MSK MRI

Essential Principles and Practical Applications

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Requisites and Goals

- Requisites: Understanding of basic MR physics

Goals:

- Learn what is *currently* available on clinical MRI machines and will be increasingly utilized in MSK imaging
  - ie: Quatar and SIKER use WE-DESS
- Understand limitations of relatively "new" sequences and what will supplement or surpass the last generation of sequences

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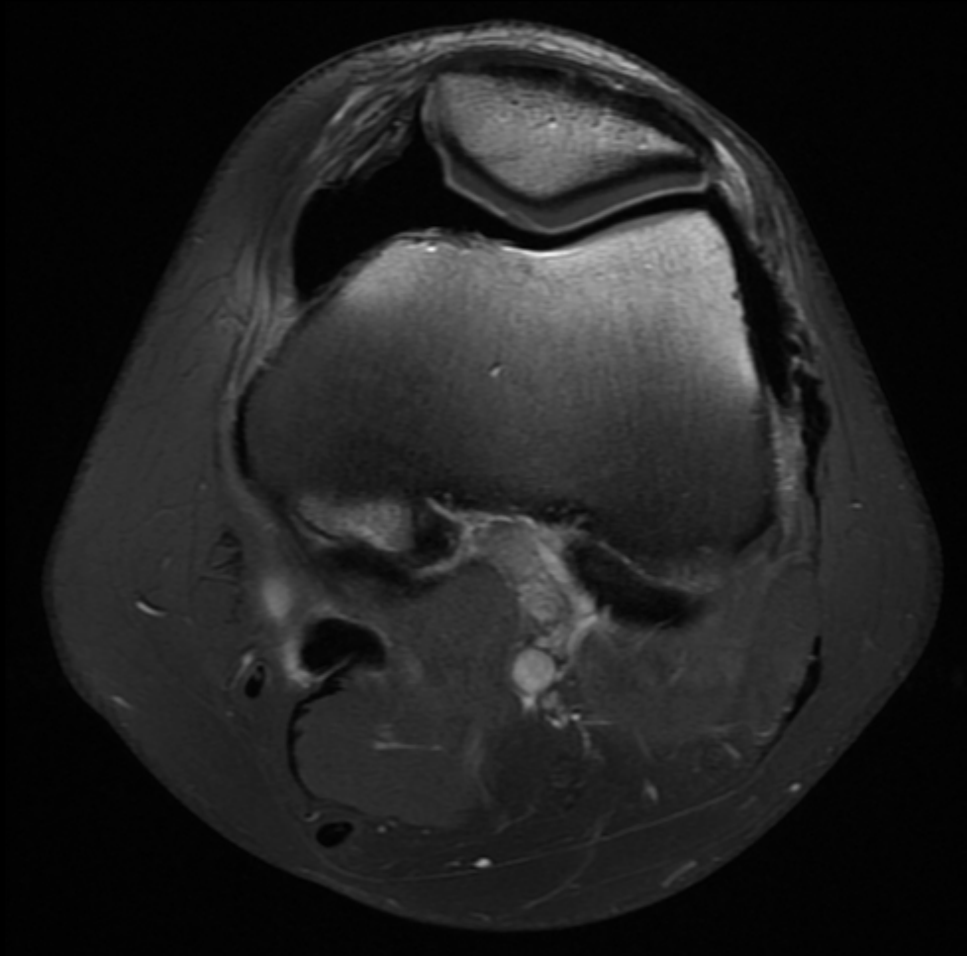
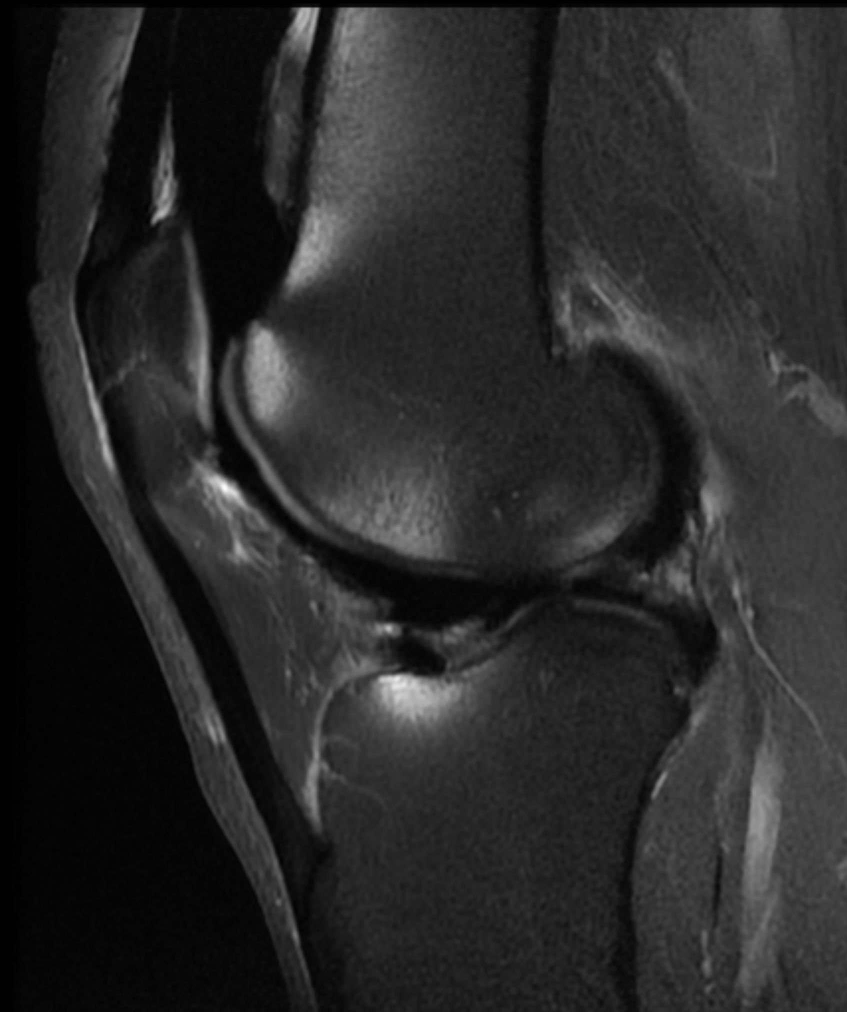


T1w FS



T1w FS

Supportive Faculty

At least you injected the correct joint.

At least you injected the correct side.

At least you injected the correct person.

See? Time Out Works!
But clearly not for everything.

What happened?

- 50 cc 1:1 mixture dilute Multihance/Omnipaque 240
- "Dilute" Multihance
  - 1 cc of Multihance in 50cc bag of NS

Nondilute Magnevist or Multihance -> 0.5 mol/L

1 cc Gad/50 cc NS -> 1/50 dilution
1:1 mixture Gad/Omni -> 1/100 dilution

0.5 mol/L * 1/100 = 0.005 mol/L = **5 mmol/L**

2x "typical dose"
performed here

Effects of Gadolinium Contrast Agents

* Contains 7 unpaired electrons
* Magnetic moment is inverse to mass
* Mass of an electron is very small compared with a proton
* Therefore, magnetic moment of gadolinium is huge
* Relaxation rates vary with square of magnetic moment

Effects of Gadolinium Contrast Agents

Gad shortens both T1 and T2

Observed relaxation rates are calculated by:

$$\left[\frac{1}{T1}\right]_{observed} = \left[\frac{1}{T1}\right]_{tissue} + R1\,[gad]$$

$$\left[\frac{1}{T2}\right]_{observed} = \left[\frac{1}{T2}\right]_{tissue} + R2\,[gad]$$

T1 >> T2

R1[gad] and R2[gad] are comparable

Effects of Gadolinium Contrast Agents

L
O
W

$$\left[\frac{1}{T1}\right]_{observed} = \left[\frac{1}{T1}\right]_{tissue} + R1\,[gad]$$

$$\left[\frac{1}{T2}\right]_{observed} = \left[\frac{1}{T2}\right]_{tissue} + R2\,[gad]$$

H
I
G
H

Effects of Gadolinium Contrast Agents

L
O
W

$$\left[\frac{1}{T1}\right]_{observed} = \left[\frac{1}{10}\right]_{tissue} + \frac{1}{10} = \frac{2}{10} \qquad T1 = 5$$

$$\left[\frac{1}{T2}\right]_{observed} = \left[\frac{1}{1}\right]_{tissue} + \frac{1}{10} = \frac{11}{10} \qquad T2 = 0.9$$

H
I
G
H

Effects of Gadolinium Contrast Agents

LOW

$$\left[\frac{1}{T1}\right]_{\text{observed}} = \left[\frac{1}{10}\right]_{\text{tissue}} + \frac{1}{10} = \frac{2}{10}$$

T1 = 5

$$\left[\frac{1}{T2}\right]_{\text{observed}} = \left[\frac{1}{1}\right]_{\text{tissue}} + \frac{1}{10} = \frac{11}{10}$$

T2 = 0.9

HIGH

$$\left[\frac{1}{T1}\right]_{\text{observed}} = \left[\frac{1}{10}\right]_{\text{tissue}} + \frac{10}{10} = \frac{11}{10}$$

T1 = 0.9

$$\left[\frac{1}{T2}\right]_{\text{observed}} = \left[\frac{1}{1}\right]_{\text{tissue}} + \frac{10}{10} = \frac{20}{10}$$

T2 = 0.5

Effects of Gadolinium Contrast Agents

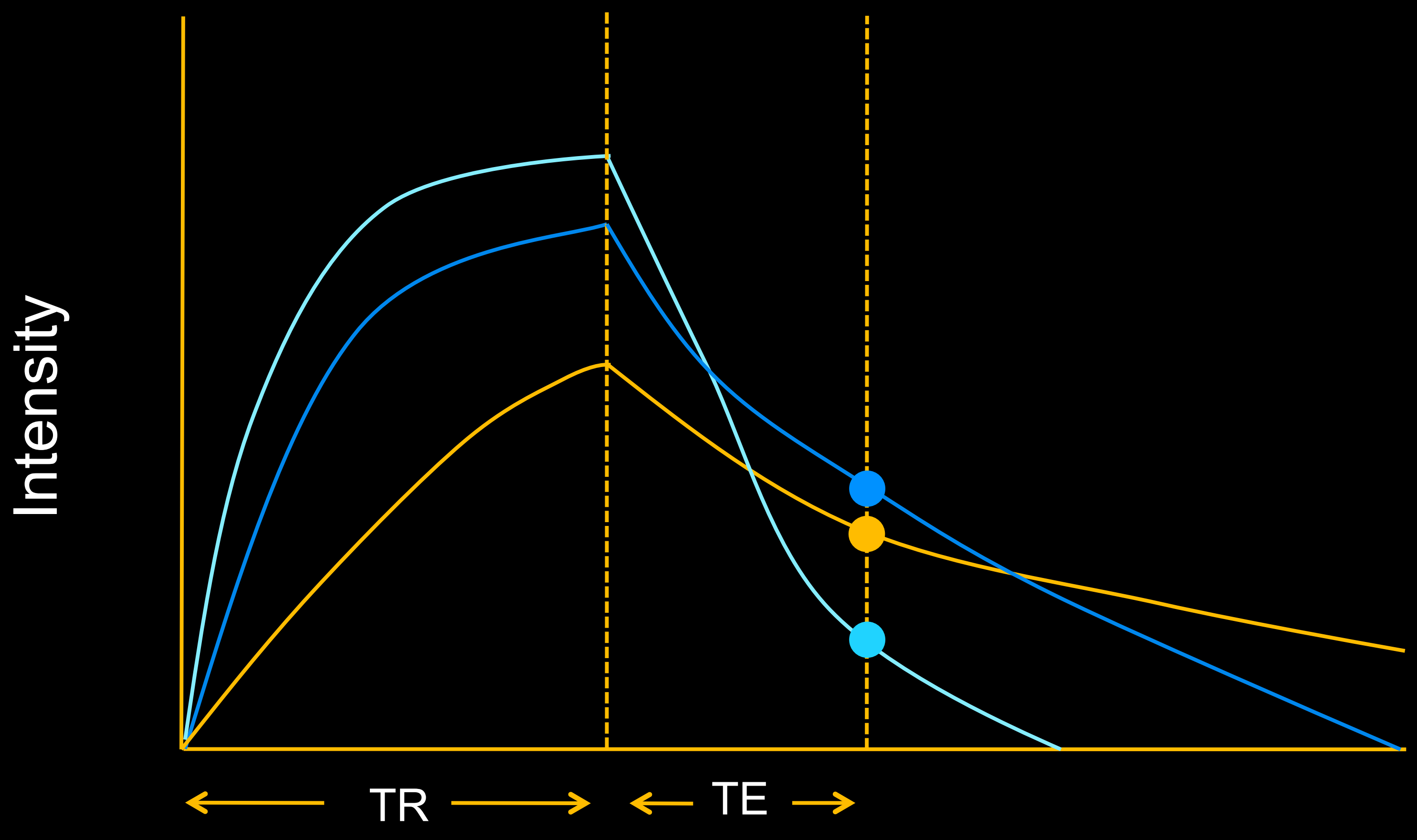
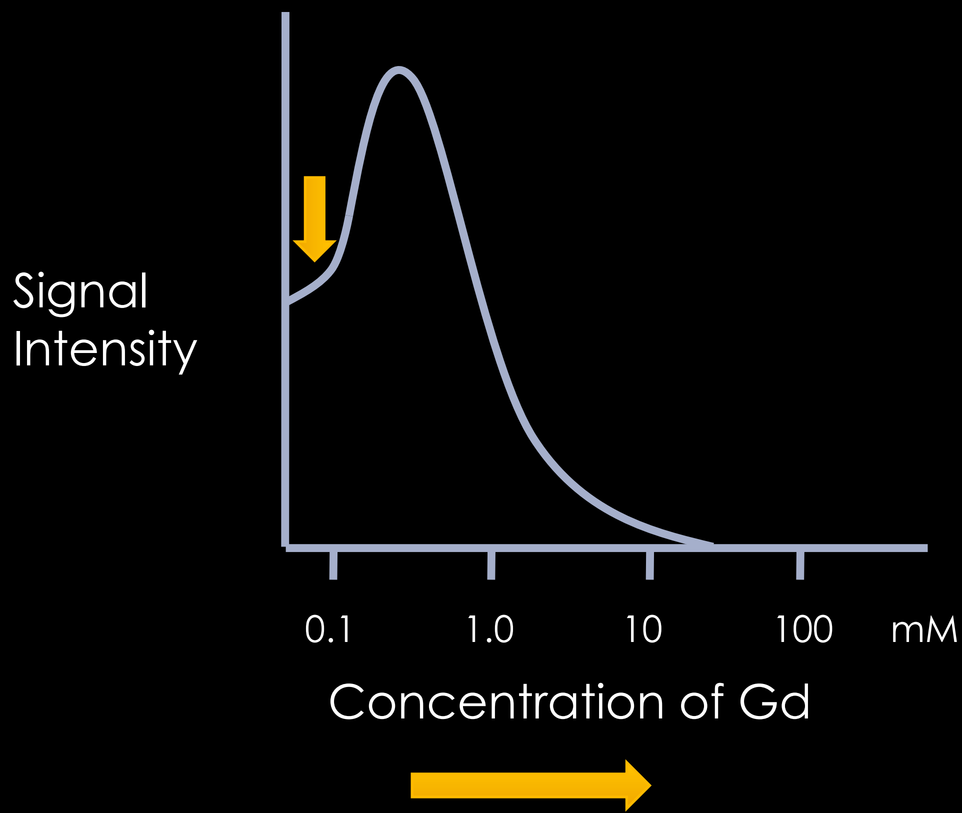
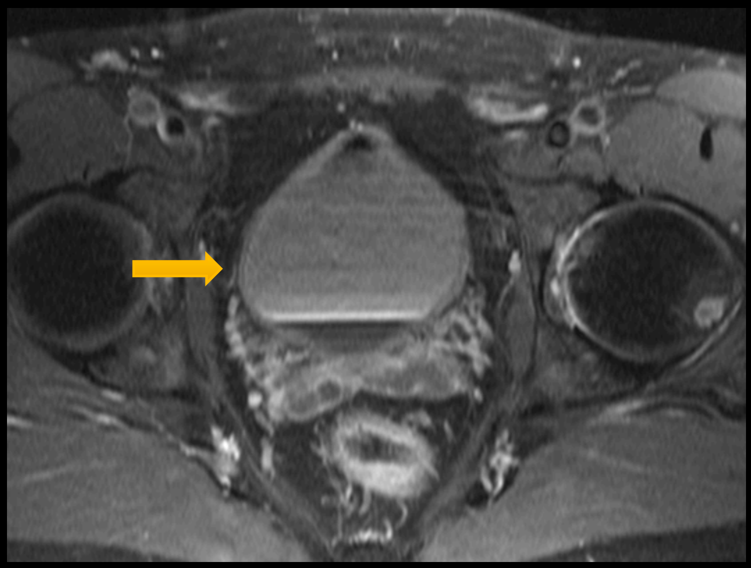


diagram not to scale

Routine Spin Echo Signal Intensity





T1w TSE FS

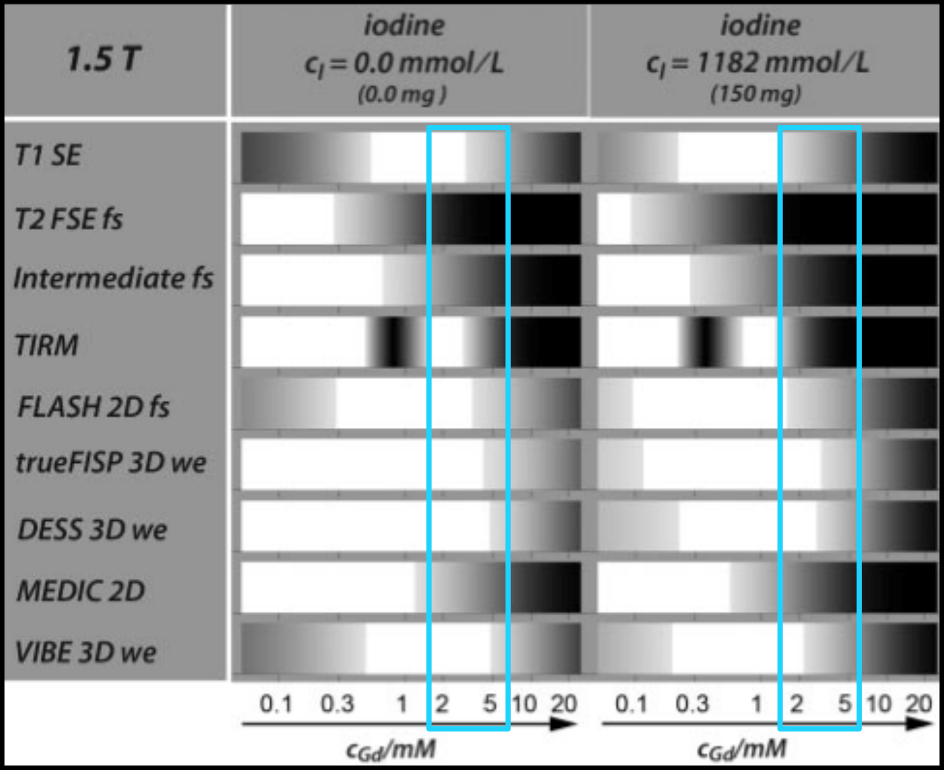
Exact concentration beyond which signal falls depends on particular tissue and sequence parameters

MR properties of Omnipaque

* Mechanism of iodinated contrast behavior on MRI is not known
  * Fact: Omnipaque is not paramagnetic (no free unpaired electrons at contrast media molecule)
  * Fact: Empirically, Omnipaque has weak T1/T2 shortening effects

* Proposed mechanisms
  * Increase in viscosity (Montgomery, JMRI 2002)
  * Lower proton density of mixture (Montgomery, JMRI 2002)
  * Magnetic susceptibility of iodine (Masi, AJR 2005)
  * Hydration layer water model (Jinkins, AJNR 1992; Hergan, EJR 1995)

Emperic SNR



Omni 300 (300 mg I/ml)
1:1 dilution = 150 mg I

Andreisek et al. Radiology. 2008. 247: 706-716.

Direct MR Arthrography

- Iodinated contrast reduces T1 and T2 of mixture
- Iodinated contrast narrows the optimum gadolinium concentration range
- Optimum gadolinium concentration typically ranges from 0.7 – 3.4 mmol/L at 1.5T and 3.0T
  - Most suggest <2mmol/L if iodinated contrast used[1,2]

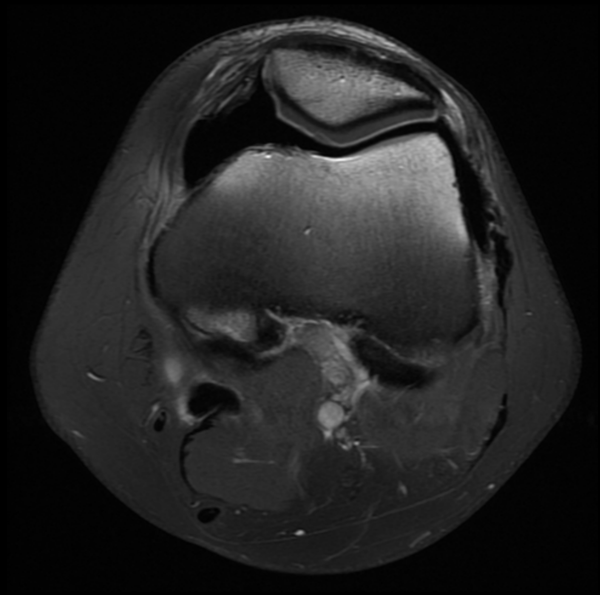
[1]Andreisek et al. Radiology 2008. 247: 706-716.
[2]Montgomery et al. JMRI 2002. 15:334-343

Additional Considerations

- Multihance (Gd-BOPTA) binds reversibly to proteins such as albumin
  - Slows down rotation of molecule
  - Increases T1/T2 relaxivity
- If patient has joint effusion (~1.7g/dL albumin[1]) prior to injection, relaxivity increases → optimal range ↓
- In human blood plasma:
  - R1 of Multihance is up to 131% higher than Magnevist
  - R2 of Multihance is up to 244% higher than Magnevist[2]

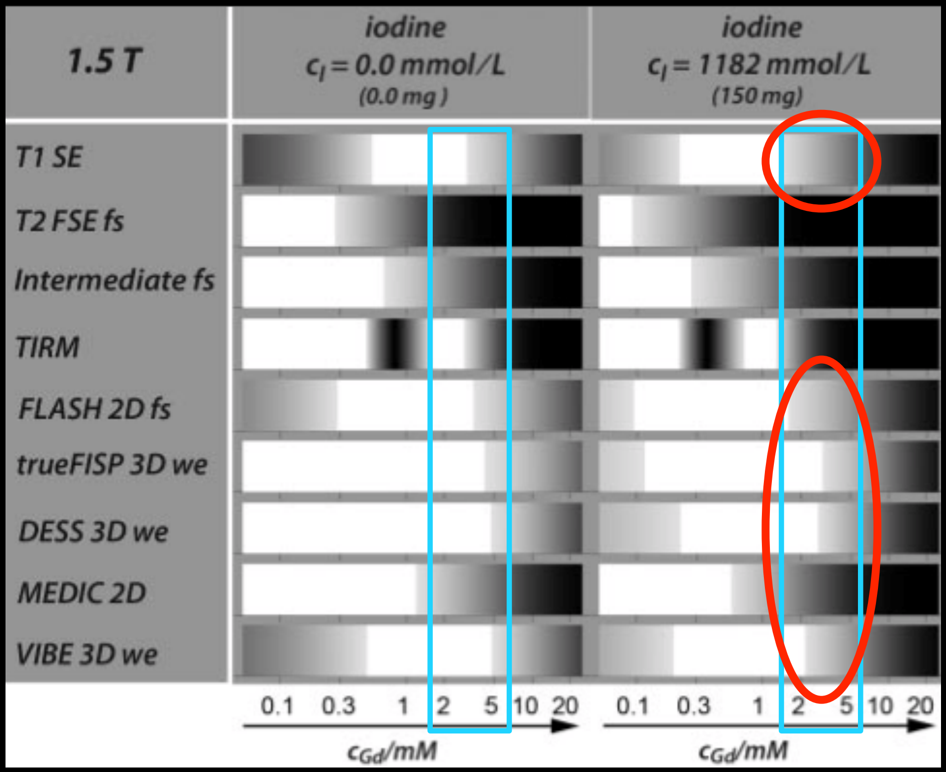
1Montgomery et al. JMRI 2002. 15:334-343
2Pintaske et al. Invest Rad 2006. 41:213-221

Salvage Techniques



* Utilize GRE sequence
* Delayed imaging
  * Anecdotal, no literature to guide us

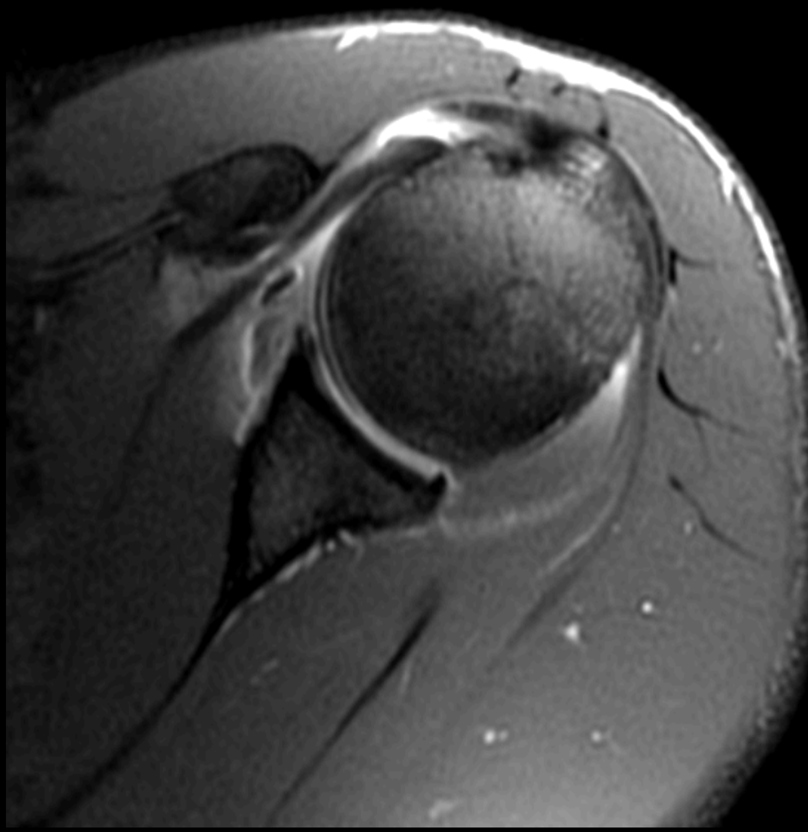
Postcontrast SNR of FSE vs GRE



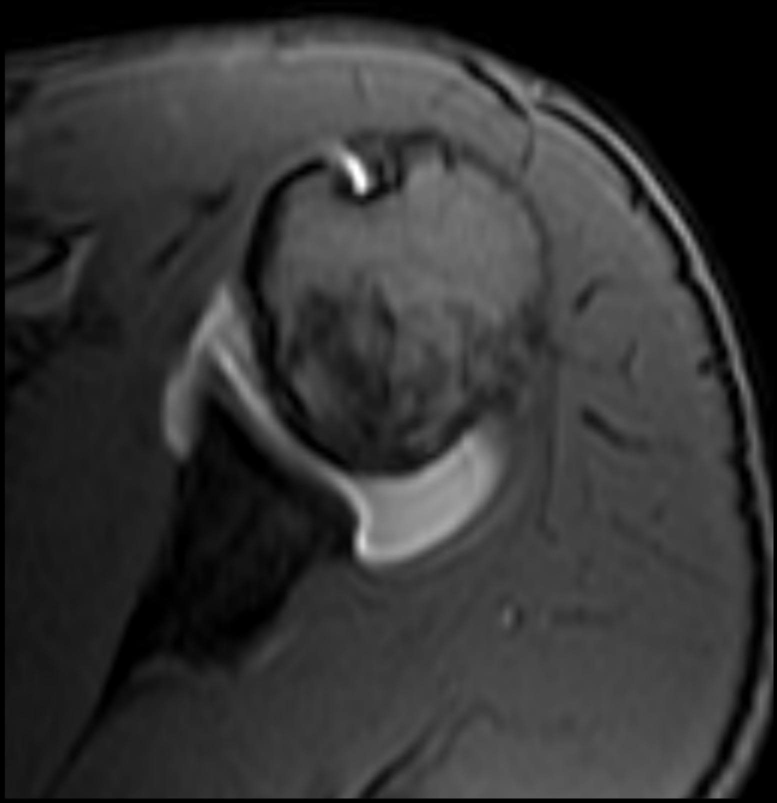
Andreisek et al. Radiology. 2008. 247: 706-716.

Postcontrast SNR of FSE vs GRE

Low SNR on T1w FSE images can
sometimes be salvaged with GRE

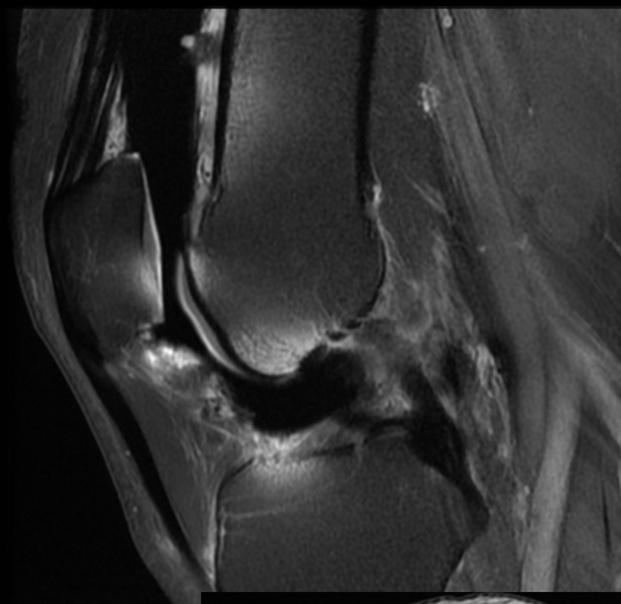


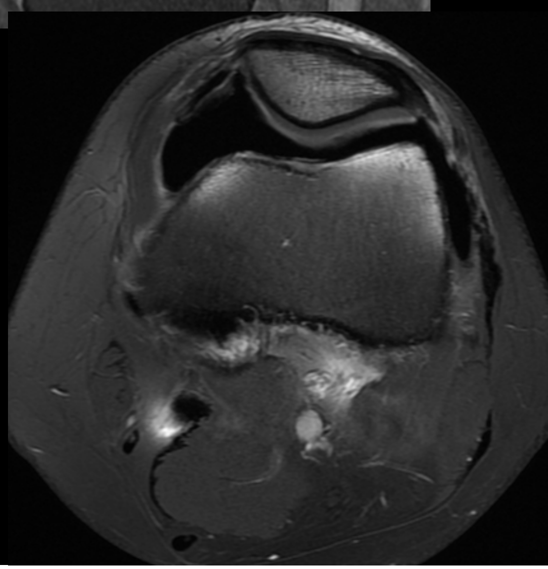
FSE



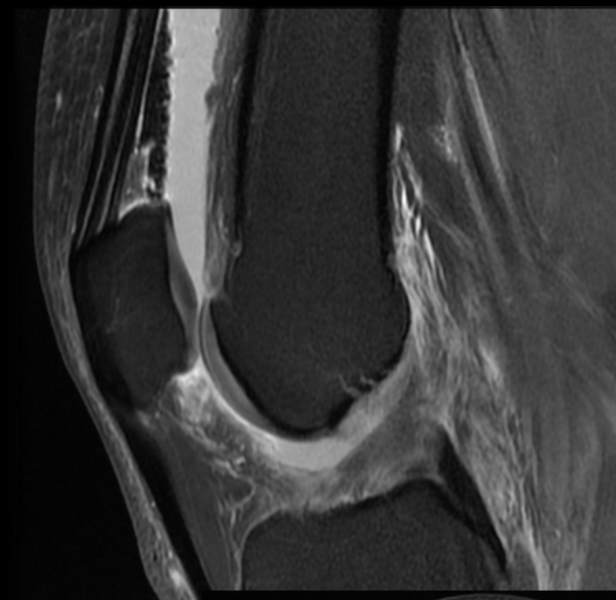
GRE localizer

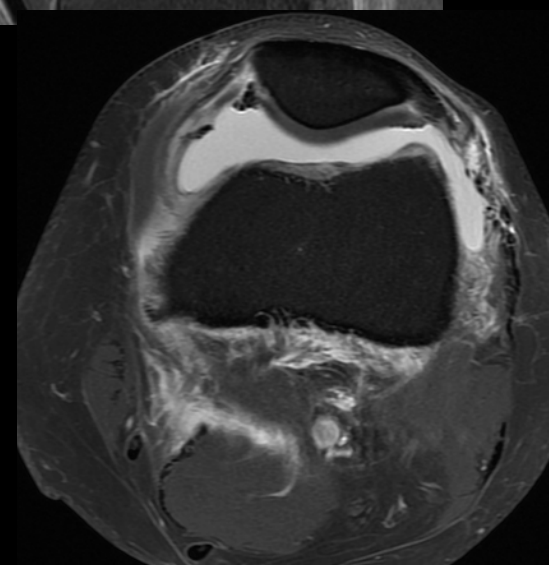
Delayed Imaging



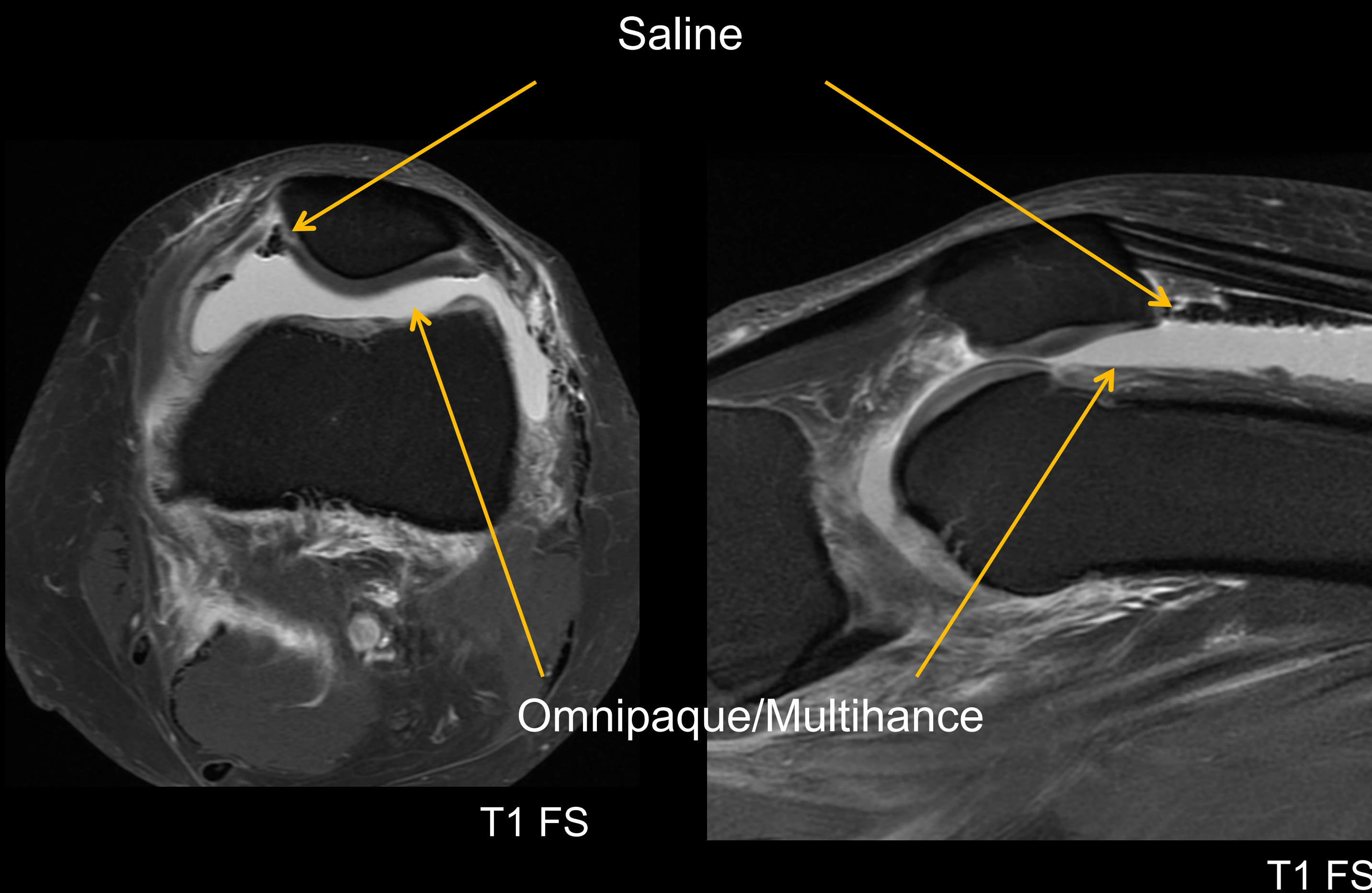


3.5 hrs



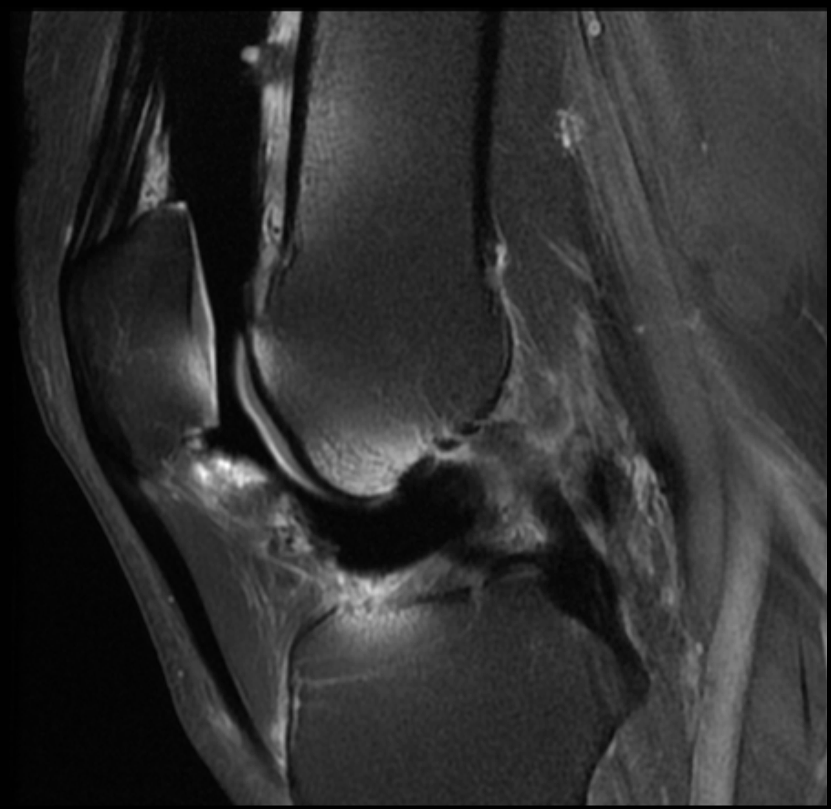


Delayed Imaging

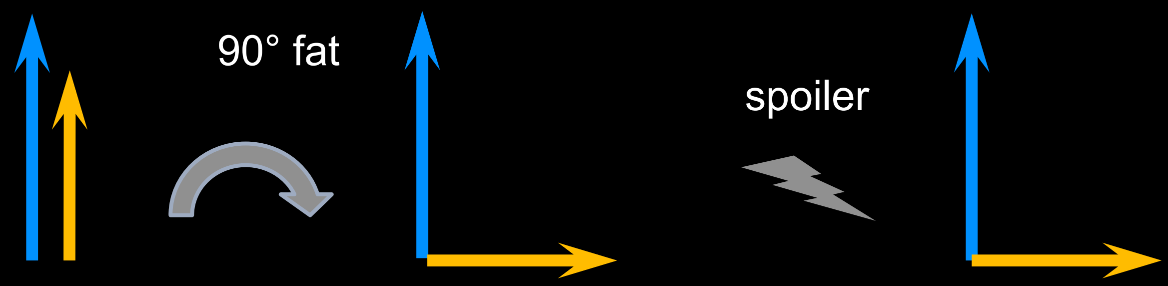


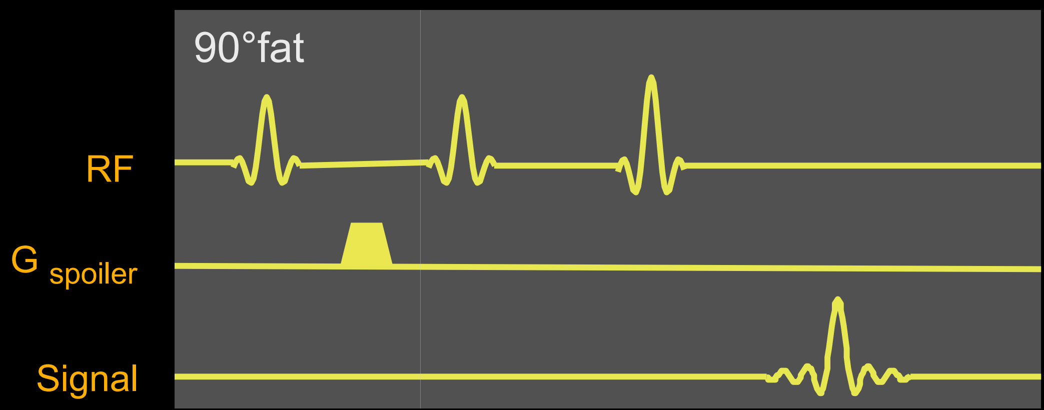
Physical Density:	Saline 1.0g/ml
	Gadobenate dimeglumine (Multihance) - 1.22g/mL
	Iohexol (Omnipaque) - 1.35g/mL

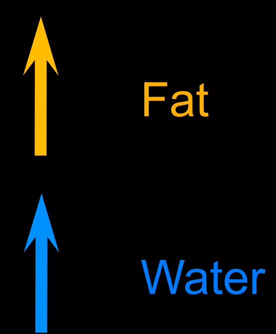
Fat Suppression



CHESS
(chemical shift selection)



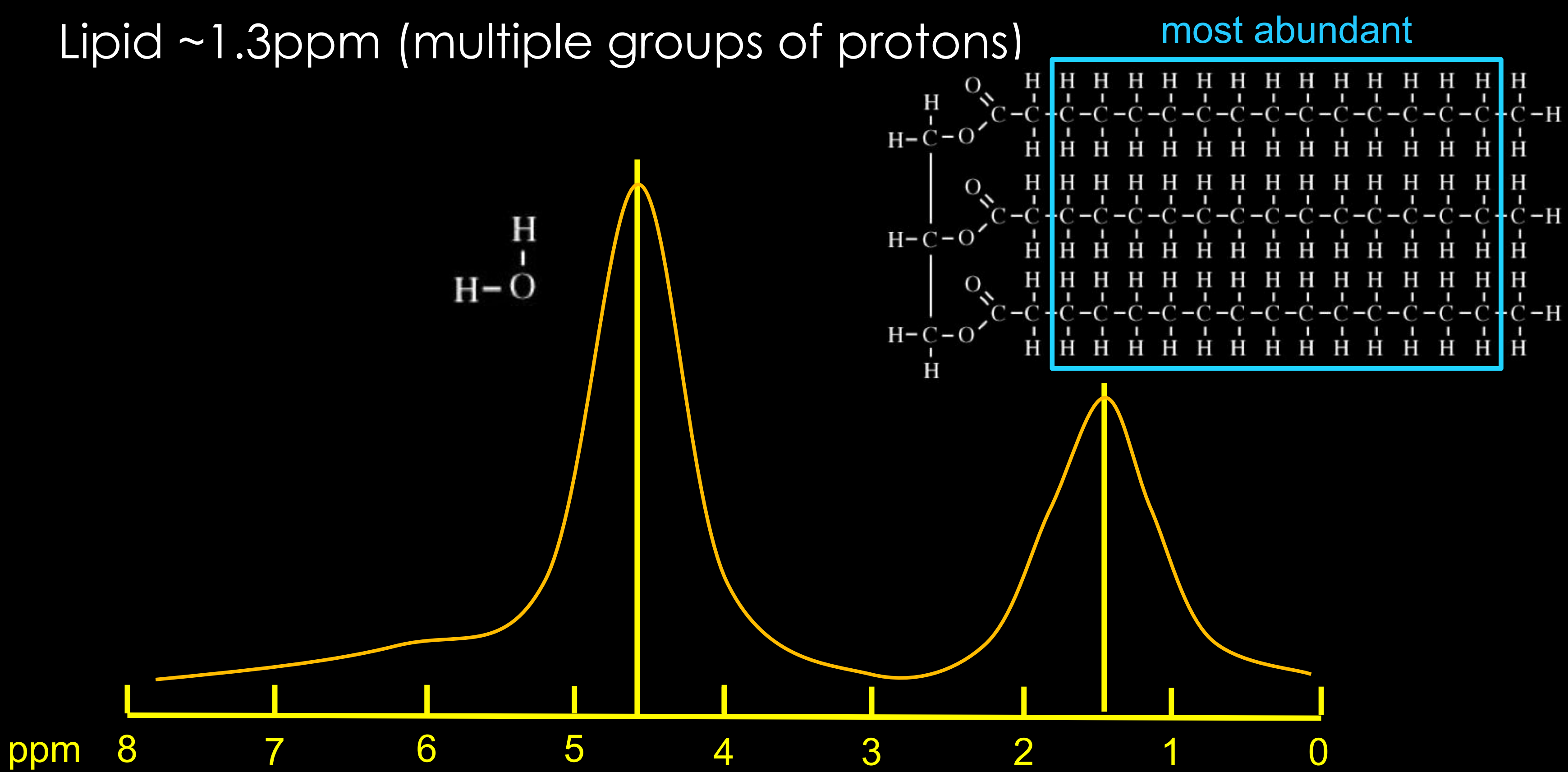




CHESS
(*che*mical *s*hift *s*election)

Spectrally selective RF pulse to suppress lipid

- Water ~4.7ppm (2 protons are identical)
- Lipid ~1.3ppm (multiple groups of protons)



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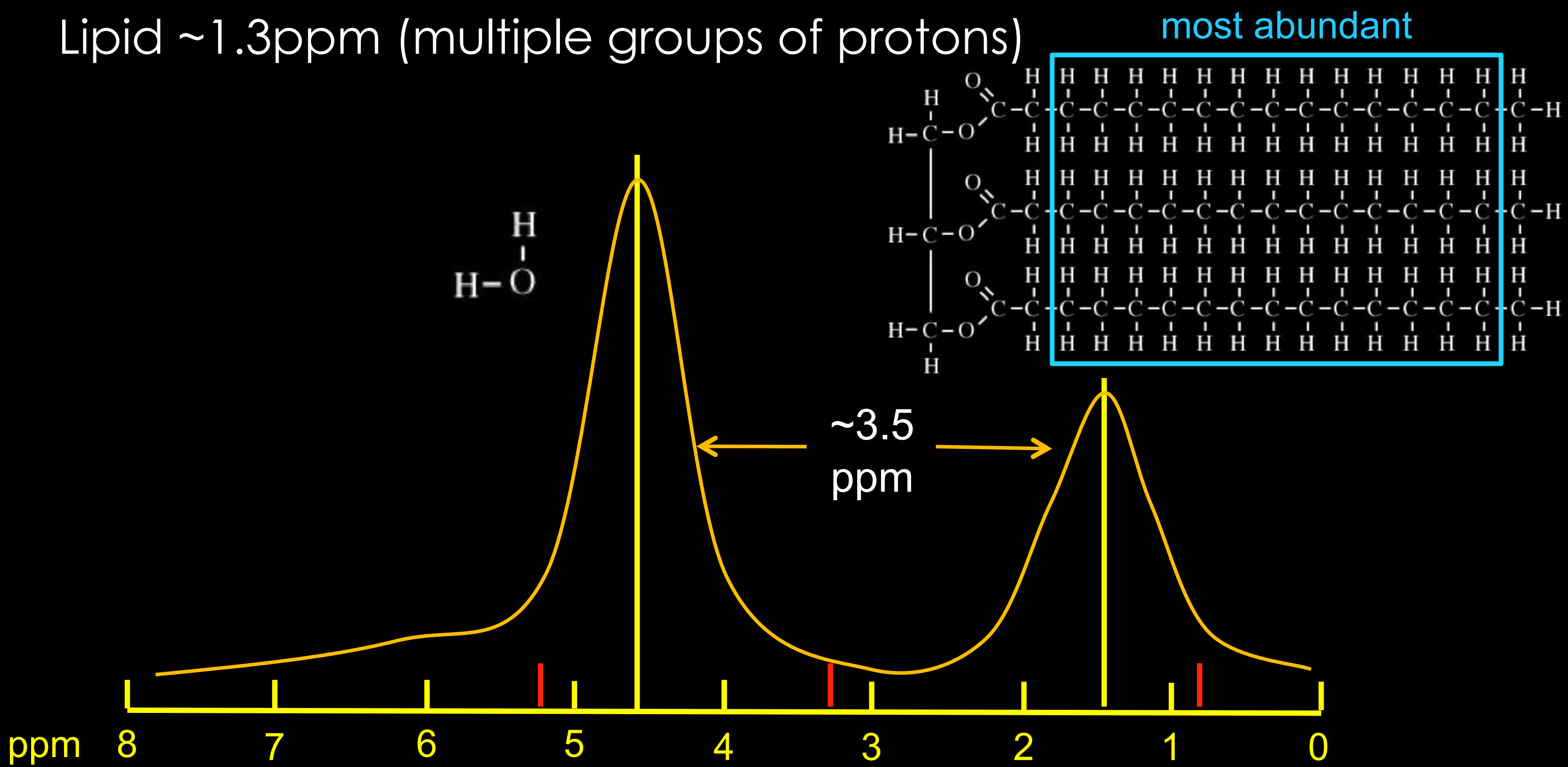
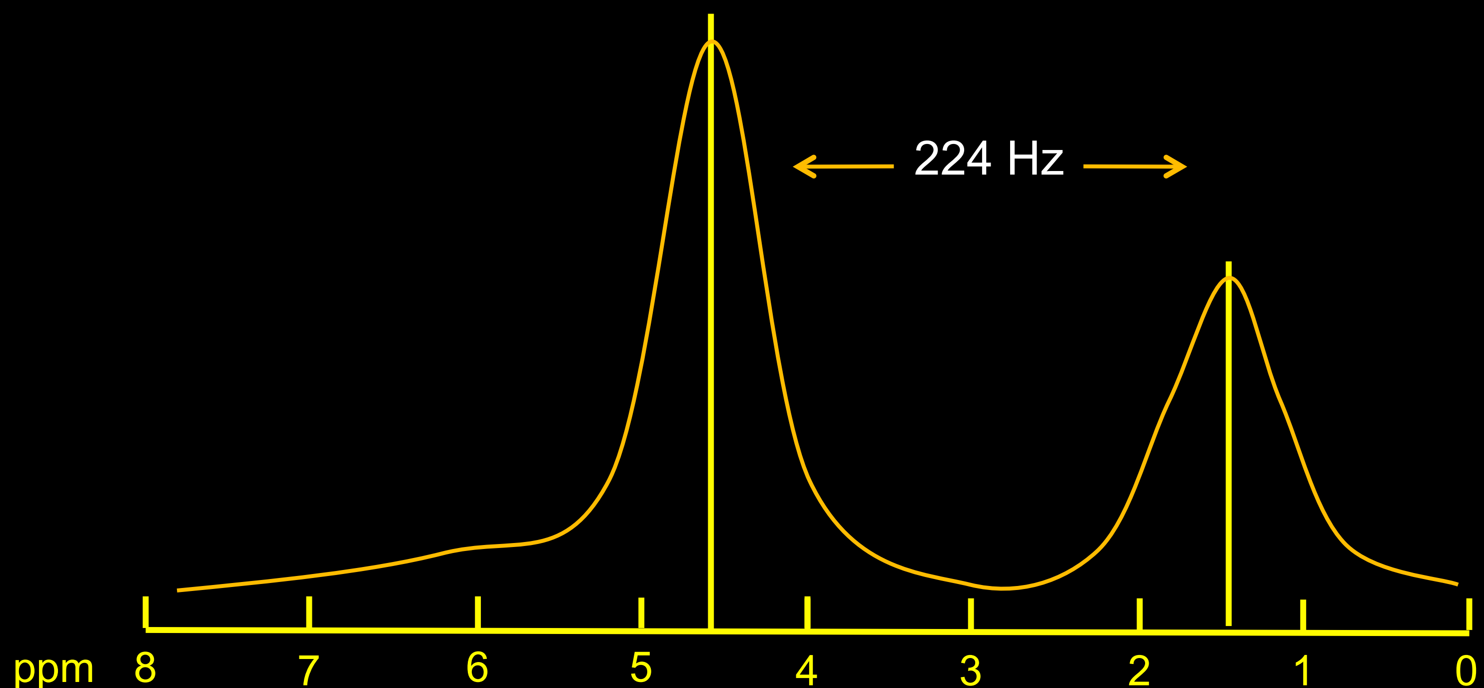


CHESS
(chemical shift selection)

- Chemical shift between water and fat ~3.5ppm
- @1.5T 64MHz * 3.5ppm = 224 Hz as a difference



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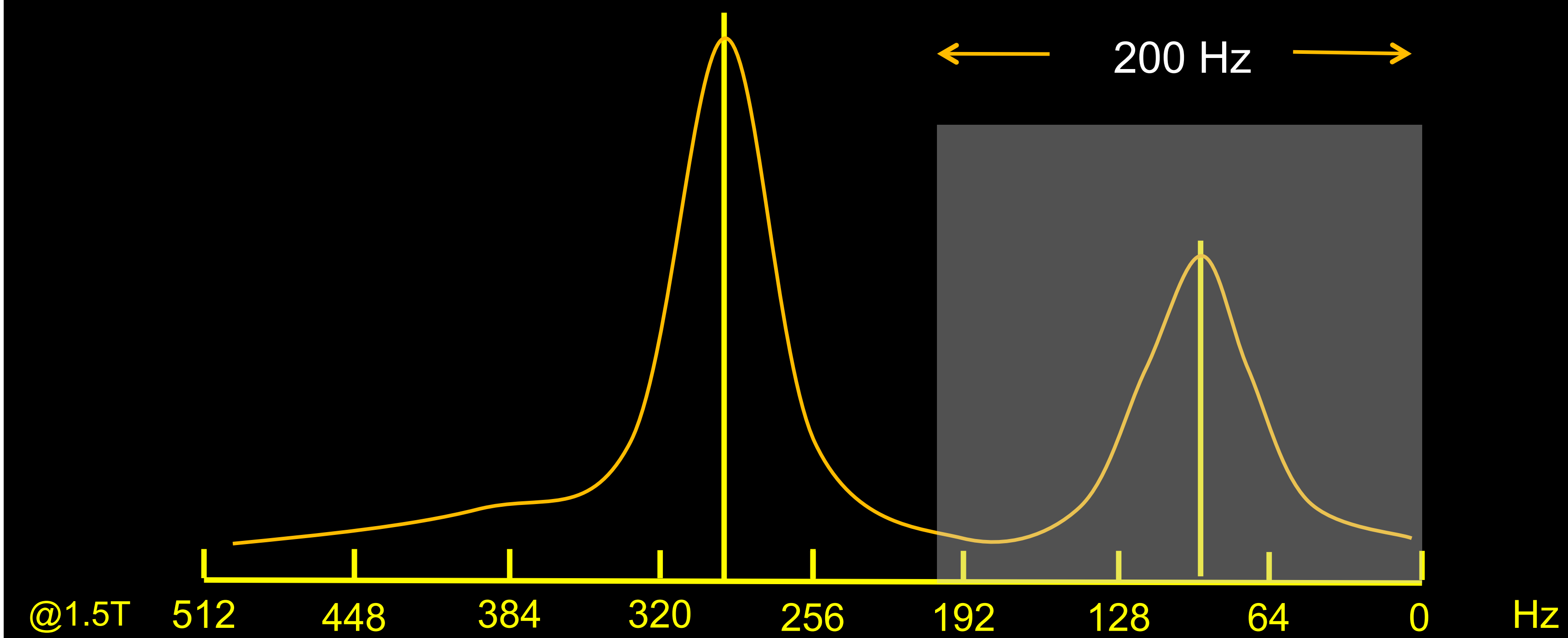
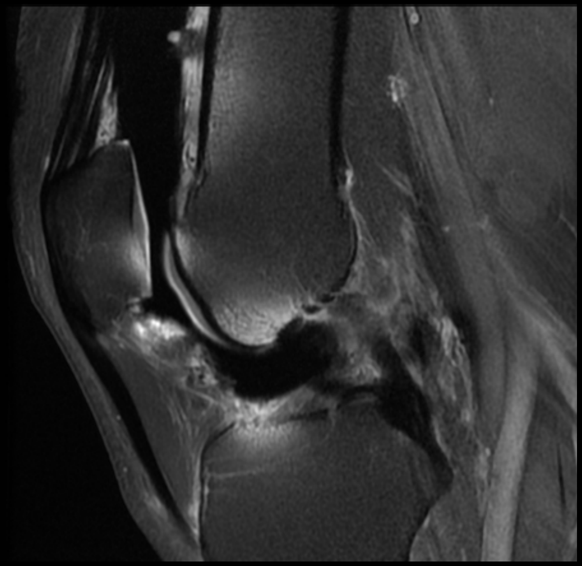
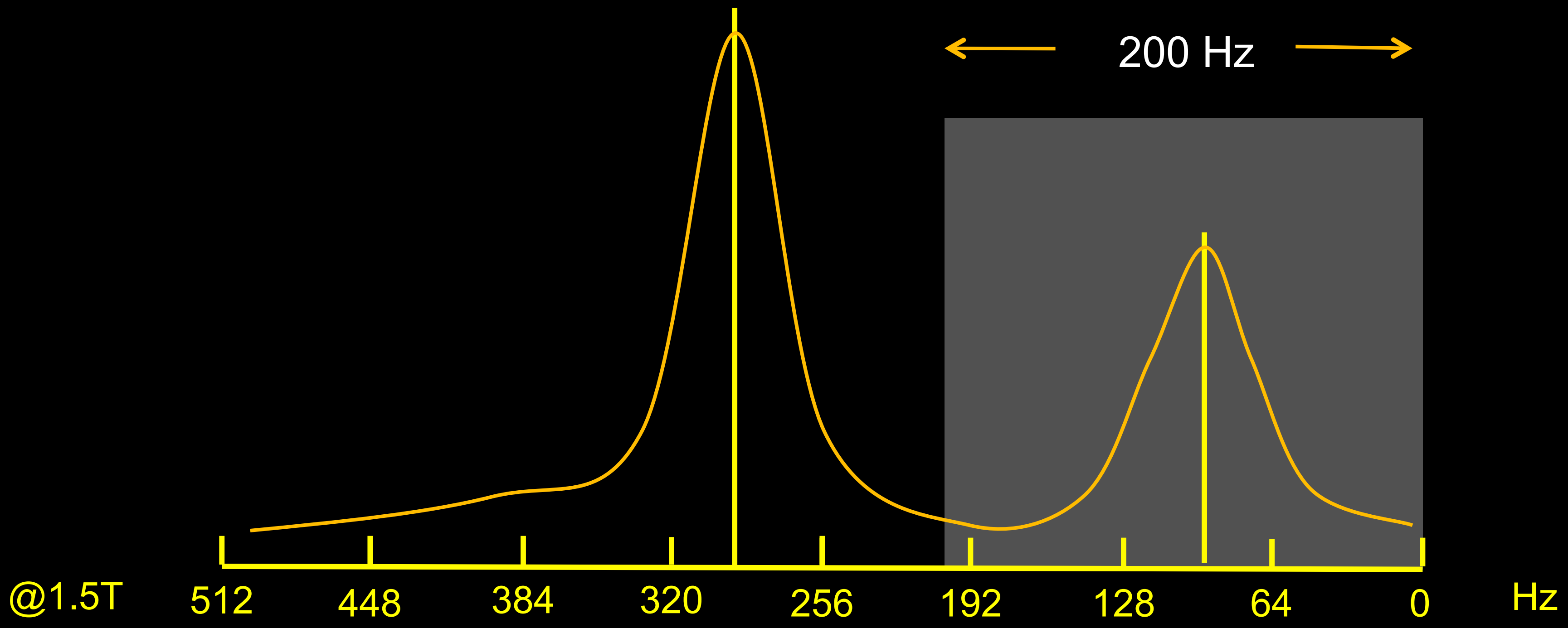


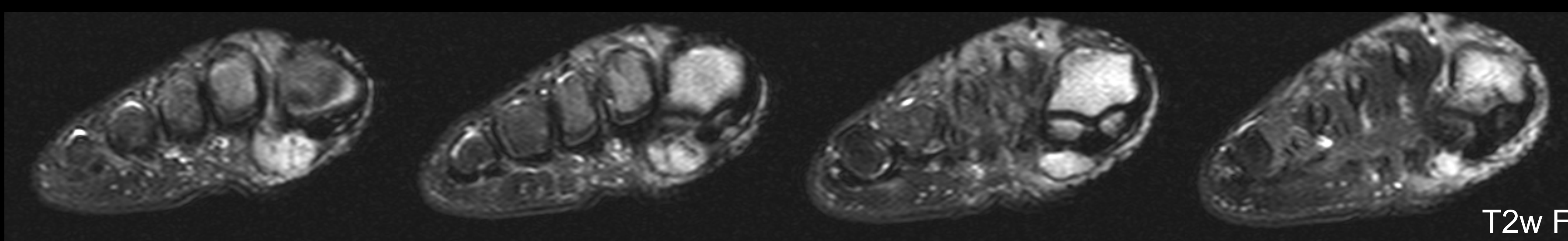


Gadolinium is paramagnetic, enhances B0 magnetic field (positive susceptibility)



B0 is inhomogenous
- asymmetric volume
- curved surfaces
- magnetic susceptibility difference (air/tissue at toes)
- poor shim

B1 may be inhomogenous
- i.e. a 45°pulse would provide only partial suppression

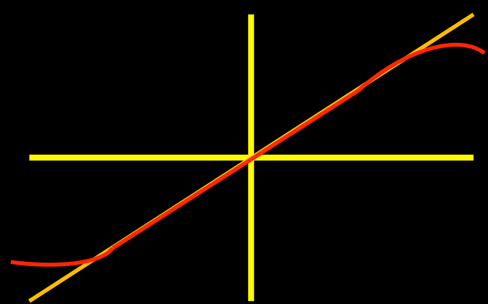


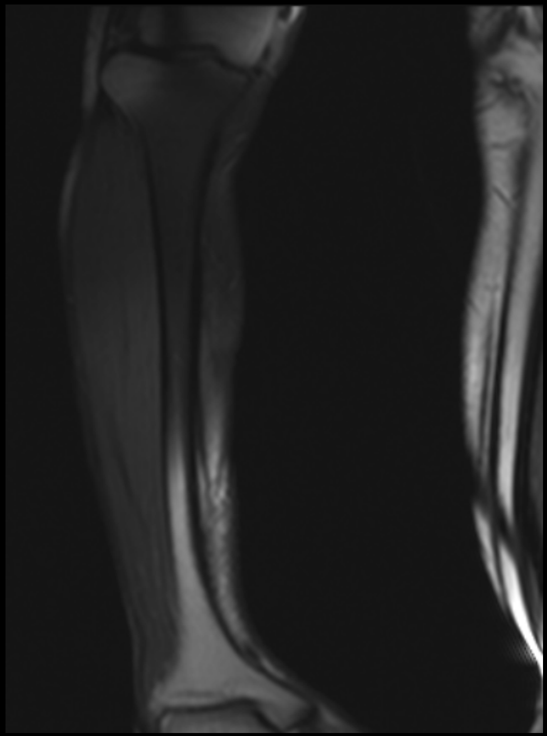
B1 is inhomogenous

Gradient field nonlinearity

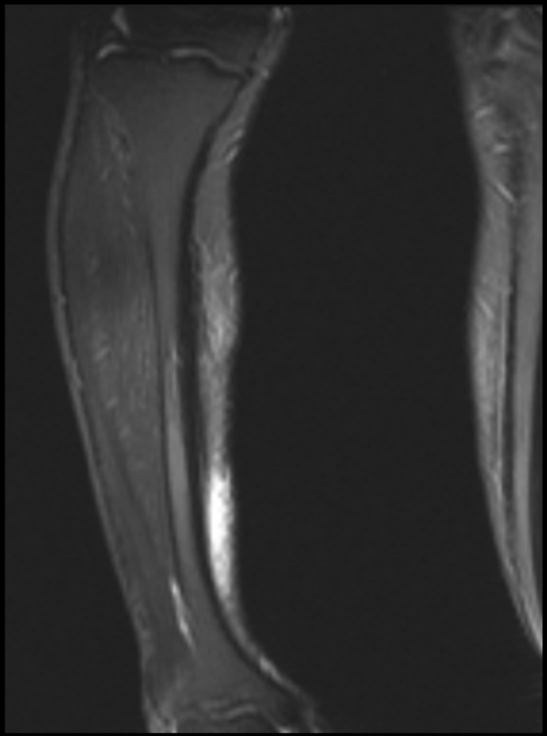
Fat sat pulse does not cover fat

Inaccurate map of frequency (spatial distortion)





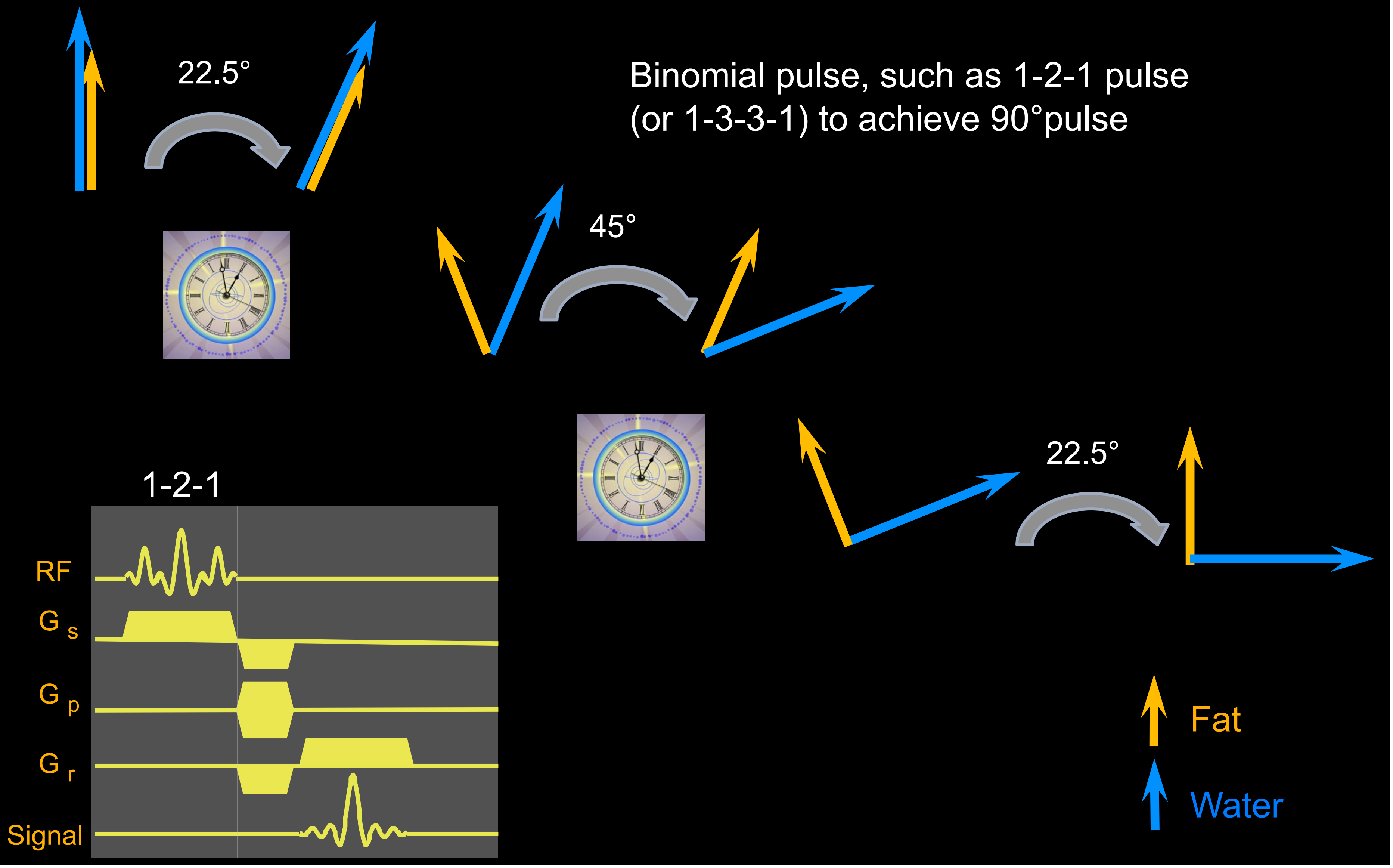
PD FS



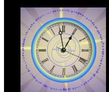
TIRM

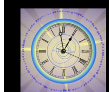
Water Excitation

Binomial pulse, such as 1-2-1 pulse (or 1-3-3-1) to achieve 90°pulse

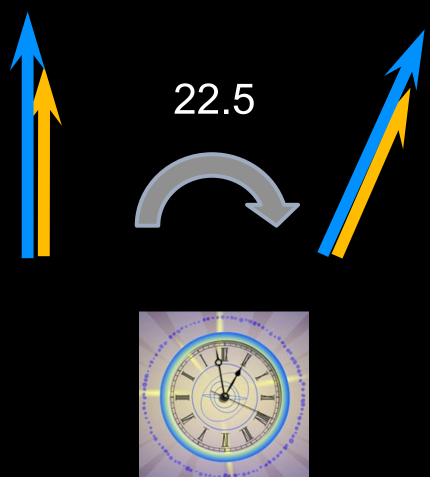


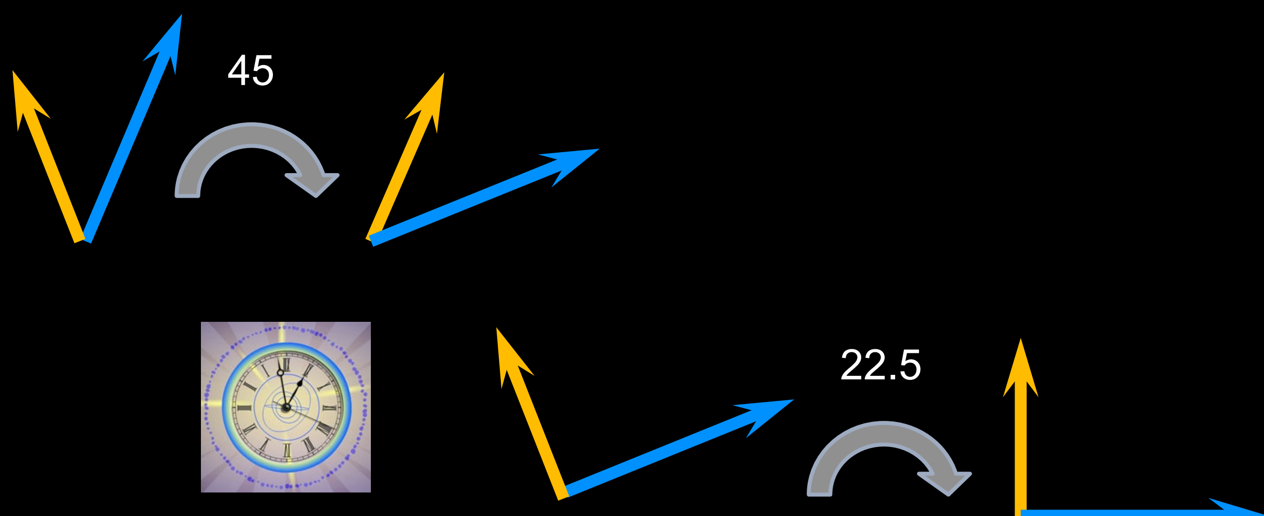
Water Excitation

 = ~2.2ms @ 1.5T

 = ~1.1ms @ 3T

- Advantages
  - Relatively insensitive to B1 inhomogeneity, avoids incomplete fat suppression that requires uniform RF flip angles across the FOV
  - Less sensitive to B0 inhomogeneity than CHESS, especially at higher field strengths
  - Shorter RF pulses can be used (as short as 3.6ms) on 3T





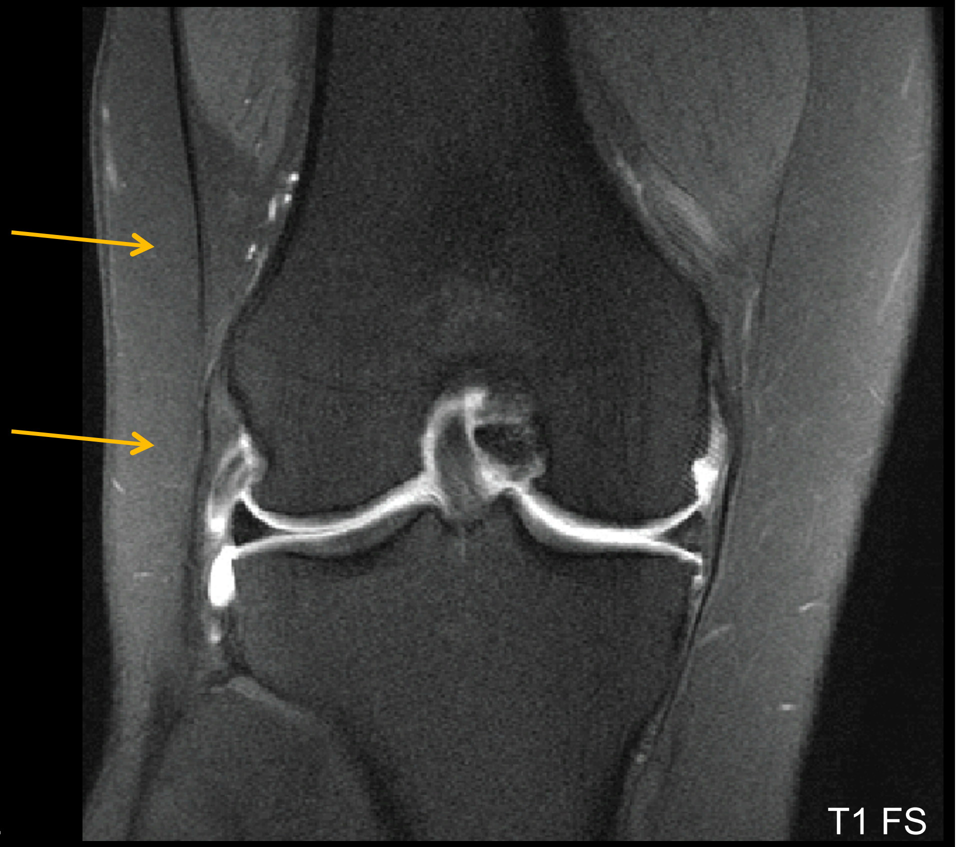
WE-VIBE

T1 FS arthrogram

5.5 minutes

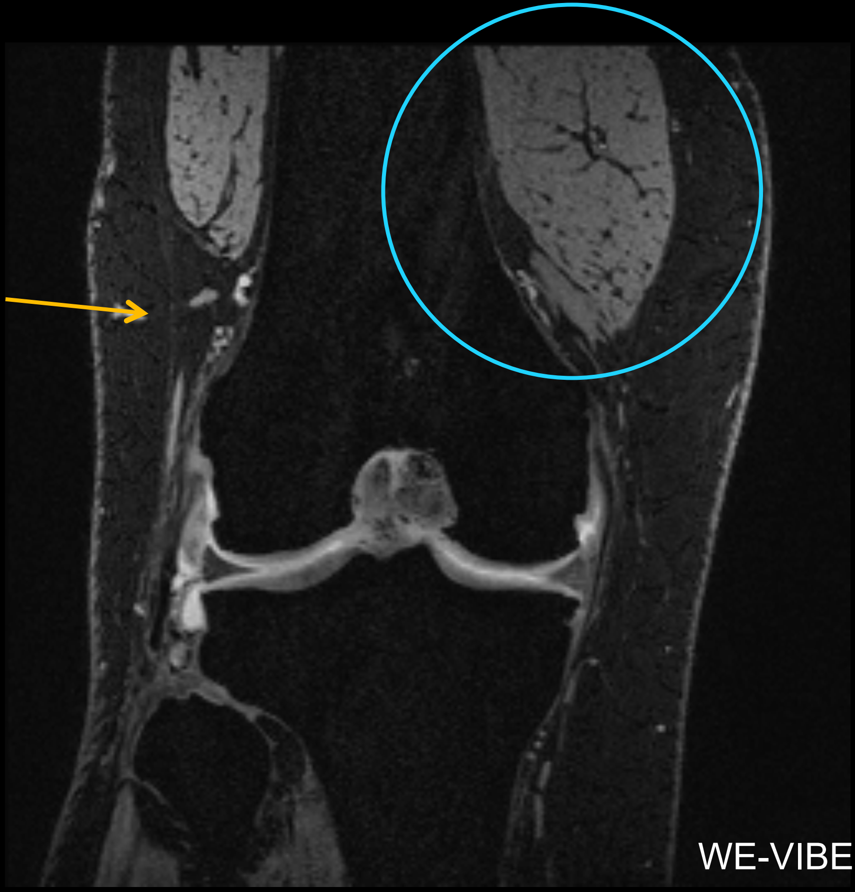
3D WE-VIBE versus Routine

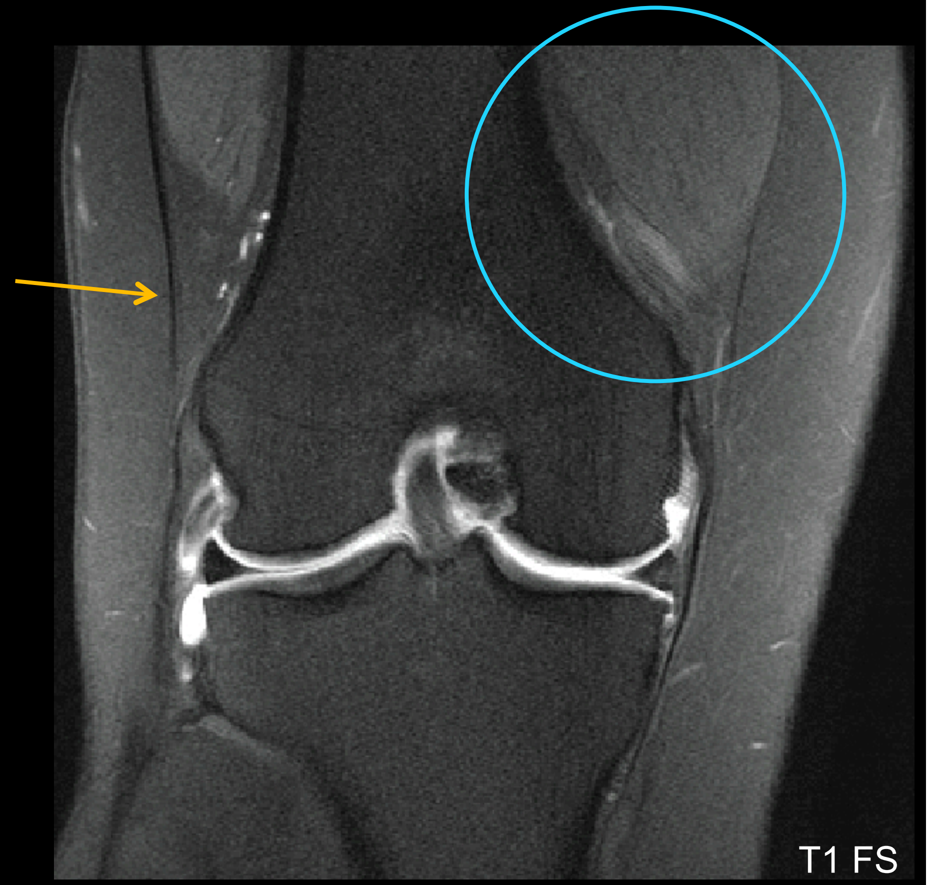
Homogeneous fat suppression



Inhomogeneous “gray” fat suppression

3D WE-VIBE versus Routine





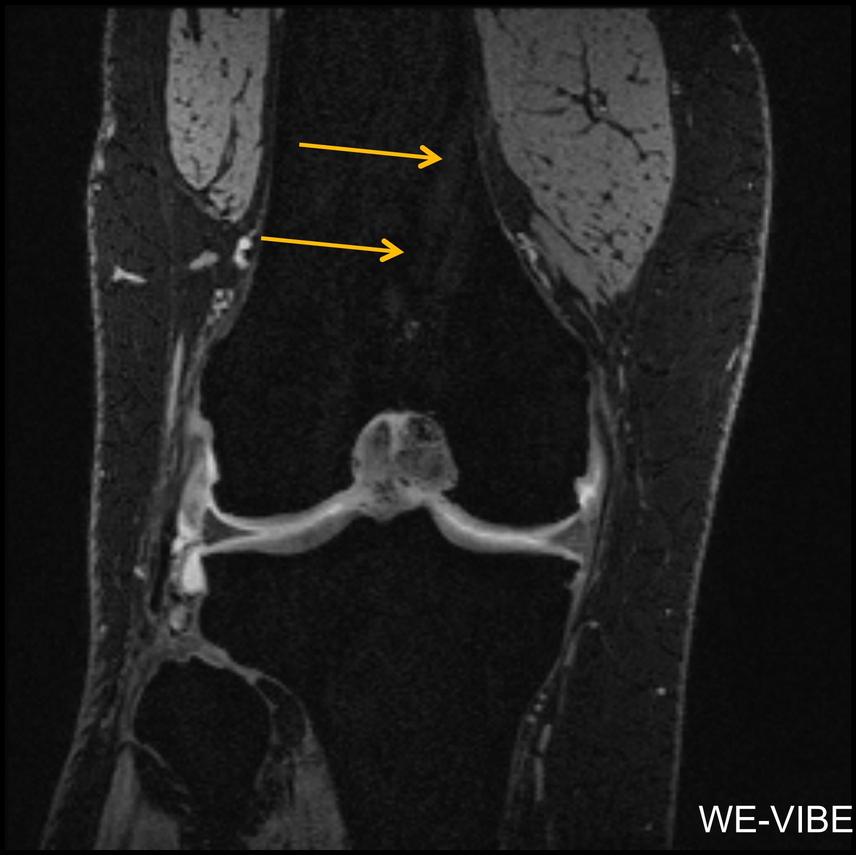
Contrast between “dark” fat/ “gray” muscle

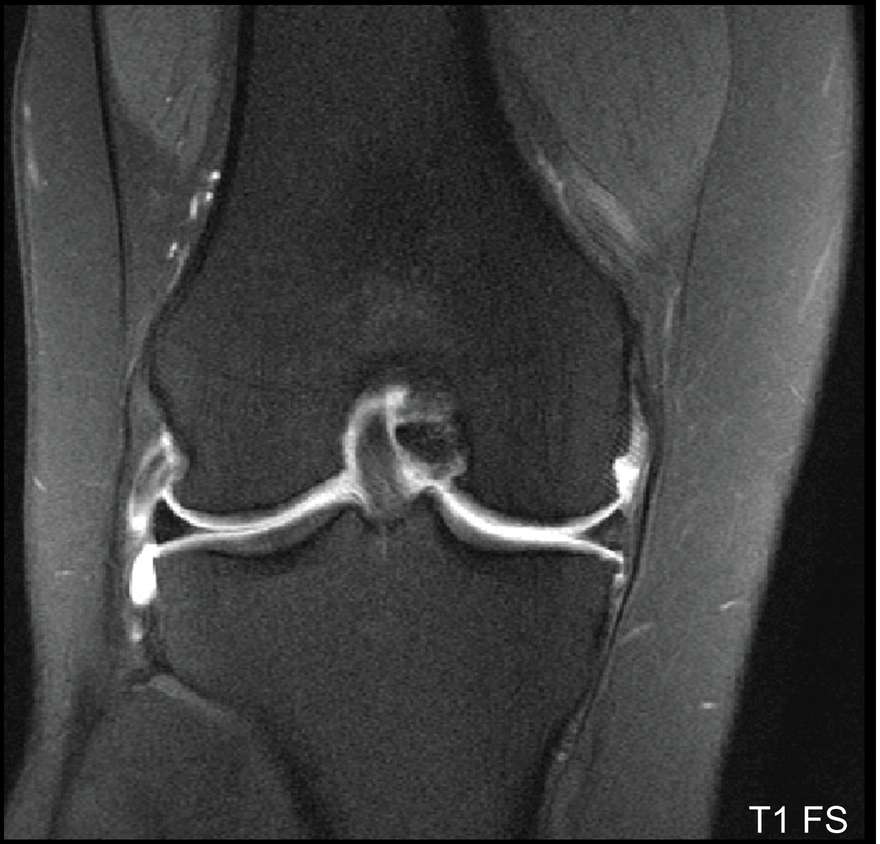
No contrast between “dark” fat/IT band

No contrast between “gray” fat/muscle

Contrast between “gray” fat/fibrous IT band

3D WE-VIBE versus Routine





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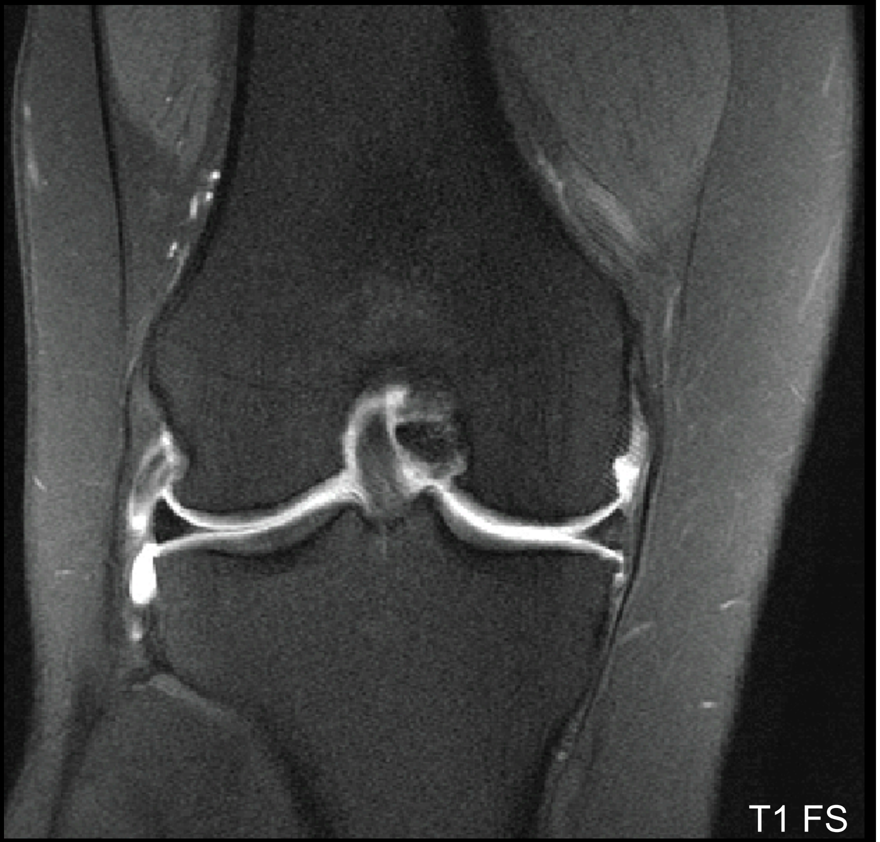
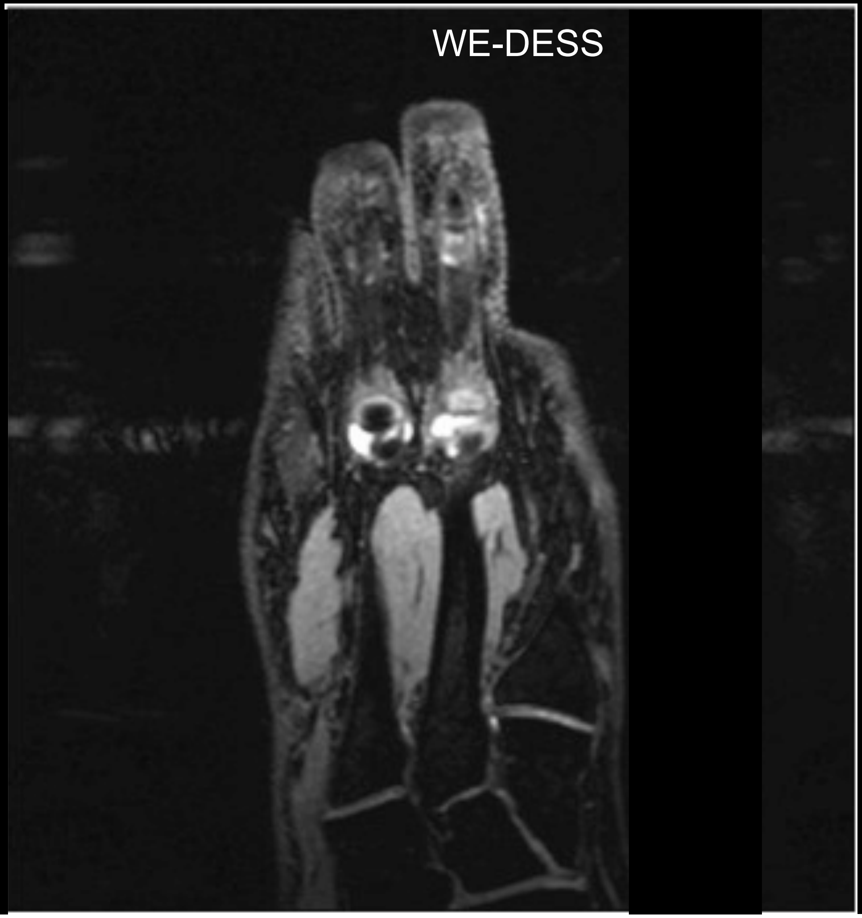
3D WE-VIBE versus Routine



Two phase encode directions!

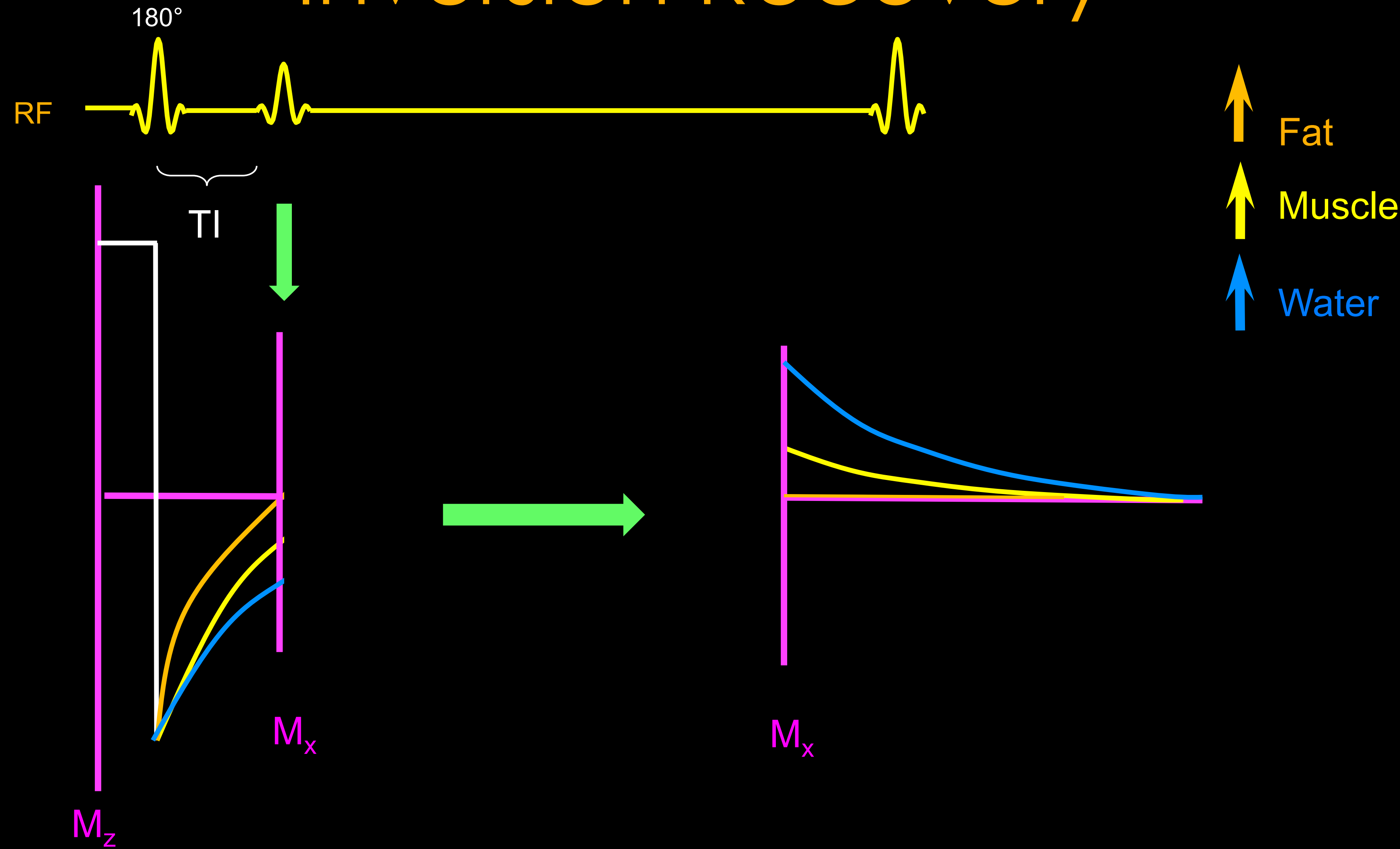
Water Excitation

- Prep pulse for "fat suppression"
- Can be used in nearly any sequence but are better suited for GRE sequences



- We may start seeing them in FSE sequences, but additional steps are necessary because of B0 eddy currents

Inversion Recovery



TI chosen to null undesired signal (~150ms for fat @ 1.5T)

STIR

* Advantage
  * Can be used with low field magnets (due to insufficient separation of fat and water)
  * Insensitive to B0 inhomogeneities
    * Remember STIR is based on T1 relaxation
    * T1 is related to B0, but not linearly

TABLE 3 In Vivo T1 Relaxation Times at 1.5 and 3.0 T

Tissue	Relaxation Times (msec) for T1-Weighted Imaging		% Increase	p^a
	At 1.5 T	At 3.0 T		
Muscle	1,130 ± 91.7	1,420 ± 38.1	20.4	0.002
Cartilage	1,060 ± 155	1,240 ± 107	14.5	0.04
Synovial fluid	2,850 ± 279	3,620 ± 320	21.2	0.01
Subcutaneous fat	288 ± 8.42	371 ± 7.94	22.3	0.0001
Marrow fat	288 ± 5.27	365 ± 9.0	21.1	0.0001

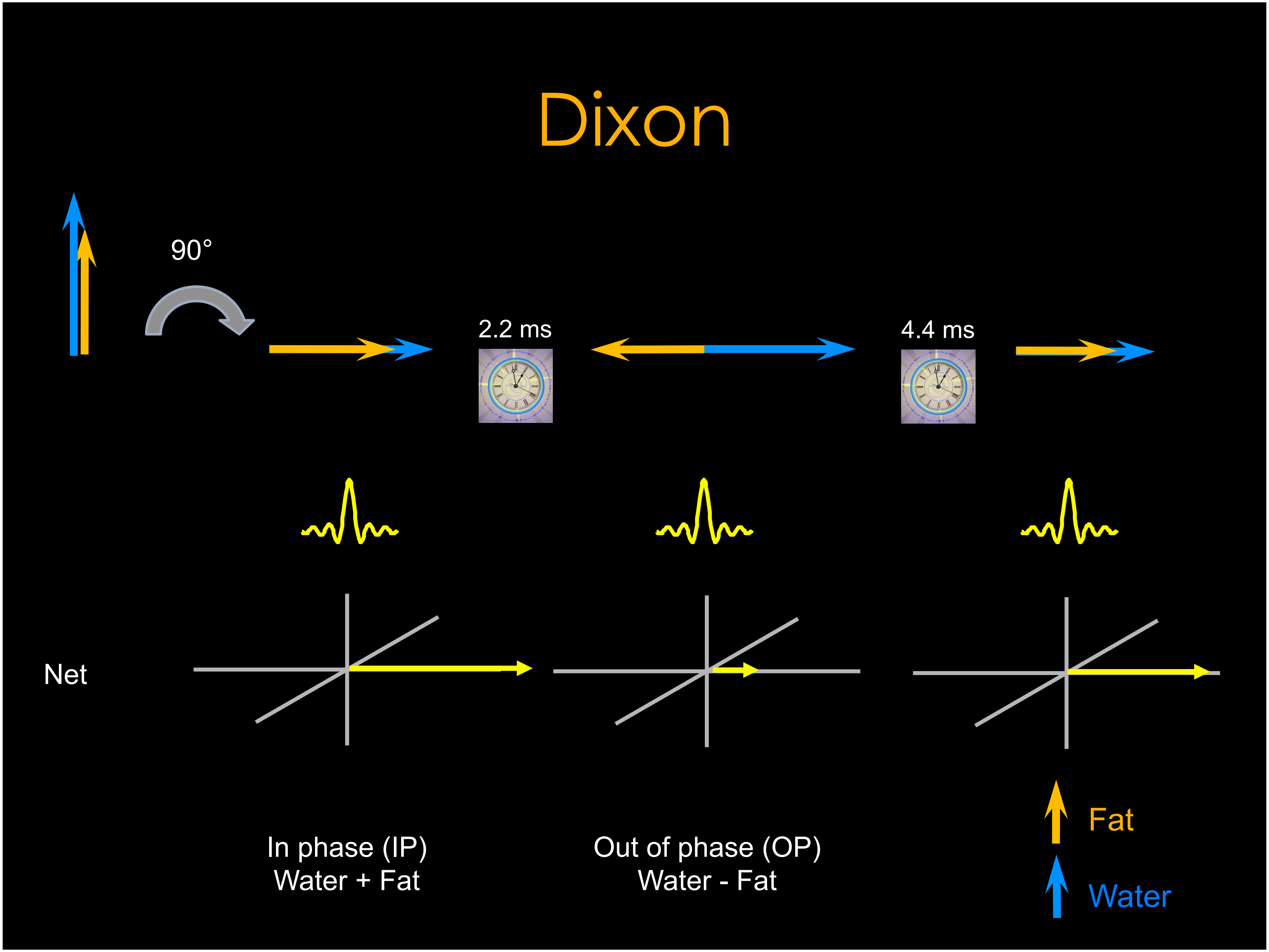
Gold GE et al. MSK MRI at 3T: Relaxation Times and Image Contrast. AJR 2004.

STIR

* Disadvantages
  * Not to be used with postcontrast images
  * Long sequence (TI @ 1.5T ~150 ms)
  * Can be sensitive to B1 (less than 180° RF pulse = signal from fat)
  * **Degrades SNR of remaining water signal by ~40-50%**

Dixon

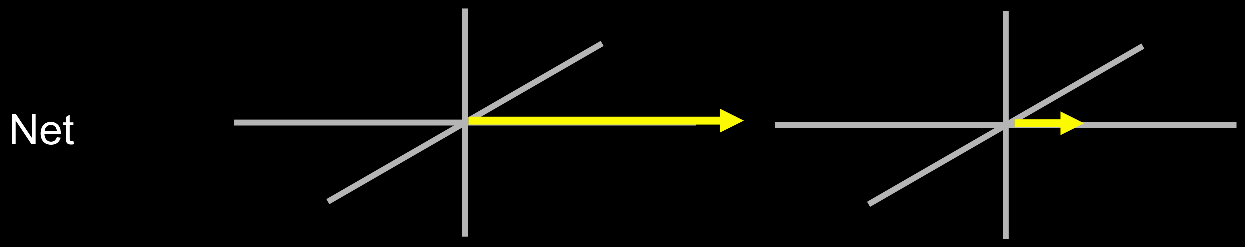
* Separates water-fat based on phase shifts
* Acquire at specific TE to decompose separate water and fat images


Dixon
90°
2.2 ms
4.4 ms
Net
In phase (IP)
Water + Fat
Out of phase (OP)
Water - Fat
Fat
Water

Dixon

2 series of images acquired

* In phase (IP)
* Out of phase (OP)



In phase (IP)
Water + Fat

Out of phase (OP)
Water - Fat

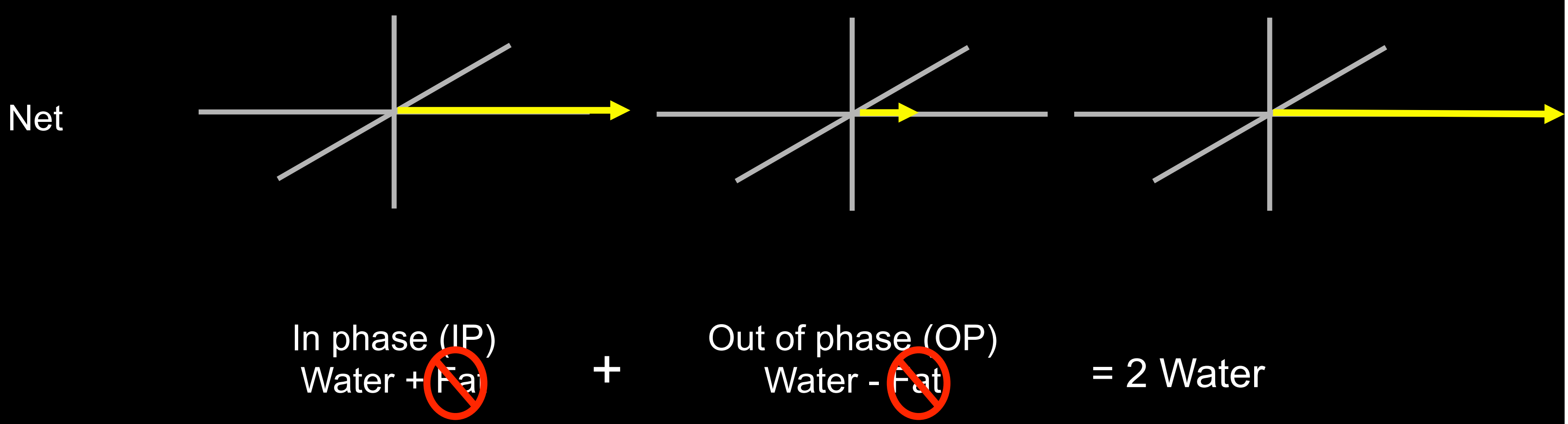
Dixon

2 series of images acquired

- In phase (IP)
- Out of phase (OP)

2 series of images calculated

- Water only = IP + OP



Dixon

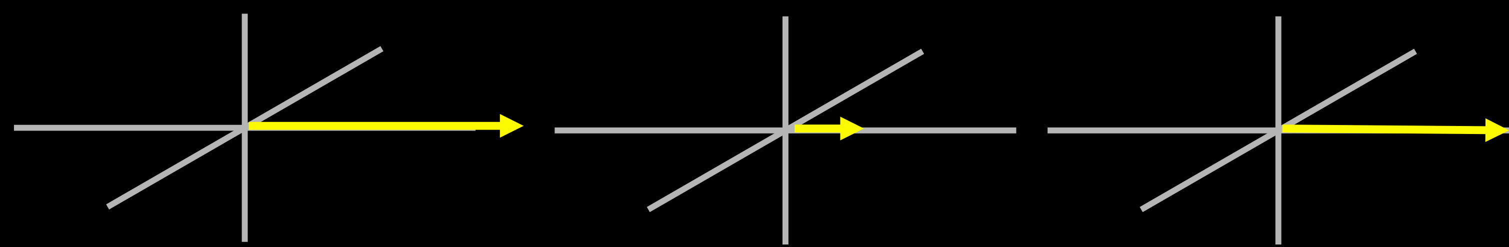
2 series of images acquired

- In phase (IP)
- Out of phase (OP)

2 series of images calculated

- Fat only = IP - OP

Net



In phase (IP)
Water + Fat

-

Out of phase (OP)
Water - Fat

= 2 Fat

Dixon

* Initial description sensitive to B0 field inhomogeneity, resulted in "swapping" of fat and water
* Unlike chemical fat sat, postprocessing phase correction could be performed to correct this
* Many phase correction techniques: 3-point Dixon or 2-D phase unwrapping

Dixon

* Compensates for B0 inhomogeneity
* Insensitive to B1 inhomogeneity
* Universal compatibility (GRE or FSE)
* <u>Chemical shift artifact can be removed</u>
  * @3T 2x chemical shift artifact, generally corrected by ↑ BW and therefore ↓SNR √BW
* If chemical shift considerations are eliminated, we can image with ↓↓BW and use the increased SNR to image very small voxels

GE Dixon Techniques

LAVA-FLEX (formerly MEDAL)

Multi-Echo with 2-point Dixon Reconstruction for Decoposition of Aqua/Lipid

* 2-point Dixon with phase correcting algorithm which determines signal of a given pixel based on amplitude and phase of surrounding pixels (Jingfei Ma, MRM 2004)
* 3D spoiled GRE

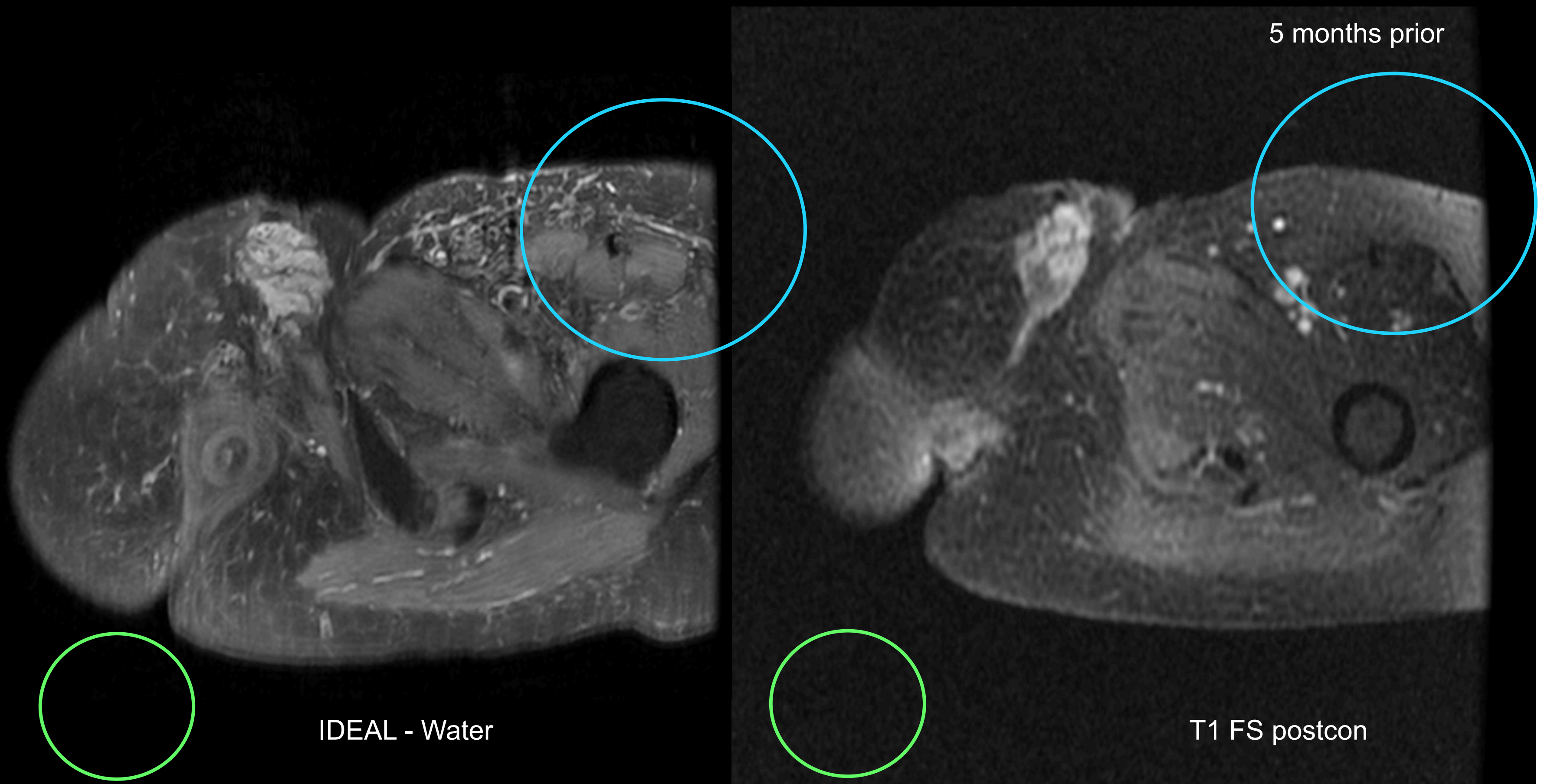
IDEAL

Iterative DEcomposition of Water and Fat with Echo Asymmetry and Least Squares Estimation

* 3-point Dixon with asymmetrically acquired echoes whose combination gives effective signal averaging of 3 for all combinations of water/fat
* 2D or 3D, GRE or FSE

IDEAL

66 year old man with urethral cancer status post right hemipelvectomy

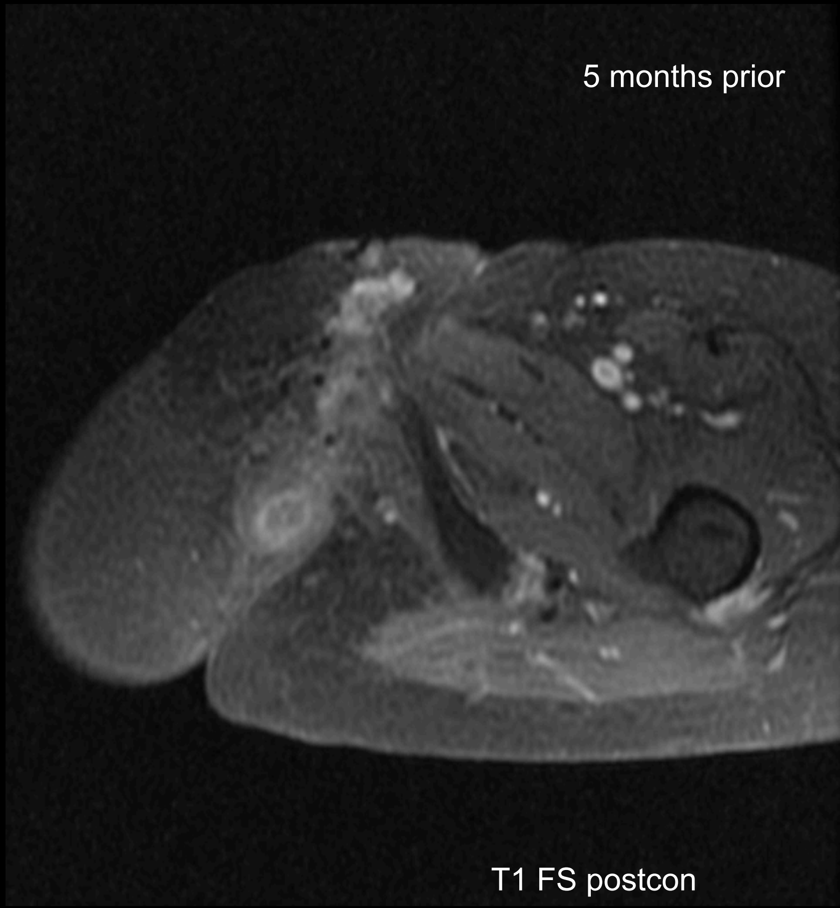


Better fat suppression

Higher SNR

IDEAL

66 year old man with urethral cancer status post right hemipelvectomy



Recurrent urethral cancer was larger

IDEAL

Better fat saturation at the edge of the ankle coil

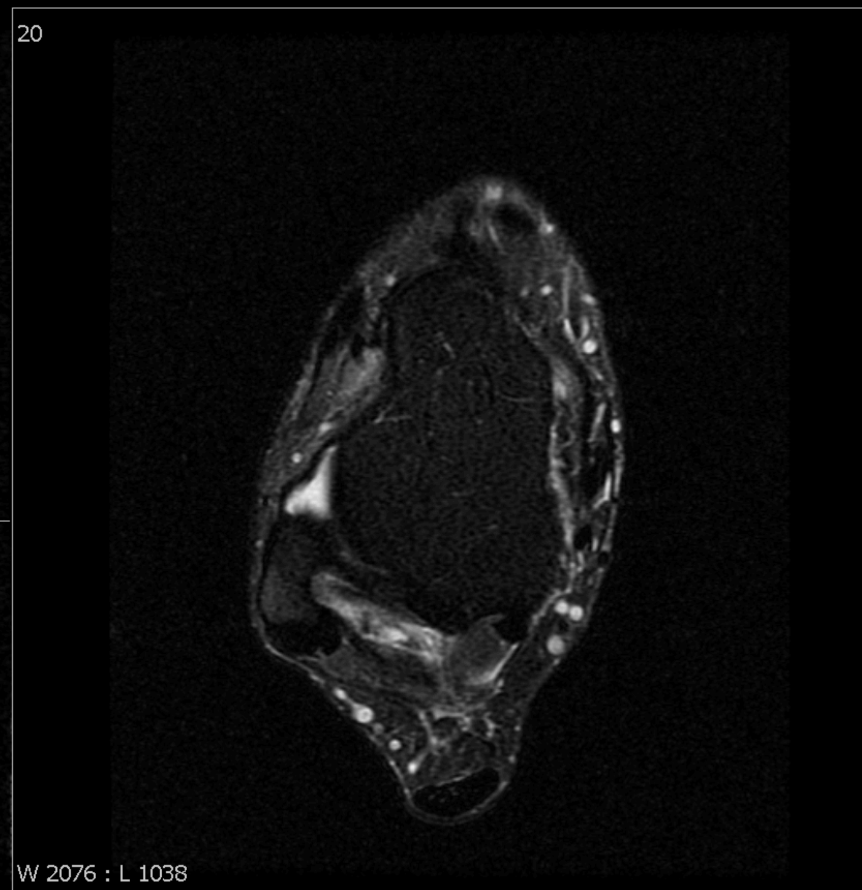
IDEAL - Water

T2 FS (3783/86)

IDEAL

Better fat saturation at the edge of the ankle coil

IDEAL - Water



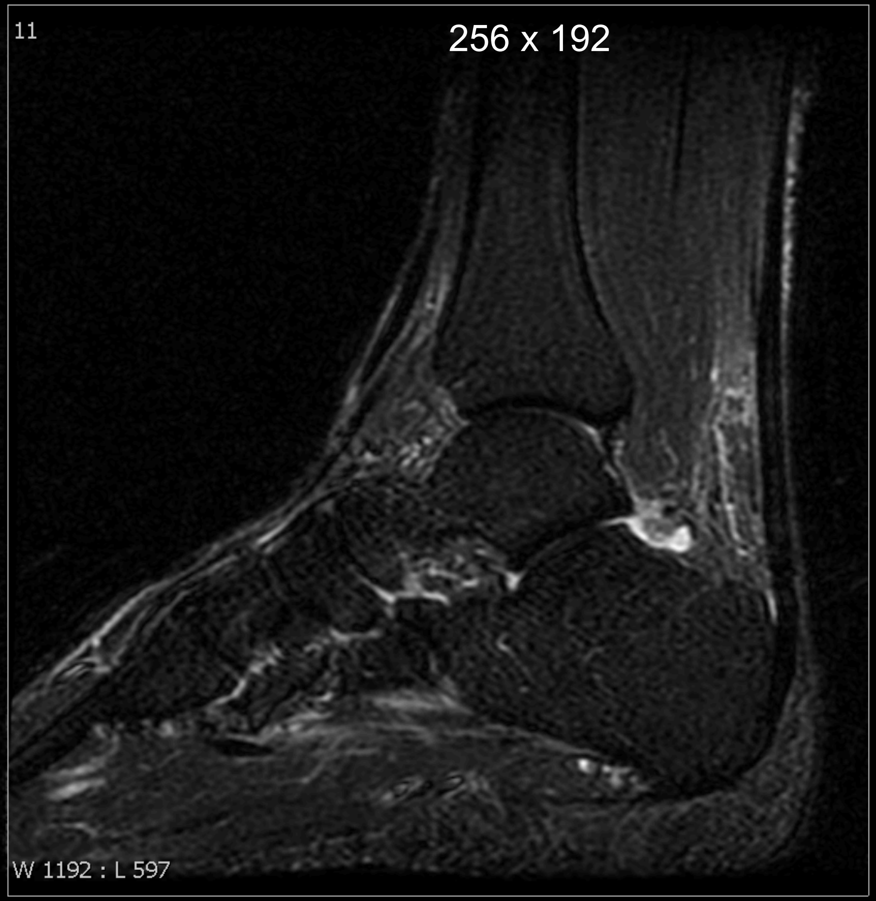
T2 FS (3783/86)

IDEAL

4.5 min TR/TE 2050/31

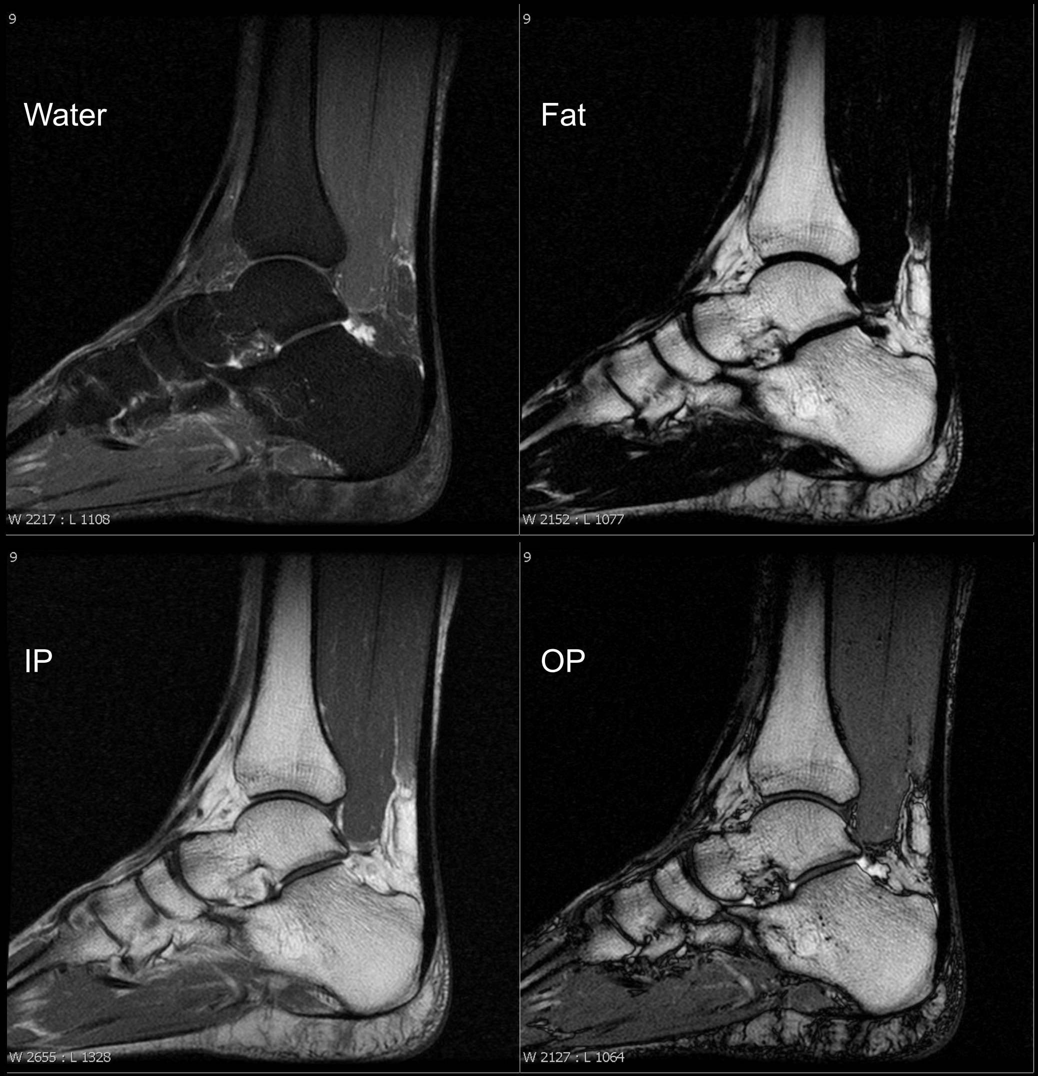
IDEAL - Water

5.0 min TR/TE 3000/49



STIR

IDEAL


9
Water
W 2217 : L 1108
9
Fat
W 2152 : L 1077
9
IP
W 2655 : L 1328
9
OP
W 2127 : L 1064

Dixon

- Disadvantages
  - Time due to acquisition of multiple echoes (IDEAL with 3 echos takes 3 times as long)

  - However, with increased SNR Dixon techniques can be run with:
    - Partial k-space acquisitions (half NEX or fractional echoes)
    - Parallel imaging (SENSE, GRAPPA)

Can be run with 3D acquisitions

Future of MSK

3D Imaging

- Workflow
  - All else being equal (which it is <u>not</u> right now), 1 3D dataset can be acquired over 3 2D datasets
- User defined planes
  - Interpretation by anatomy, not by planes

Future of MSK

3D Imaging

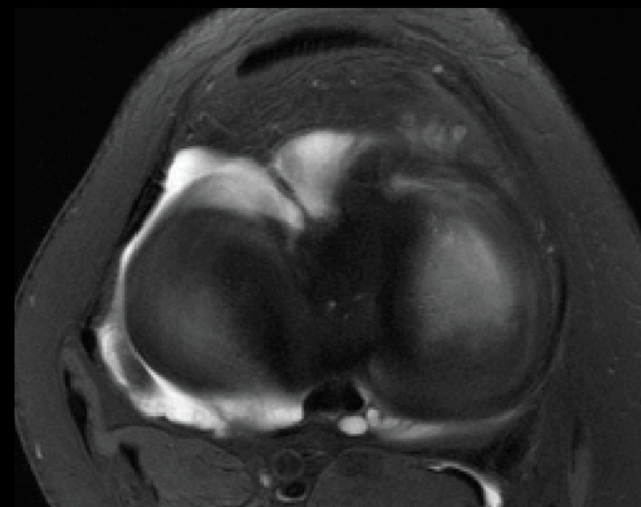
- In general, there is increased SNR (↓ voxel size)
  - SNR advantage over 2D sequences increases with:
    - Tissues with short T1 ($T1 << T_{seq}$)
    - Increasing number of slices (↑by √slices)

3D Imaging with Dixon

- Superior water-fat separation
- Increased SNR (smaller voxels, half Nex, parallel image)

Standard 2D Imaging

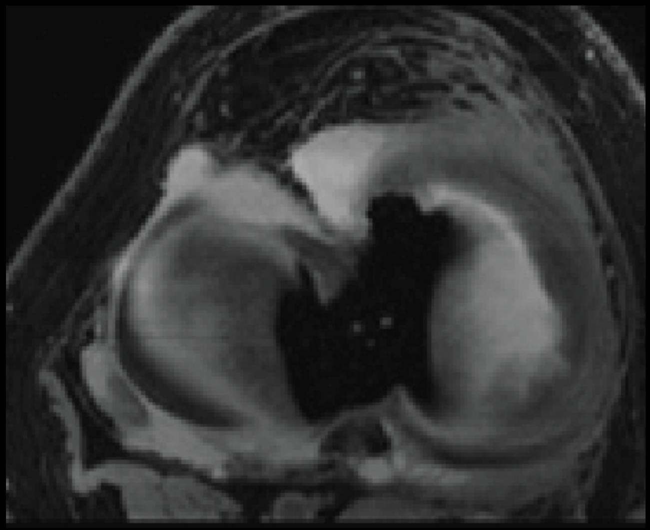
TSE T1 FS



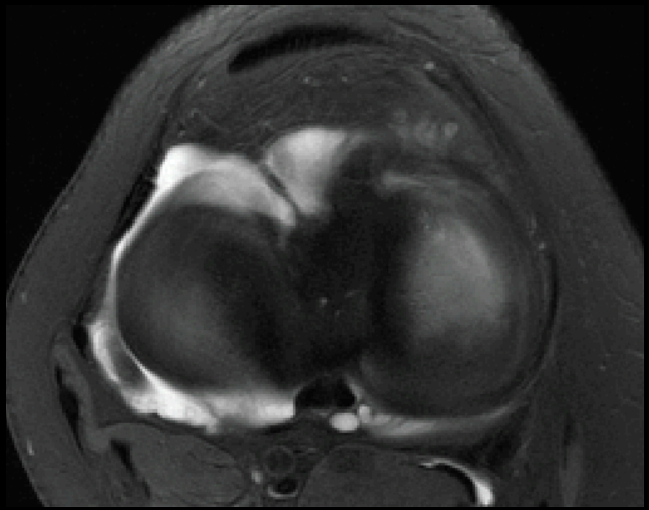
TSE T1 FS

TSE T1 FS

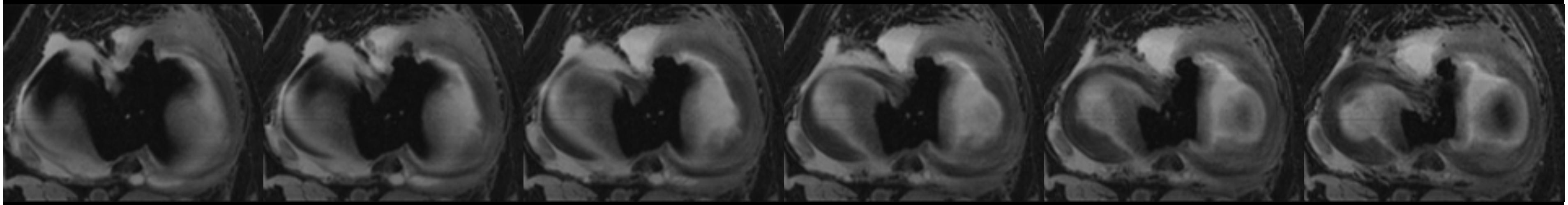
3D WE-VIBE versus Routine



3D WE-VIBE

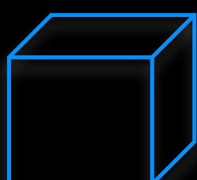


2D TSE T1 FS



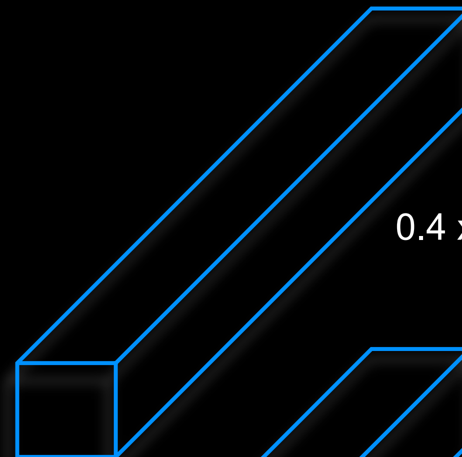
Spatial Resolution

3D WE-VIBE

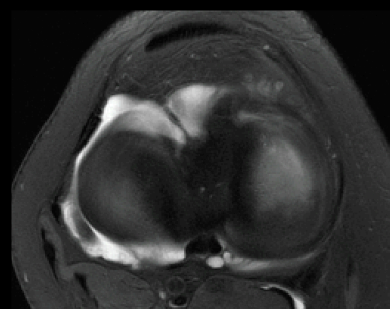


0.6 x 0.6 x 0.6 mm

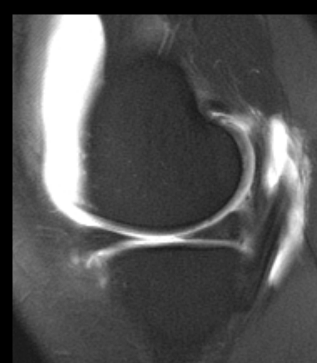
2D TSE T1 FS



0.4 x 0.4 x 3.5 mm



0.4 x 0.4 x 3.5 mm

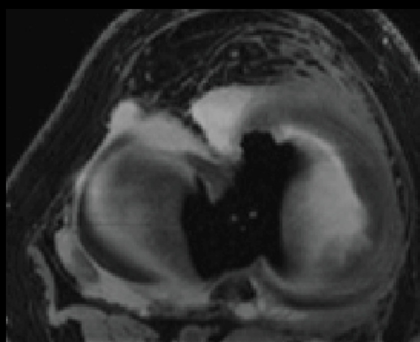


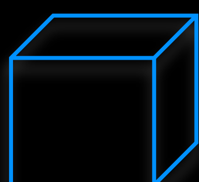
0.4 x 0.4 x 3.5 mm

Spatial Resolution

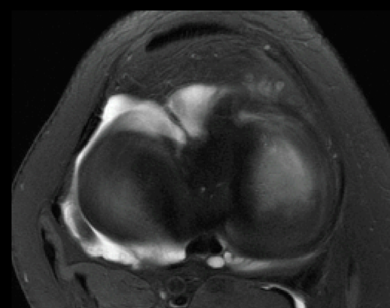
2D TSE T1 FS

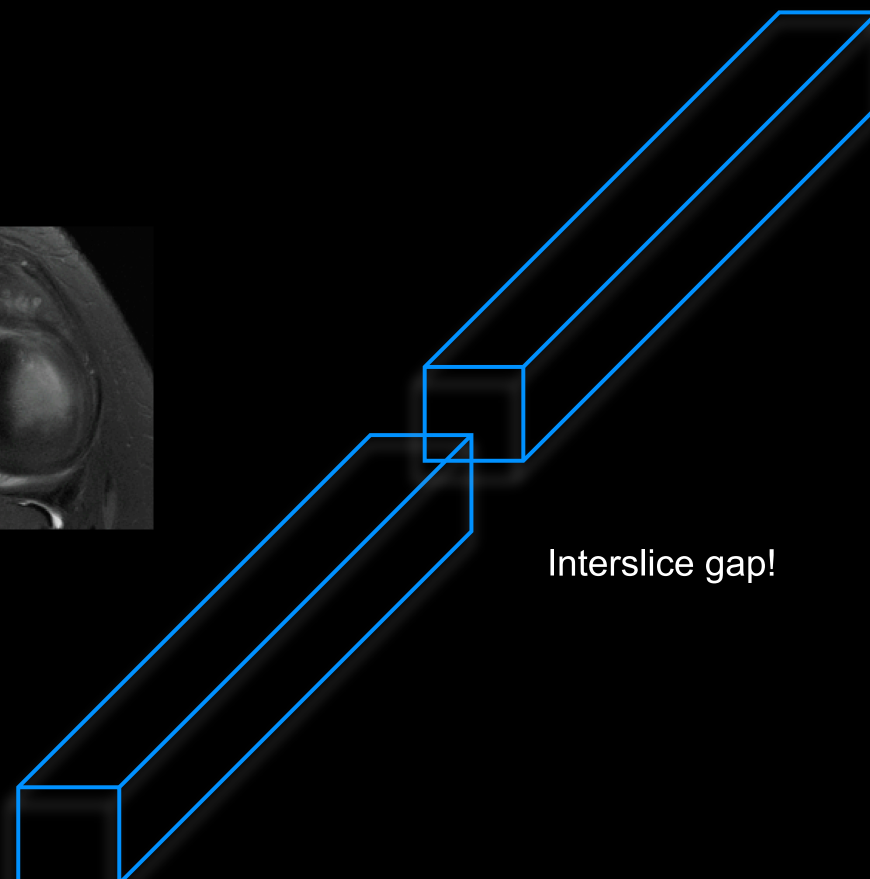
3D WE-VIBE





0.6 x 0.6 x 0.6 mm





Interslice gap!

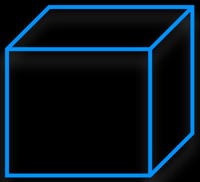
Spatial Resolution

Computed Tomography

3D WE-VIBE

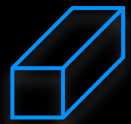
Highest spatial resolution of GE VCT

0.35 x 0.35 x 0.625 mm



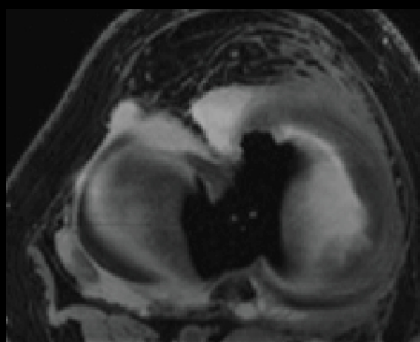
0.6 x 0.6 x 0.6 mm

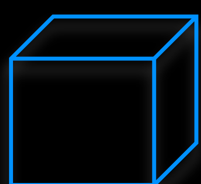
Highest spatial resolution of GE CT 750 in HiRes mode



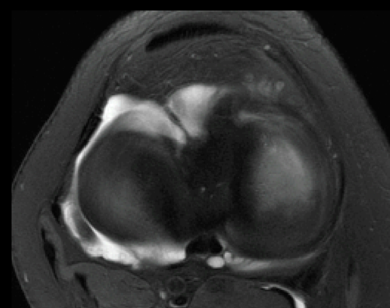
0.23 x 0.23 x 0.625 mm

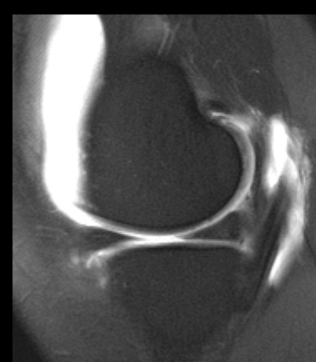
Time

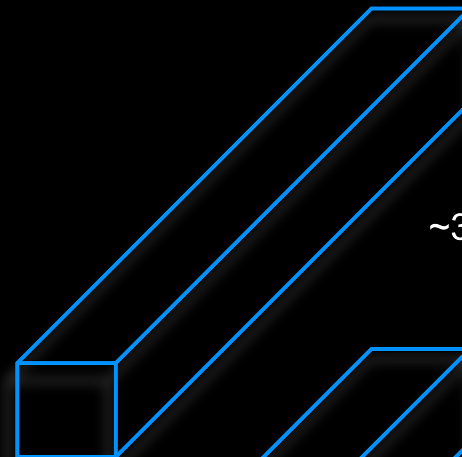




5.5 minutes





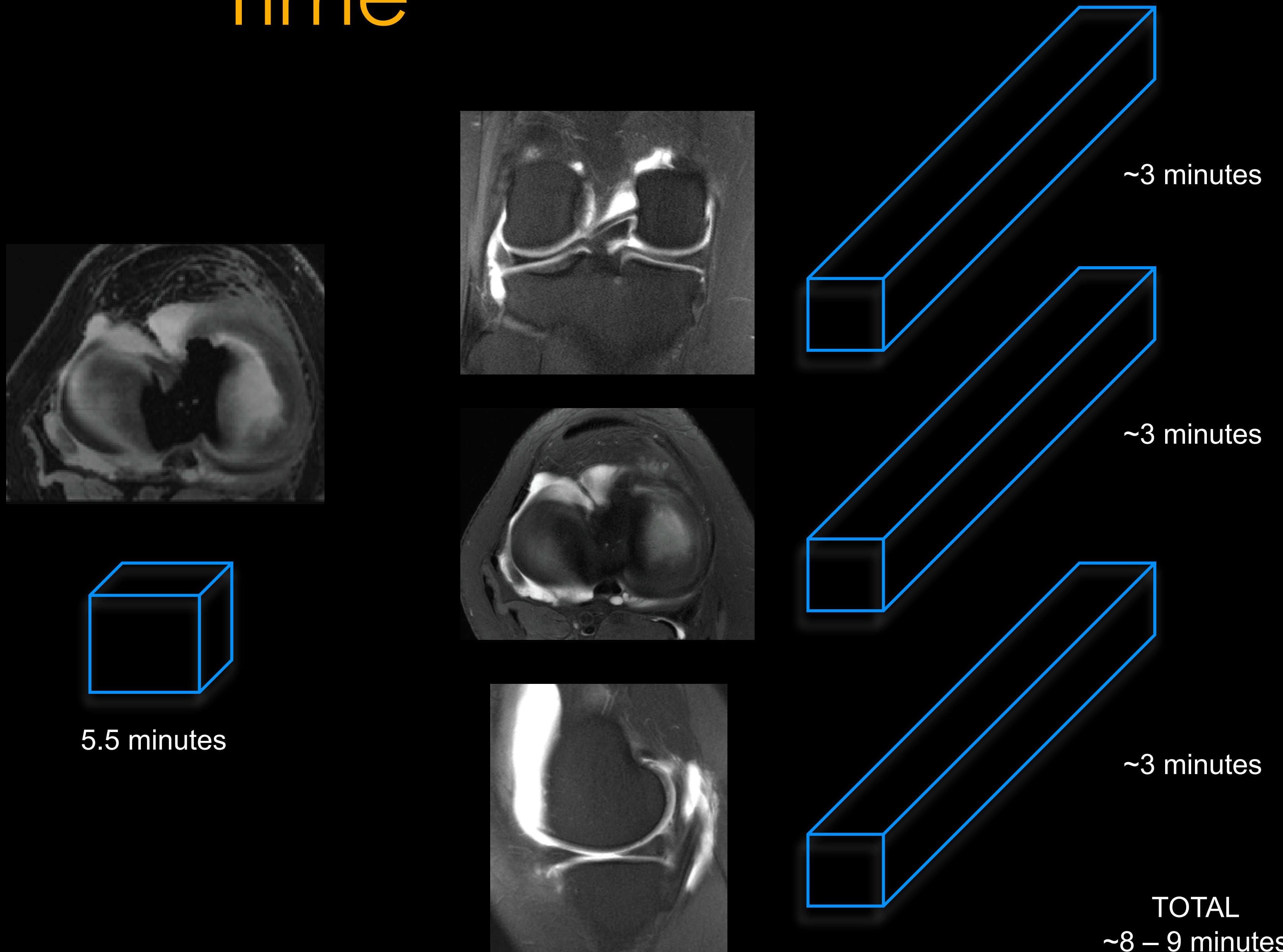


~3 minutes

~3 minutes

~3 minutes

Time



3D Sequences

* Gradient Echo
  * SPGR
  * VIBE
  * DESS
* Fast Spin Echo

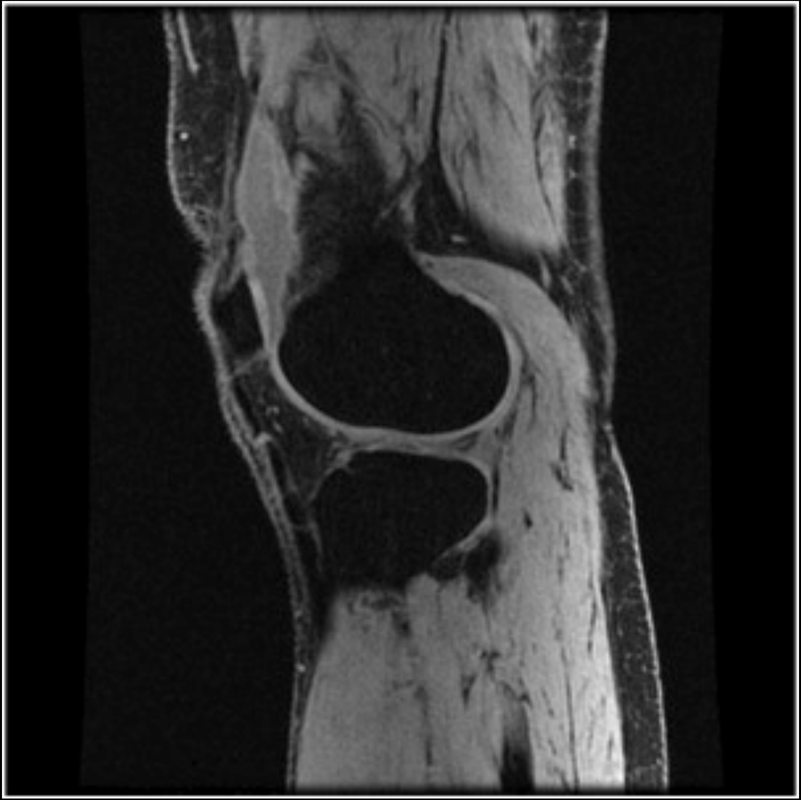
Spoiled GRE are more often used with T1 weighting

GRE versus FSE

3D SPGR

* SPGR or FLASH
* Transverse steady state is spoiled
* Poor contrast between cartilage and fluid (T1 weighted)
* Takes a long time to acquire

3D SPGR



2mm slice, ZIP 2
256 x 256
2 NEX
TR/TE/FA 19/4/12
9 minutes!

Reconstruction

Volumetric Interpolated Breath-Hold Examination (VIBE)

* 3D spoiled GRE sequence with low flip angles
* Developed at NYU for abdominal imaging (Rofsky, Radiology 1999)
* Very fast
* Zeros are used to fill portions of k-space (interpolated), requiring less time while maintaining resolution

Volumetric Interpolated Breath-Hold Examination (VIBE)

Strong T1 contrast

- Not intended for fluid sensitivity
- Very useful for arthrography

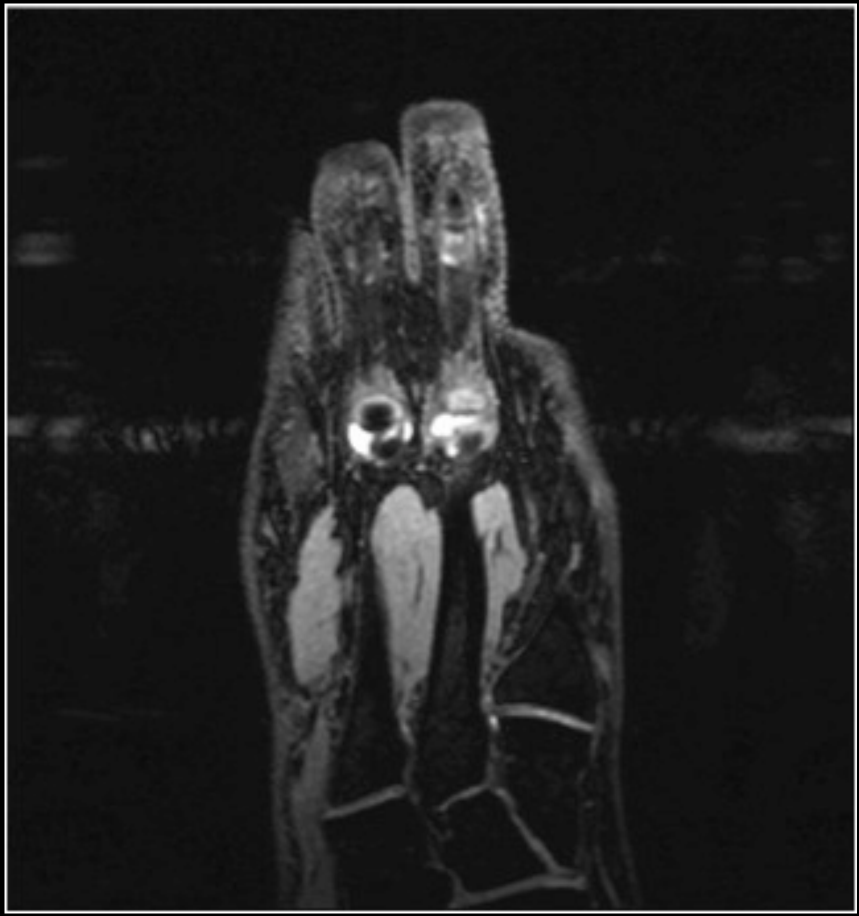
0.35 x 0.4 x 0.4 mm

<4 mins

Duel-Echo Steady-State (DESS)

- 3D refocused GRE sequence
- Two or more echoes are acquired and combined for higher T2 weighting
- Acquisition for DESS is shorter than for 3D SPGR
- Contrast for DESS is complex

WE-DESS



WE-DESS

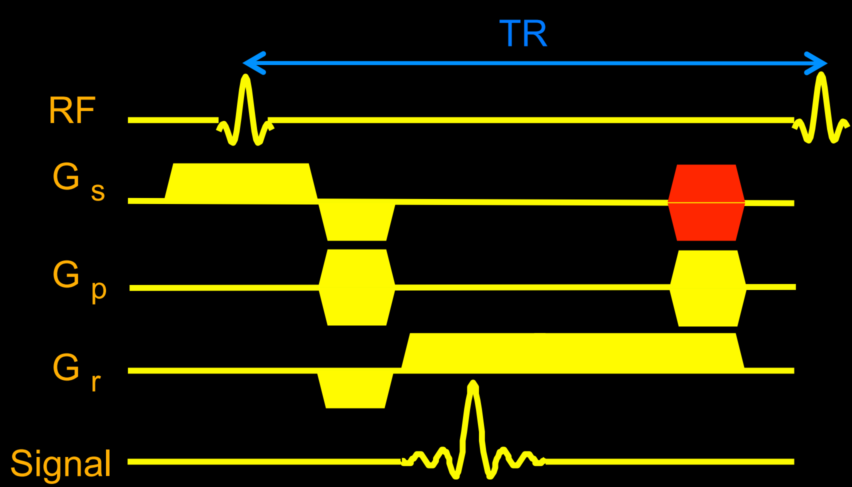
0.50 x 0.58 x 0.60 mm

<4 mins

Gradient-Echo Sequences

* Residual transverse magnetization is RF spoiled

SPGR
VIBE



Assuming TR < T2<T1

* Residual transverse magnetization is refocused (steady state)

DESS
bSSFP (FIESTA)

3D Fast Spin Echo

* Benefits of refocusing pulses
  * Decreased artifacts from field inhomogeneity
    * More of a problem with early magnets
    * Orthopedic hardware
* 3D FSE

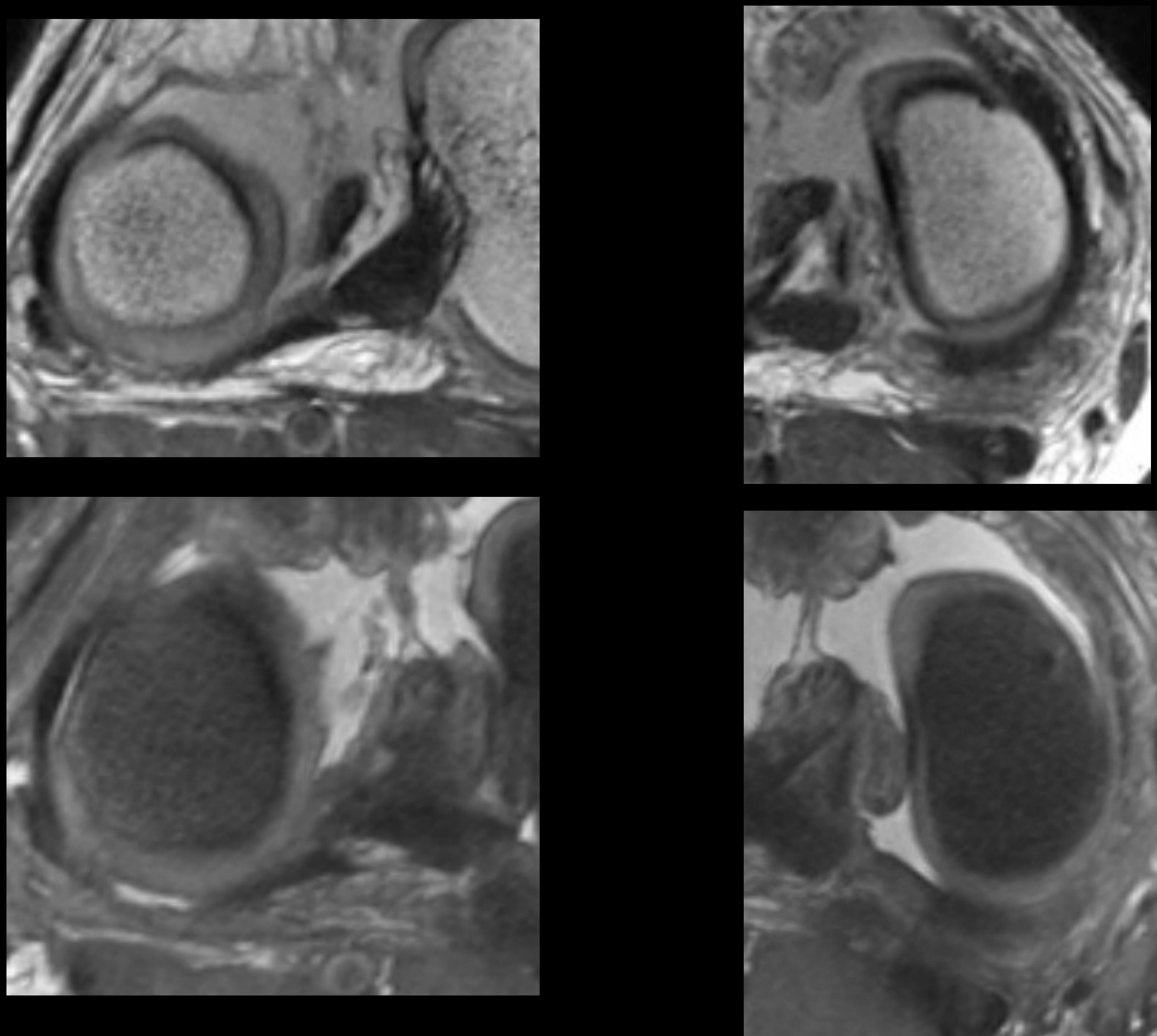
  SPACE

  Sampling Perfection with Application optimized Contrasts using different flip angle Evolution

  CUBE

SPACE

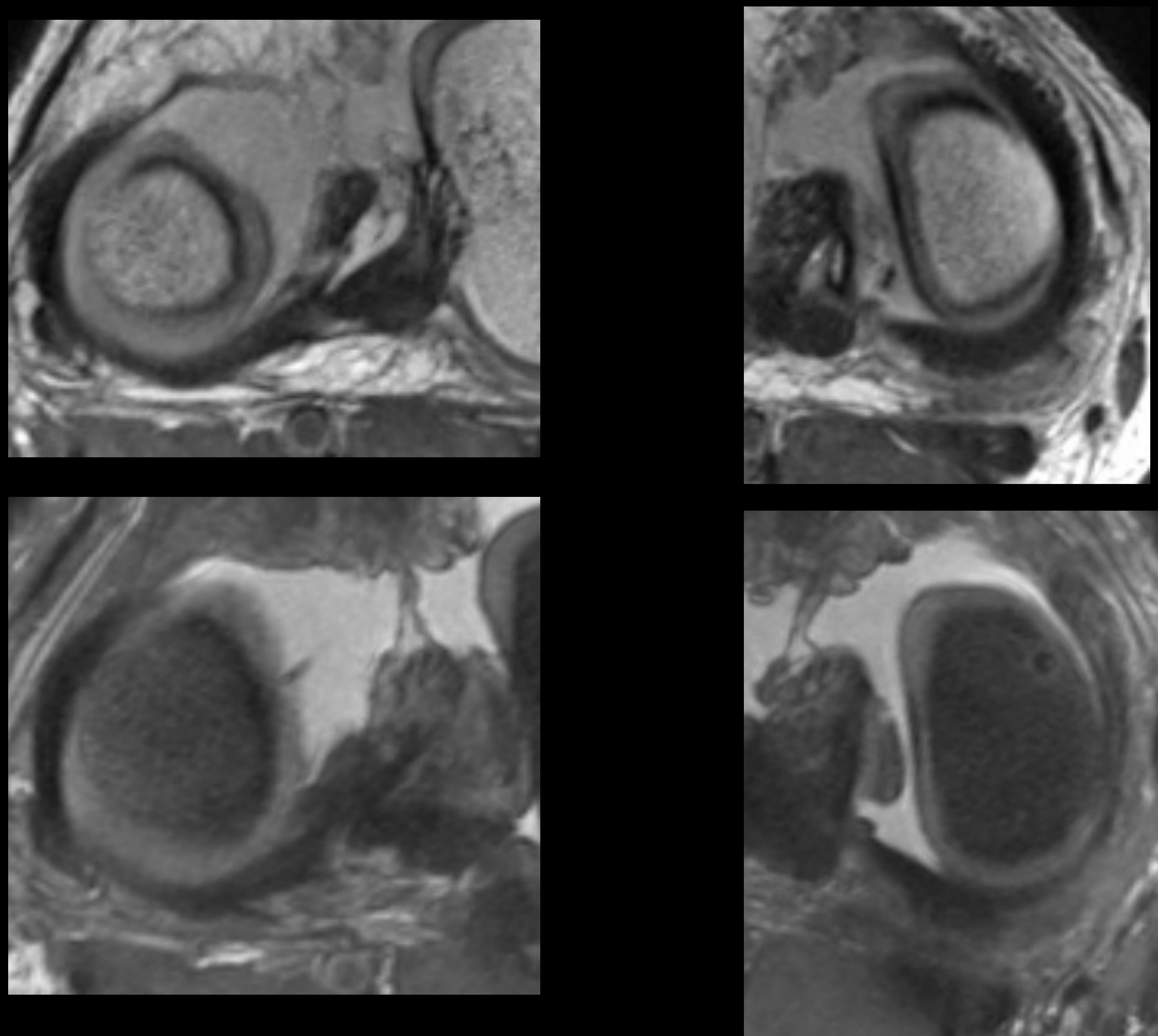
Sagittal acquisition: 0.53mm thick   320 x 320 (0.47mm)   ~5 mins



w/o FS

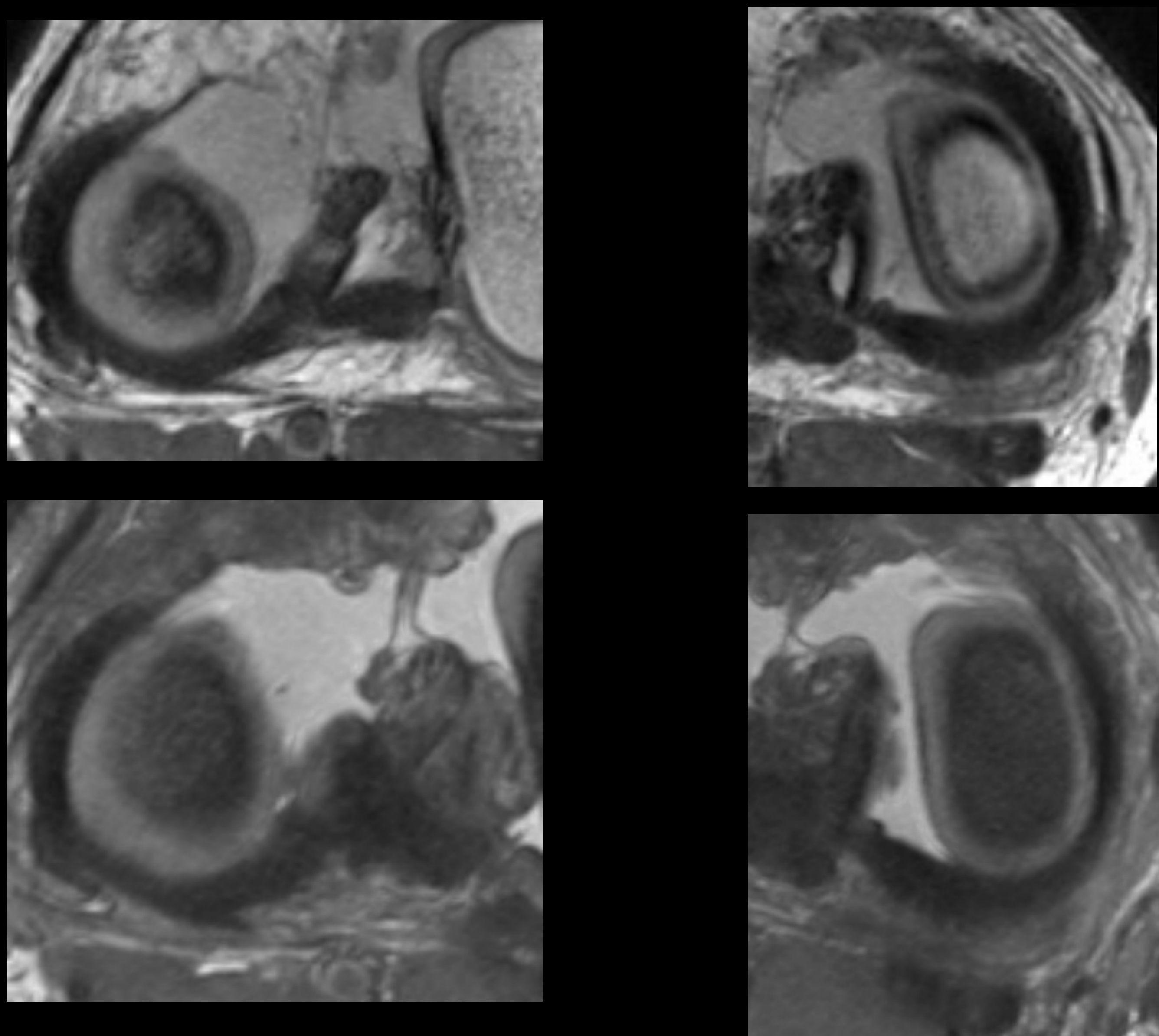
w/ FS

Reformatted from sagittal acquisition



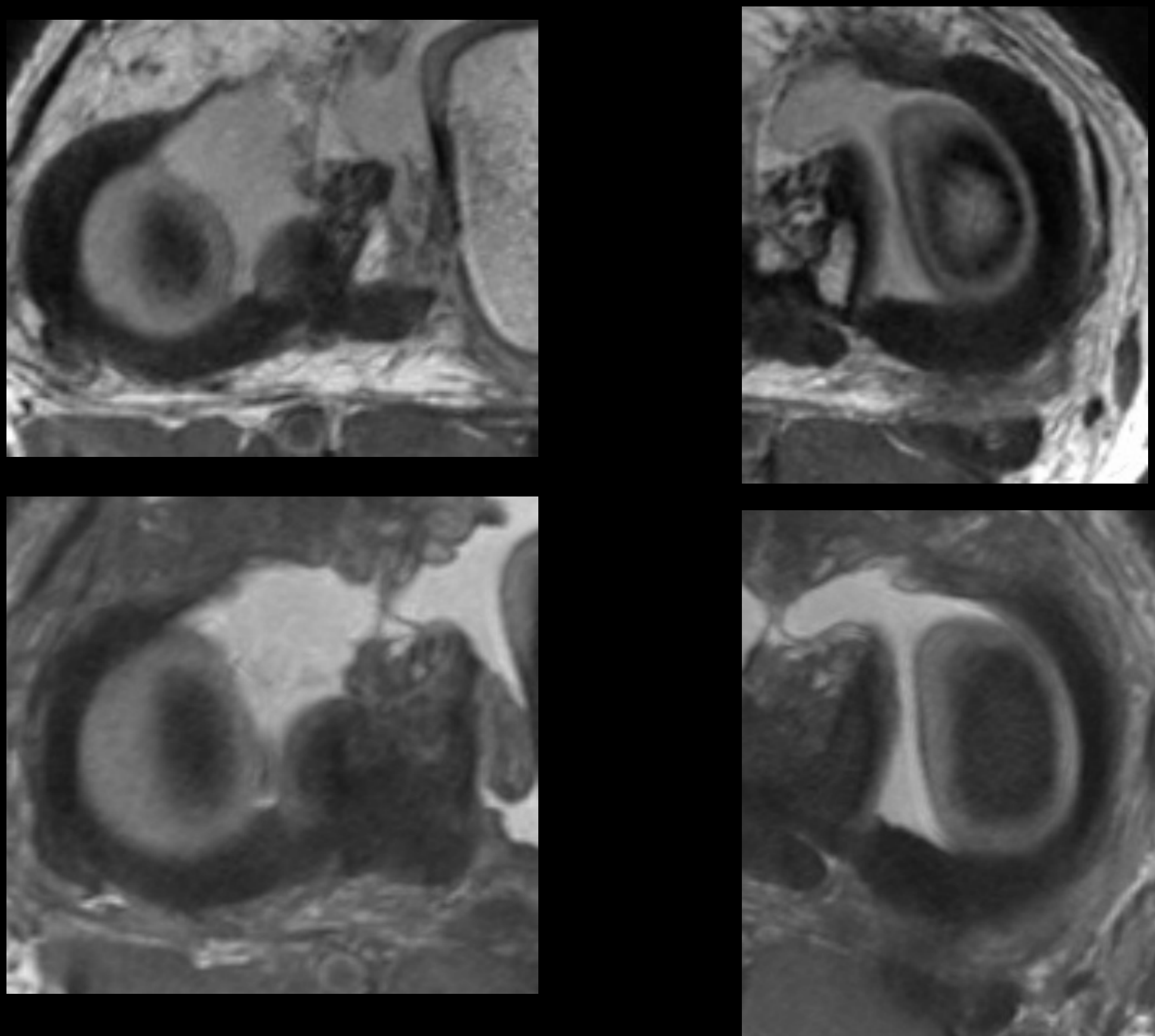
w/o FS

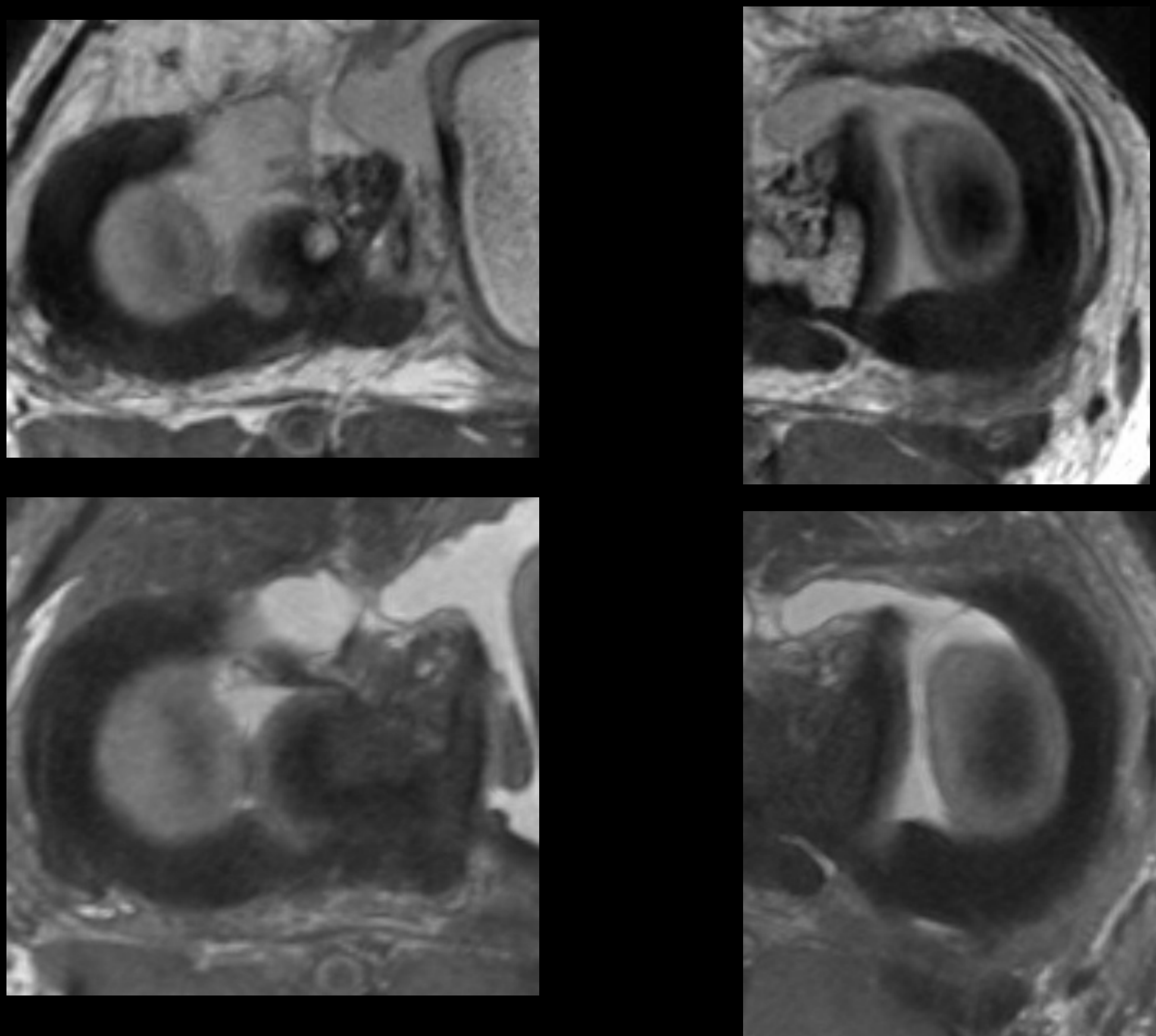
w/ FS



w/o FS

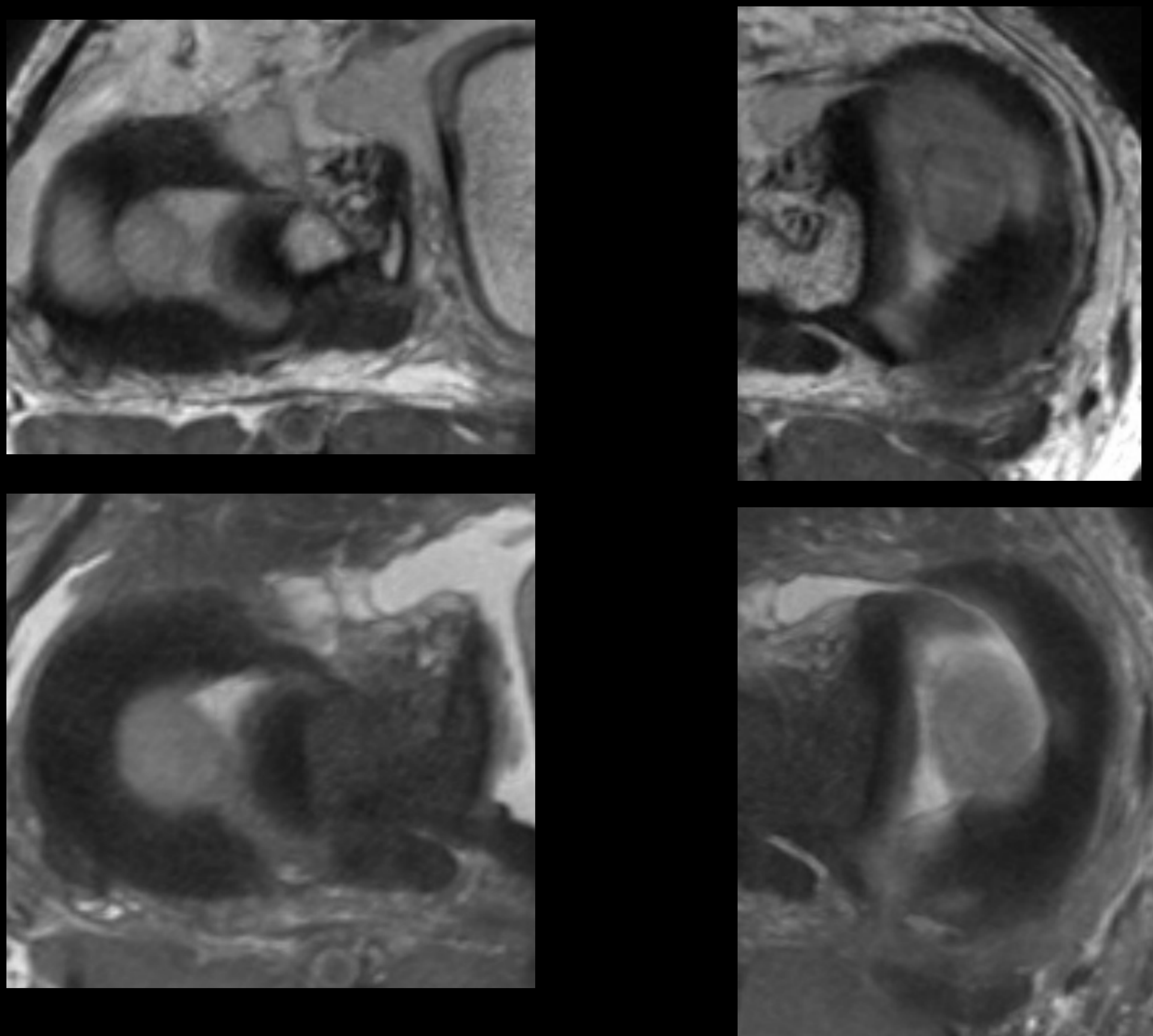
w/ FS


w/o FS
w/ FS



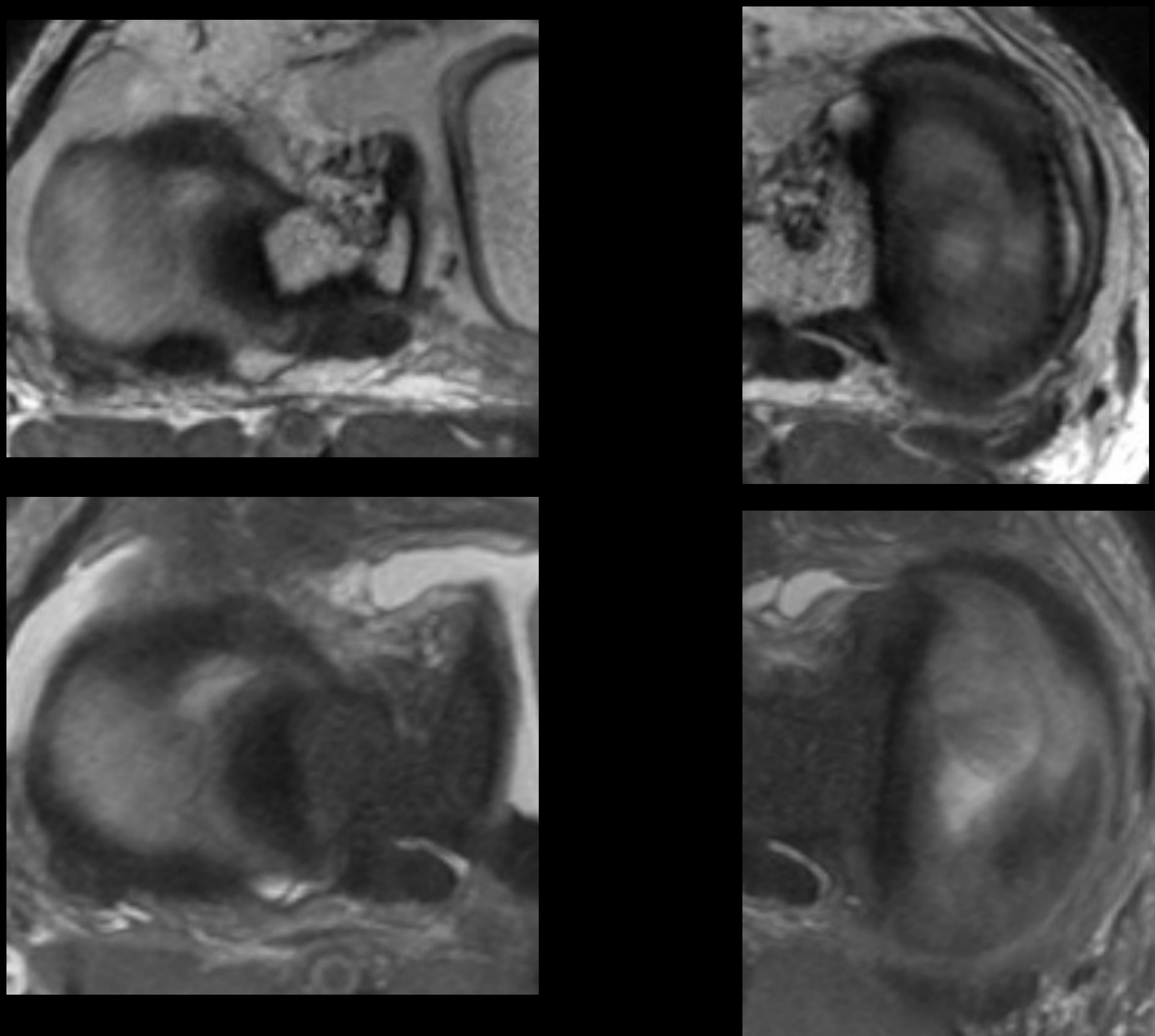
w/o FS

w/ FS



w/o FS

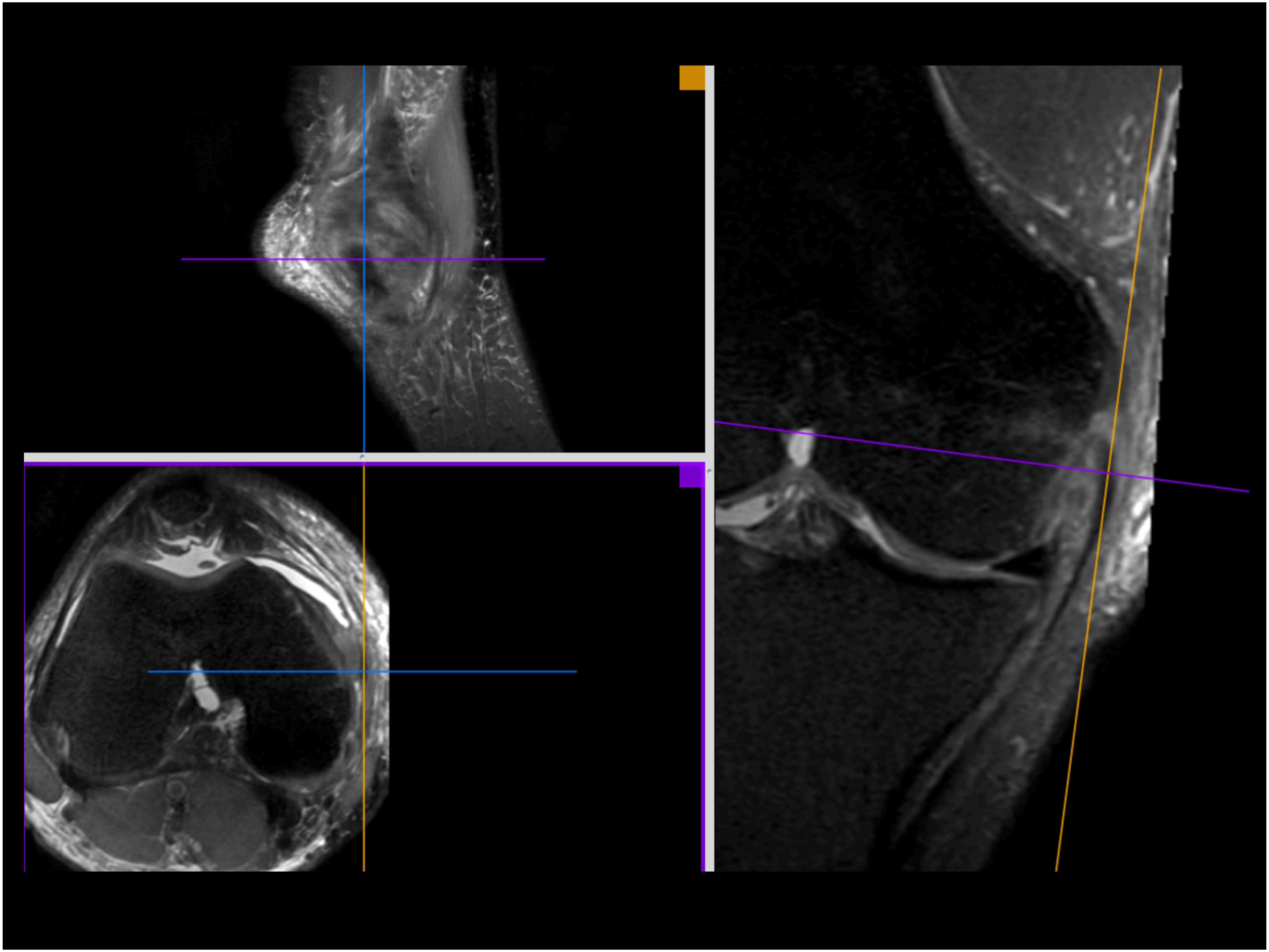
w/ FS



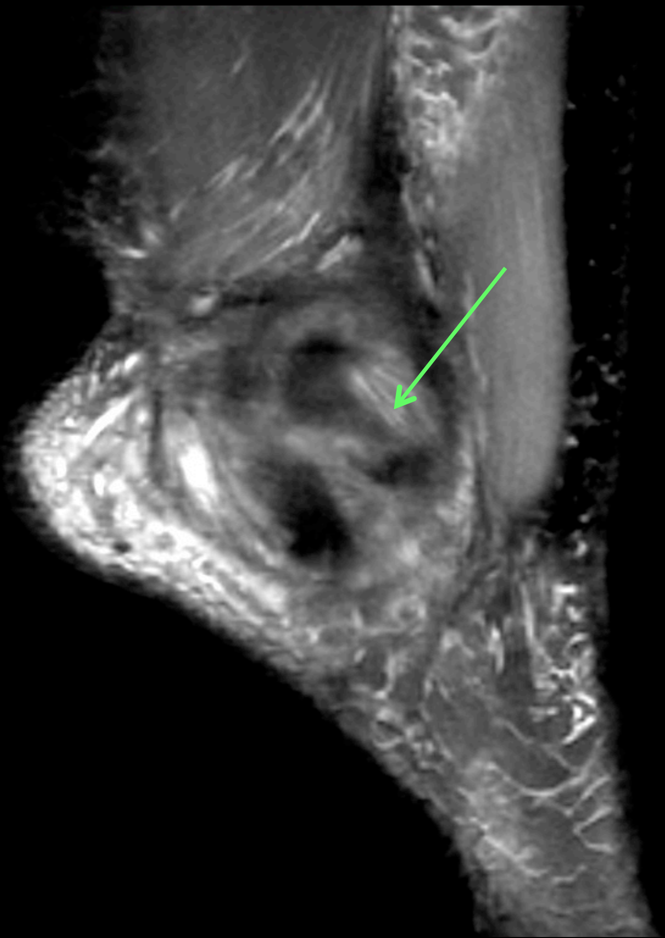
w/o FS

w/ FS

7 axial slices through the menisci



Deep MCL complex (meniscofemoral)
Superficial MCL complex (TCL)



POL
Superficial component
Central (tibial) component
Capsular component

Historic Limitations of 3DFSE

* Time
  * Partial Fourier encoding (half Nex)
  * Parallel imaging
    * GE (ARC)
    * Siemens (GRAPPA, SENSE)
* Equipment
  * Fast gradients to fill k-space before there is no signal left due to decay (contrast was also difficult to manage)
* SAR (power deposition)
  * Lower flip angles (flip angle modulation, flip angle sweep)
* Blurring

Flip Angle Modulation

- Variable flip angles
  - Decreases SAR
  - Decreases blurring
- “Conventional” refocusing pulses were 180°

90-180 90-100 90-180(x6)

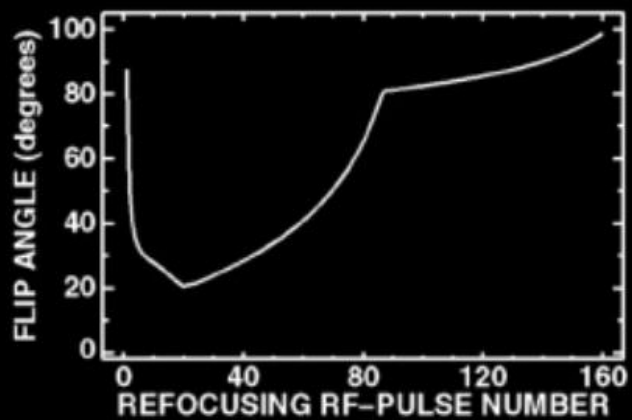
Flip Angle Modulation

- Refocusing pulses <180°
  - Decreases SAR
  - Decreases blurring
  - Stimulated echoes which scramble initial magnetization vector into some weird distribution (makes conceptualization difficult)

“Pseudo” steady state of FSE

- Variable flip angles (VFA)
- Unlike “steady state” of GRE where we repeat alpha, FSE “steady state” amplitude is 0 (complete T2 relaxation)
- Prescribe flip angles to optimize contrast for the tissue we interested in

Pseudo-steady state for 60° using VFA



Mugler et al. 9th ISMRM;2001, 0438.

CUBE

* Importance of optimization

1.6mm slice thickness, ZIP 2 (0.8mm)
288x288; ETL 64; Nex 0.5; ARC 1.0
BW 244 Hz/pixel
TR/TE 2000/23

4-5 mins

Reconstruction 8mm thickness

CUBE

* Problem Solving

1.6mm slice thickness, ZIP 2 (0.8mm)
288x288; ETL 64; Nex 0.5; ARC 1.0
BW 244 Hz/pixel
TR/TE 2000/23

Reconstruction 8mm thickness

* Technician
  * Wrap in 2 separate dimensions
  * 8mm slice thickness reconstructions
* Protocol
  * Maximize spatial resolution
  * Optimize Contrast/Time

Spatial Resolution
(FOV/matrix)
0.55 x 0.55 x 1.6 mm

CUBE

* Problem Solving

1.6mm slice thickness, ZIP 2 (0.8mm)
288x288; ETL 64; ARC 1.0
BW 244 Hz/pixel
TR/TE 2000/23

Reconstruction 8mm thickness

* After many hours of optimization

1.5T protocol

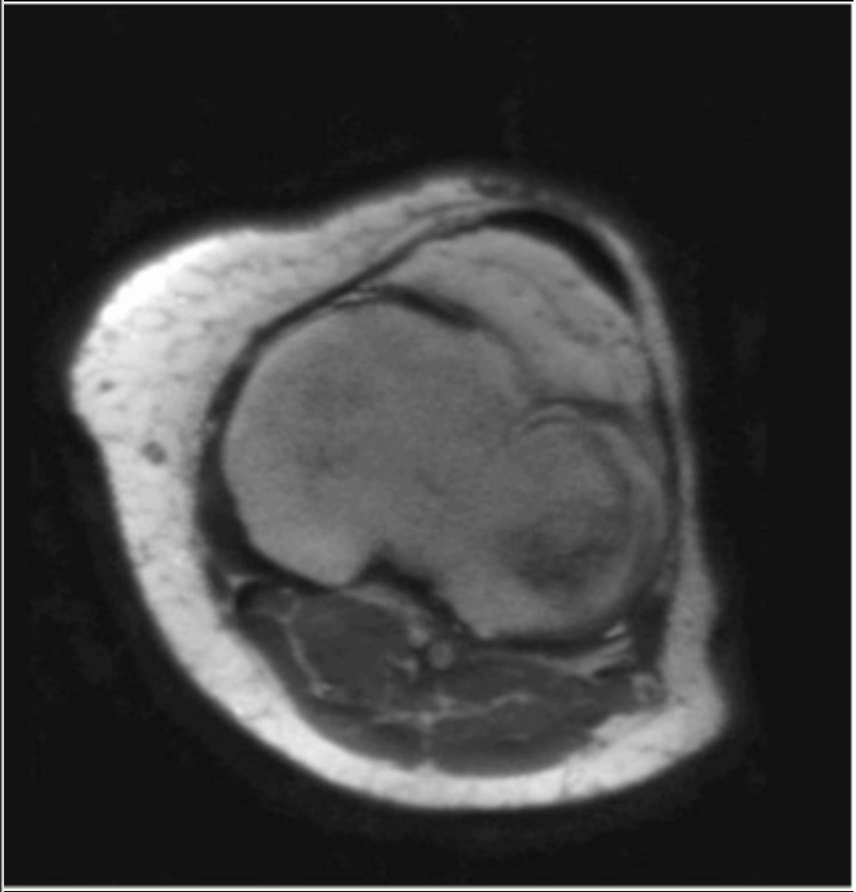
* 14-16 cm FOV
* Slice thickness 0.7mm
* 288 x 288 matrix
* ETL 100
* TR/TE 1500/100
* BW 35.1kHz (122 Hz/pixel)
* Nex 0.5
* ARC 1.7 (maximum)

Spatial Resolution
(FOV/matrix)
0.55 x 0.55 x 1.6 mm

Spatial Resolution
(FOV/matrix)
0.48 x 0.48 x 0.7 mm

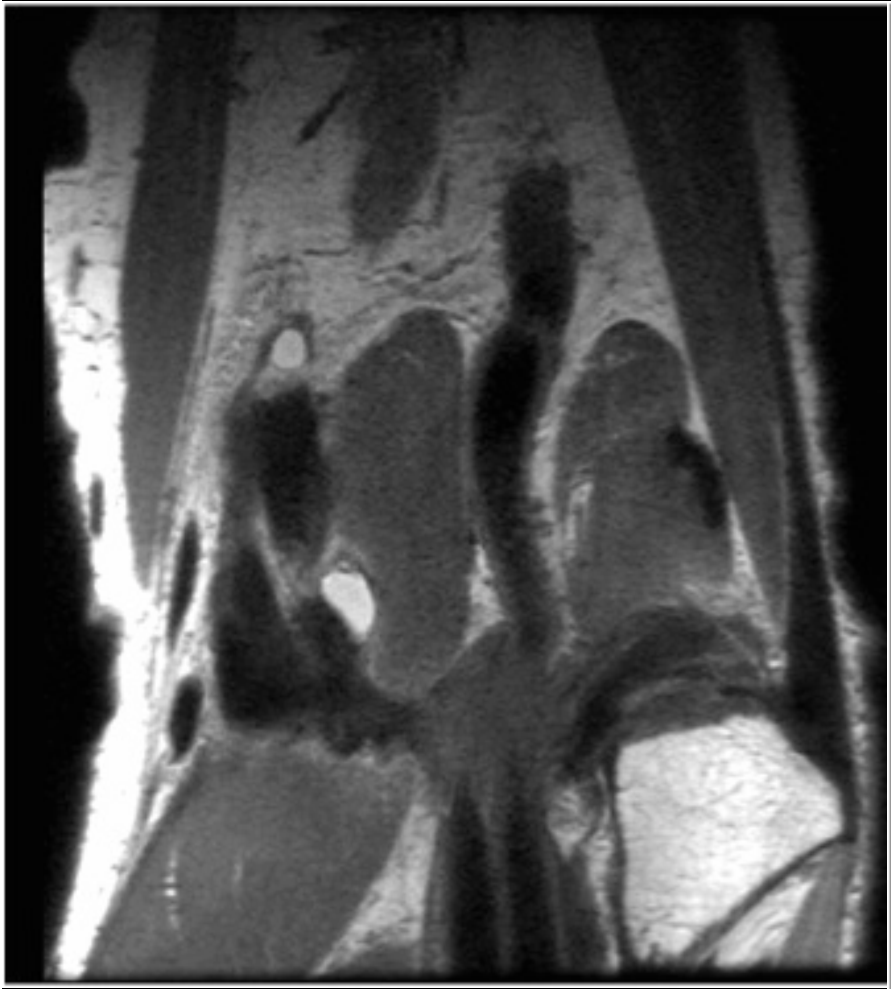
Optimized 1.5T CUBE

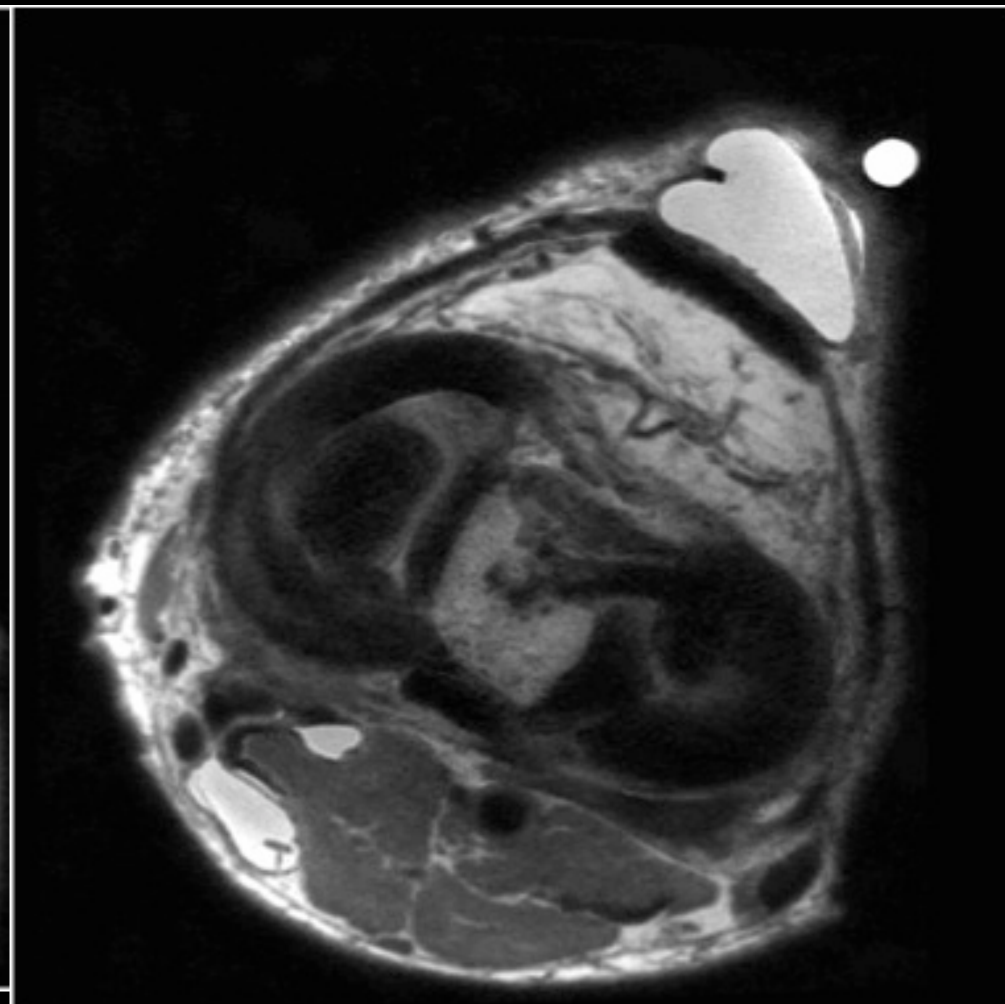
4-5 mins



1mm reformat (30 seconds), technologist sends images over

Optimized 3.0T CUBE





3 mins

Current Limitations of 3DFSE

- SNR
  - Especially with chemical fat saturated images, however with the right combination of a different fat saturation technique and parallel imaging/half Fourier, this will be overcome
- Blurring
  - Main limitation of 3D FSE with the current techniques
  - Big problem with high ETL
  - Not enough time to cover the physics, but due to T2 decay as k-space is being filled

Thank You