Water-Fat MRI

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Outline

- Fat in MRI
- Fat Suppression
- Fat-Water-Separated MRI
- Fat Quantification

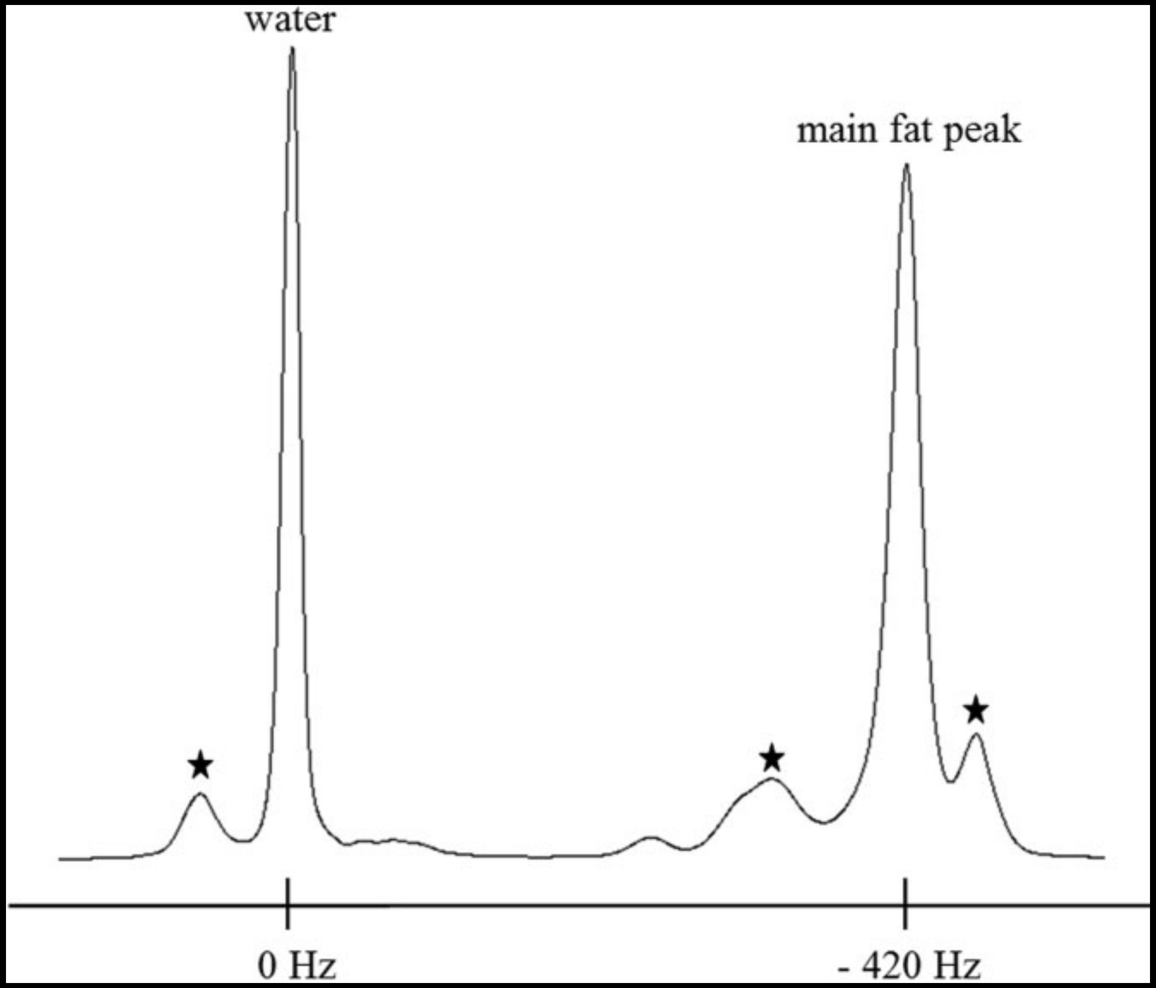
Fat in MRI

- ^{1}H MRI signal mainly from water & fat
- Bright fat signal
  - Short T_1 ~ 300 ms @ 1.5 T
  - can obscure structures of interest
  - can be mistaken for pathology
- Presence of fat
  - may indicate disease state:
    liver, cardiac, breast, body, bone, muscle, cancer, etc.

Chemical Shift of Fat

Triglycerides (fat) have a complex spectrum

main peak from methylene (-CH2-) is at $\Delta\delta \approx$ -3.5 ppm from water



$$\Delta f_{cs}[\mathrm{Hz}] = \frac{\gamma}{2\pi} \mathrm{B}_0 \cdot \Delta\delta[\mathrm{ppm}] \cdot 10^{-6}$$

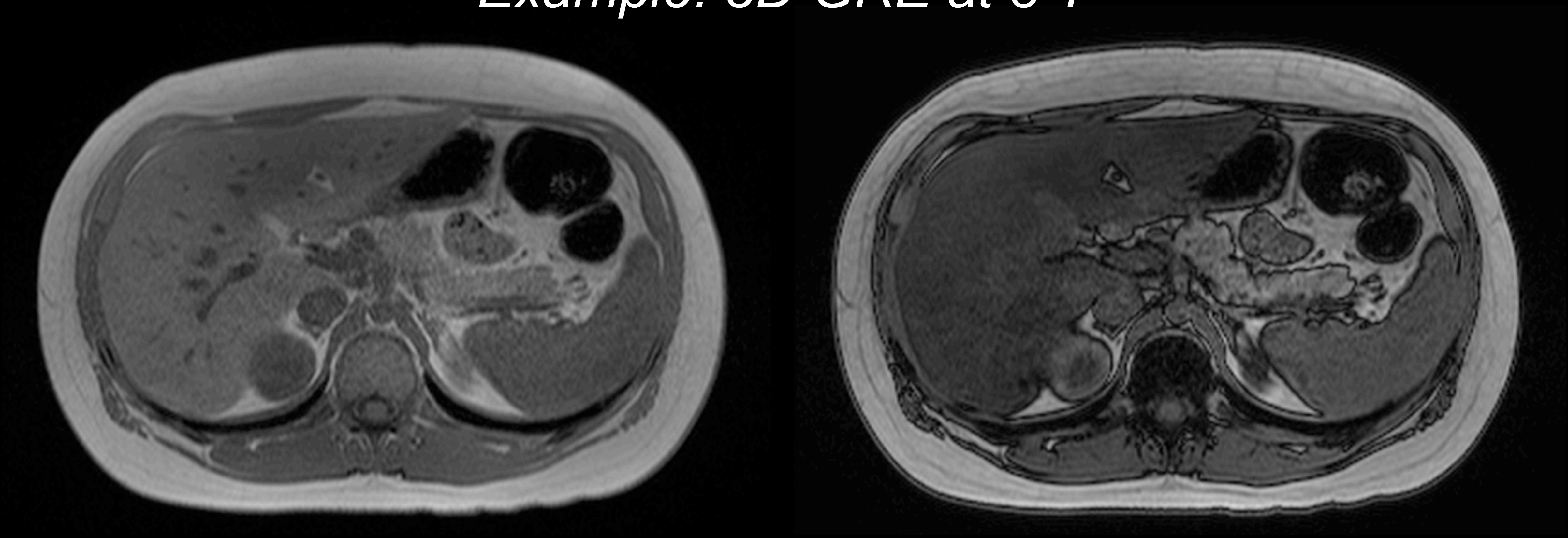
at B_0 = 1.5 T, $\Delta f_{cs} \approx$ -210 Hz

at B_0 = 3.0 T, $\Delta f_{cs} \approx$ -420 Hz

Chemical Shift of Fat

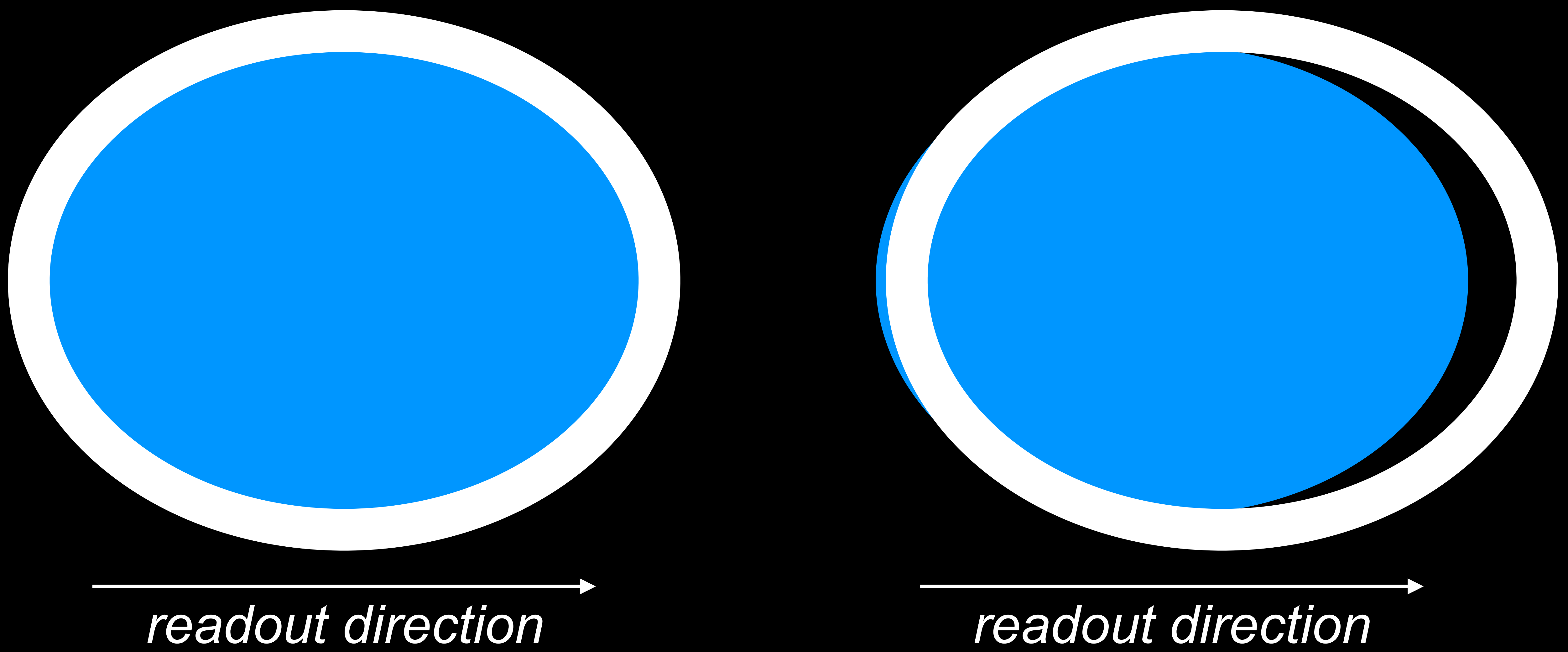
- Dark line artifacts
  - GRE
  - bSSFP

Example: 3D GRE at 3 T



Chemical Shift of Fat

- Chemical shift artifacts
  - Cartesian



Chemical Shift of Fat

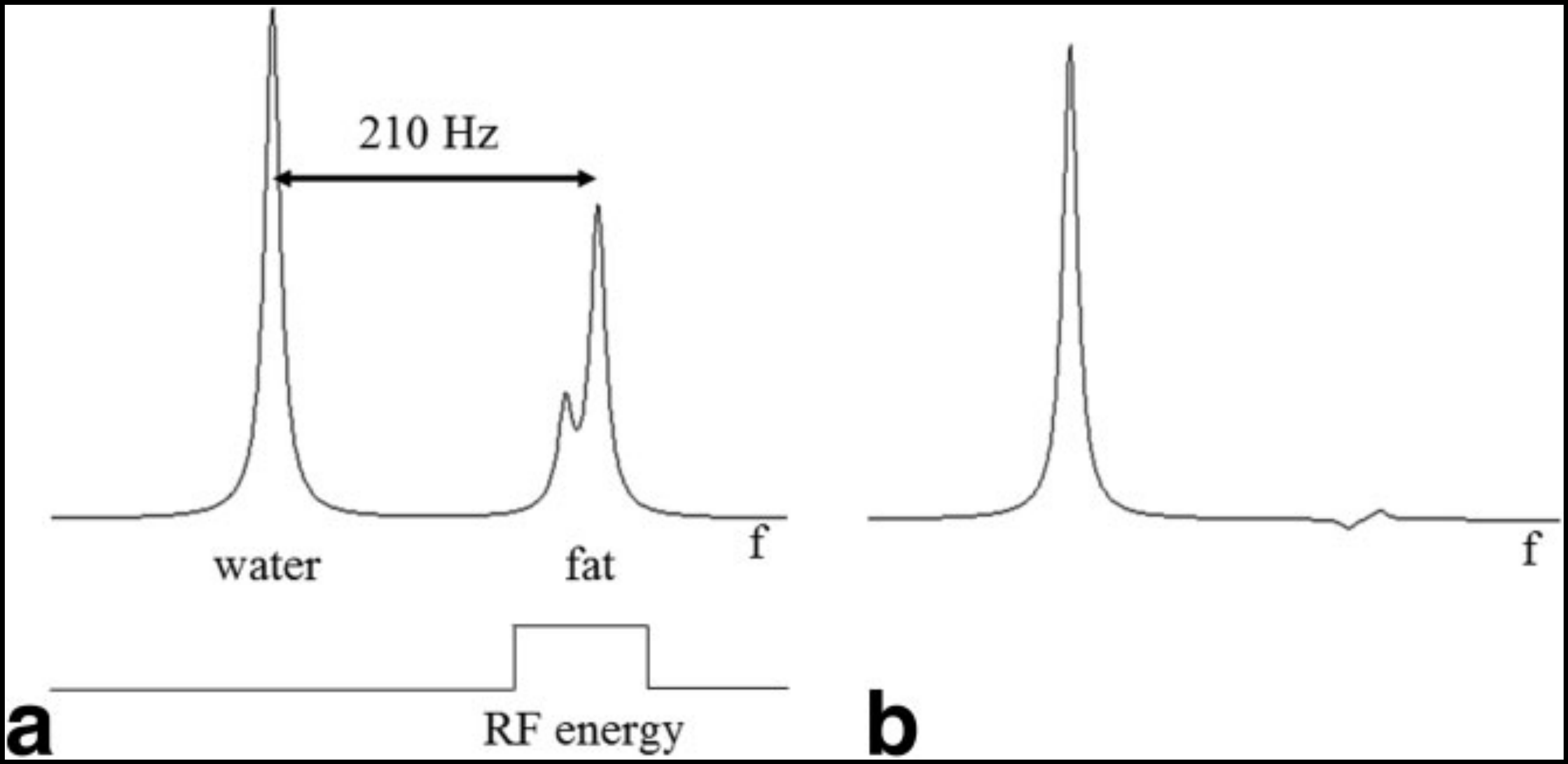
- Blurring artifacts
  - EPI, non-Cartesian

Example: Concentric Rings

Wu et al., MRM 2009; 61: 639-649

Fat Suppression

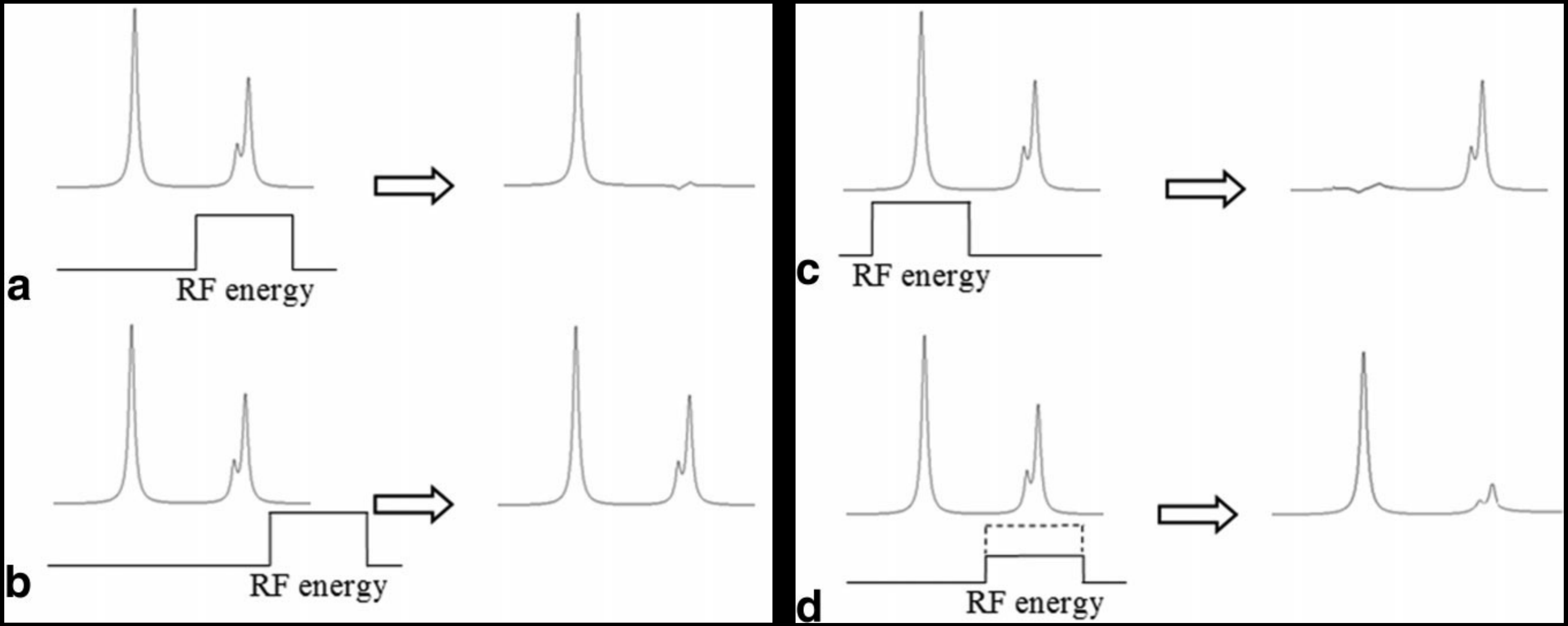
- Fat saturation
  - chemical shift selective (CHESS) saturation
    excite fat signal, and then spoil



Bley TA et al., JMRI 2010; 31: 4-18, Fig. 2

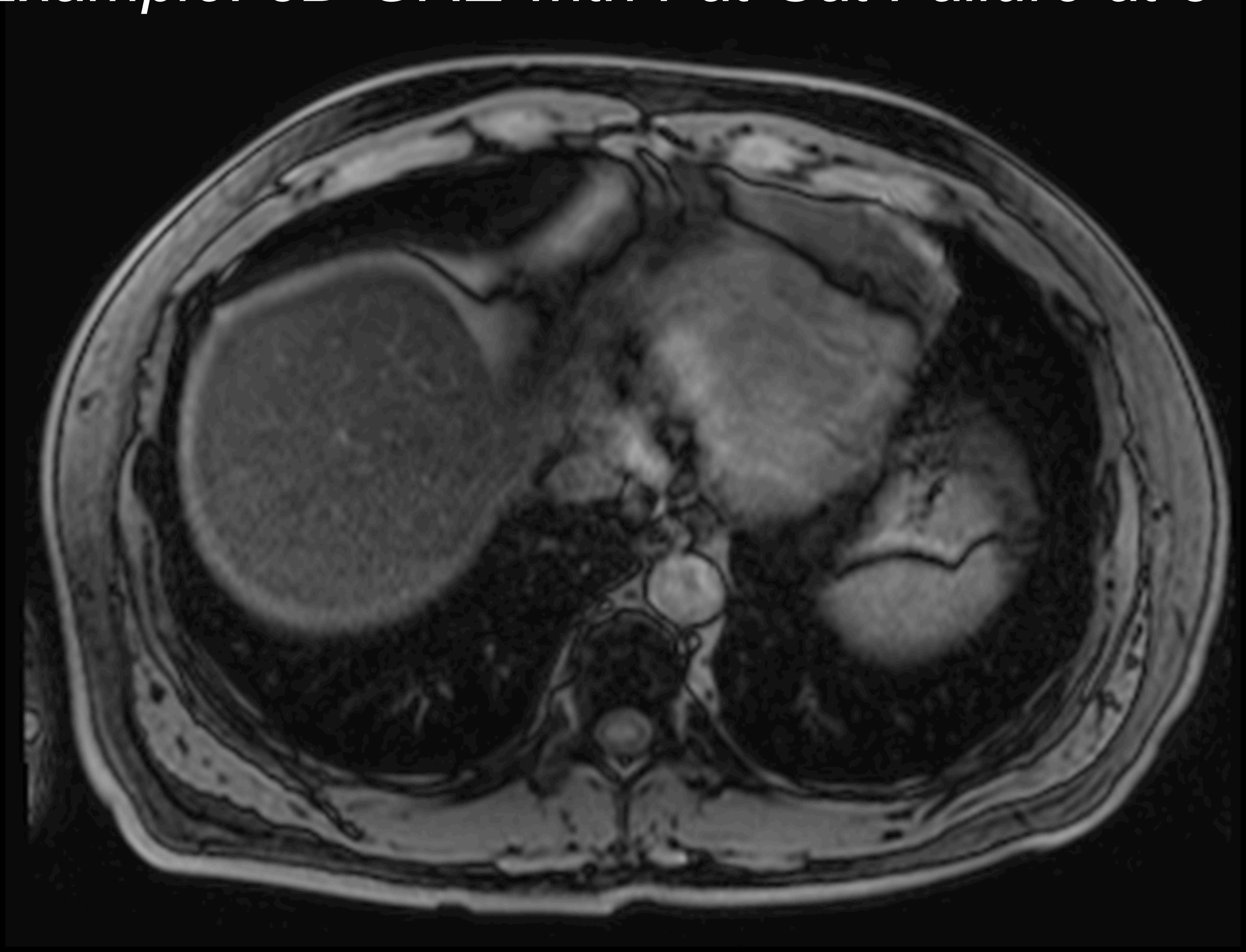
Fat Suppression

- Fat saturation
  - sensitive to B_0 and B_1 variations



Fat Suppression

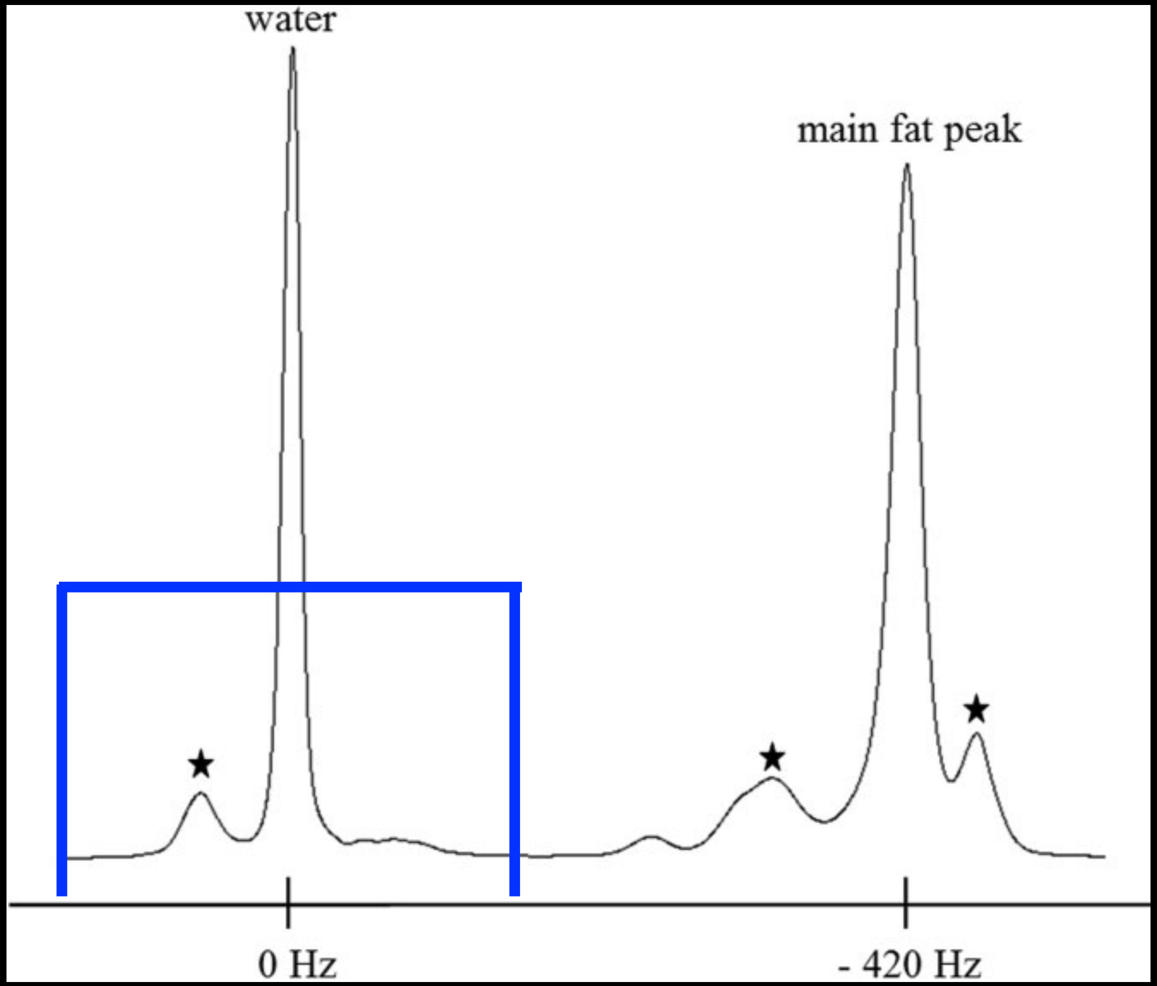
Example: 3D GRE with Fat-Sat Failure at 3 T



Note that B_0 and B_1 variations are greater at 3.0 T

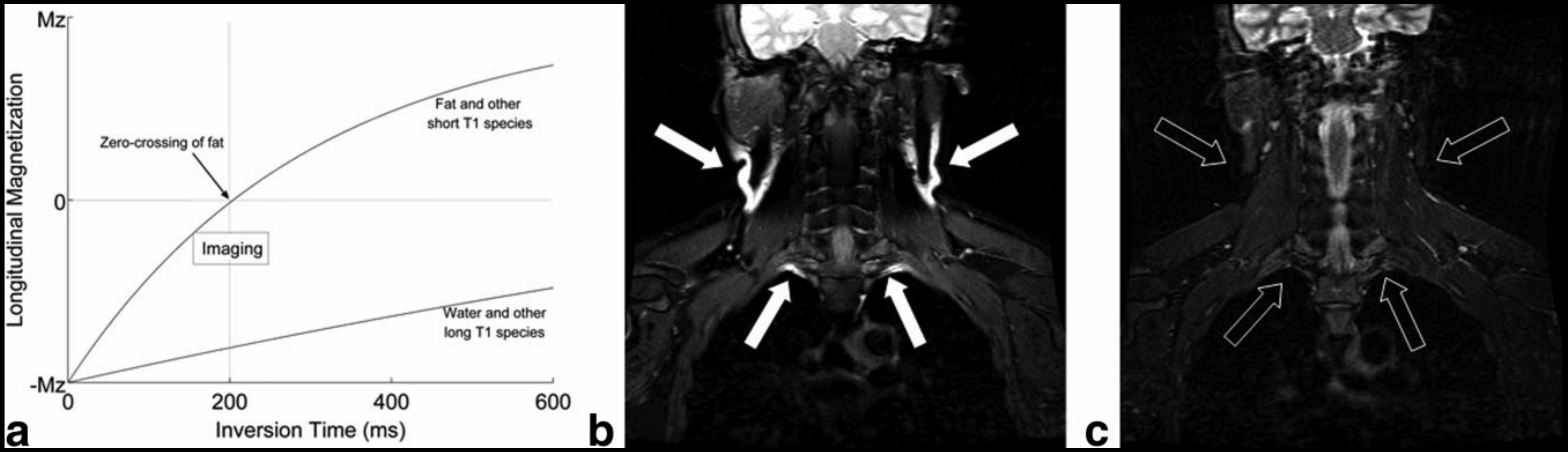
Fat Suppression

- Water-only excitation
  - relatively insensitive to B_1 variations
  - sensitive to B_0 variations



Fat Suppression

- Short-TI inversion recovery (STIR)
  - can be insensitive to B_0 variations
  - sensitive to B_1 variations
  - limits image contrast



Bley TA et al., JMRI 2010; 31: 4-18, Fig. 5

Fat Suppression

Table 1
Most Commonly Used Techniques for Fat Suppression and Fat-Water Imaging

Method	Advantages	Disadvantages	Suggested applications
Chemically selective fat suppression	• Versatile • Relatively fast • Applicable to most pulse sequences	• Sensitive to B_0 and B_1 inhomogeneities • Low sequence efficiency	• Most applications except: • Head and neck • Mediastinum • Extremities with metal implants
Spatial-spectral pulses, water excitation	• Insensitive to B_1 inhomogeneities • Versatile • Relatively fast • Practical to most pulse sequences except FSE	• Sensitive to B_0 inhomogeneities • Low sequence efficiency • Longer excitation pulses	• 3D imaging of cartilage in knee • Most applications except: • Head and neck • Mediastinum • Extremities
STIR	• Robust to B_0 and B_1 inhomogeneities • Reliable fat suppression	• Mixed contrast • Inherent T_1weighting • Only works with PD and T_2W • Low SNR efficiency • Suppresses short T_1 species and enhancing tissue after contrast	• Head and neck • Chest • Abdomen • Extremities • Large field of view • Inhomogeneous B_0 • T2/PD applications

Bley TA et al., JMRI 2010; 31: 4-18, Table 1

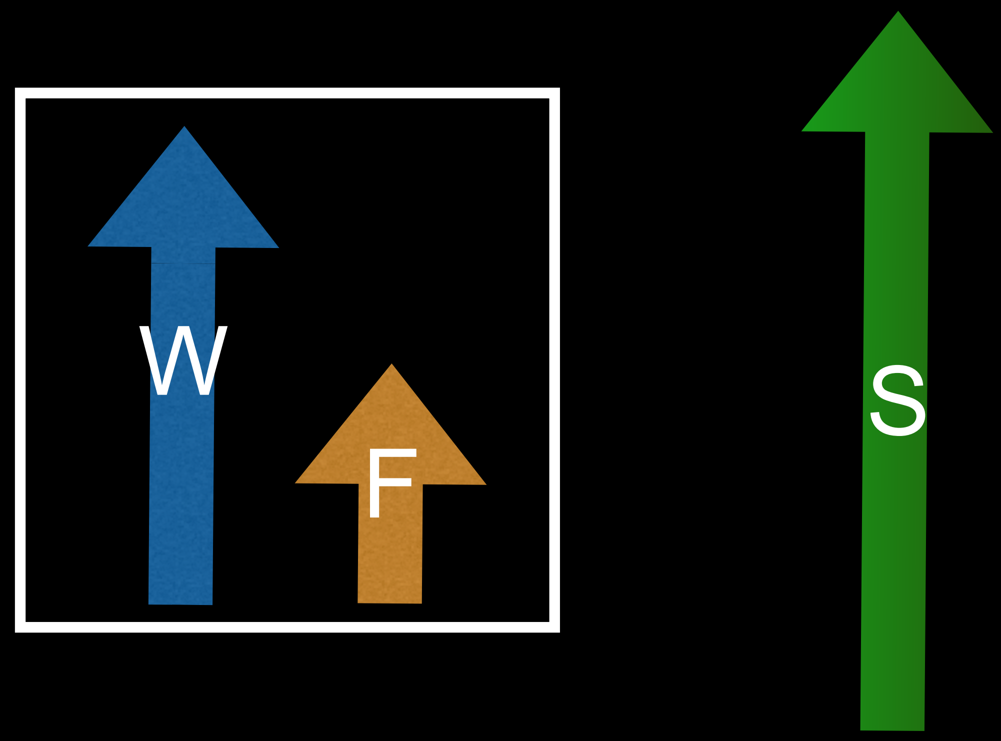
Fat-Water-Separated MRI

- Separate fat from water
  - based on chemical shift freq differences
- Robust fat suppression
  - improve image contrast, esp. at 3.0 T
- Accurate fat quantification
  - tissue characterization: distribution and composition

Fat-Water-Separated MRI

Fat and water exhibit different MR frequencies

i.e., fat is slightly out-of-sync with water signal

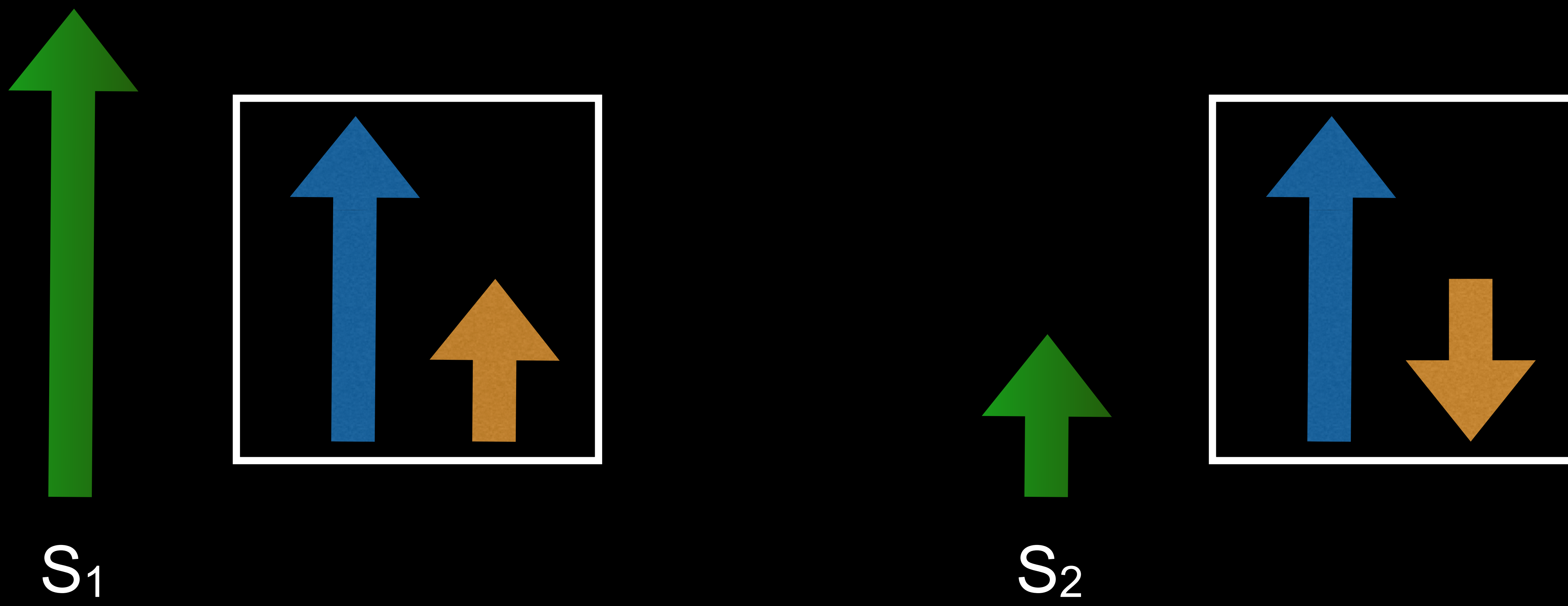


voxel signal dep. on TE

Fat-Water-Separated MRI

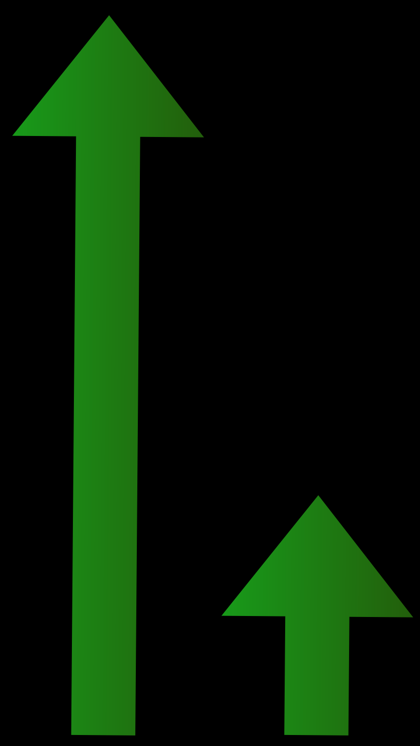
Acquire multiple images with different fat/water sync

in phase *out of phase*



Fat-Water-Separated MRI

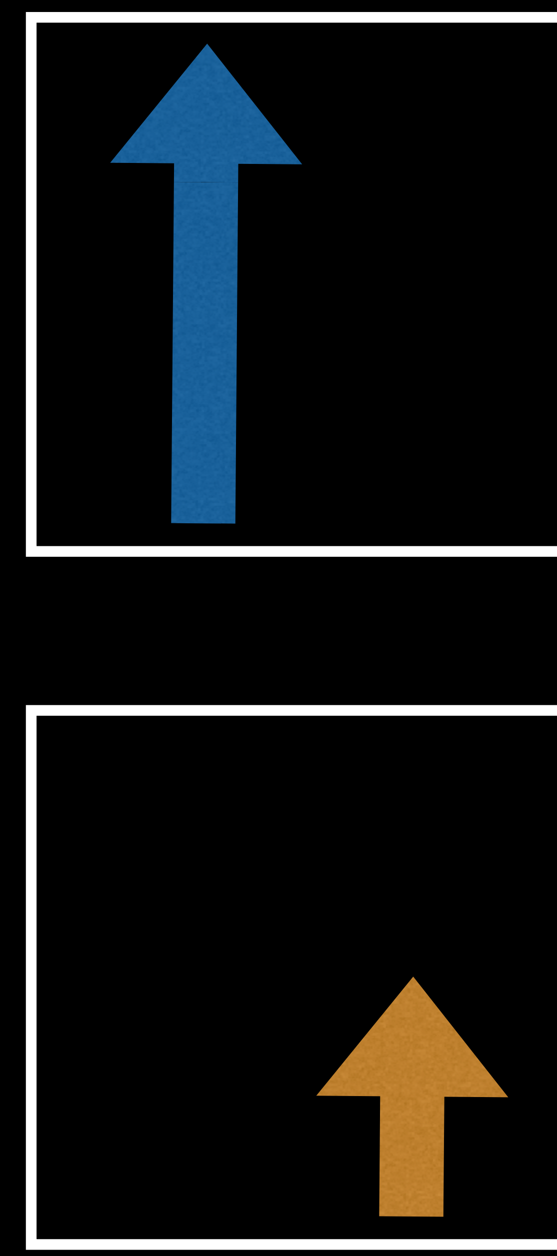
Estimate the water and fat component in each voxel



S_1 S_2

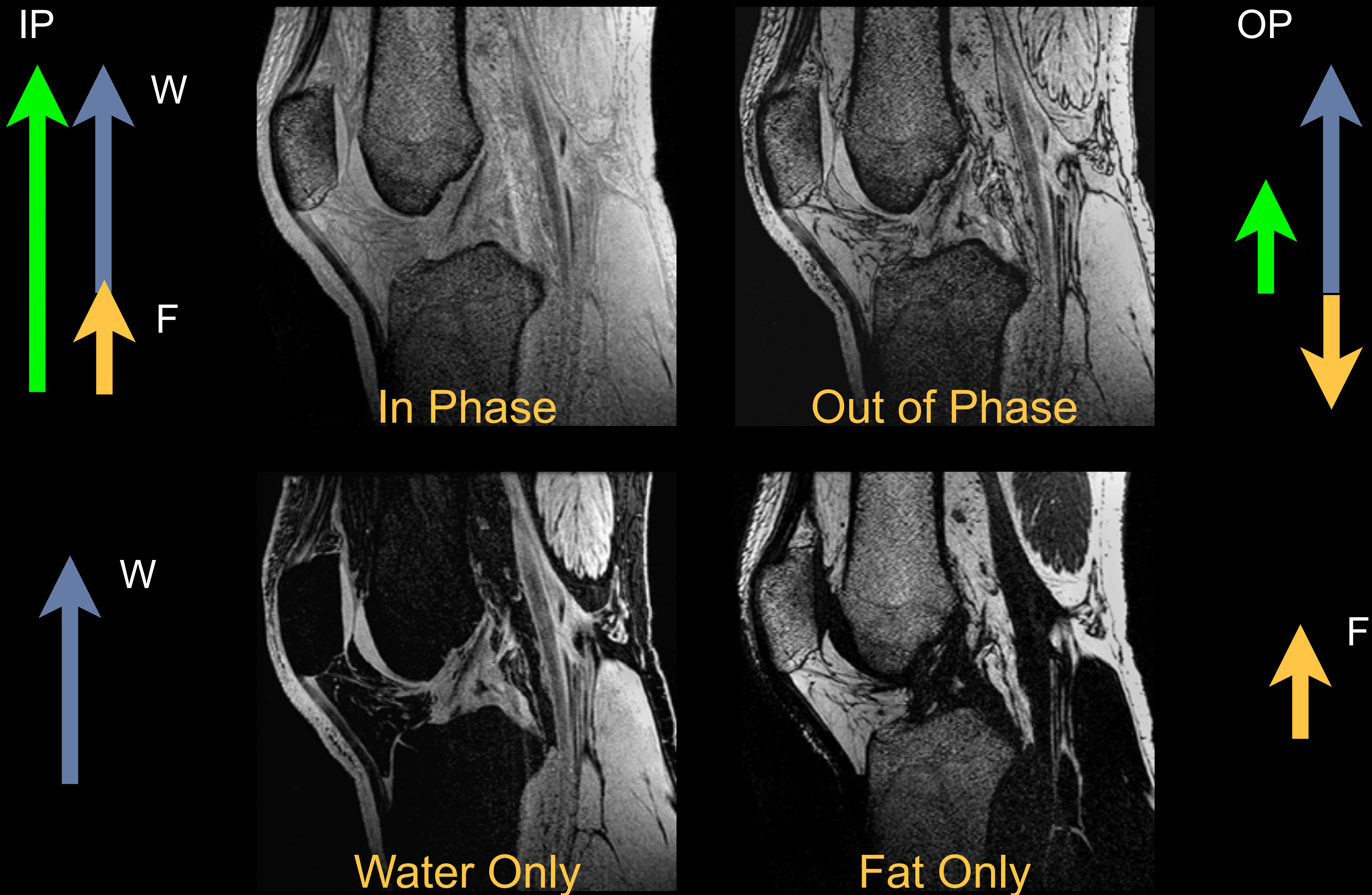
$(S_1+S_2)/2 = W$

$(S_1-S_2)/2 = F$



Dixon WT, *Radiology,* 1984; 153: 189-194.

Fat-Water-Separated MRI



Fat-Water-Separated MRI

2-Point Dixon

$$s(\mathbf{r};\mathrm{TE}_n) = s_W(\mathbf{r}) + s_F(\mathbf{r})e^{-i2\pi\Delta f_{cs}\mathrm{TE}_n}$$

$s_0 = s_W + s_F$ “in-phase” TE

$s_1 = s_W - s_F$ “out-of-phase” TE

$$s_W = \frac{1}{2}(s_0 + s_1)$$

$$s_F = \frac{1}{2}(s_0 - s_1)$$

	in-phase TE (ms)	out-of-phase TE (ms)
1.5 T	0, 4.6, 9.2, 13.8, …	2.3, 6.9, 11.5, …
3.0 T	0, 2.3, 4.6, 6.9, …	1.2, 3.5, 5.8, …

not so simple in practice …

Fat-Water-Separated MRI

- In practice
  - other factors affect MR frequency
  - fat contains multiple subcomponents
  - need more than 2 measurements pts (TEs)
  - need robust fat/water estimation algorithm
  - extra steps for quantitative fat fraction

Fat-Water-Separated MRI

- Other algorithms
  - 3-point Dixon
  - Extended 2-point Dixon
  - IDEAL
  - Single-point Dixon (π/2 acquisition)
    $s = (s_W + i s_F)$
  - Direct phase encoding (θ_0, $\theta_0+\theta$, $\theta_0+2\theta$)
  - 2PD with flexible TEs
  - Graph cut
  - Magnitude-based F/W separation
  - *and more!*

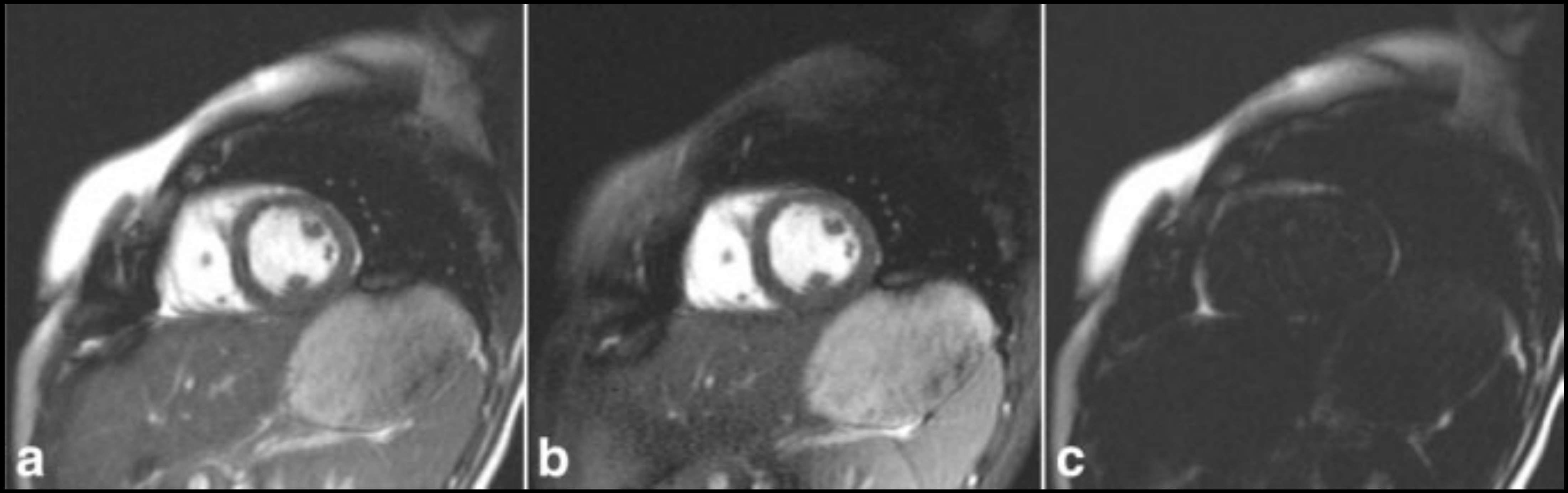
Fat-Water-Separated MRI

Knee: PDw FSE, 1.5 T, TE shifts of (-1, 0, 1) ms, IDEAL

source water fat

Fat-Water-Separated MRI

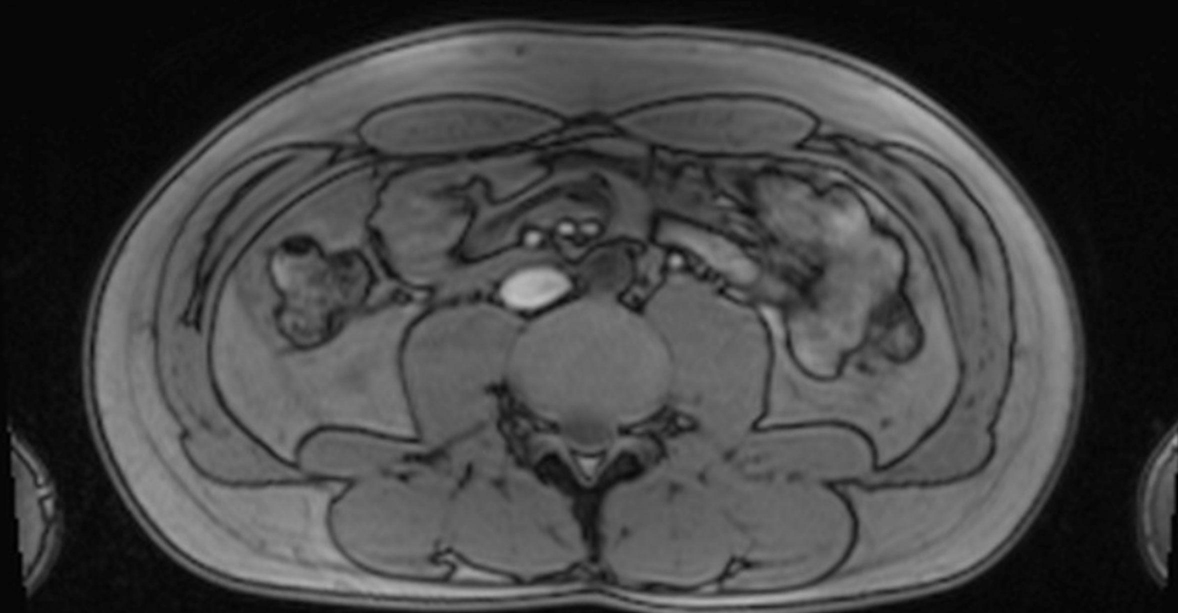
Cardiac: bSSFP, 1.5 T, TE/TR = (0.9, 1.9, 2.9)/5.2 ms, IDEAL



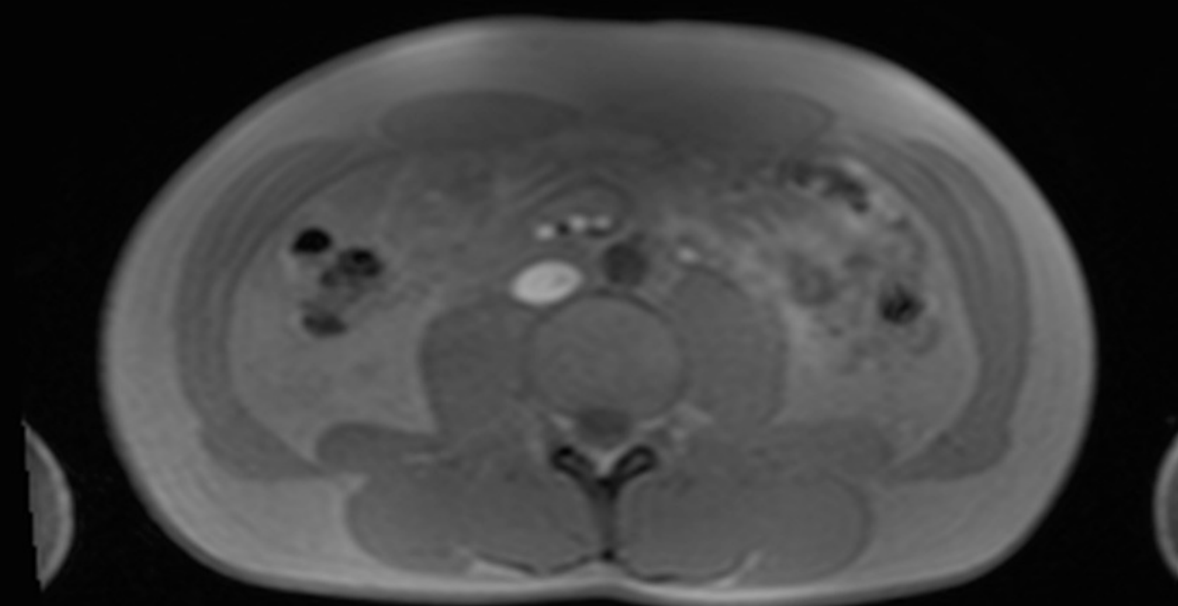
source water fat

Fat-Water-Separated MRI

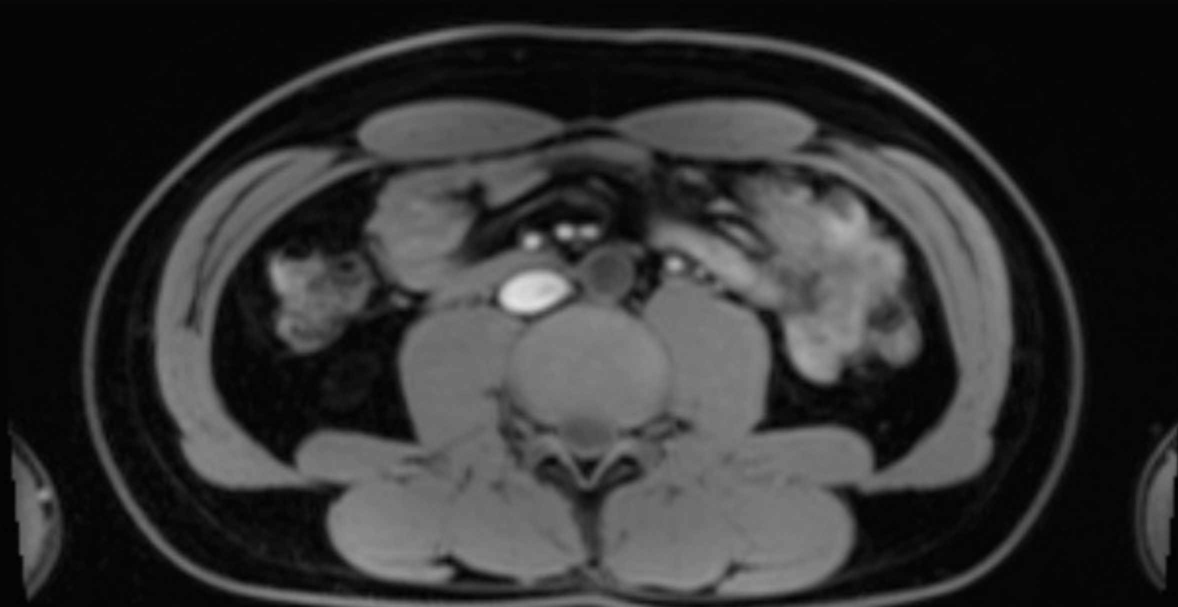
Liver: T1w 3D VIBE, 3 T, Extended 2P-Dixon



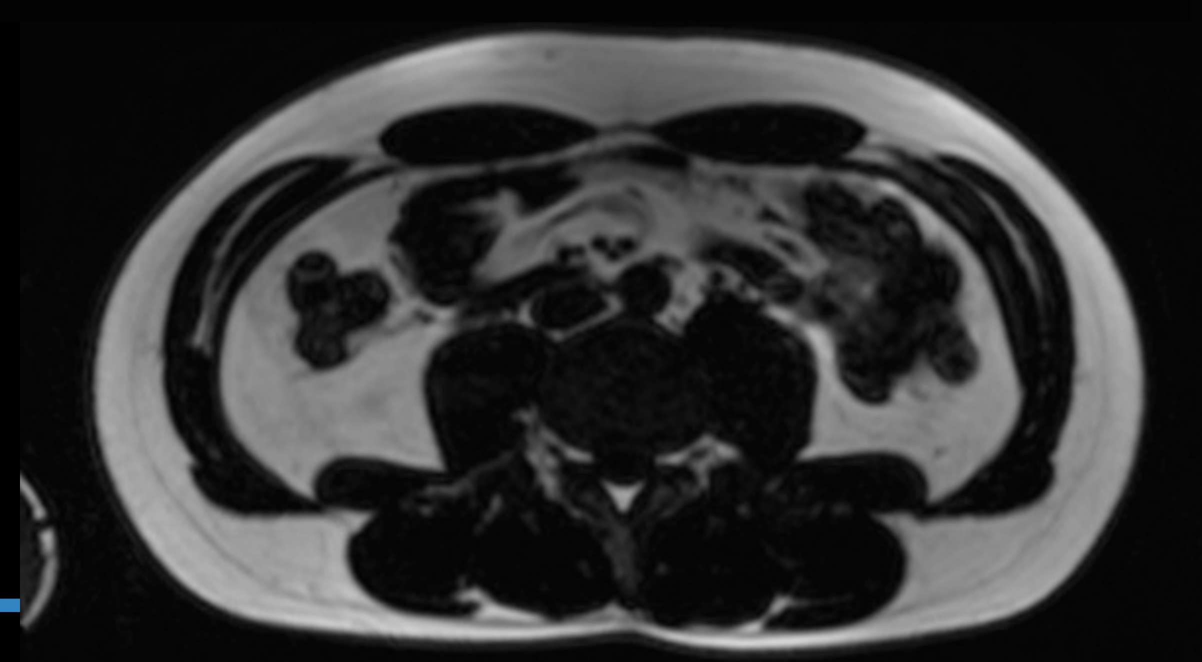
Out-of-phase (3 T), TE = 1.3 ms



In-phase (3 T), TE = 2.6 ms



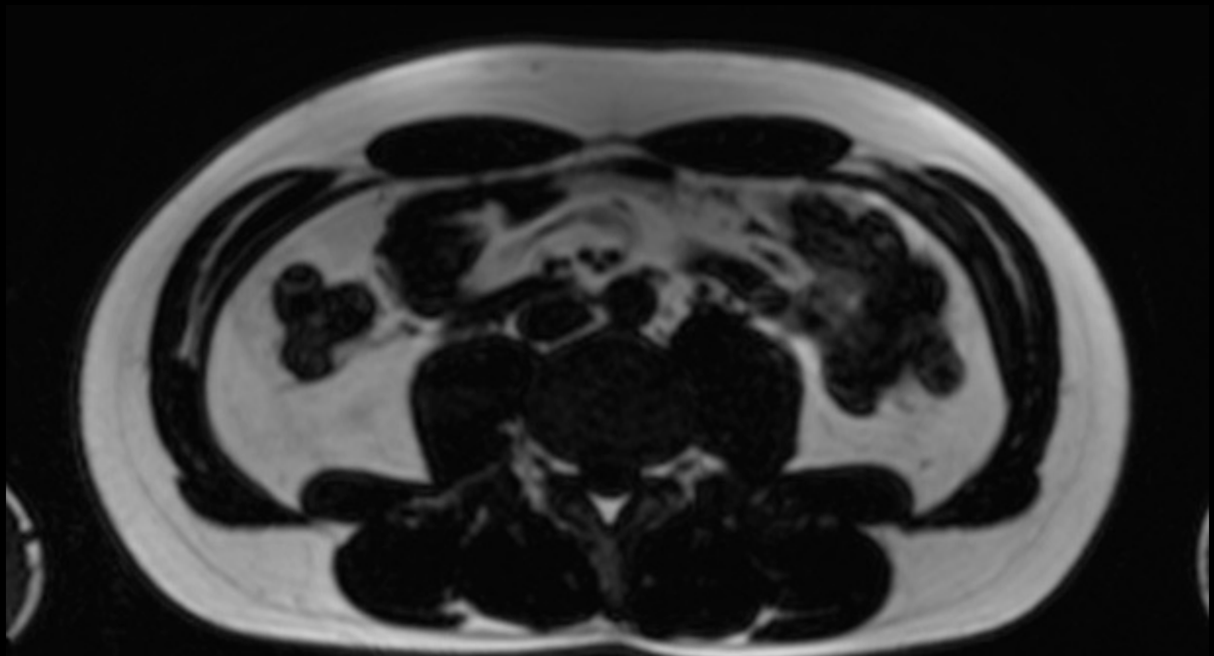
Water



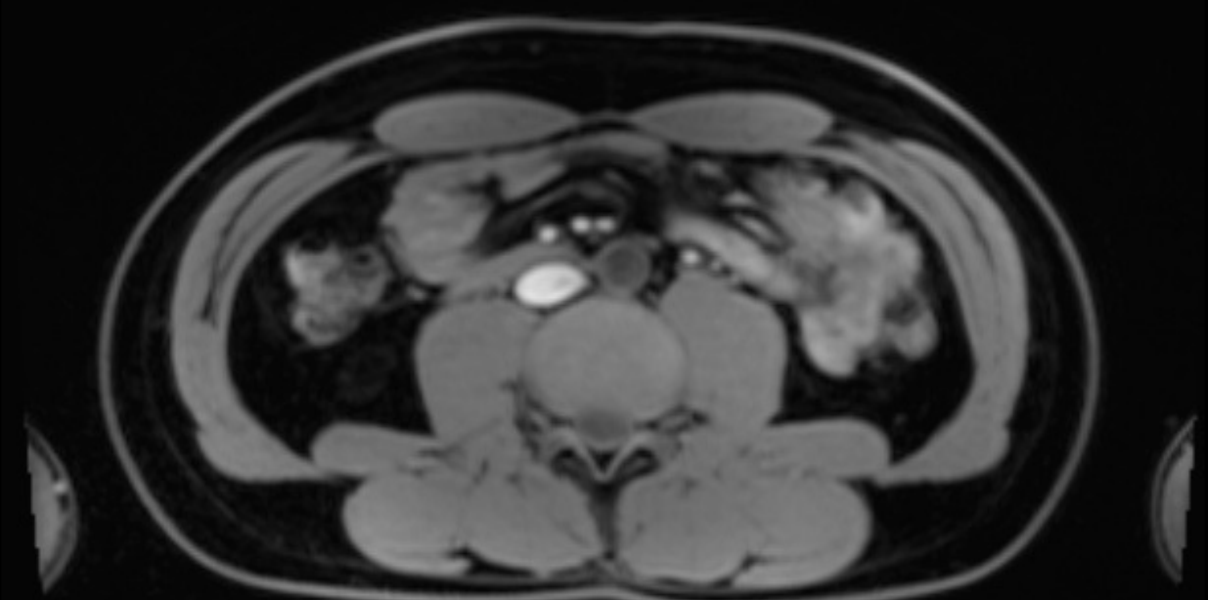
Fat

Fat-Water-Separated MRI

Fat-Water Swapping



“Water”



“Fat”

can also have regional swaps

F/W MRI Sequence Design

- Can be GRE, bSSFP, SE, TSE, etc.
  - 2D or 3D
  - e.g., VIBE-Dixon, TSE-Dixon
- Need multiple TEs
  - repeat scans with different TEs
  - acquire multiple TEs each TR
  - basic Dixon MRI: 2 or 3 TEs
  - quantitative Dixon MRI: ≥ 3 TEs

F/W MRI Sequence Design

- TE values depend on
  - number of readout points (resolution)
  - readout bandwidth
  - image FOV
  - bipolar or monopolar readout
  - asymmetric echo
  - RF pulse (type, slab/slice thickness)
- Examples
  - 1.5 T: TE = 2.3 and 4.6 ms, TR = 5 ms
  - 3.0 T: TE = 1.2 and 2.3 ms, TR = 3 ms
  - 3.0 T: TE = 2.3 and 3.5 ms, TR = 4 ms

Fat Quantification

- Qualitative F/W MRI
  - separate fat from water signal
  - N = 2 or 3 TEs is common
- Quantitative F/W MRI
  - distribution / volume of fat
  - composition of fat (fat/water ratio): multi-peak and T_2* modeling N = 6+ TEs is recommended

Fat Quantification

Water-Fat MR Signal Equation

$$s(\mathbf{r};\mathrm{TE}_n) = [s_W(\mathbf{r}) + s_F(\mathbf{r})\Sigma_{j=1}^{M}\alpha_j e^{-i2\pi\Delta f_{cs,j}\mathrm{TE}_n}] \cdot e^{-\mathrm{TE}_n/T_2^*(\mathbf{r})} e^{-i2\pi\psi(\mathbf{r})\mathrm{TE}_n}$$

- T_2* decay as TE_n increases
- fat spectrum has multiple components (peaks)
- eq'n accommodates arbitrary choice of TEs
- can assume single T_2* and reference fat spectrum
- solve for water s_W, fat s_F, T_2*, and field map ψ
- need more measurements ($N \geq 4$)

Fat Quantification

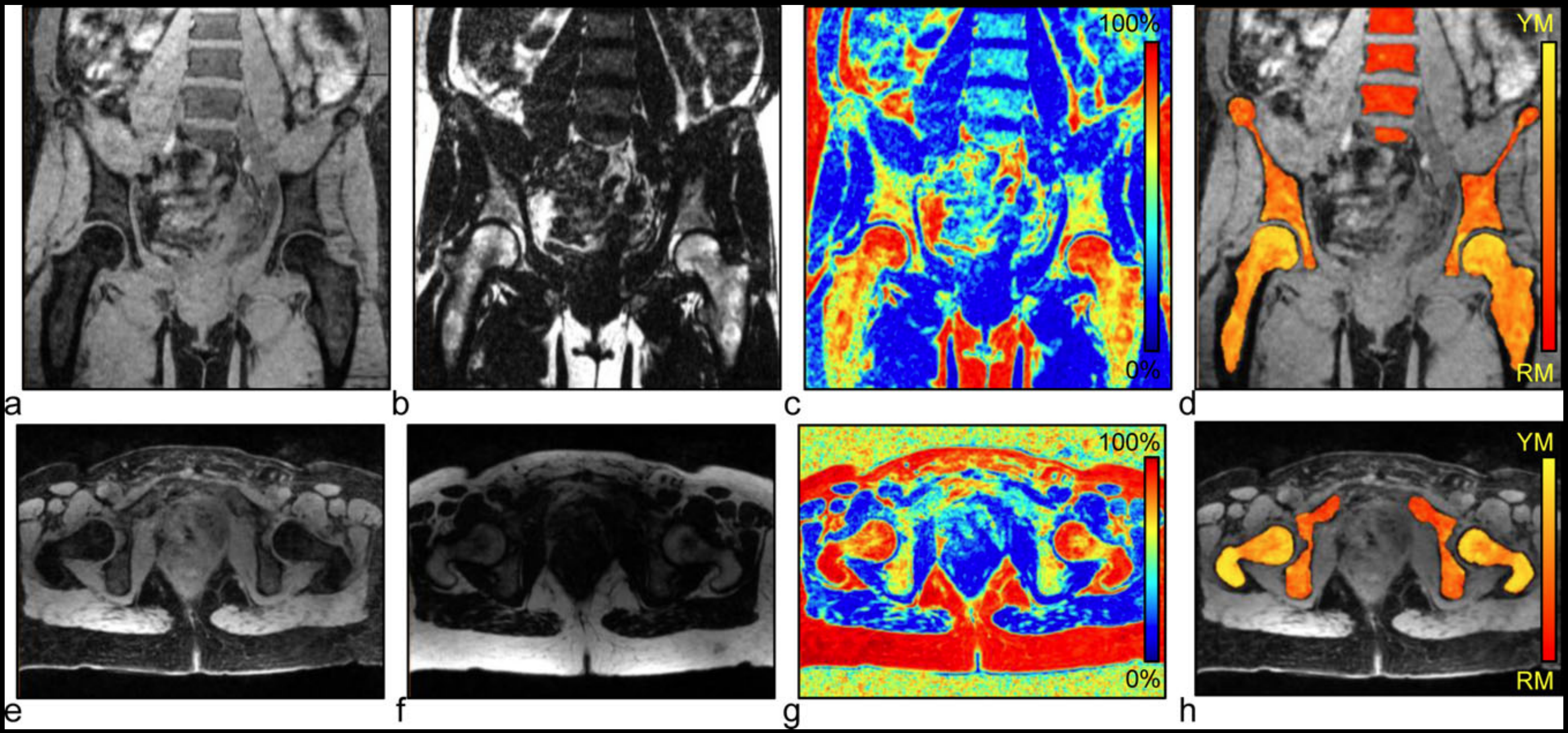
Signal Fat Fraction

$$\mathrm{sFF}(\mathbf{r}) = \frac{|s_F(\mathbf{r})|}{|s_W(\mathbf{r})| + |s_F(\mathbf{r})|}$$

- easy to calculate
- amount of fat “signal” in each voxel
- not necessarily amount of “fat”
- hard to reproduce with different scan parameters

Fat Quantification

Signal Fat Fraction



Fat Quantification

Signal Equation (RF-spoiled GRE)

$$s_X(T_1, \mathrm{TR}, \theta) = \rho_X \cdot \frac{(1 - e^{-\mathrm{TR}/T_1}) \sin\theta}{1 - e^{-\mathrm{TR}/T_1} \cos\theta}$$

- *s* depends on T_1, TR, θ
- T_1 bias for sFF calculations

  minimize with low θ and long TR
- different equations for SE, bSSFP, etc.

Fat Quantification

Proton Density Fat Fraction

$$\mathrm{PDFF}(\mathbf{r}) = \frac{\rho_F(\mathbf{r})}{\rho_W(\mathbf{r}) + \rho_F(\mathbf{r})}$$

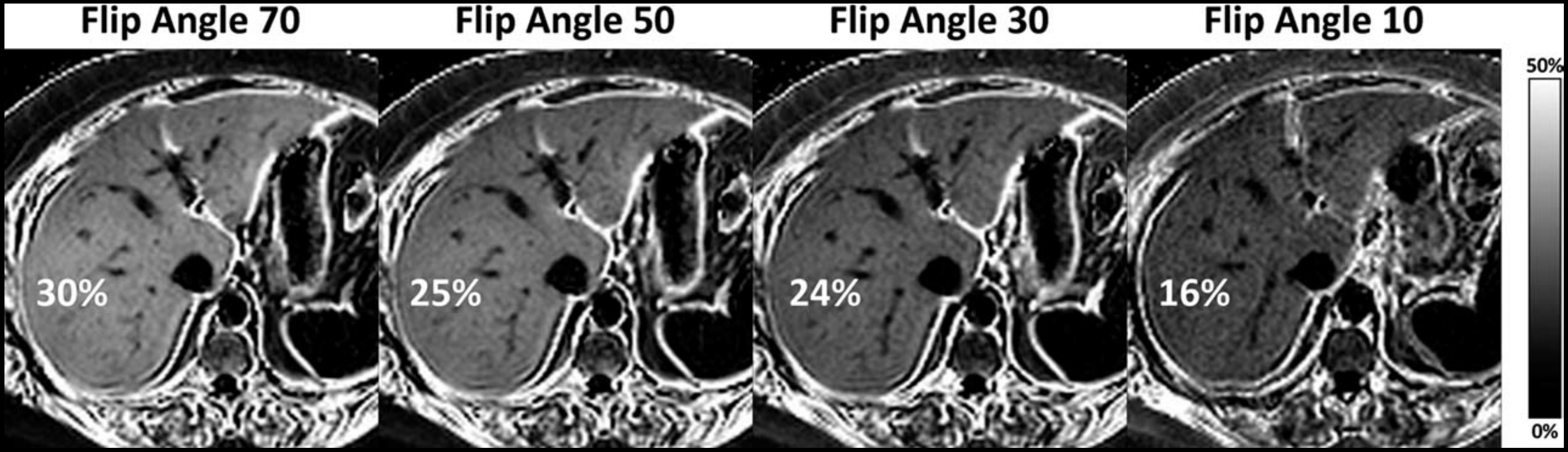
- need to correct for T_1, θ, noise effects
- potential role as an imaging biomarker

Liver Fat Quantification

- Non-alcoholic fatty liver disease (NAFLD) is the leading cause of chronic liver disease
- Current gold standard is biopsy
- MRI fat quantification is becoming the new gold standard

Liver Fat Quantification

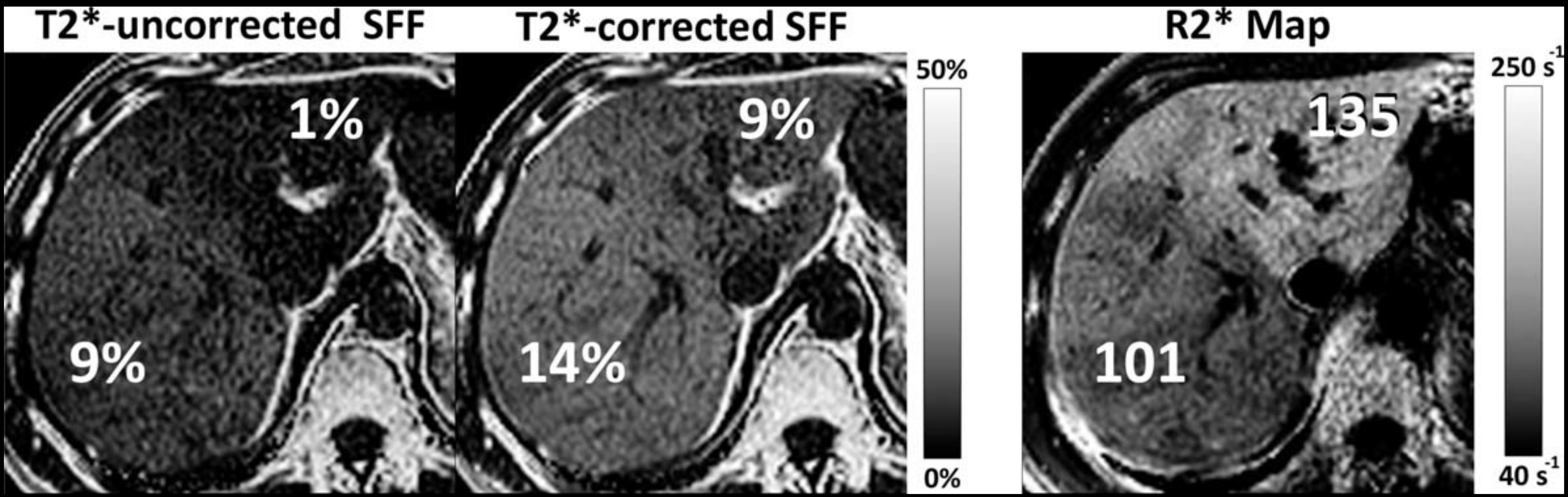
Reduce T_1 bias by using low flip angle



Reeder SB, et al., JMRI 2011; 34: 729-749, Fig. 5

Liver Fat Quantification

Account for T_2* effects



Liver Fat Quantification

Account for multiple peaks in fat spectrum

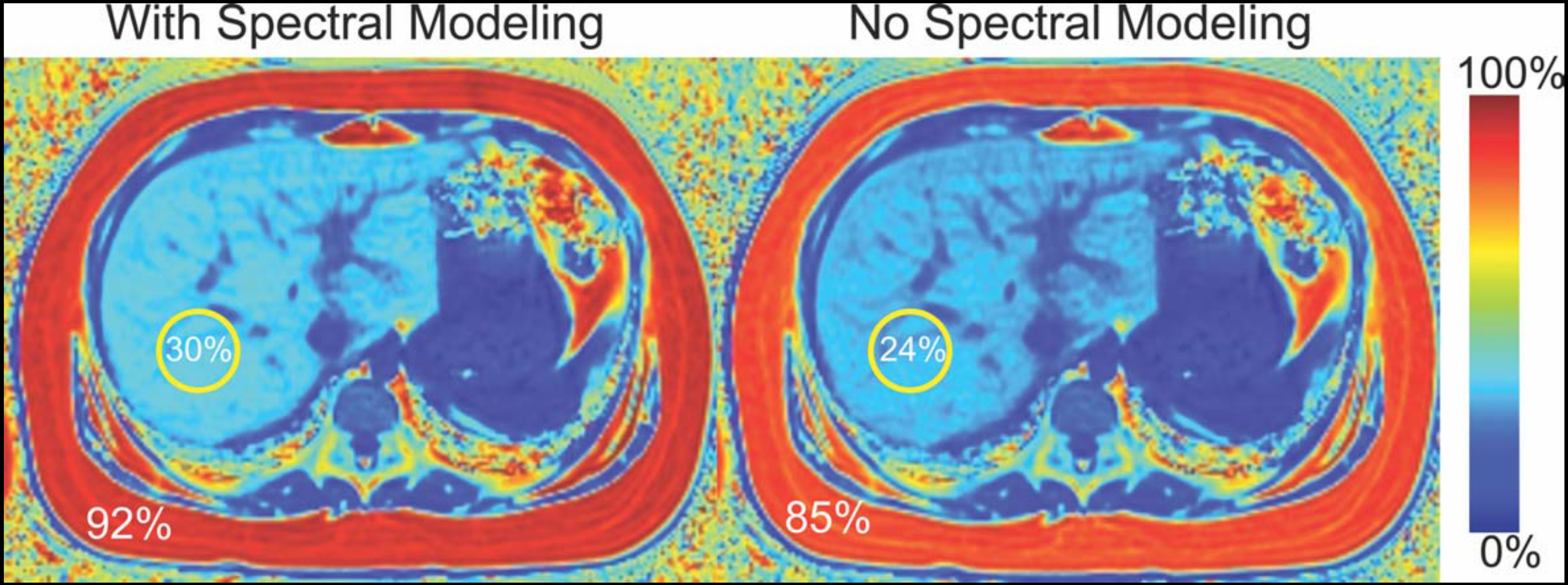
Table 1
Proton MR Spectrum of Liver Triglycerides

Peak	In vivo ppm	Ex vivo ppm	Chemical environment	Type	Relative magnitude
1	5.3	5.29	-**CH** =**CH**-	Olefinic	4.7%
		5.19	-**CH**-O-CO-	Glycerol	
Water	4.7	4.70	H_2O	—	—
2	4.2	4.20	-CH_2-O-CO-	Glycerol	3.9%
3	2.75	2.75	-CH=CH-CH_2-CH=CH-	Diacyl	0.6%
4	2.1	2.24	-CO-CH_2-CH_2-	α-Carboxyl	12.0%
		2.02	-CH_2-CH=CH-CH_2-	α-Olefinic	
5	1.3	1.60	-CO-CH_2-CH_2-	β-Carboxyl	0.7
		1.30	-$(CH_2)_n$-	Methylene	
6	0.9	0.9	-$(CH_2)_n$-CH_3	Methyl	0.088

fat peaks near water account for ~8% of fat signal

Liver Fat Quantification

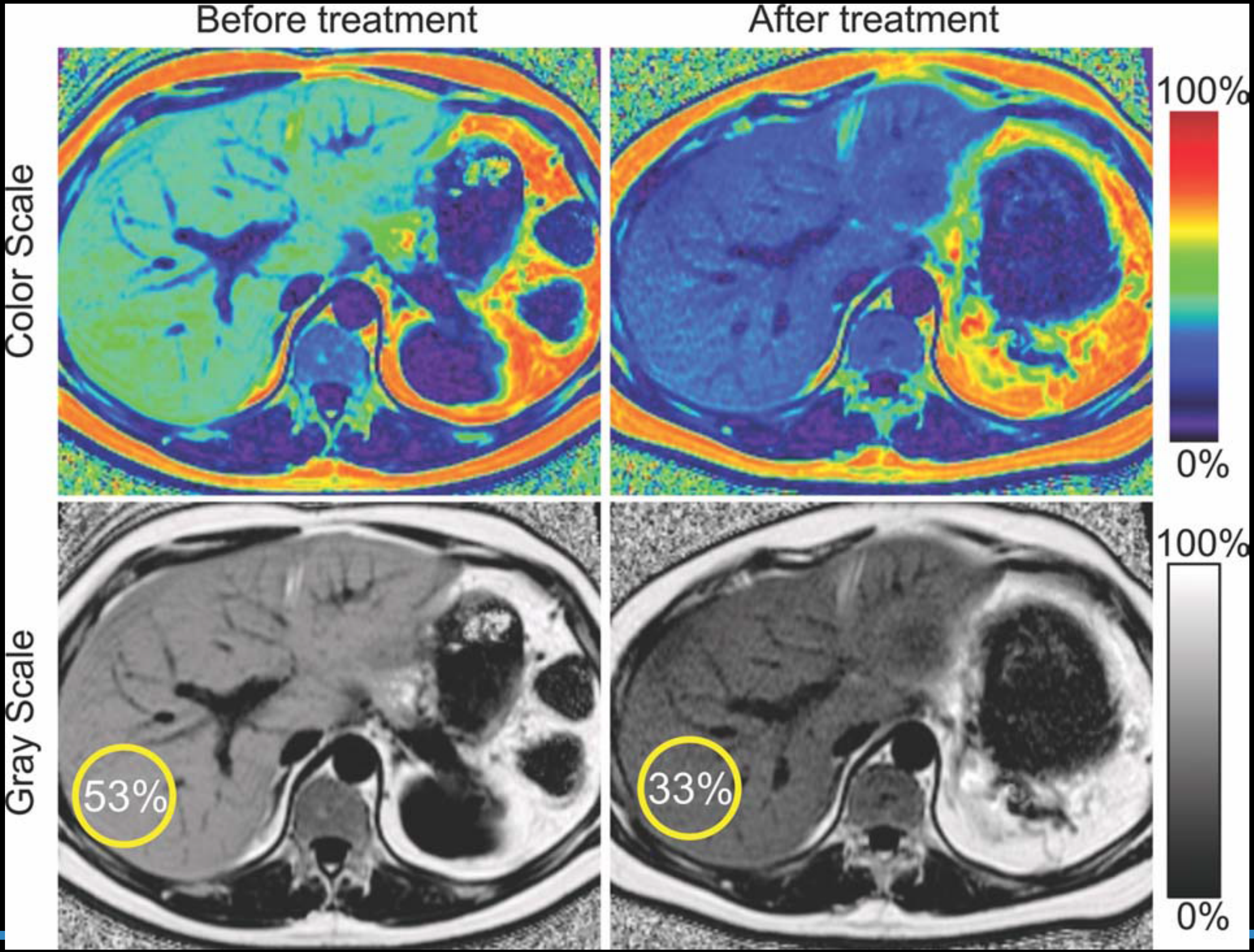
Account for multiple peaks in fat spectrum



fat peaks near water account for ~8% of fat signal

Liver Fat Quantification

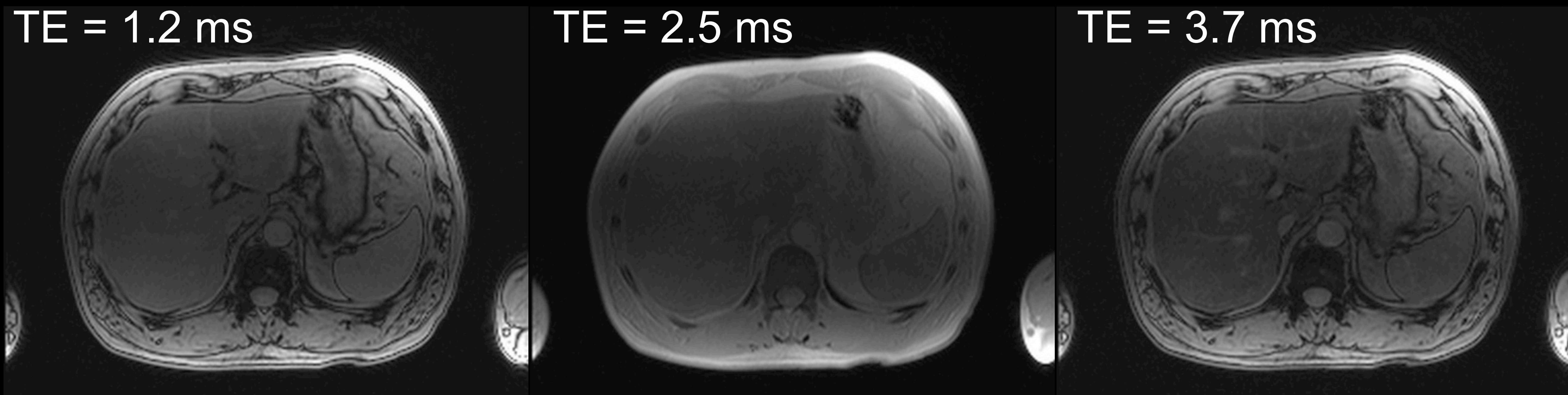
Hepatic PDFF as an imaging biomarker



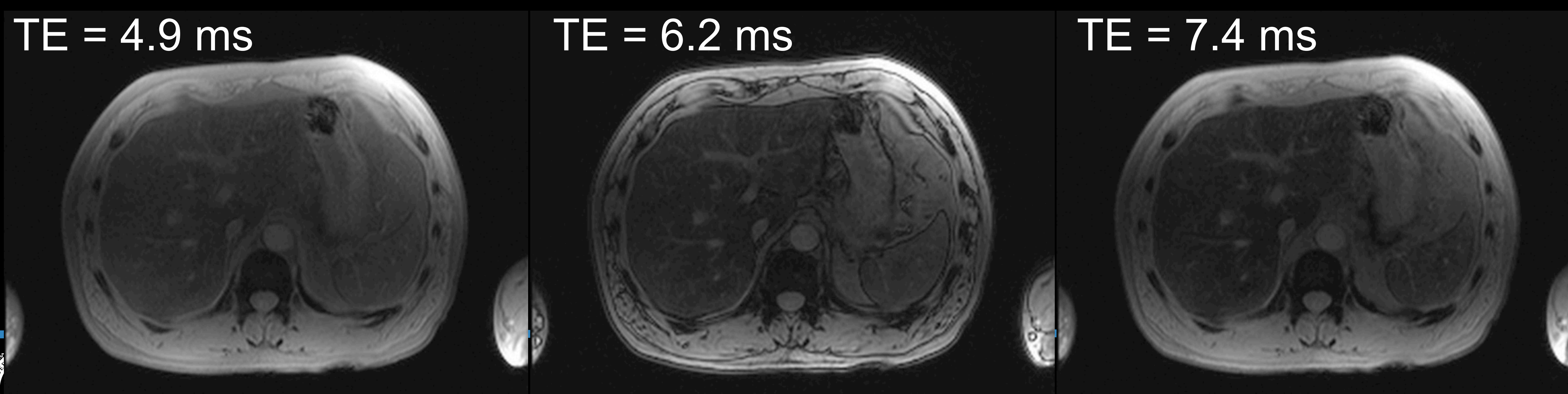
Reeder SB, et al., JMRI 2011; 34: 729-749, Fig. 13

Liver Fat Quantification

Example: Multi-echo 3D GRE in liver at 3 T (qDixon)

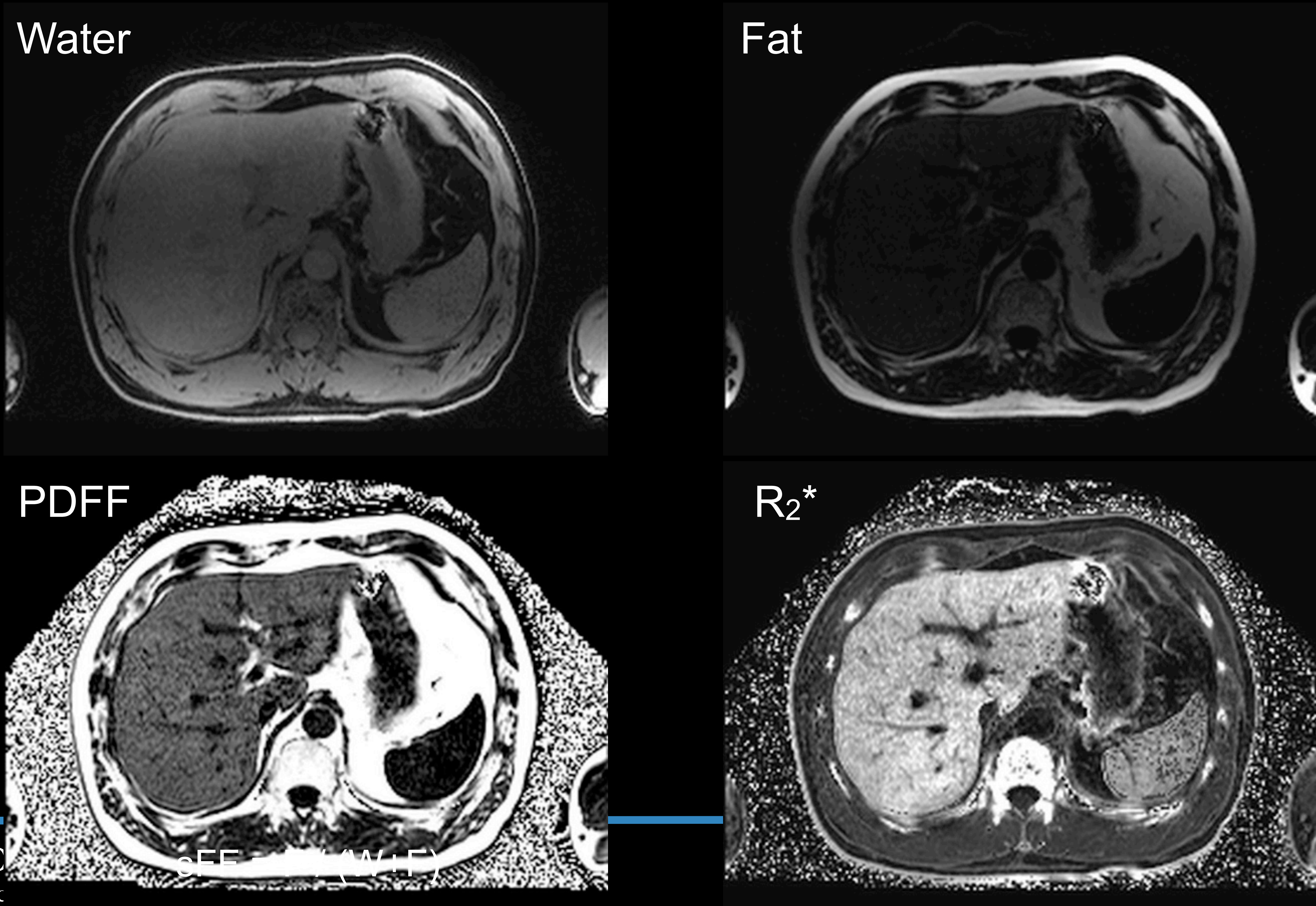


TR = 9.2 ms, θ = 4°, 18 sec BH scan



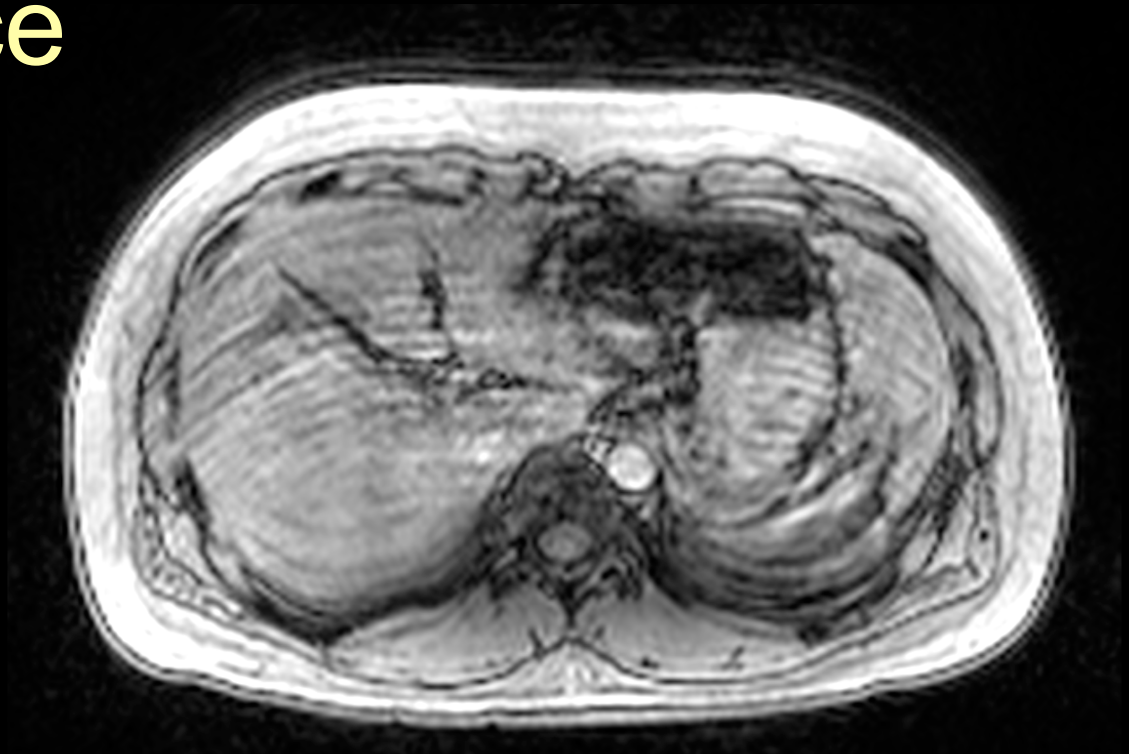
Liver Fat Quantification

Example: Multi-echo 3D GRE in liver at 3 T (qDixon)



Free-Breathing Fat Quantification

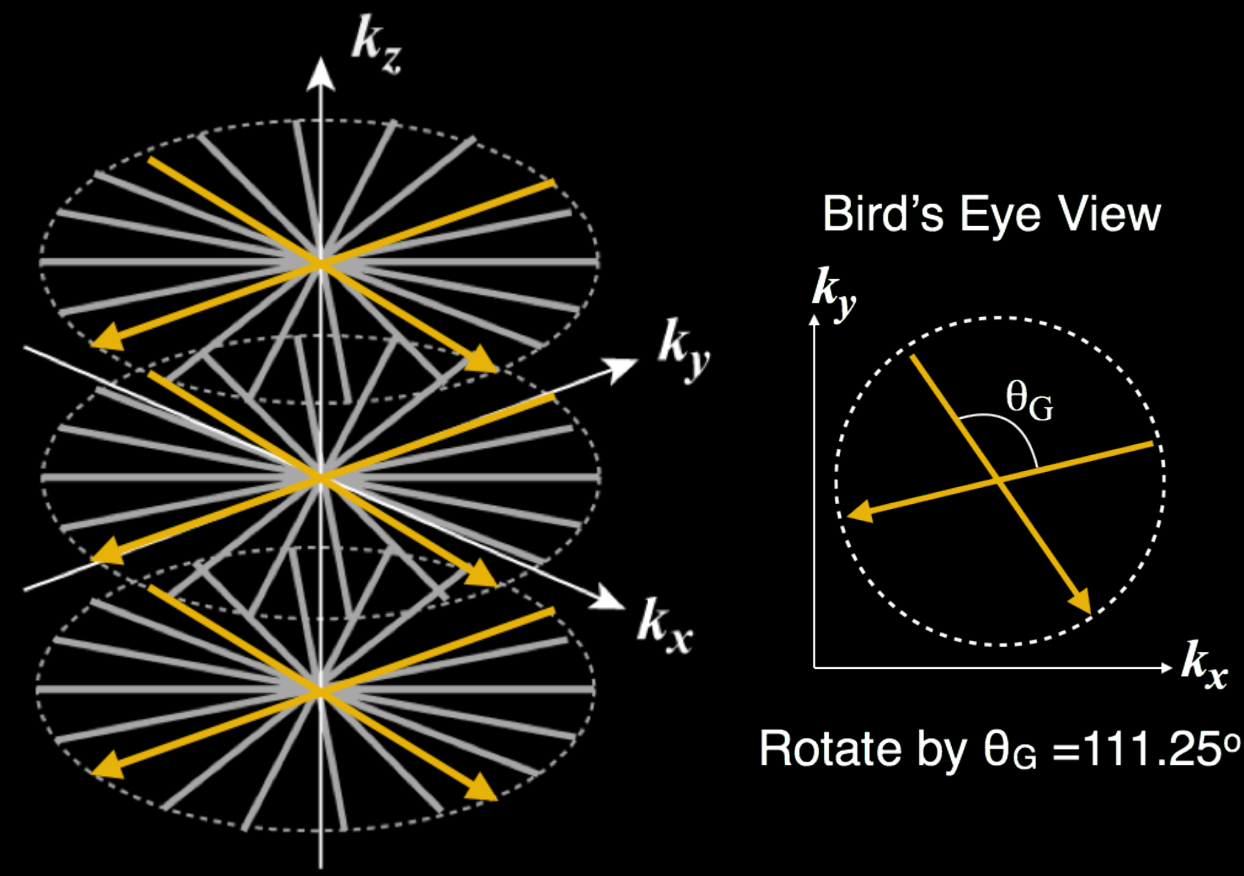
- Cartesian acquisitions limited by motion
  - Breath-hold (BH) imaging, 10-30 sec
- BH imaging limits image quality and fat quantification performance
- Many patients cannot BH

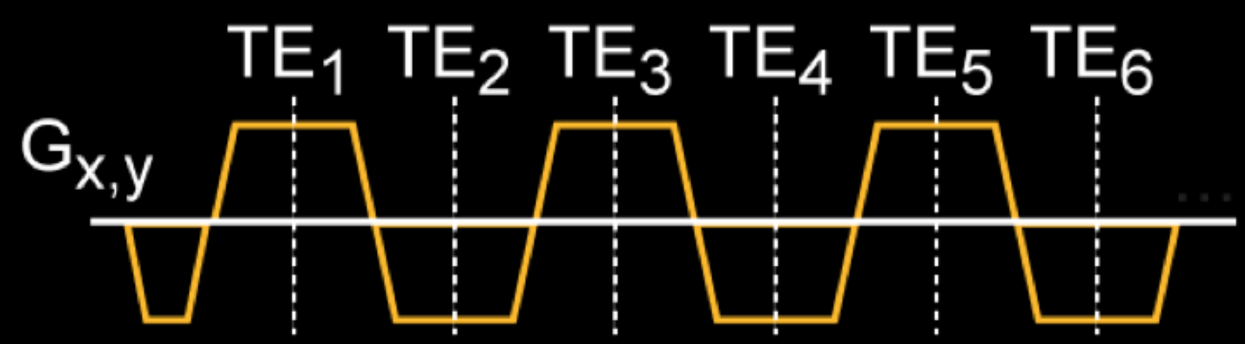


Cartesian Free-Breathing Scan

Free-Breathing Fat Quantification

3D Stack-of-Radial MRI
- golden angle ordering
- bipolar multi-echo
- gradient calibration
- multi-peak F/W and R_2*
- proton density fat fraction

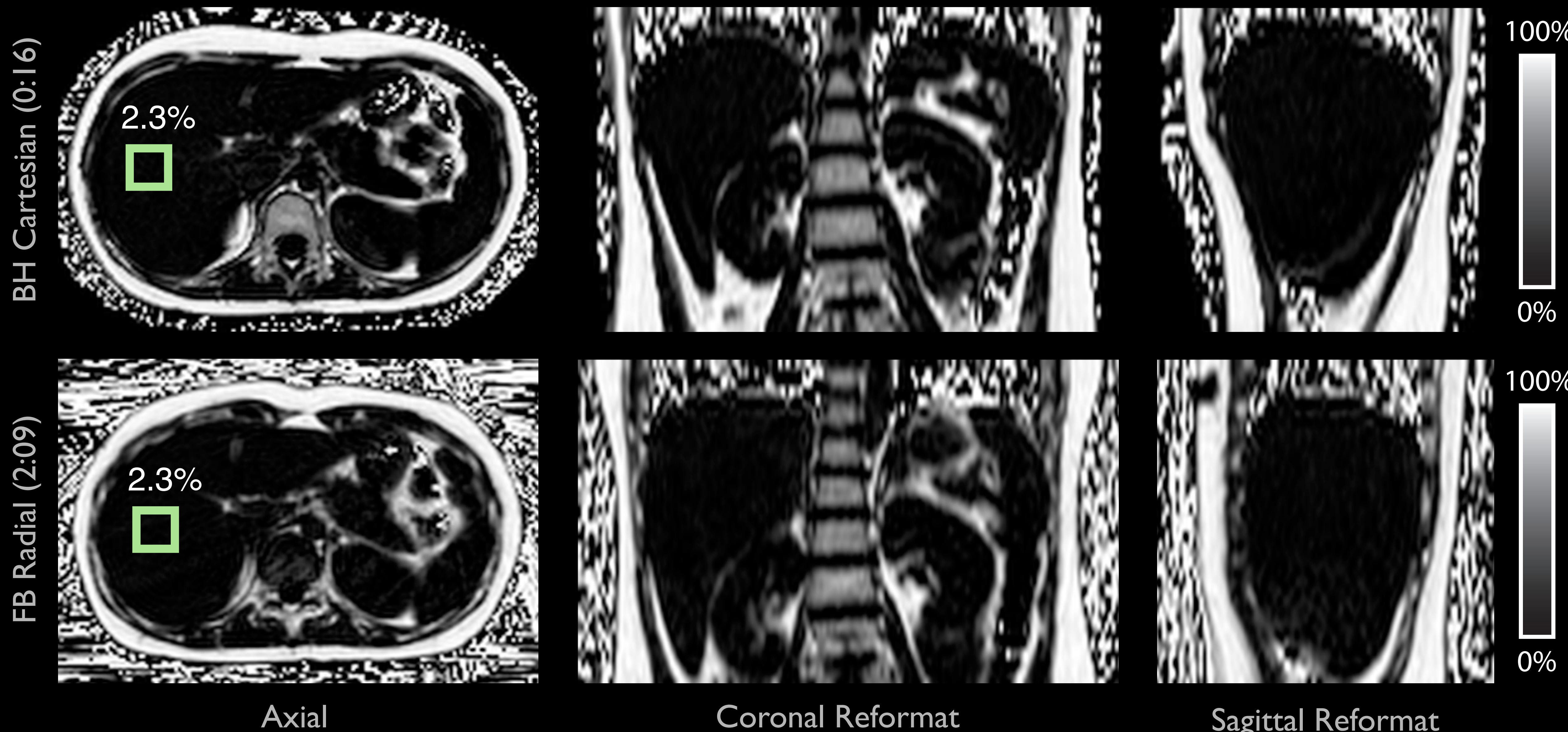




Free-Breathing Fat Quantification

New Techniques: FB 3D Stack-of-Radial MRI

Healthy Pediatric Subject

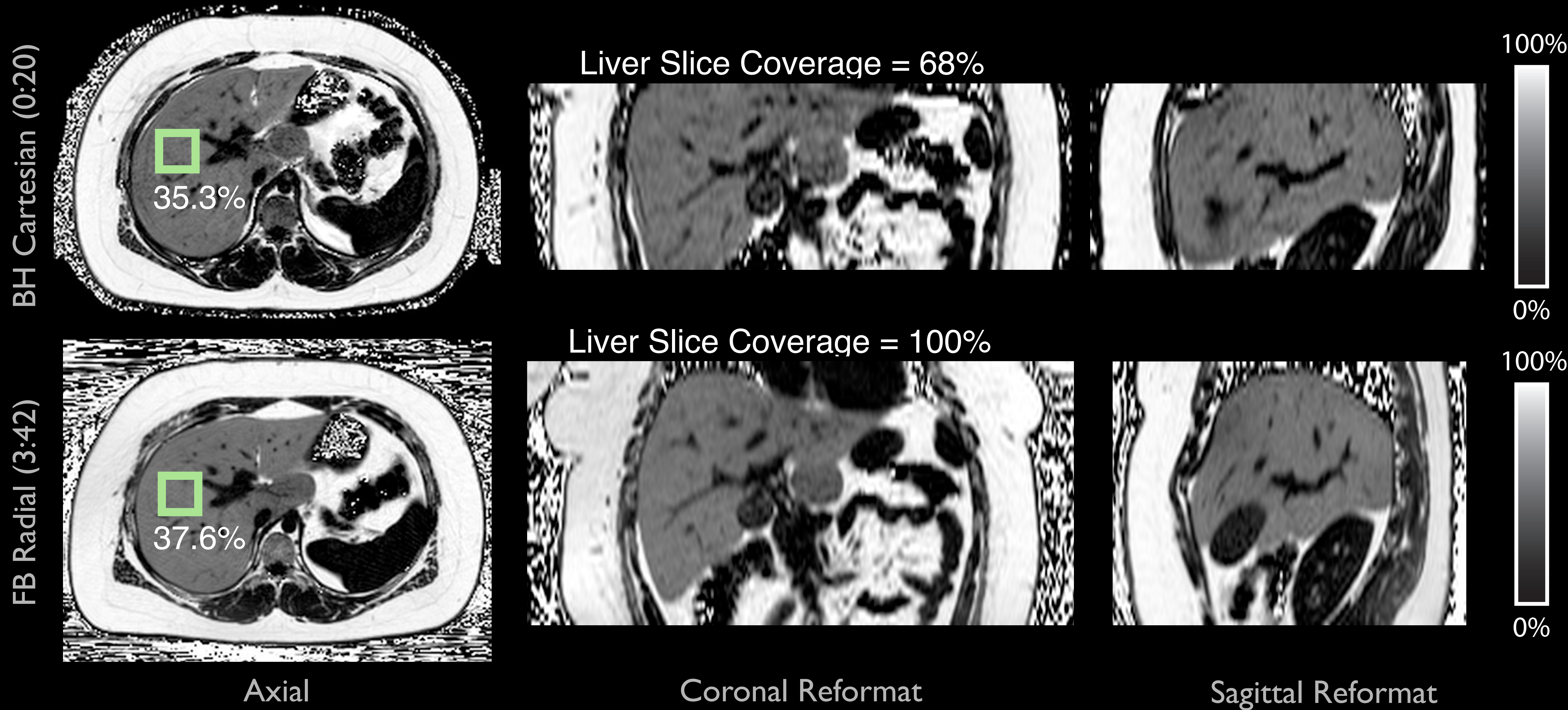


Armstrong T, et al., Ped Rad 2018

Free-Breathing Fat Quantification

New Techniques: FB 3D Stack-of-Radial MRI

NAFLD Pediatric Subject



Summary

- Fat in MRI
- Fat Suppression
- Fat-Water-Separated MRI
- Fat Quantification: PDFF

Q&A Time

Acknowledgments

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