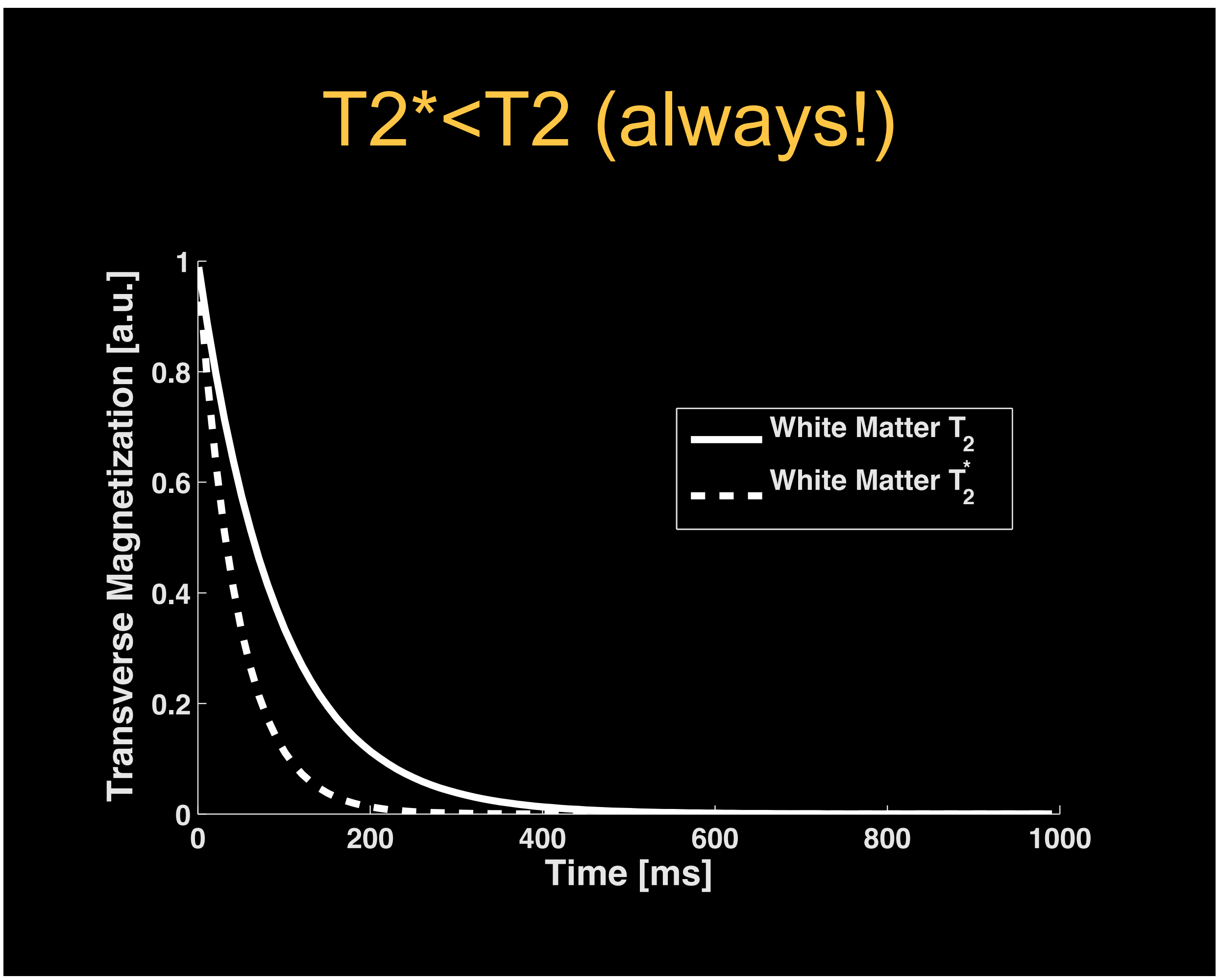
Kyung Sung, Ph.D.
Assistant Professor of Radiology
Magnetic Resonance Research Labs

Review of Spin Echo MRI

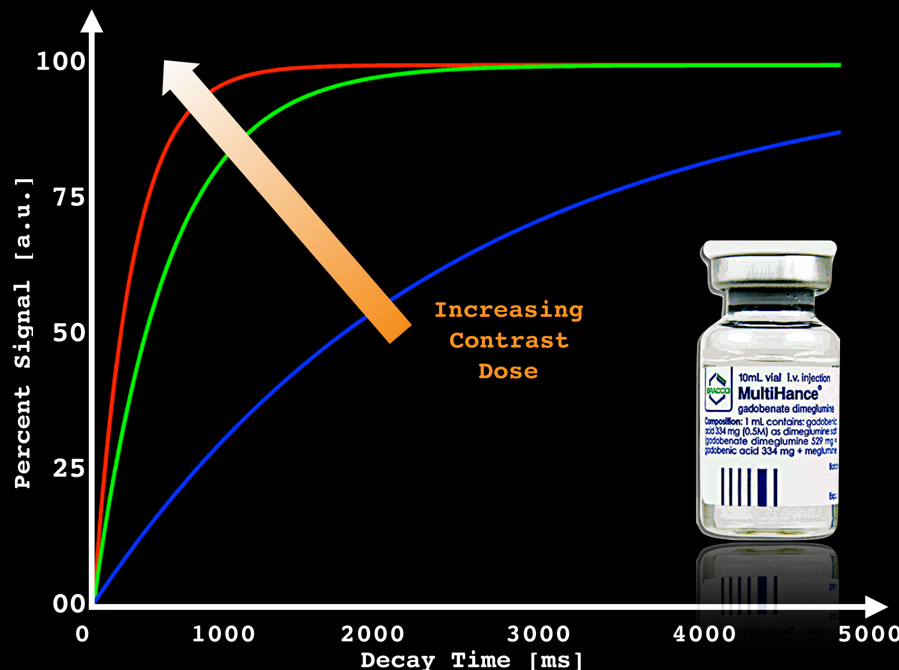

SNR vs Resolution vs Scan Time
High SNR
Sharp Images
Fast Scans
Coils, field strength, pulse sequence affect starting point!


T1 Contrast
Short Repetition
Long Repetition
Signal
Time
White/Gray Matter
Signal
CSF
Time


T2 Contrast
Short Echo-Time
Long Echo-Time
Signal
CSF
White/Gray Matter
Time


T2*<T2 (always!)
Transverse Magnetization [a.u.]
1
0.8
0.6
0.4
0.2
0
0
200
400
600
800
1000
Time [ms]
White Matter T2
White Matter T2*

T1 Shortening Agents



Increasing dose of a T1 shortening agent increases signal, ***but*** too much contrast is unsafe and will compromise image quality.

Spin Echo Contrast

$$A_{Echo} \propto \rho \left(1 - e^{-TR/T_1}\right) e^{-TE/T_2}$$

Longer TR minimizes T1 contrast

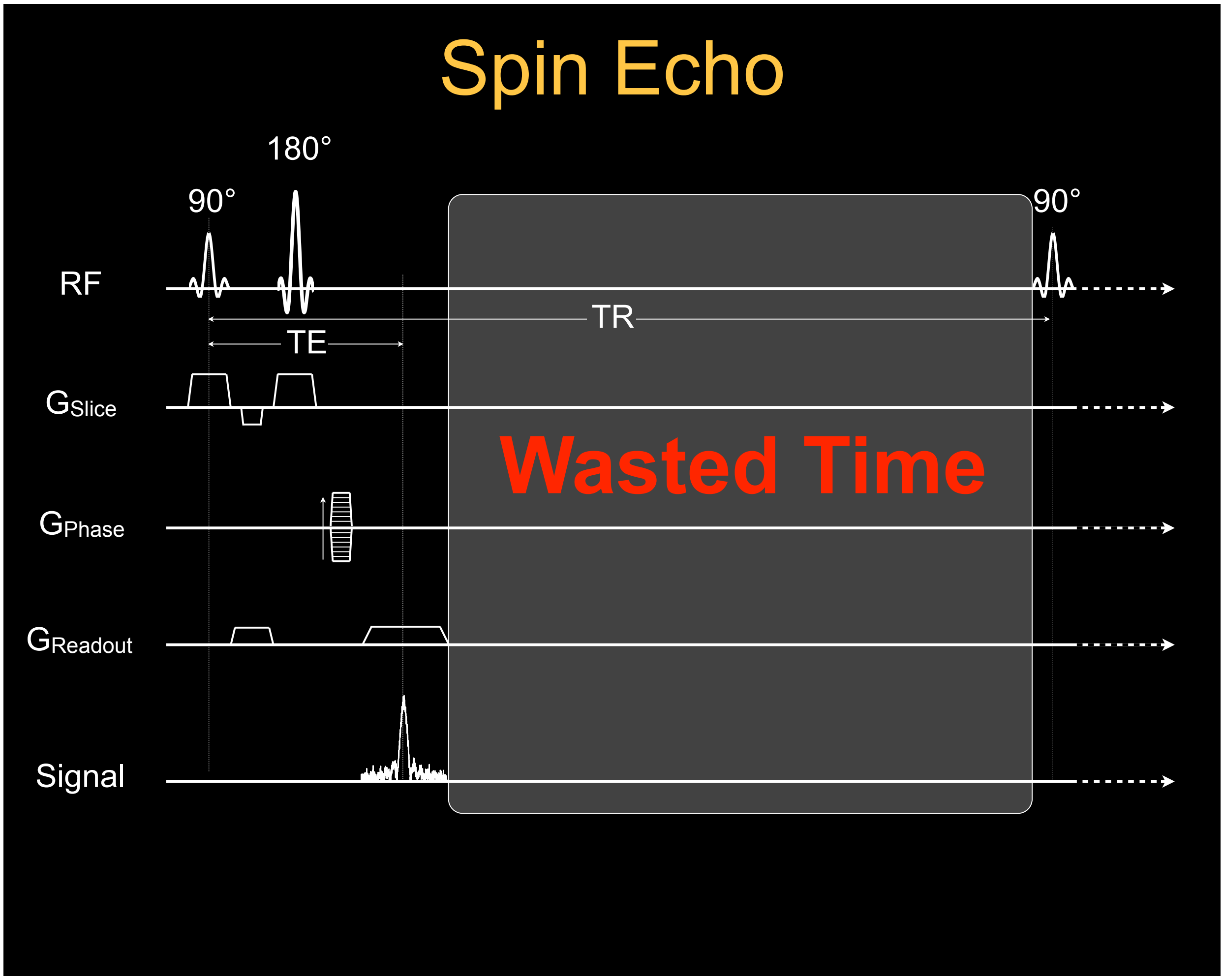
Short TE minimizes T2 contrast

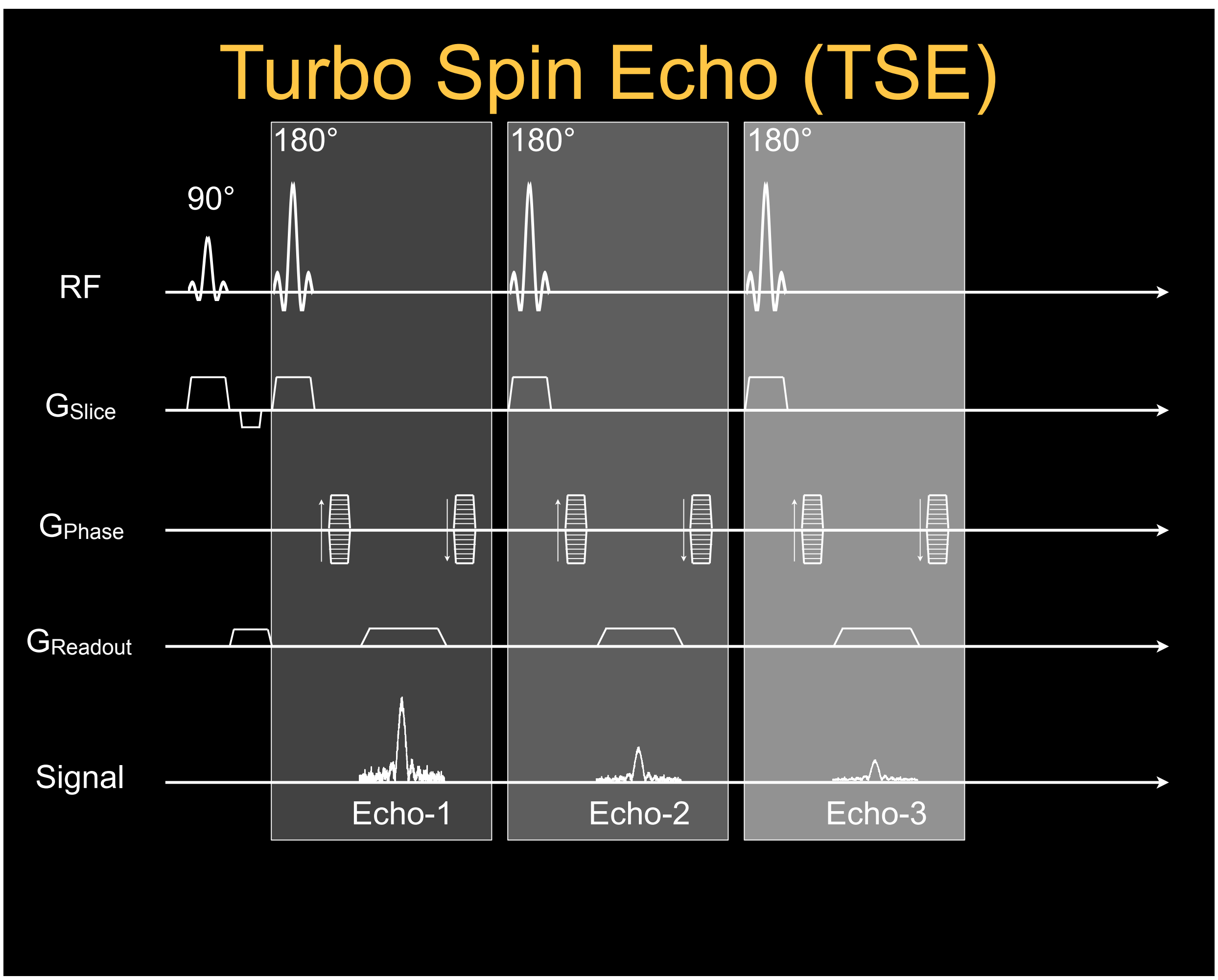
Intermediate TR maximizes T1 contrast

Intermediate TE maximizes T2 contrast

Spin Echo Parameters

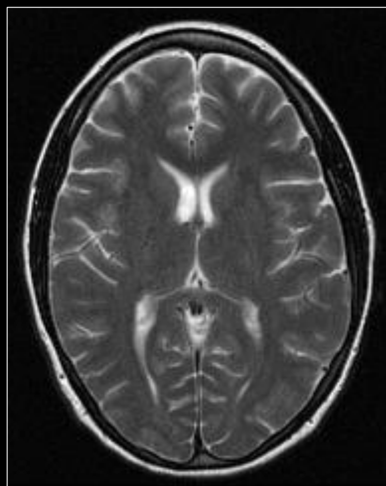
	TE	TR
Spin Density	Short	Long
T_1-Weighted	Short	Intermediate
T_2-Weighted	Intermediate	Long


Spin Echo
180°
90°
90°
RF
TR
TE
GSlice
Wasted Time
GPhase
GReadout
Signal


Turbo Spin Echo (TSE)
180°
180°
180°
90°
RF
GSlice
GPhase
GReadout
Signal
Echo-1
Echo-2
Echo-3

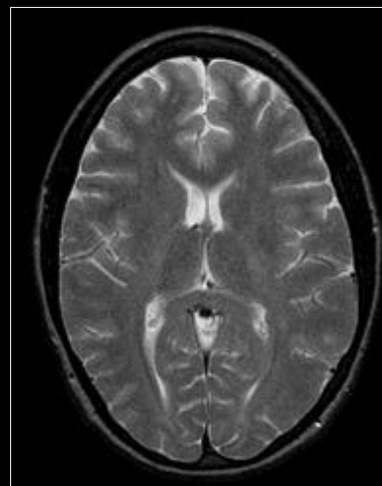
Turbo Spin Echo vs. Spin Echo

Fast Spin Echo



TR = 2500
TE = 116
ETL = 16
NEX = 2
24 slices
17 slices/pass
2 passes
Time = 2:51

Spin Echo



TR = 2500
TE = 112
ETL = N/A
NEX = 1
24 slices
20 slices/pass
2 passes
Time = 22:21

Shorter scan time.
More T2-weighted.
Fat is brighter.
Higher SAR.

Images: Courtesy Frank Korosec

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	

Relaxation - True or False?

1. $T_2^* > T_2 > T_1$

2. Long T_1s appear bright on a T_1-weighted image

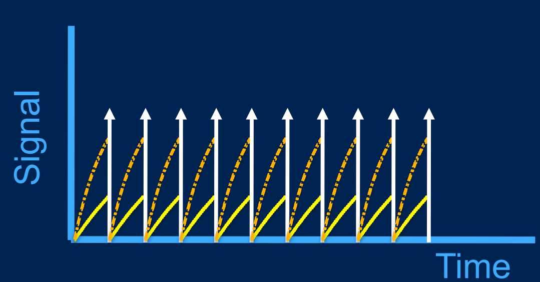
3. Short T_2s appear dark on a T_2-weighted image

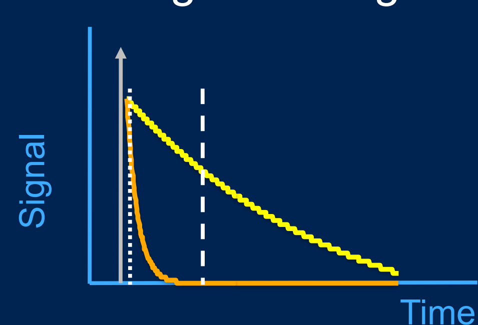
Relaxation - True or False?

1. $T_2^* > T_2 > T_1$

2. Long T_1s appear bright on a T_1-weighted image

3. Short T_2s appear dark on a T_2-weighted image





Relaxation - True or False?

1. T_1(CSF) > T_1(Gray Matter)

2. T_2(Liver) < T_2(Fat)

Relaxation - True or False?

1. T_1(CSF) > T_1(Gray Matter)

2. T_2(Liver) < T_2(Fat)

Tissue	T_1 [ms]	T_2 [ms]
gray matter	925	100
white matter	790	92
muscle	875	47
fat	260	85
kidney	650	58
liver	500	43
CSF	2400	180

Quiz: Contrast Agents - True or False?

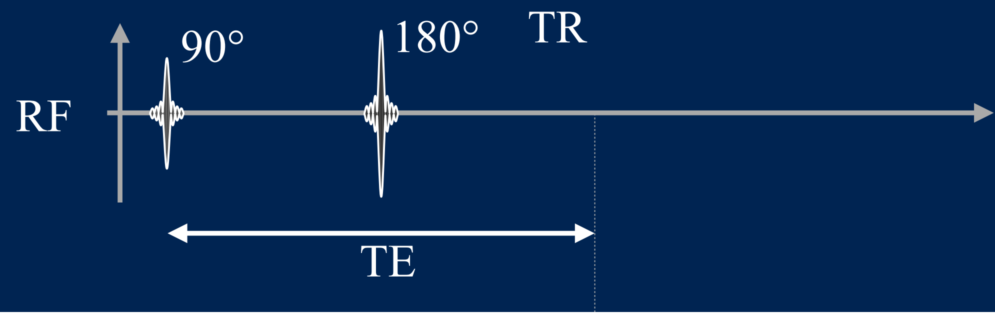
1. Gadolinium-based agents act to lengthen T_1.
2. MRI contrast agents are widely considered very safe.

Spin Echoes - True or False?

1. The 90-180 pair is the hallmark of the spin echo sequence.
2. The 180 pulse is an inversion pulse.
3. Spin echoes are ultrafast sequences that provide T_1 or T_2^* weighted images.

Spin Echoes - True or False?

1. The 90-180 pair is the hallmark of the spin echo sequence.
2. The 180 pulse is an inversion pulse.
3. Spin echoes are ultrafast sequences that provide T_1 or T_2^* weighted images.



Spin Echoes - True or False?

1. Long TE and long TR for T2-weighted.
2. Short TE and short TR for T1-weighted.
3. Spin echoes are low SAR sequences.

Spin Echoes - True or False?

1. Long TE and long TR for T2-weighted.
2. Short TE and short TR for T1-weighted.
3. Spin echoes are low SAR sequences.

$$A_{Echo} \propto \rho \left(1 - e^{-TR/T_1}\right) e^{-TE/T_2}$$

Longer TR minimizes T1 contrast

Short TE minimizes T2 contrast

Multi-Echo Imaging - True or False?

1. Multi-echo imaging can decrease scan times by 2x or more.
2. Turbo spin echo is excellent for fast T2-weighted imaging.
3. Spin Echo EPI is routine for diffusion weighted imaging.

Fast Imaging - True or False?

1. Long TRs are important for T2 weighted imaging because they eliminate T1-contrast.

2. Slice interleaving is better suited for T2-weighted imaging than T1-weighted.

3. Multi-echo imaging can be combined with multi-slice imaging.

Gradient Echo Imaging

Gradient Echo Sequences

- Spoiled Gradient Echo
  - SPGR, FLASH, T1-FFE
- Balanced Steady-State Free Precession
  - TrueFISP, FIESTA, Balanced FFE

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
- Low SAR
  - **Why?** Imaging flip angles are (typically) small
  - **When?** When heating risks are a concern

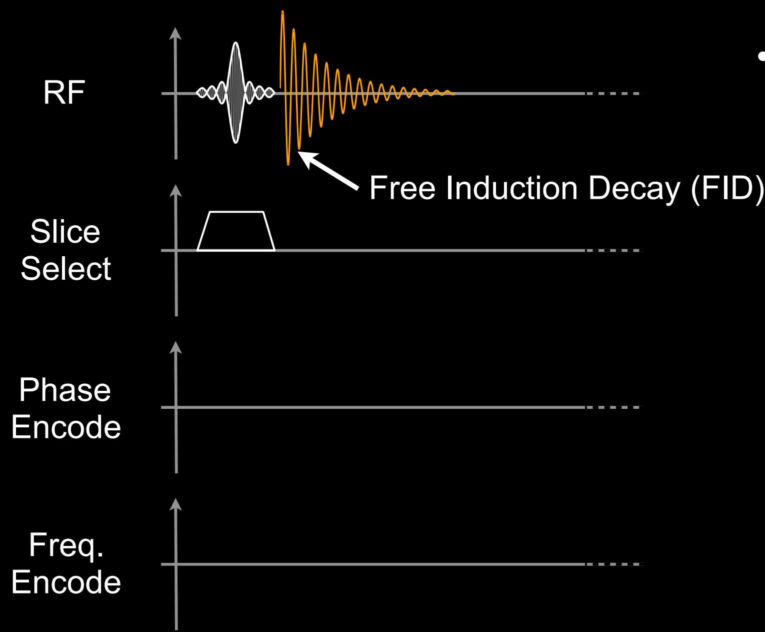
Principal GRE Advantages

- 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
- Reduced Slice Cross-talk
  - **Why?** SE hard to match slice profile of 90° & 180°
  - **When?** Little or no slice gap for 2D multi-slice
- More...

Principal GRE Disadvantages

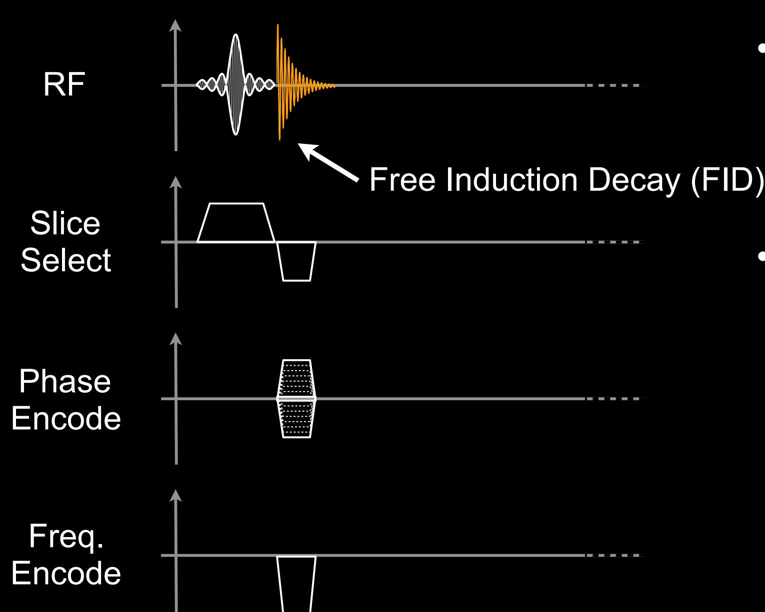
- Off-resonance sensitivity
  - **Why?** No refocusing pulse
    - Field inhomogeneity, Susceptibility, & Chemical shift
- T_2^*-weighted rather than T_2-weighted
  - **Why?** No re-focusing pulse
    - Spin-spin dephasing is not reversible with GRE
- Larger metal artifacts than SE
  - Why? No refocusing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

Basic Gradient Echo Sequence



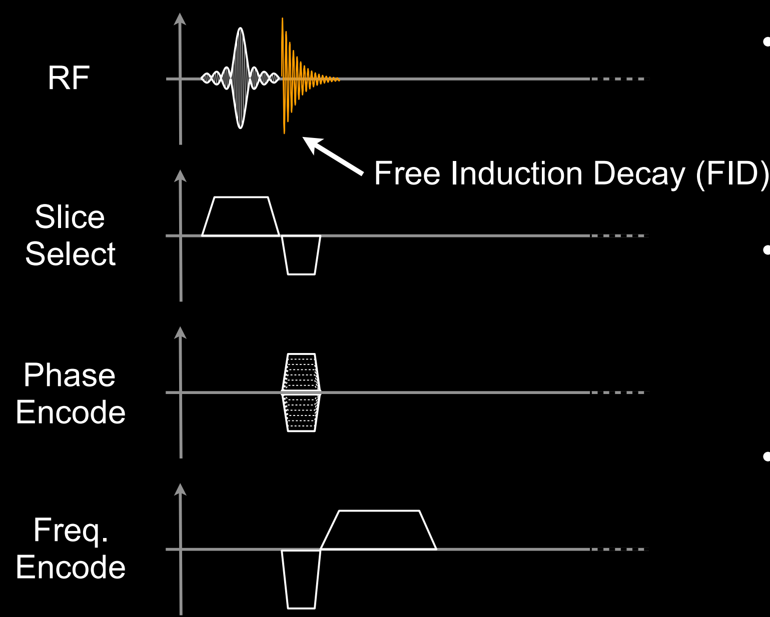
- FID Decay due to
  - T2 decay
  - Spin dephasing

Basic Gradient Echo Sequence



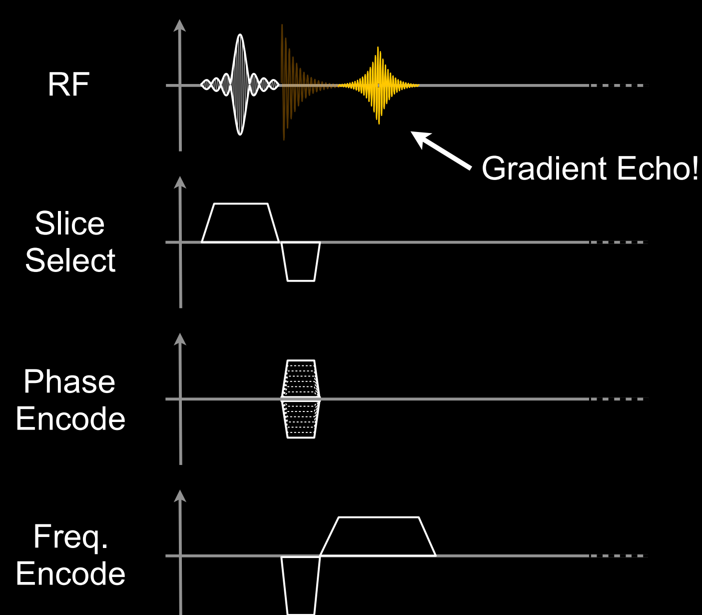
- FID Decay due to
  - T2 decay
  - Spin dephasing
- Gradients accelerate spin dephasing

Basic Gradient Echo Sequence



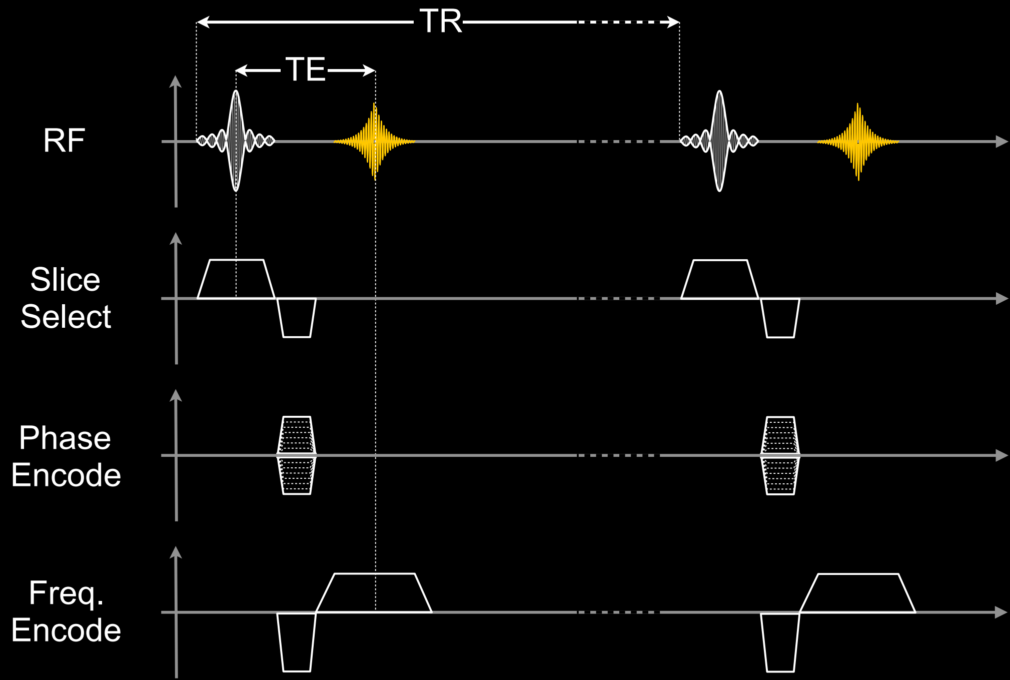
- FID Decay due to
  - T2 decay
  - Spin dephasing
- Gradients accelerate spin dephasing
- Gradients can undo gradient induced spin dephasing

Basic Gradient Echo Sequence

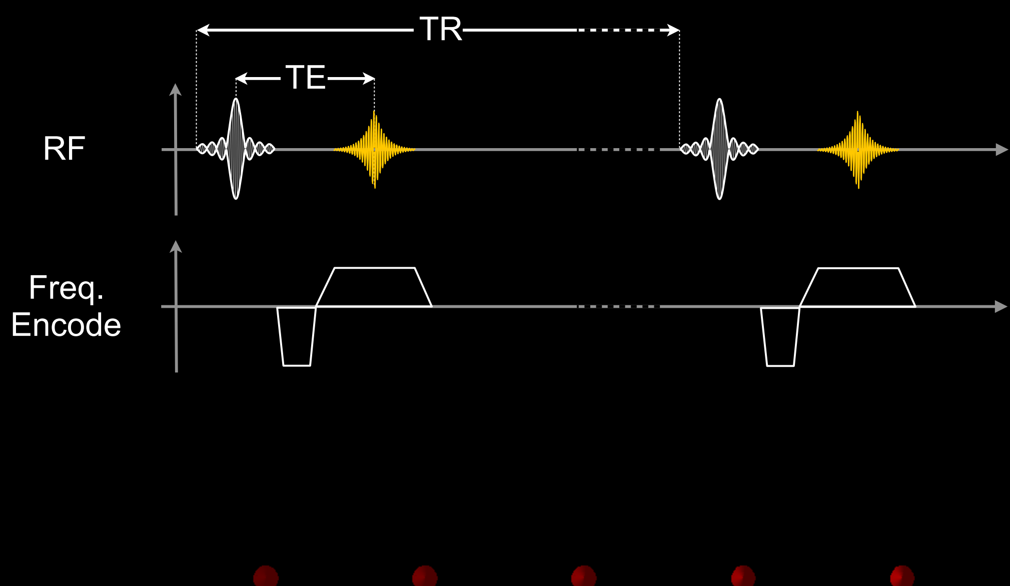


- FID Decay due to
  - T2 decay
  - Spin dephasing
- Gradients accelerate spin dephasing
- Gradients can undo gradient induced spin dephasing

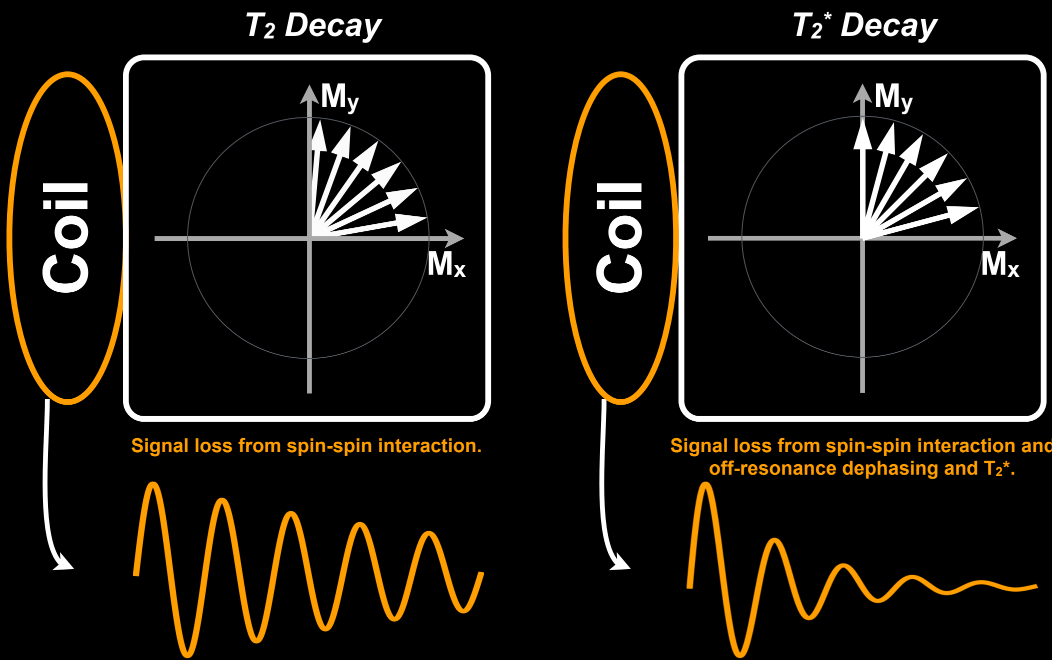
Basic Gradient Echo Sequence



Basic Gradient Echo Sequence

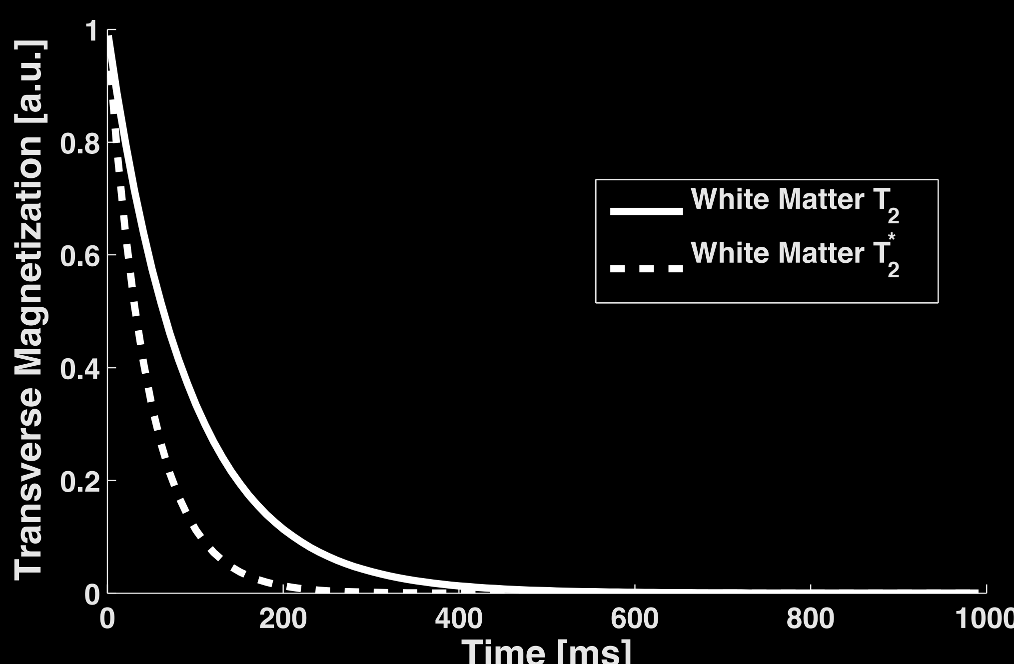


T_2 versus T_2^*



T_2^* is signal loss from spin dephasing and T_2

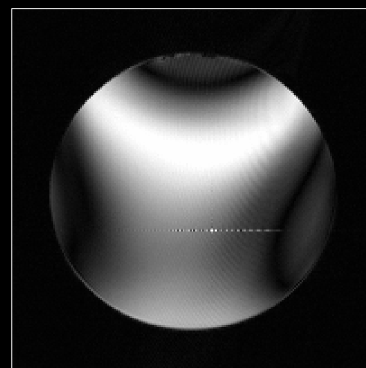
T2*<T2 (always!)



SE vs. GRE: B_0 Inhomogeneity

- Images acquired with a bad shim
  - Poor B_0 homogeneity (lots of off-resonance)

Spin Echo



Gradient Echo

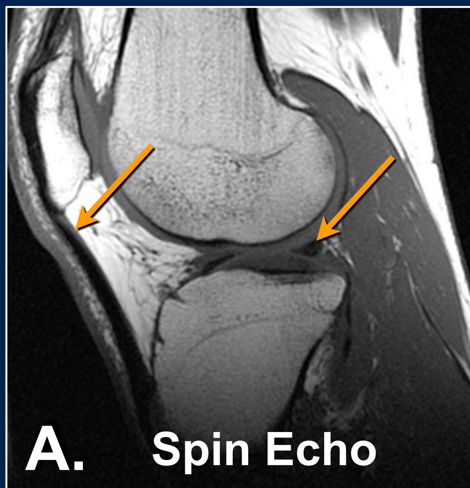
Images Courtesy of http://chickscope.beckman.uiuc.edu/roosts/carl/artifacts.html

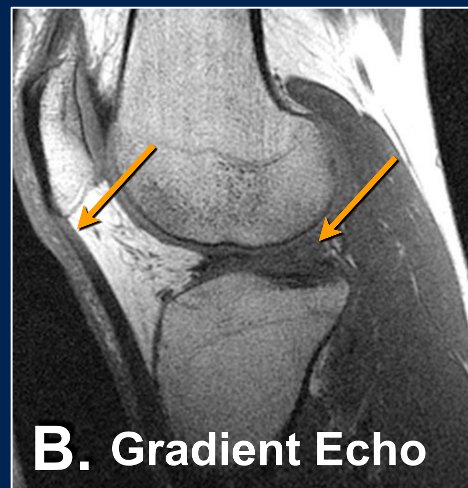
Gradient vs. Spin Echo

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 Echoes & Contrast

Spoiled Gradient Echo Contrast

Contrast depends on tissue's ρ, T_1 and T_2*.

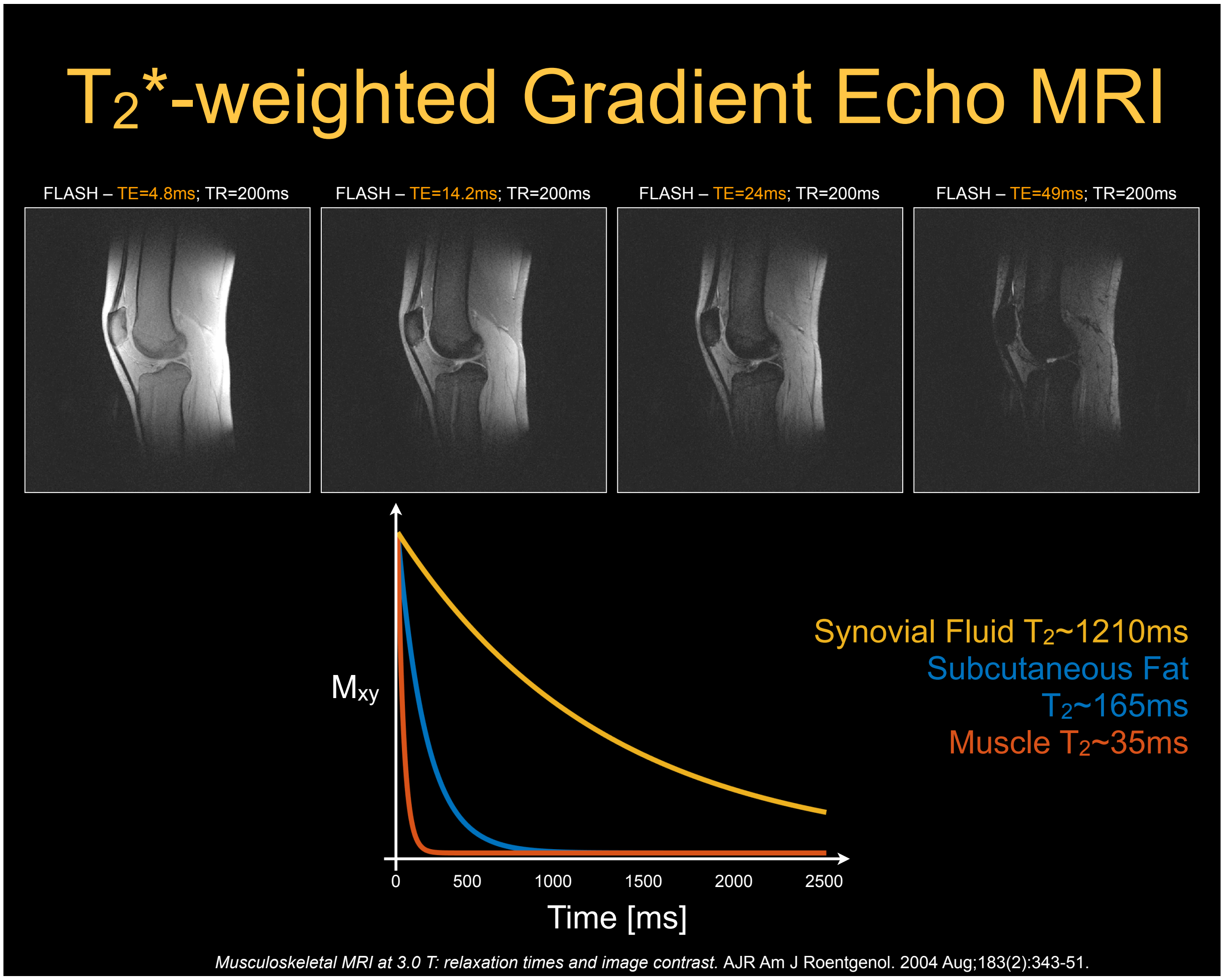
$$A_{echo} \propto \frac{\rho\left(1 - e^{-TR/T_1}\right)}{1 - \cos\alpha e^{-TR/T_1}} \sin\alpha e^{-TE/T_2^*}$$

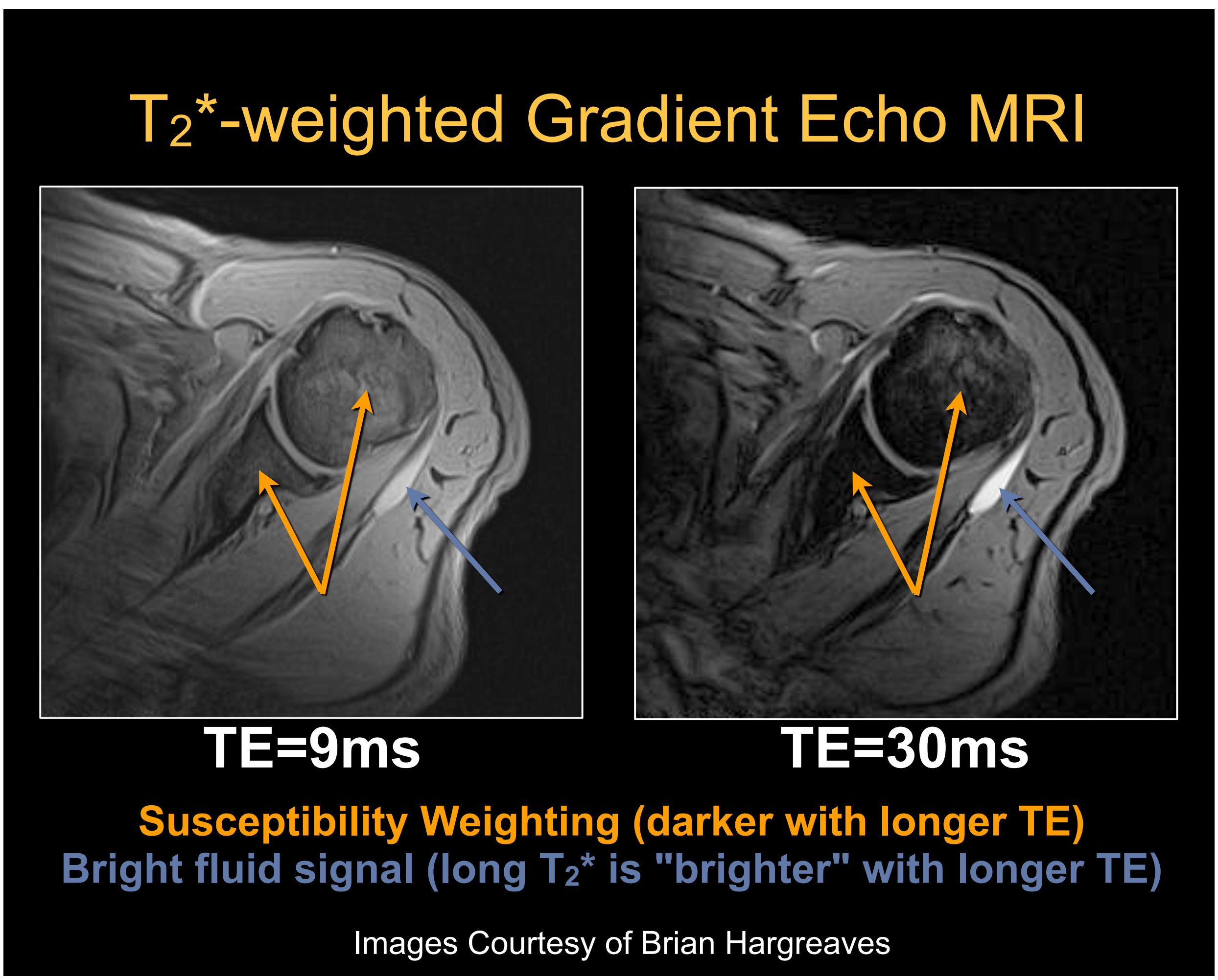
Contrast adjusted by changing TR, flip angle, and TE

Spoiled Gradient Echo Contrast

Gradient Echo Parameters

Type of Contrast	TE	TR	Flip Angle
Spin Density	Short	Long	Small
T_1-Weighted	Short	Intermediate	Large
T_2^*-Weighted	Intermediate	Long	Small


T2*-weighted Gradient Echo MRI
FLASH – TE=4.8ms; TR=200ms
FLASH – TE=14.2ms; TR=200ms
FLASH – TE=24ms; TR=200ms
FLASH – TE=49ms; TR=200ms
Mxy
Synovial Fluid T2~1210ms
Subcutaneous Fat
T2~165ms
Muscle T2~35ms
0
500
1000
1500
2000
2500
Time [ms]
Musculoskeletal MRI at 3.0 T: relaxation times and image contrast. AJR Am J Roentgenol. 2004 Aug;183(2):343-51.


T2*-weighted Gradient Echo MRI
TE=9ms
TE=30ms
Susceptibility Weighting (darker with longer TE)
Bright fluid signal (long T2* is "brighter" with longer TE)
Images Courtesy of Brian Hargreaves

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

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.

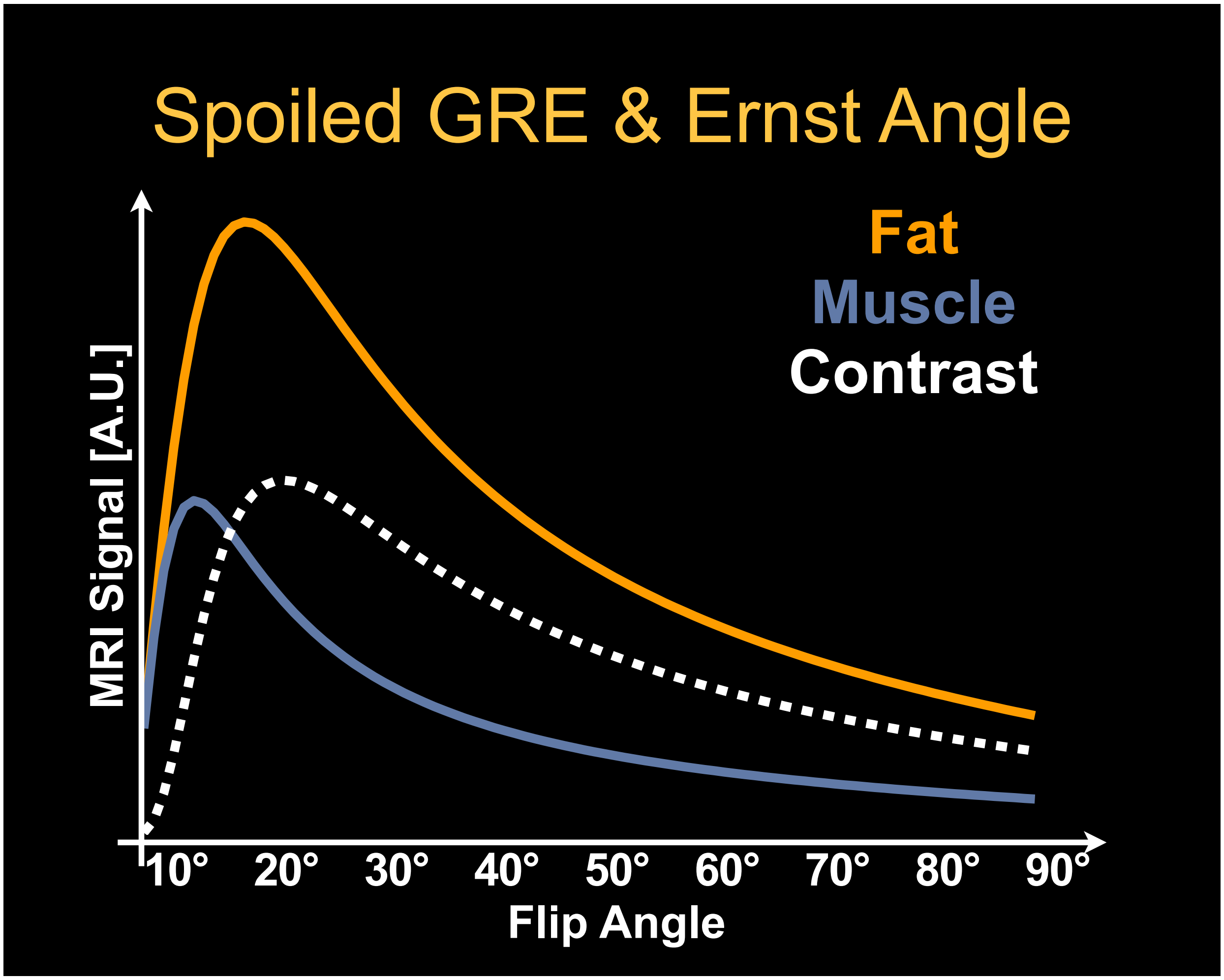
Gradient Echoes & Flip Angle

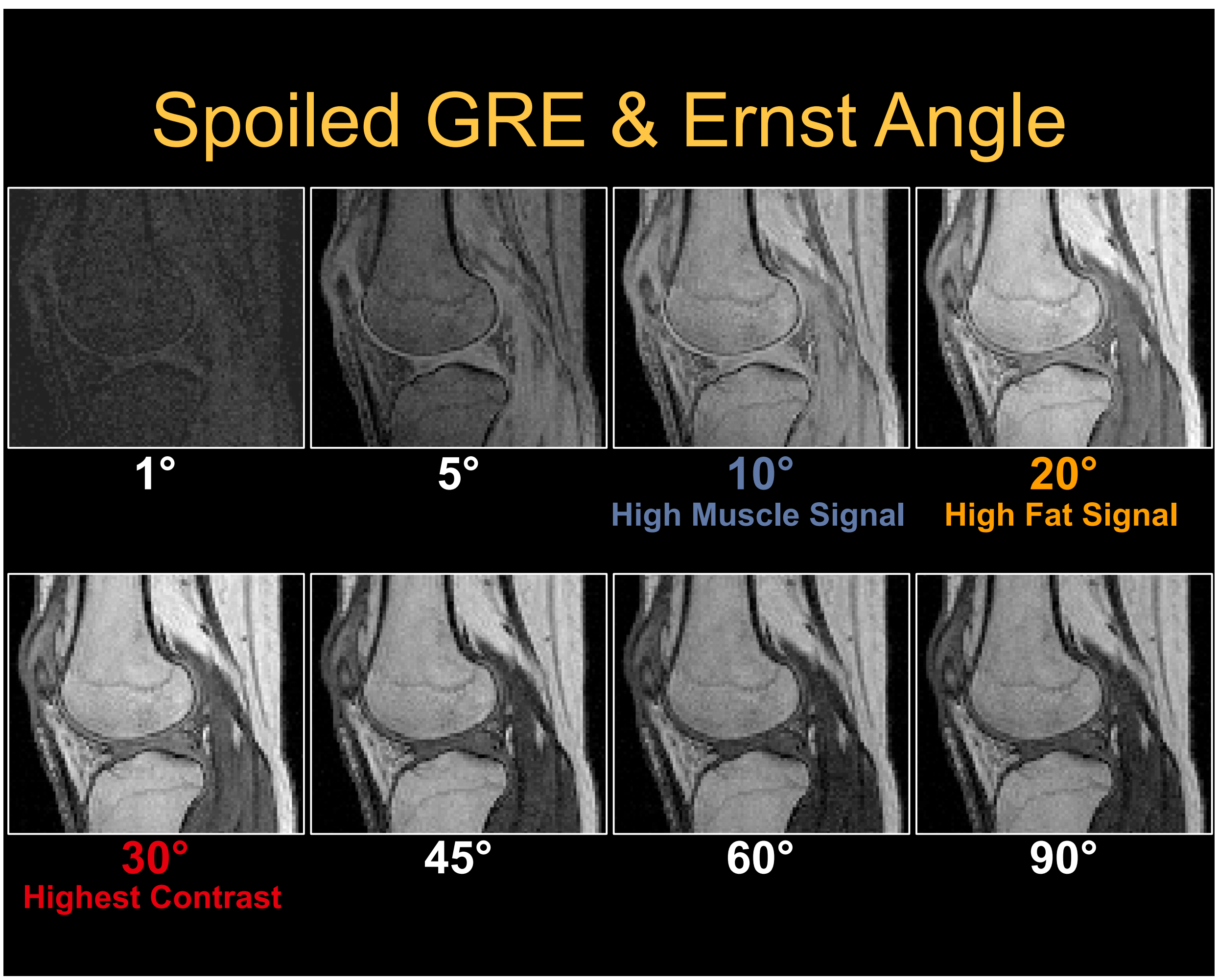
Spoiled GRE & Ernst Angle

$$\alpha_{Ernst} = \arccos\left(e^{-\frac{TR}{T_1}}\right)$$

Produces the largest MRI signal for a given TR and T_1

Tissue	T_1 [ms]	T_2 [ms]
muscle	875	47
fat	260	85


Spoiled GRE & Ernst Angle
Fat
Muscle
Contrast
MRI Signal [A.U.]
10° 20° 30° 40° 50° 60° 70° 80° 90°
Flip Angle


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

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.

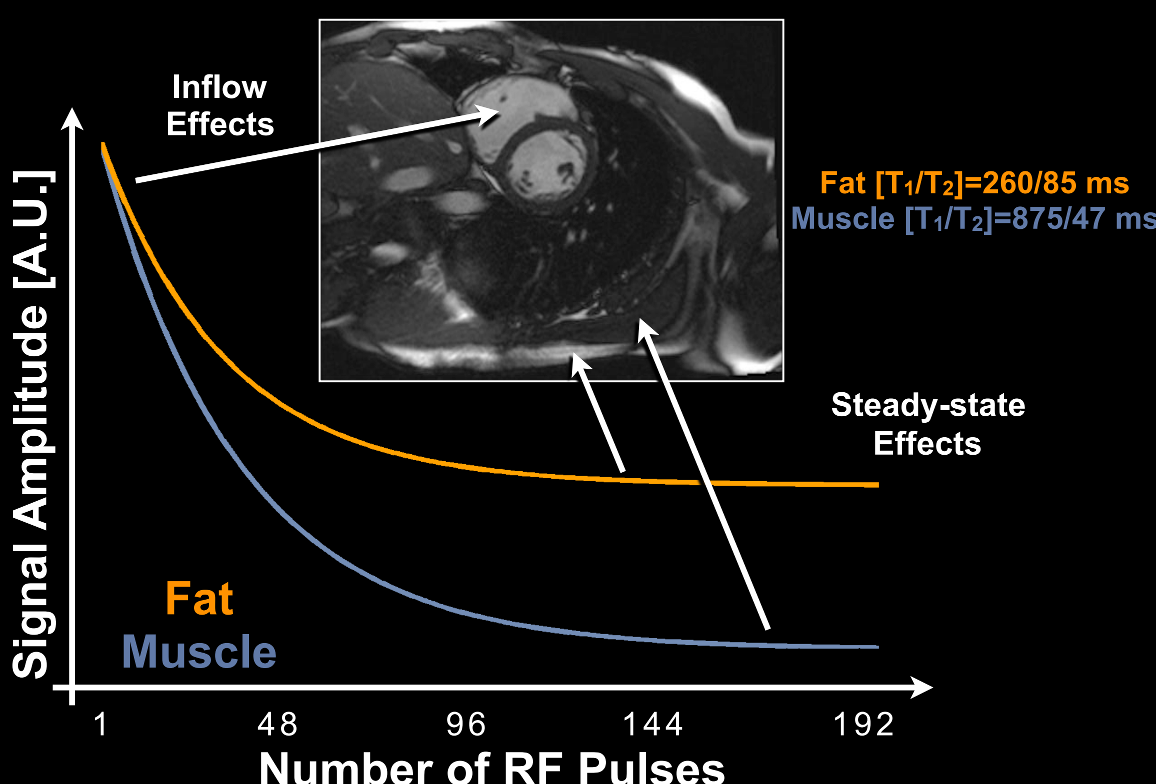
Gradient Echoes & Flow

Principle of In-flow Enhancement

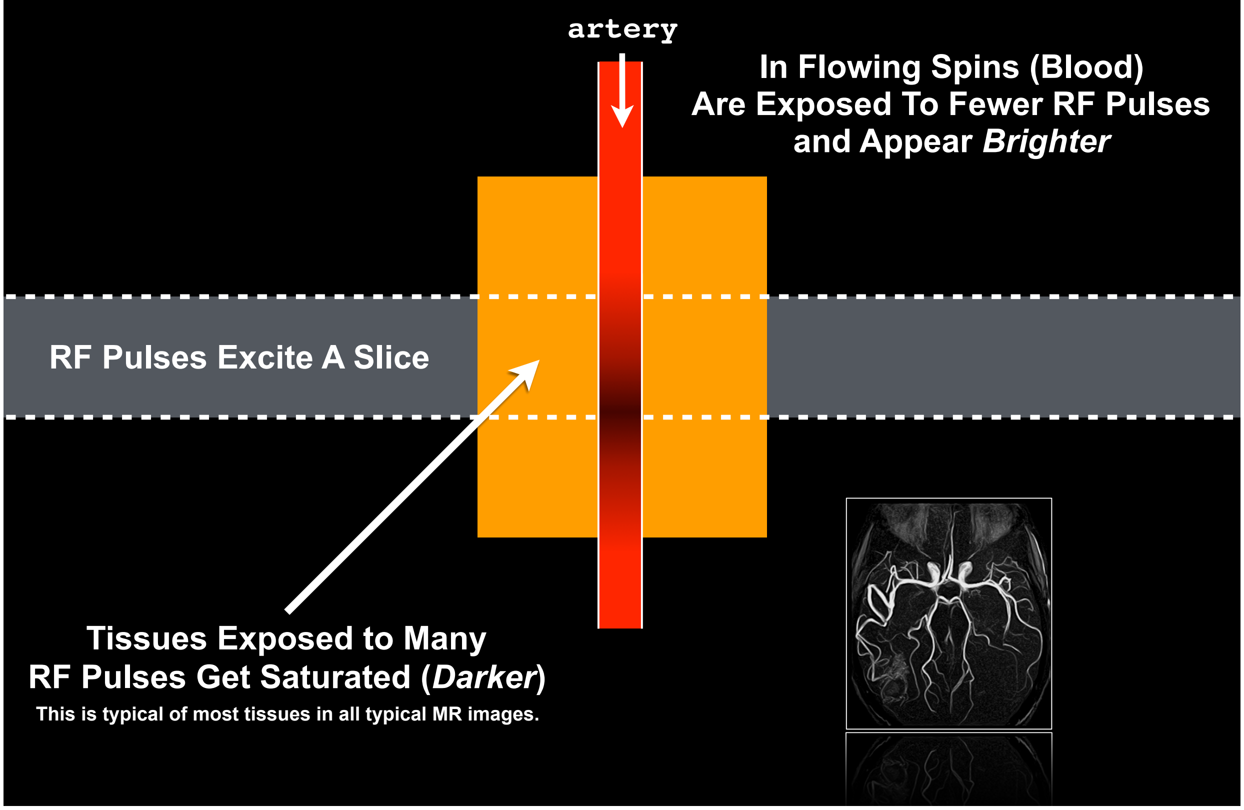
- Partial saturation of stationary tissue
  - If TR<<T1, tissue can't fully relax each TR
- Inflow of fully relaxed spins
  - These spins haven't seen an RF pulse
- In combination high contrast is achieved

Time-of-flight uses In-flow Enhancement and MIPs to visualize the vasculature.

Principle of In-flow Enhancement

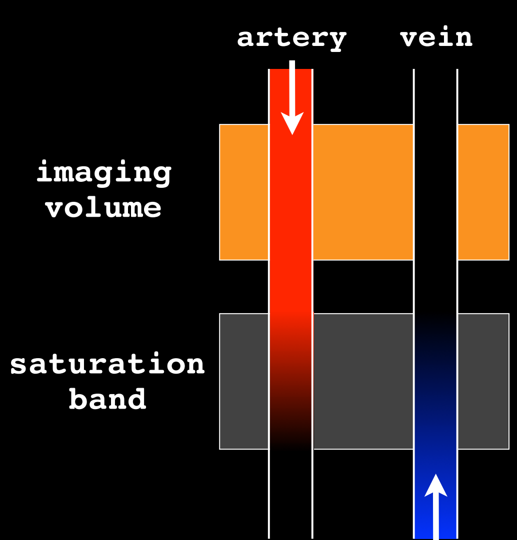


Principle of In-flow Enhancement



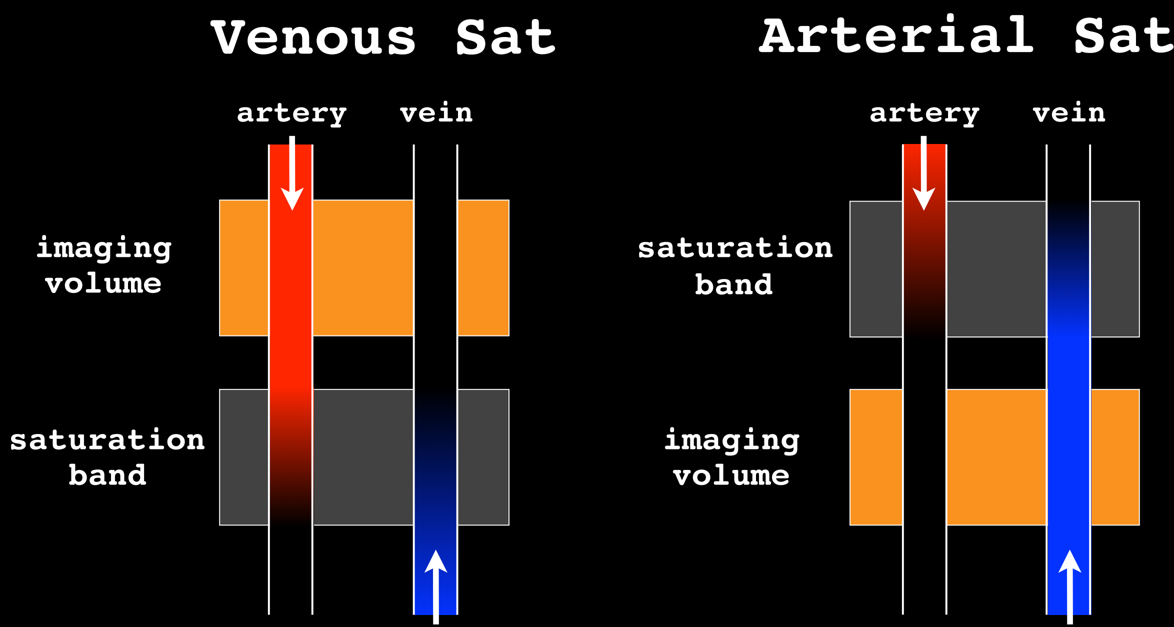
Spatial Pre-saturation

Venous Sat



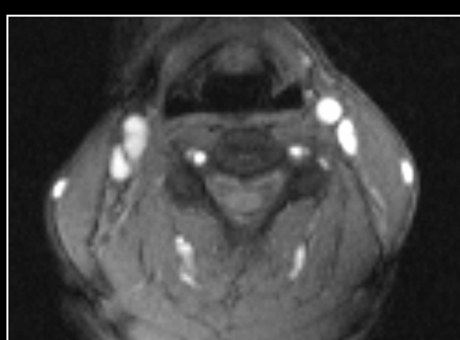
Saturation bands suppress tissue signals.

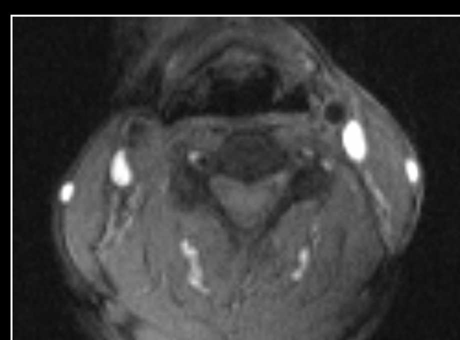
Spatial Pre-saturation

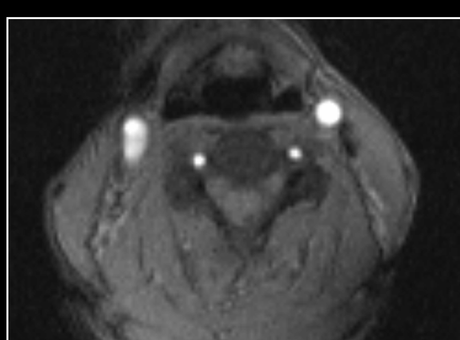


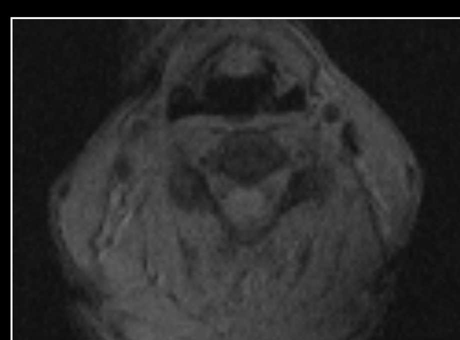
Saturation bands can suppress arterial or venous flow.

Spatial Pre-saturation


no sat


arterial sat


venous sat


parallel sat

Gradient Echoes & Spoiling

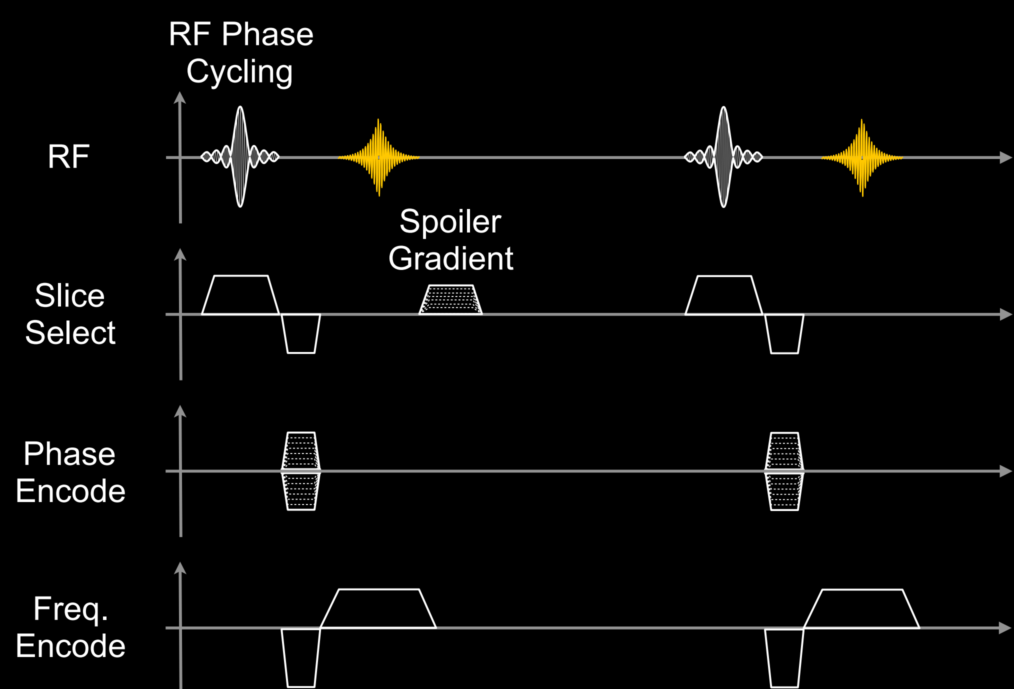
Spoiling - Why?

- Eliminates M_{xy} at end of each TR
  - Prevents cumulative errors
- Shortens the TR
  - Without spoilers have to wait 5x T_2*
  - Faster imaging
- Enhances T_1 contrast

Spoiling - How?

- Long TR
  - Choose TR 4-5x T_2*
- Gradient spoiling
  - Applied at end of TR
  - Dephases spins within voxel
- RF spoiling
  - Cycle the phase of the RF pulse
  - Minimizes coherent signal pathways

Gradient Echo + Spoiling



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

Gradient Echoes - True or False?

1. Echoes are needed because the FID disappears too quickly.
2. GRE is less sensitive to off-resonance than spin echo imaging.
3. GRE uses a refocusing pulse to form an echo.
4. Gradient and RF spoiling enable faster imaging.

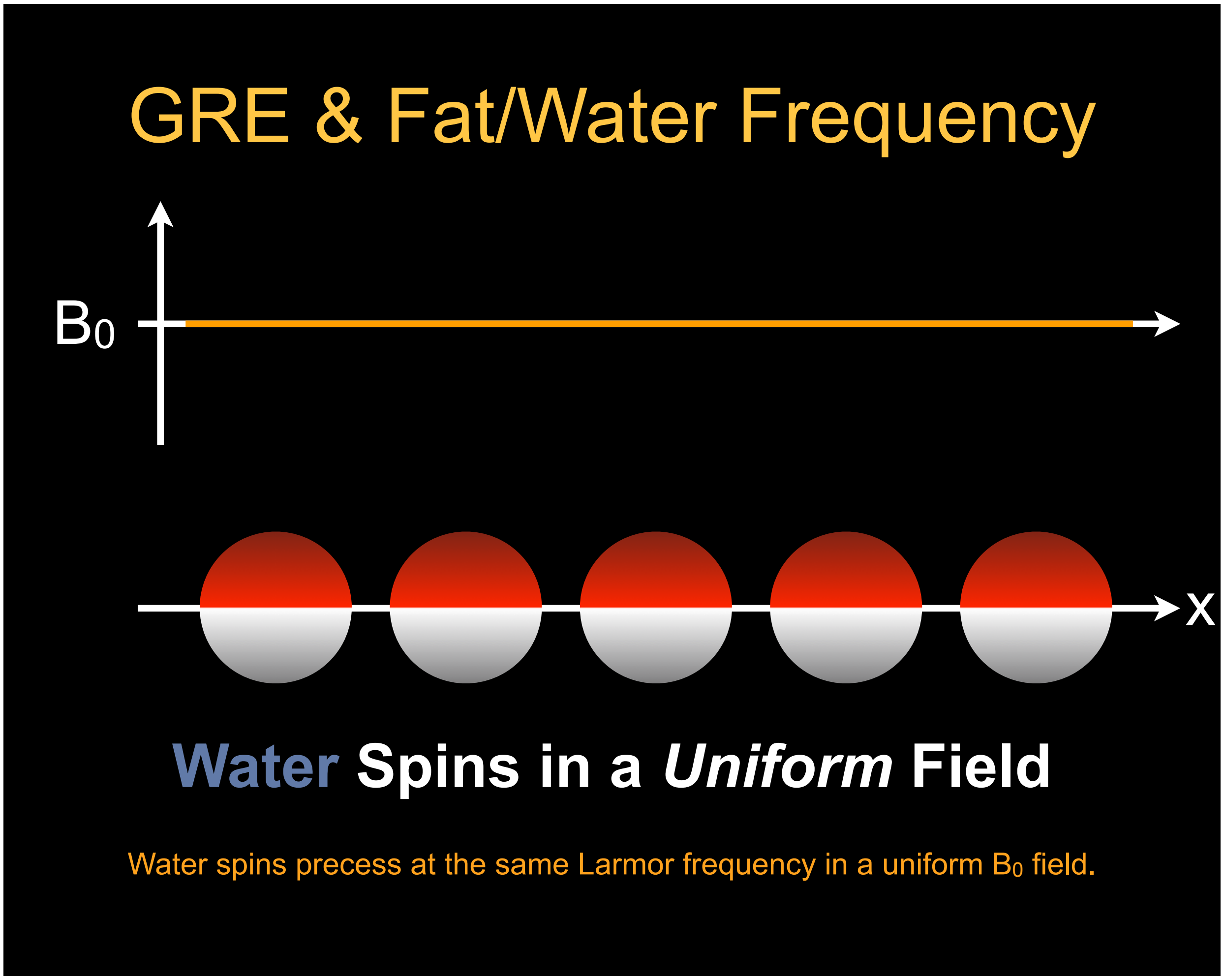
Gradient Echoes & Fat

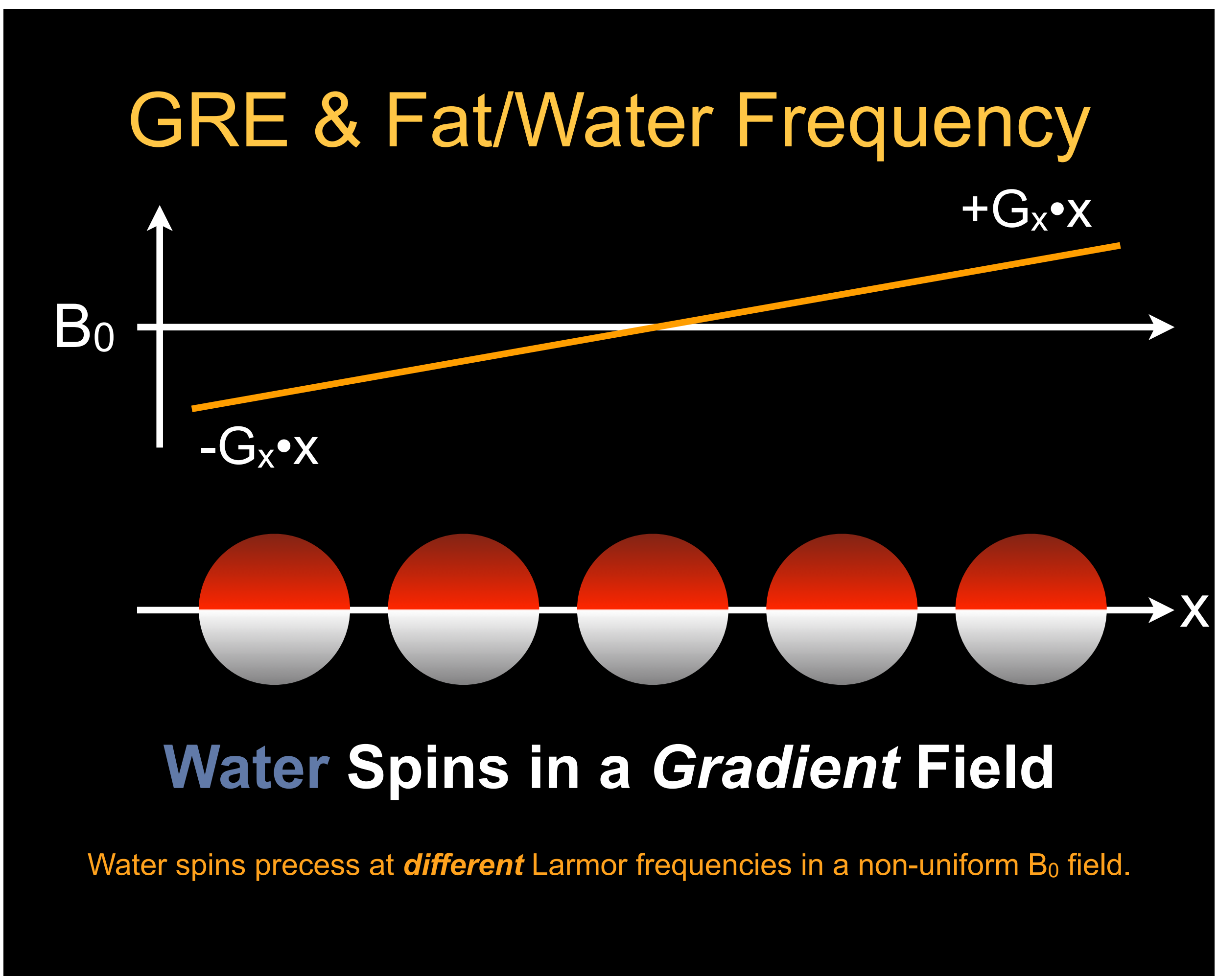
Chemical Shift - Type 1

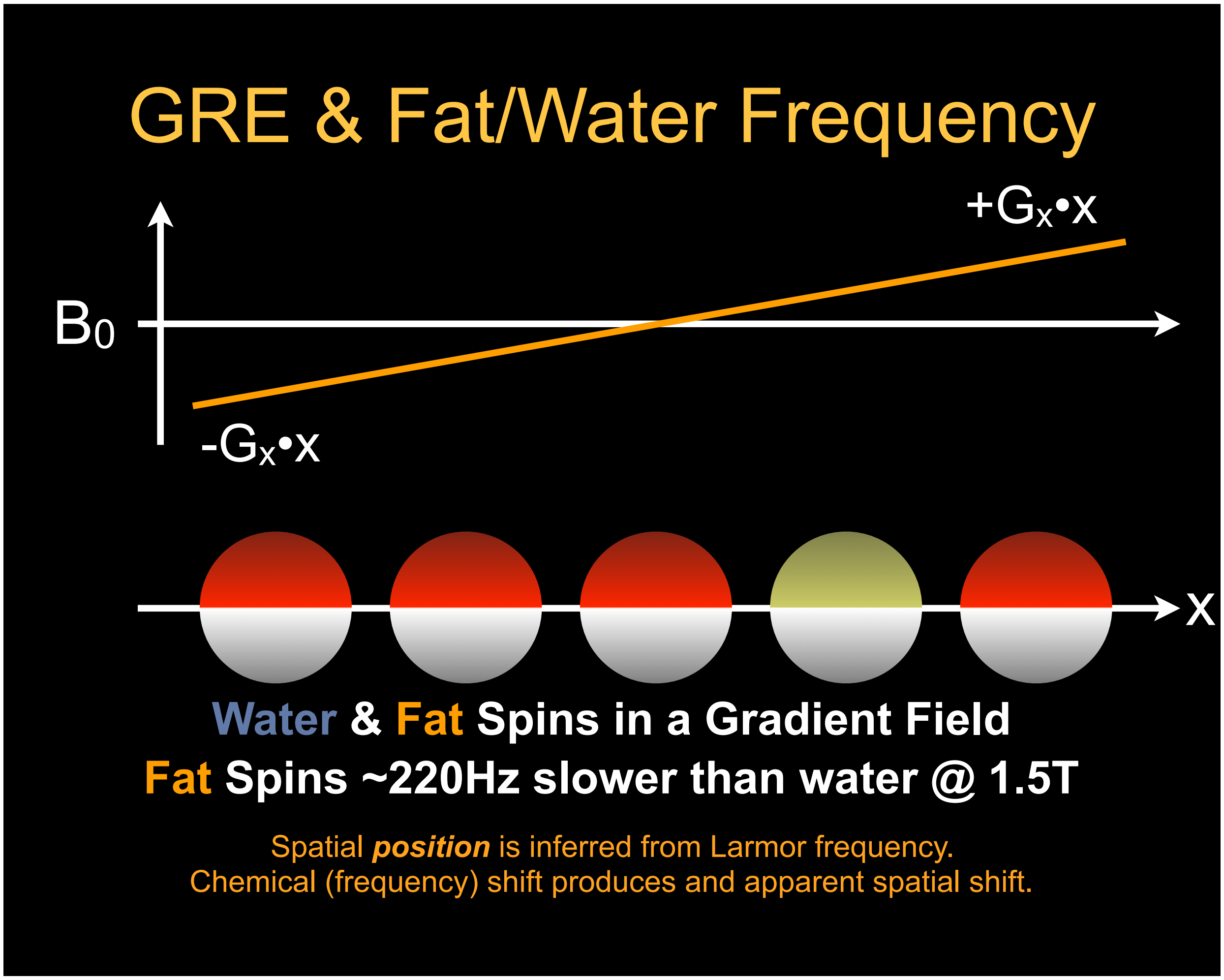
- Fat and water have different Larmor frequencies
  - ~220Hz different at 1.5T
  - ~440Hz different at 3.0T
- Spatial position is related to spin frequency in MRI.
  - Fat is ***more*** spatially mis-registered @ 3T

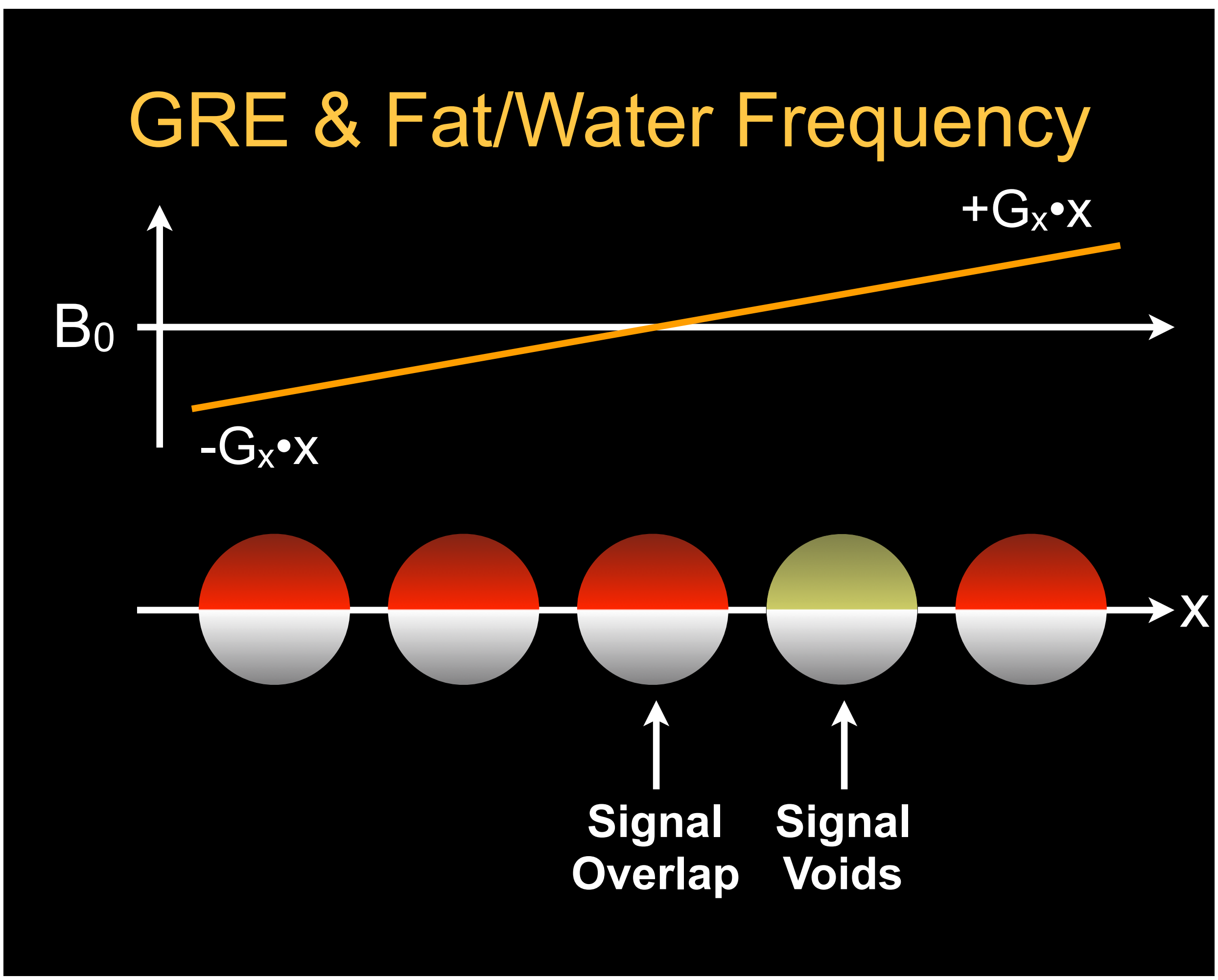
Chemical Shift – Fat (–CH_2) is ~220Hz *lower* at 1.5T

Image Courtesy of Brian Hargreaves

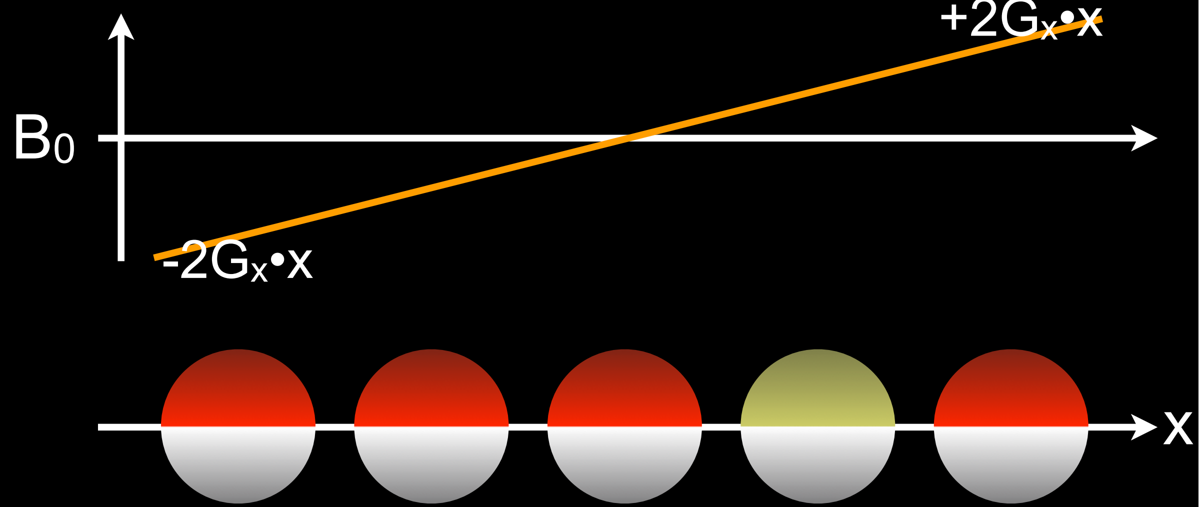

GRE & Fat/Water Frequency
B0
x
Water Spins in a Uniform Field
Water spins precess at the same Larmor frequency in a uniform B0 field.


GRE & Fat/Water Frequency
+Gx•x
B0
-Gx•x
x
Water Spins in a Gradient Field
Water spins precess at different Larmor frequencies in a non-uniform B0 field.


GRE & Fat/Water Frequency
+Gx•x
B0
-Gx•x
x
Water & Fat Spins in a Gradient Field
Fat Spins ~220Hz slower than water @ 1.5T
Spatial position is inferred from Larmor frequency.
Chemical (frequency) shift produces and apparent spatial shift.

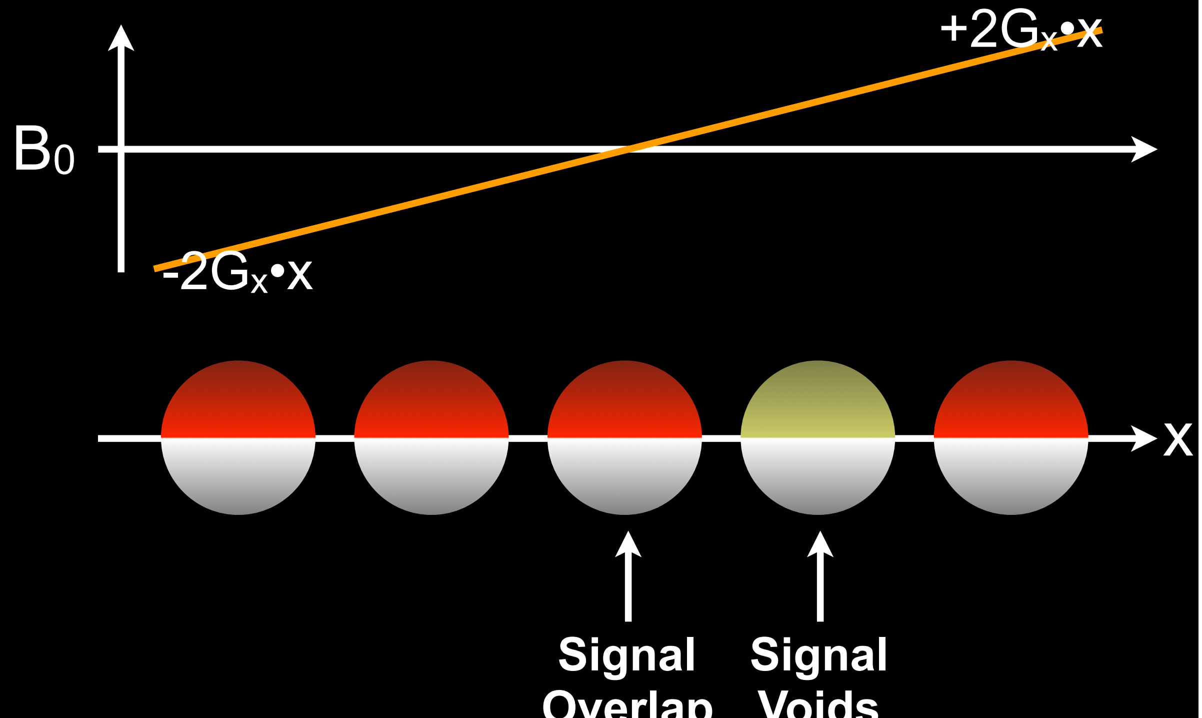

GRE & Fat/Water Frequency
+Gx•x
B0
-Gx•x
x
Signal Overlap
Signal Voids

GRE and Bandwidth



Higher bandwidths use stronger gradients and result in larger frequency differences along x.
Chemical shift (frequency) is fixed for B_0, therefore chemical shift (Δx) is a smaller percentage.

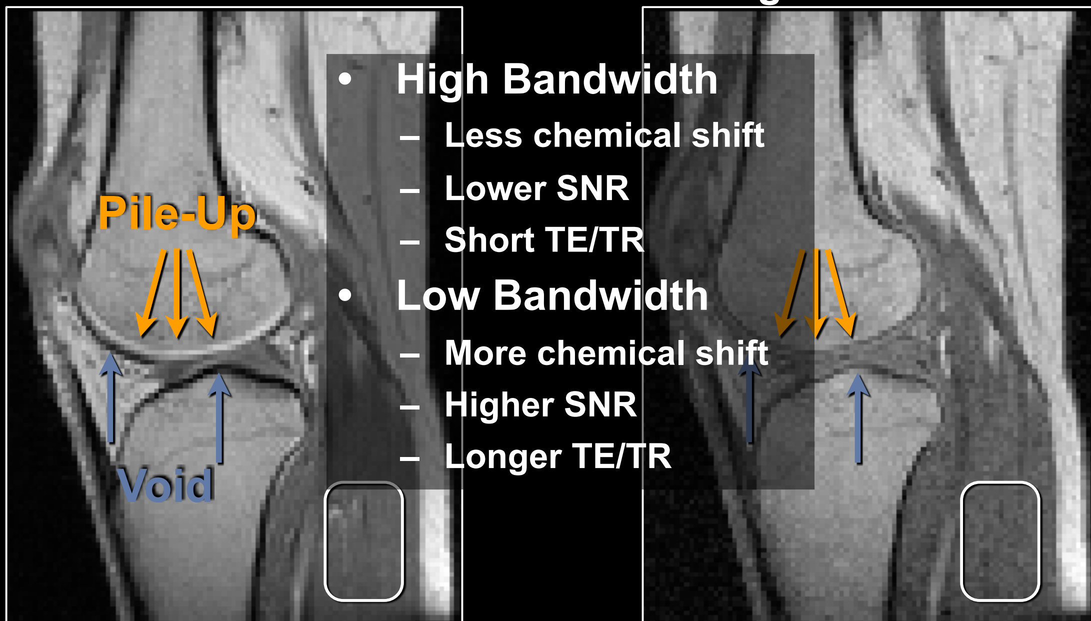
GRE and Bandwidth



High bandwidth scans have less chemical shift.

GRE, Fat/Water & Bandwidth

Low Bandwidth | **High Bandwidth**

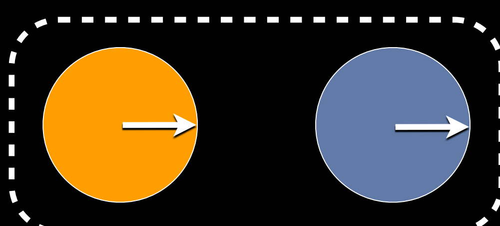


- **High Bandwidth**
  - **Less chemical shift**
  - **Lower SNR**
  - **Short TE/TR**
- **Low Bandwidth**
  - **More chemical shift**
  - **Higher SNR**
  - **Longer TE/TR**

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.

Chemical Shift - Type 2

- Pixels are frequently a mixture of fat and water
- Pixel intensity is the vector sum of fat and water



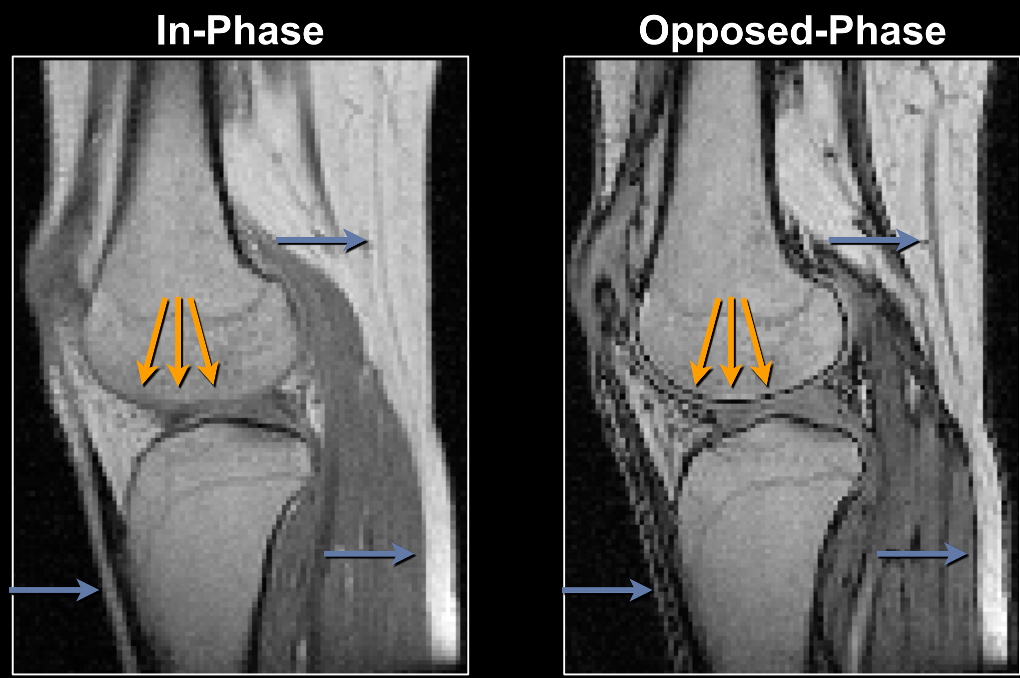
Fat Water

In-Phase Opposed-Phase

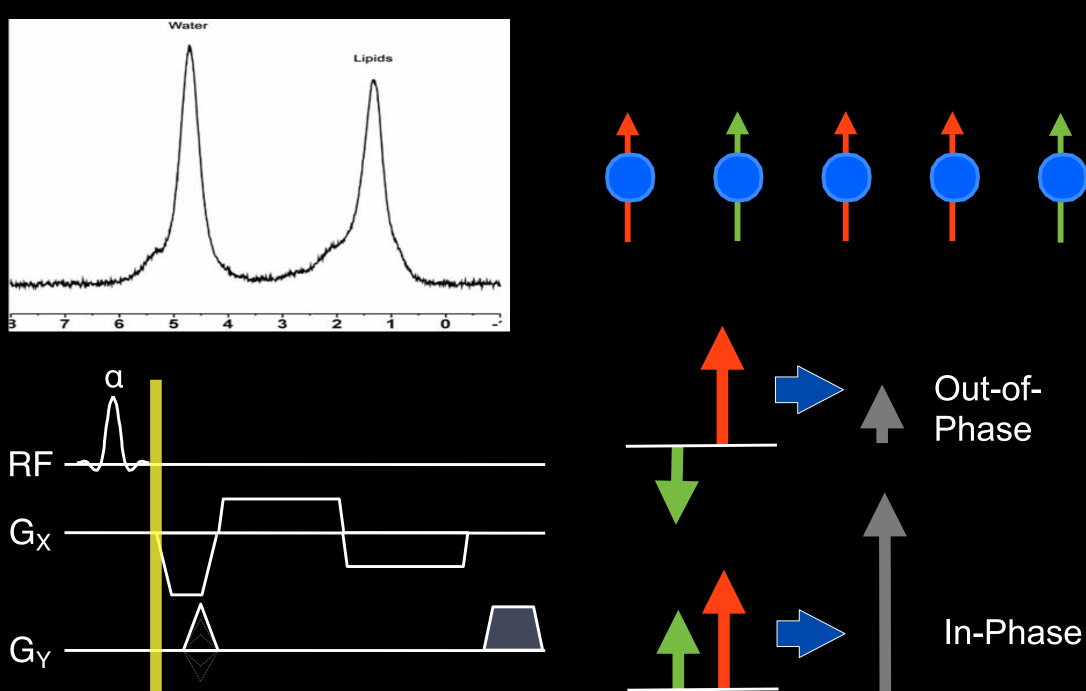
$\rightarrow + \rightarrow > 0$ $\leftarrow + \rightarrow = 0$

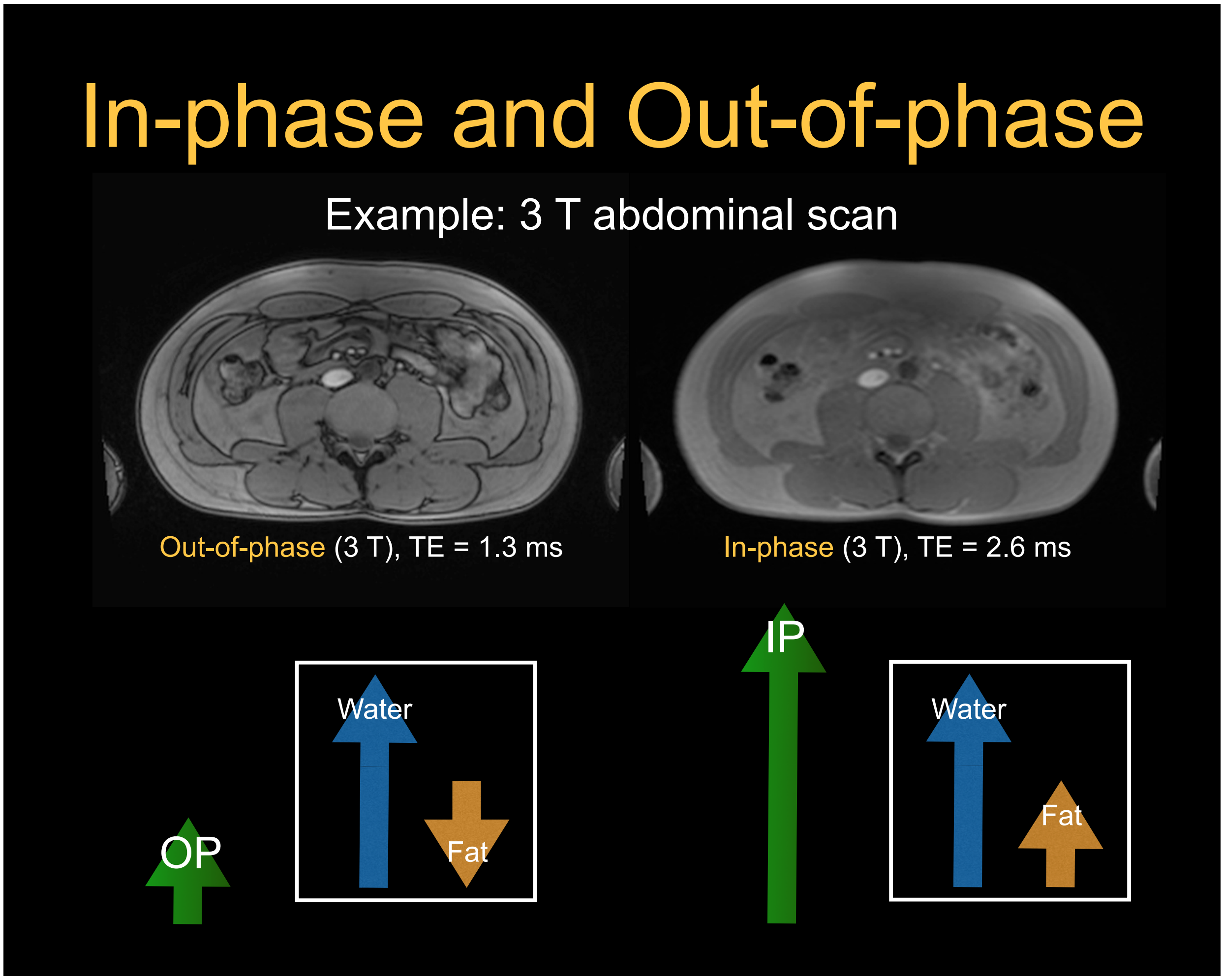
The TE controls the phase between fat and water.

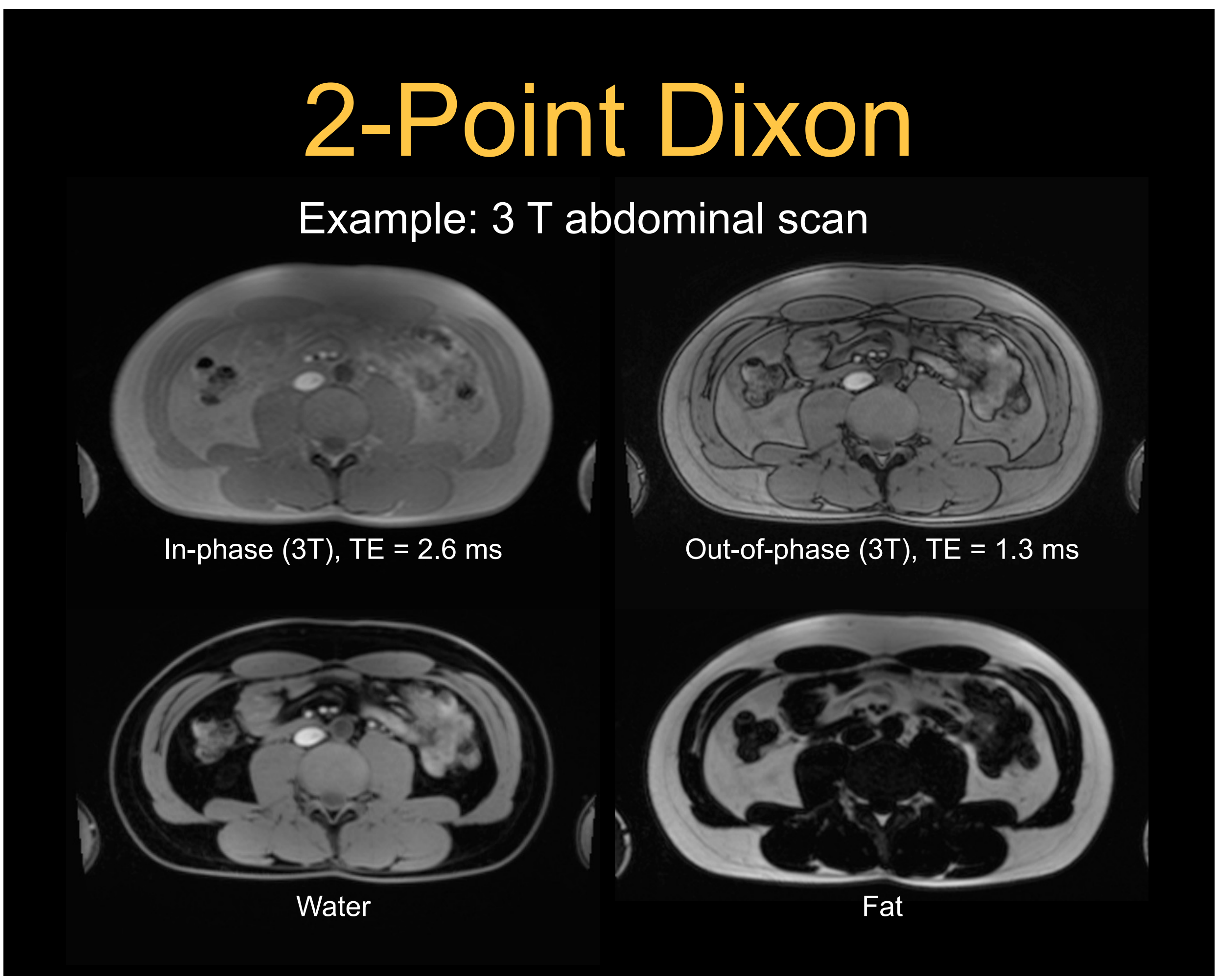
GRE and Fat/Water Phase



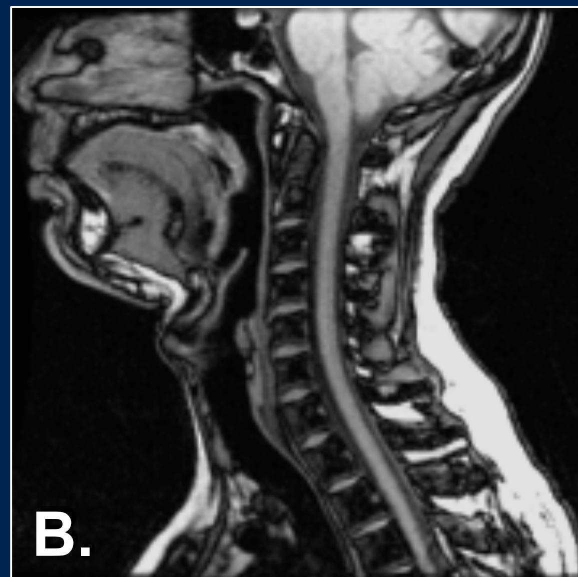
Dual-Echo Acquisition




In-phase and Out-of-phase
Example: 3 T abdominal scan
Out-of-phase (3 T), TE = 1.3 ms
In-phase (3 T), TE = 2.6 ms
IP
Water
Water
Fat
OP
Fat

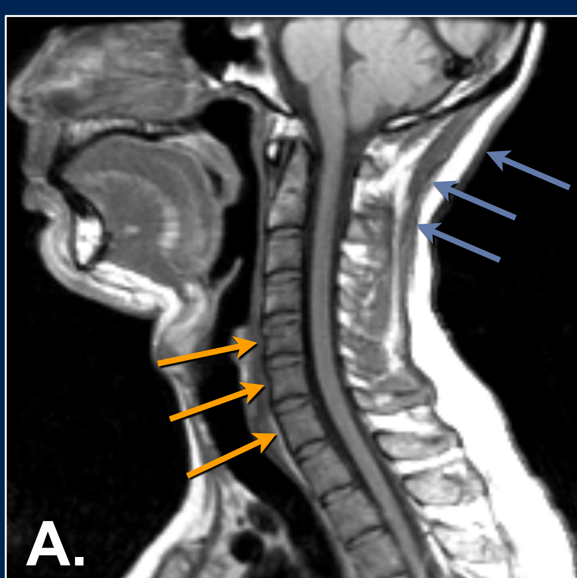

2-Point Dixon
Example: 3 T abdominal scan
In-phase (3T), TE = 2.6 ms
Out-of-phase (3T), TE = 1.3 ms
Water
Fat

Which image is the in-phase image?

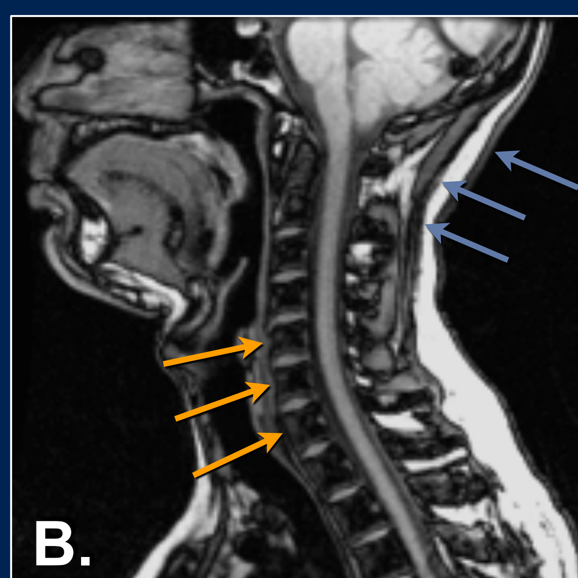


Images Courtesy of Scott Reeder

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.

Gradient Echo – Summary

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

Thanks

Kyung Sung, PhD

ksung@mednet.ucla.edu

http://mrrl.ucla.edu/sunglab/

Images/Slides Courtesy of

Daniel Ennis, Ph.D.