Water-Fat MRI

M219 Principles and Applications of MRI

Holden H. Wu, Ph.D.

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UCLA
Department of Radiological Sciences
David Geffen School of Medicine at UCLA

Learning Objectives

- Fat in MRI
  - chemical shift
- Fat Suppression
- Fat-Water-Separated MRI
  - multi-echo Dixon techniques
- Fat Quantification
  - liver fat quantification
- Free-Breathing Fat Quantification

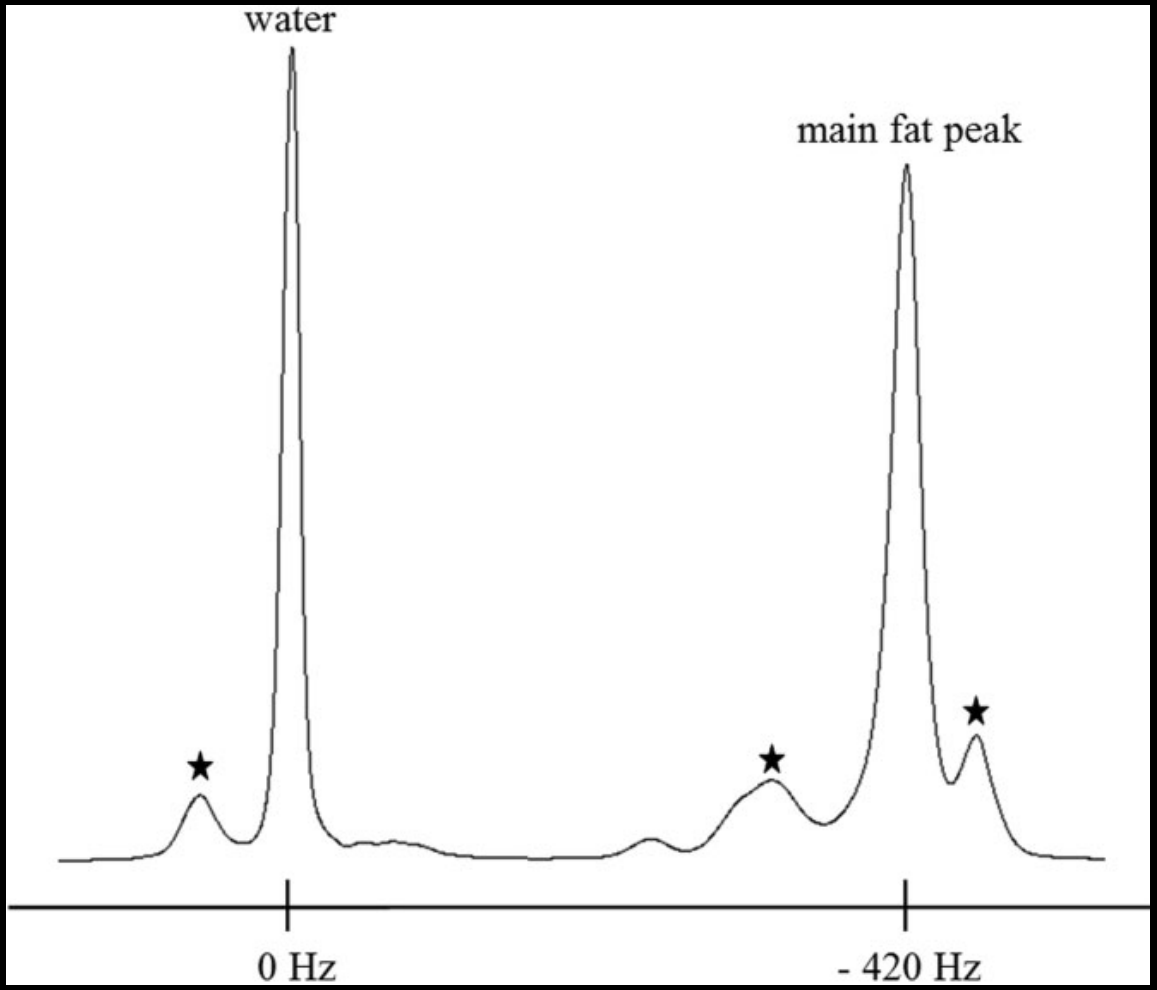
Fat in MRI

- ^{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

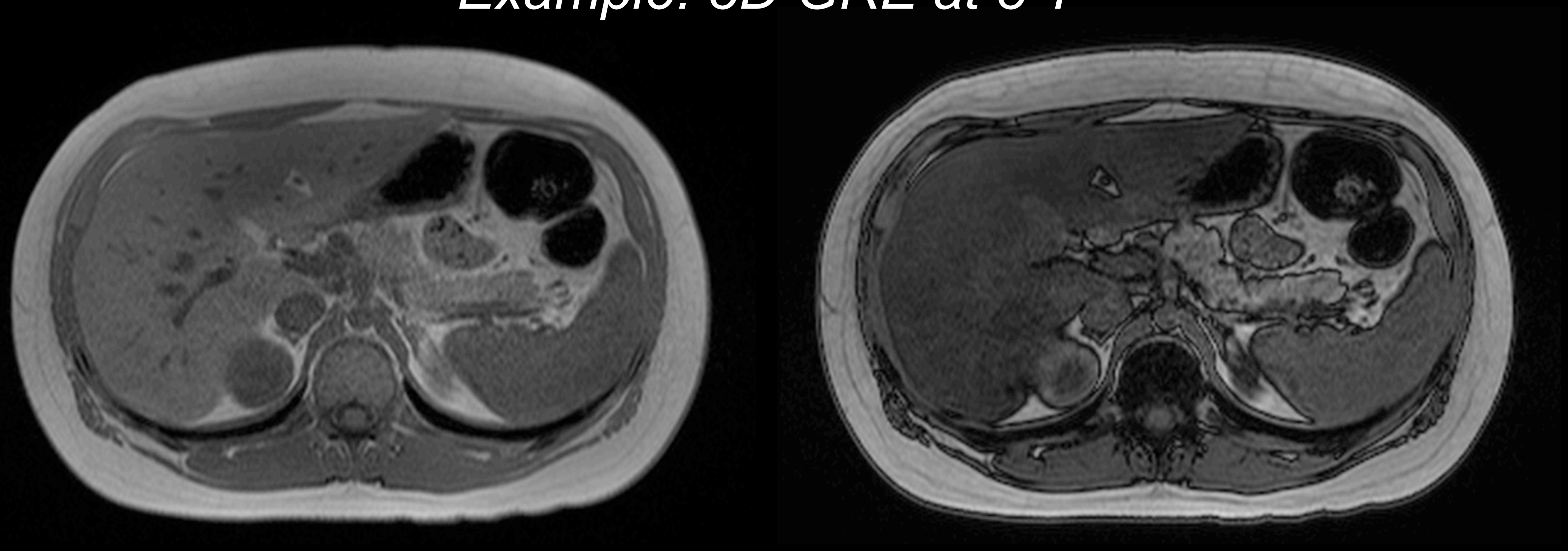
at B_0 = 3.0 T, $\Delta f_{cs} \approx -420$ Hz

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

Chemical Shift of Fat

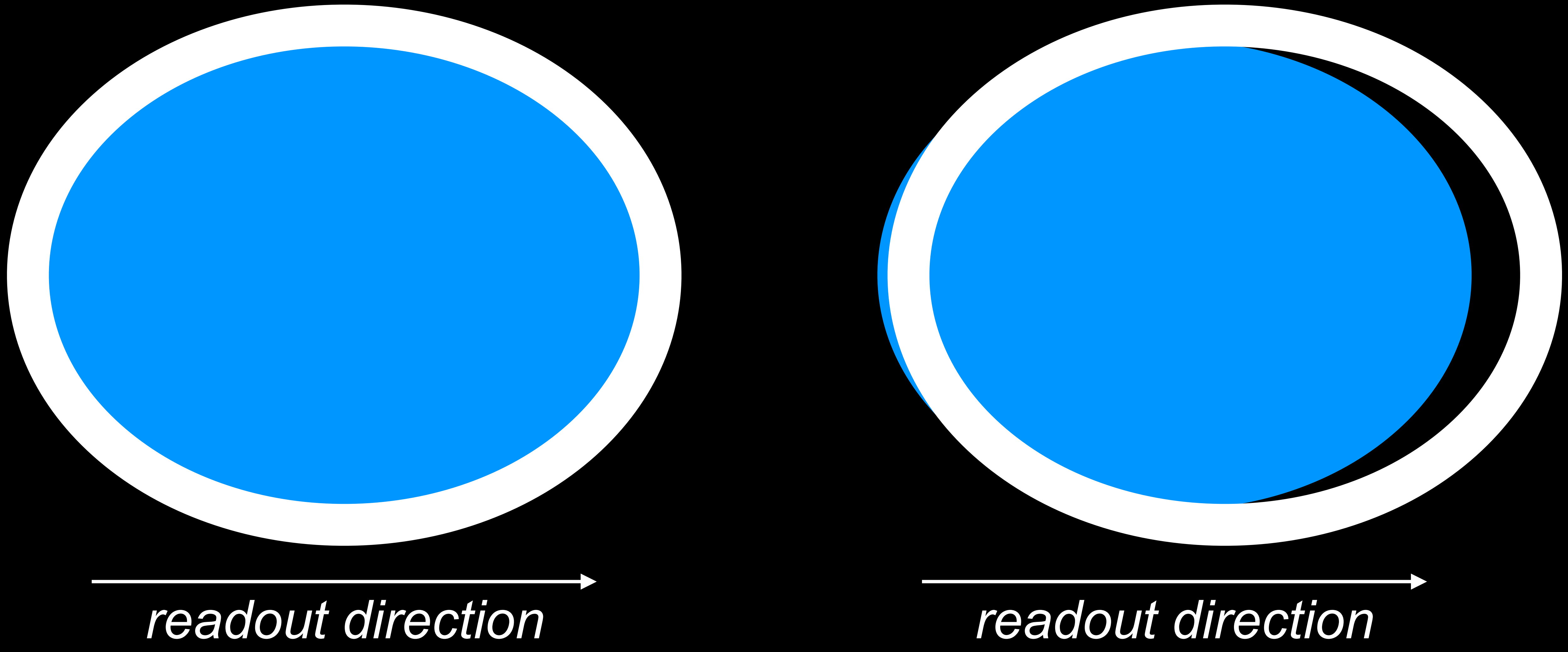
- Dark line artifacts
  - GRE
  - bSSFP

Example: 3D GRE at 3 T



Chemical Shift of Fat

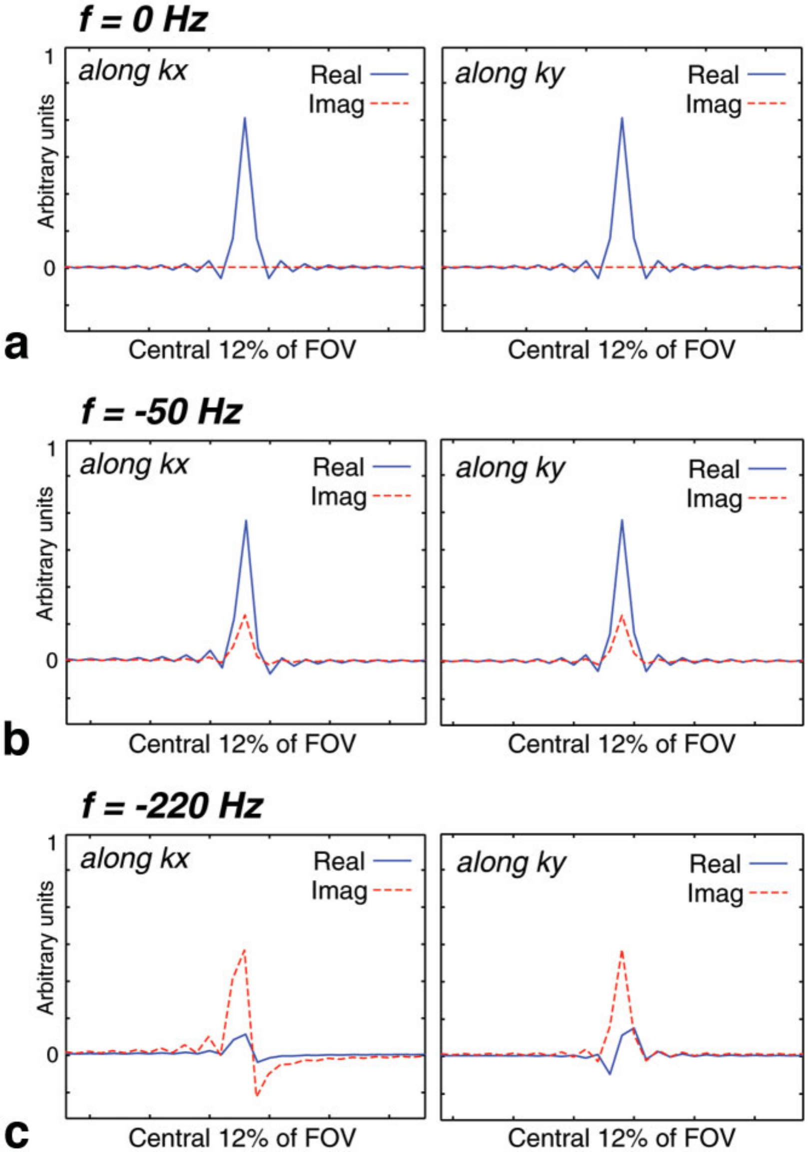
- Chemical shift artifacts
  - Cartesian

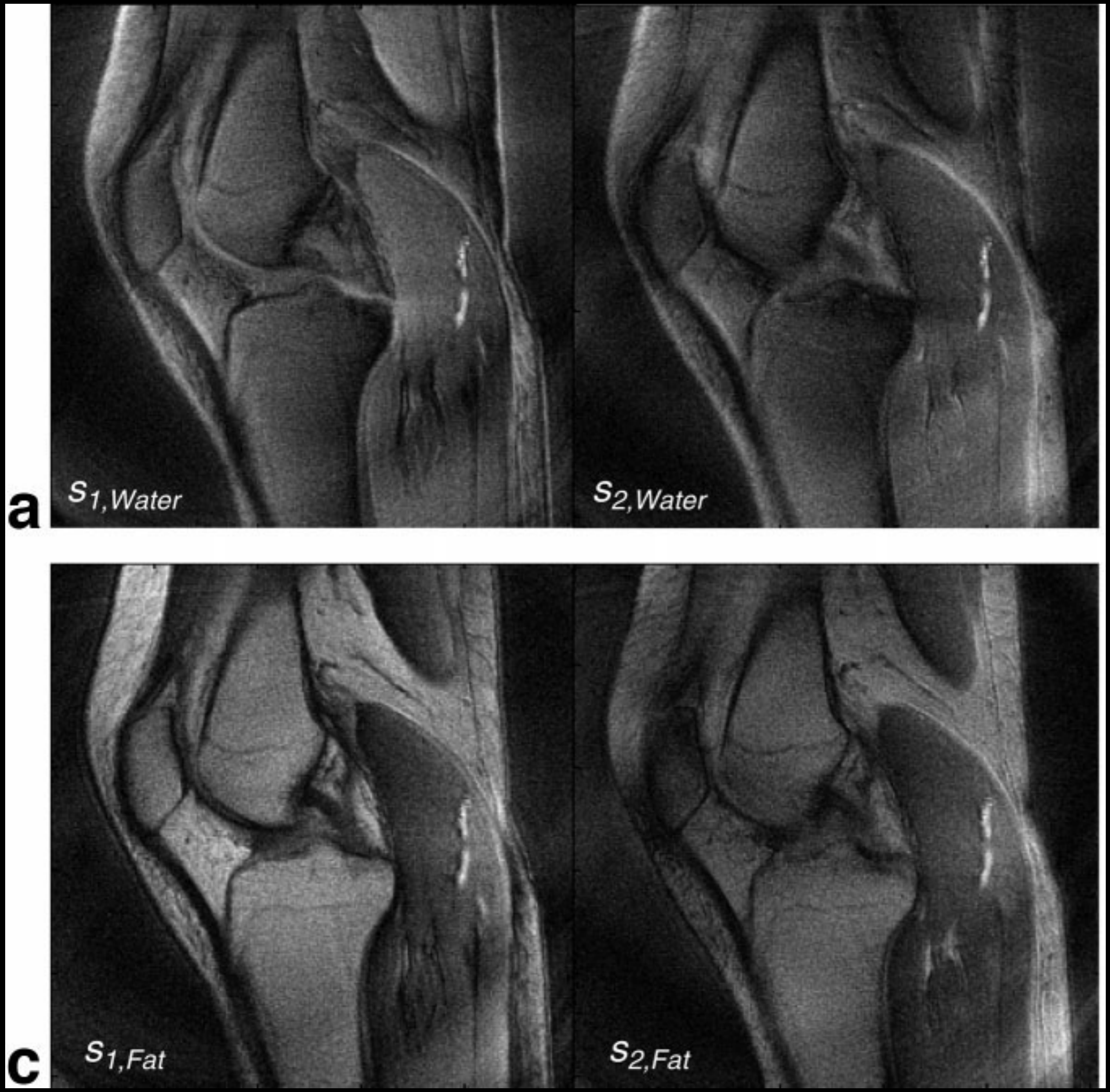


Chemical Shift of Fat

- Blurring artifacts
  - EPI, non-Cartesian

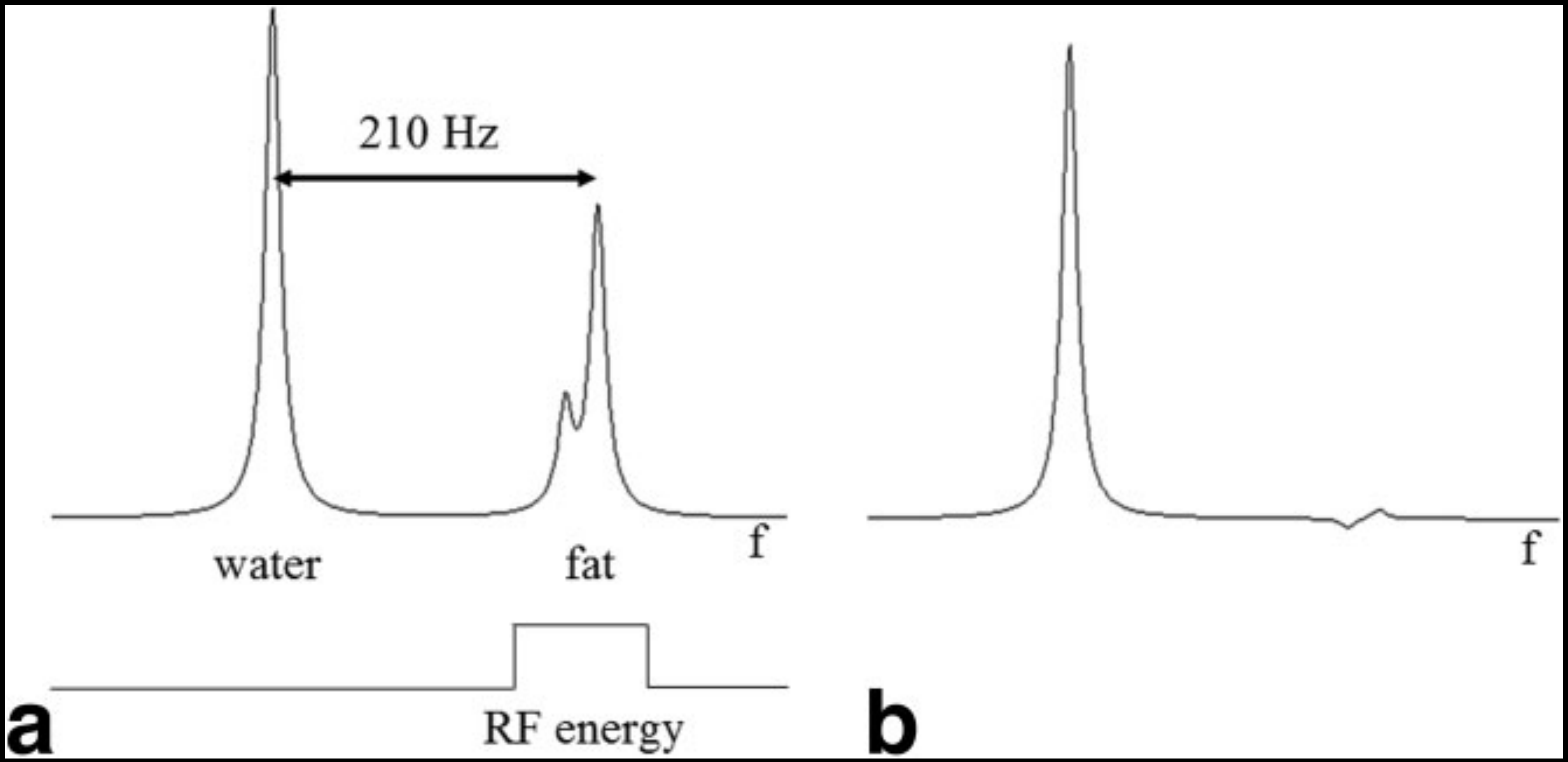
Example: Concentric Rings (Wu et al., MRM 2009)





Fat Suppression

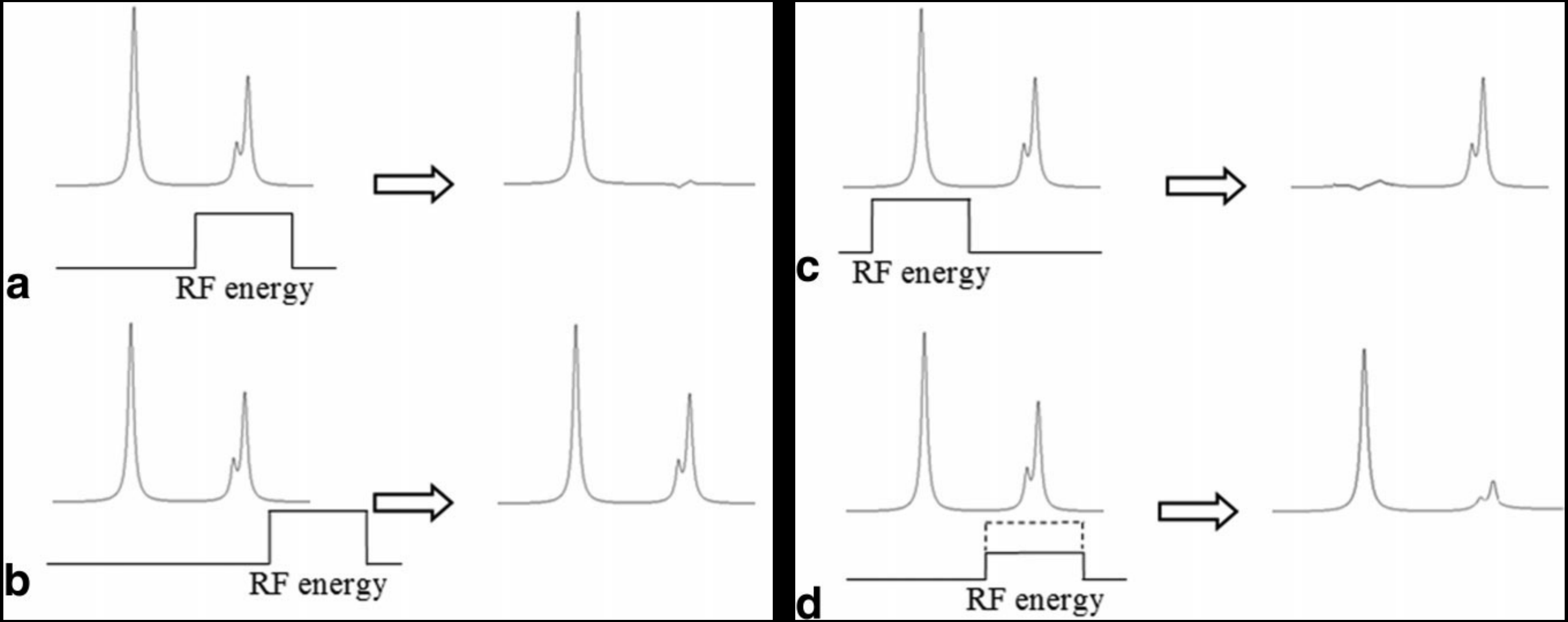
- Fat saturation
  - chemical shift selective (CHESS) saturation



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

Fat Suppression

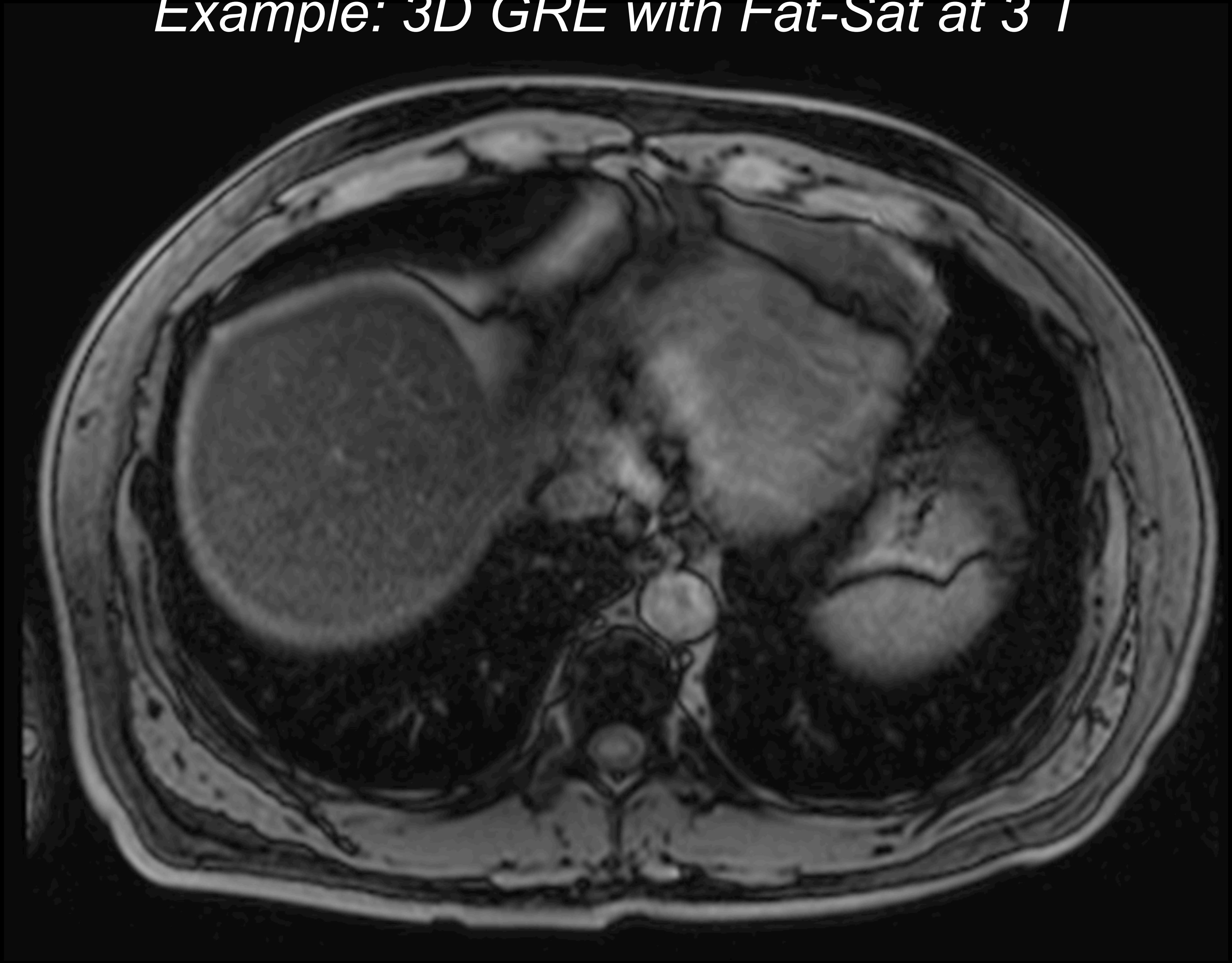
- Fat saturation
  - sensitive to B_0 and B_1 variations



Bley TA et al., JMRI 2010; 31: 4-18, Fig. 3

Fat Suppression

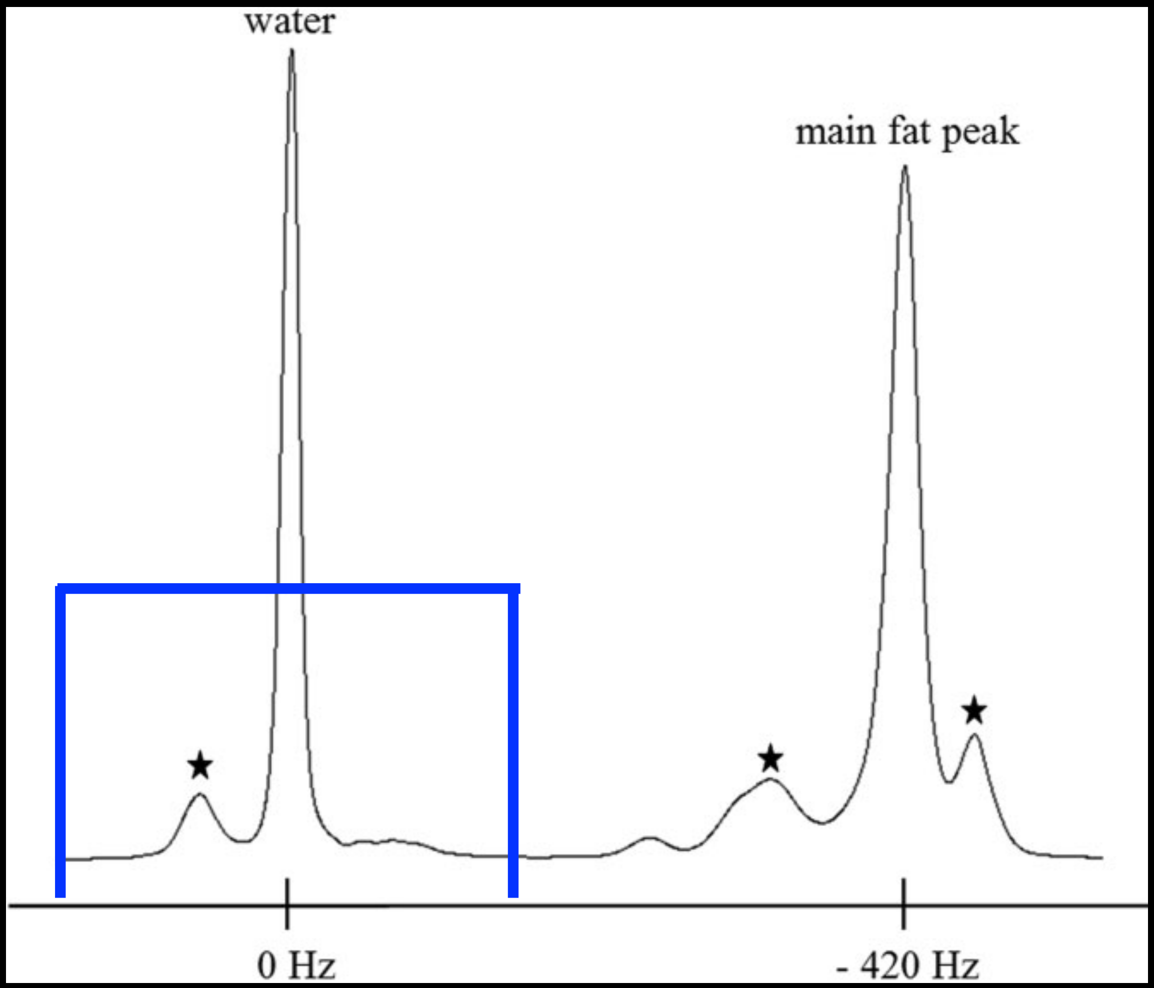
Example: 3D GRE with Fat-Sat at 3 T



Note that B_0 and B_1 variations are greater at 3.0 T

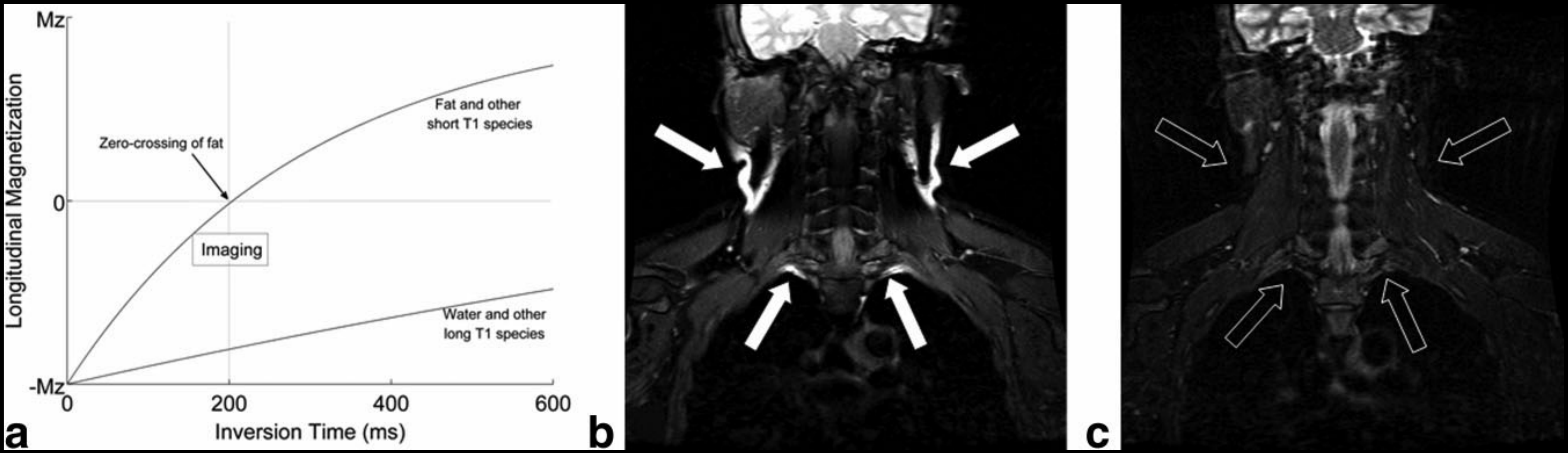
Fat Suppression

- 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

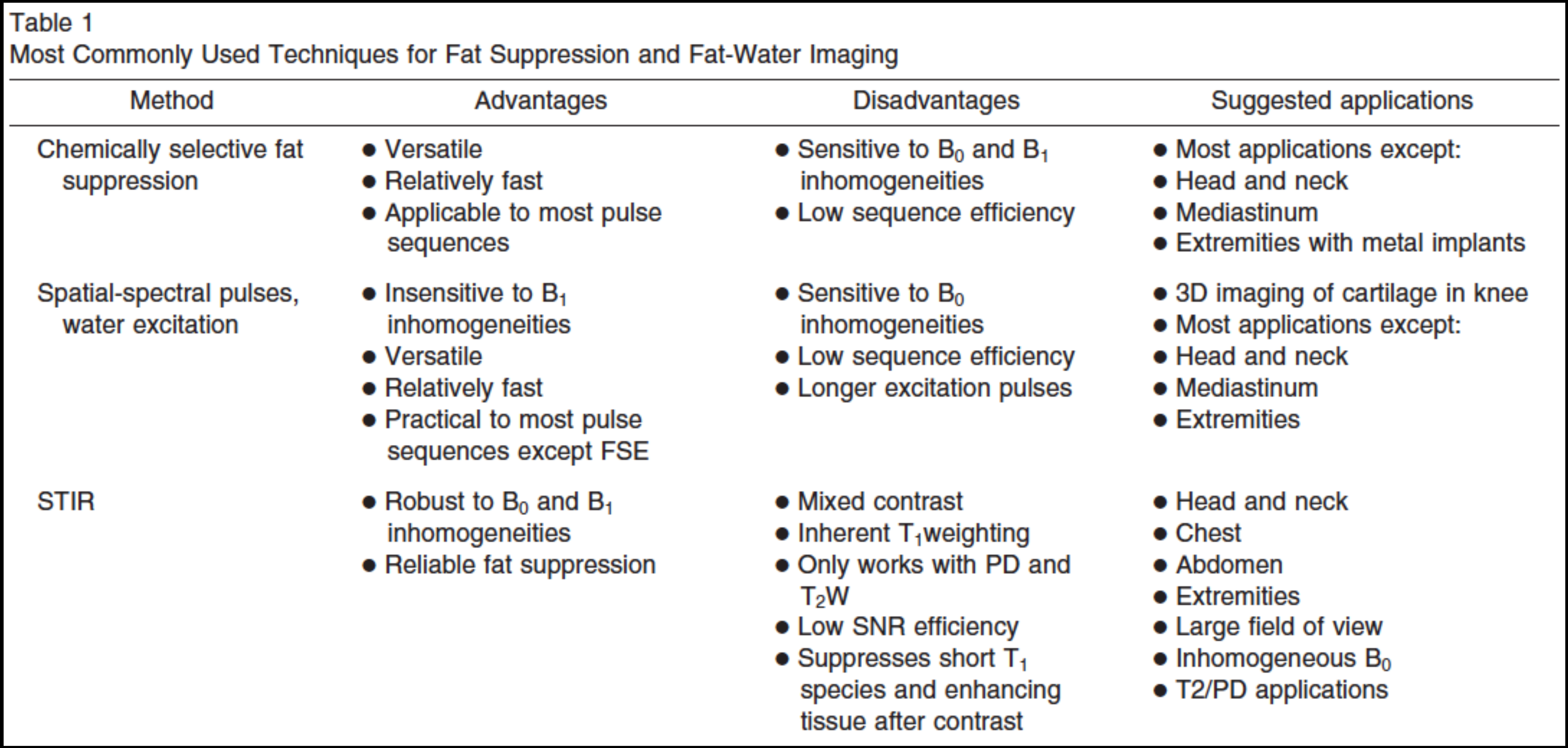


Table 1
Most Commonly Used Techniques for Fat Suppression and Fat-Water Imaging

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

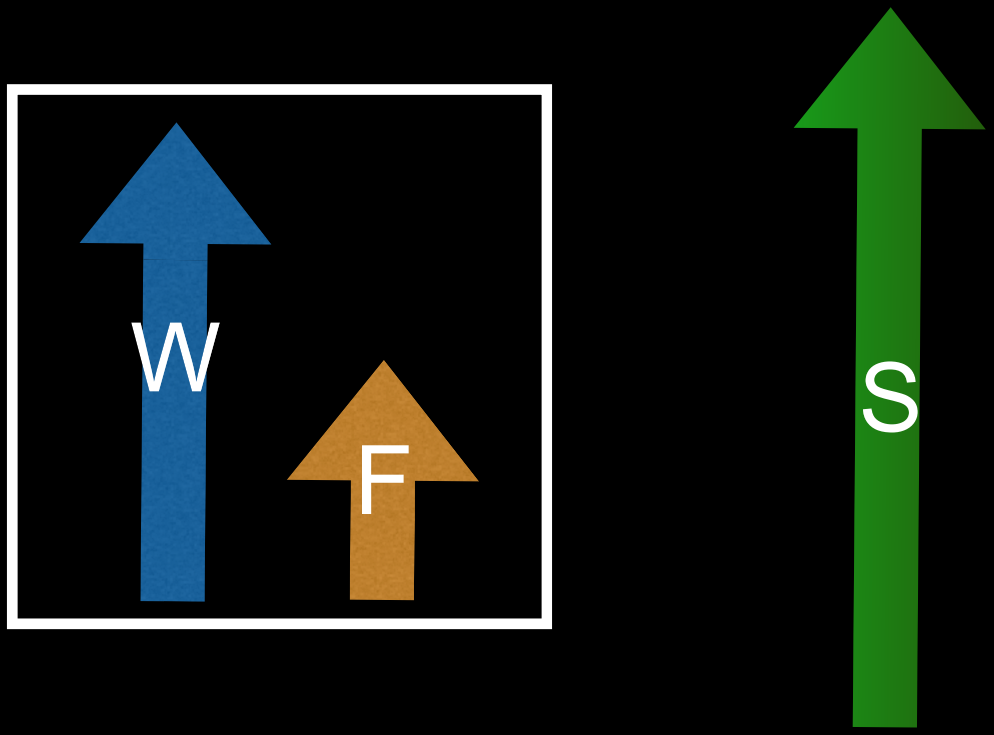
Fat-Water-Separated MRI

- 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

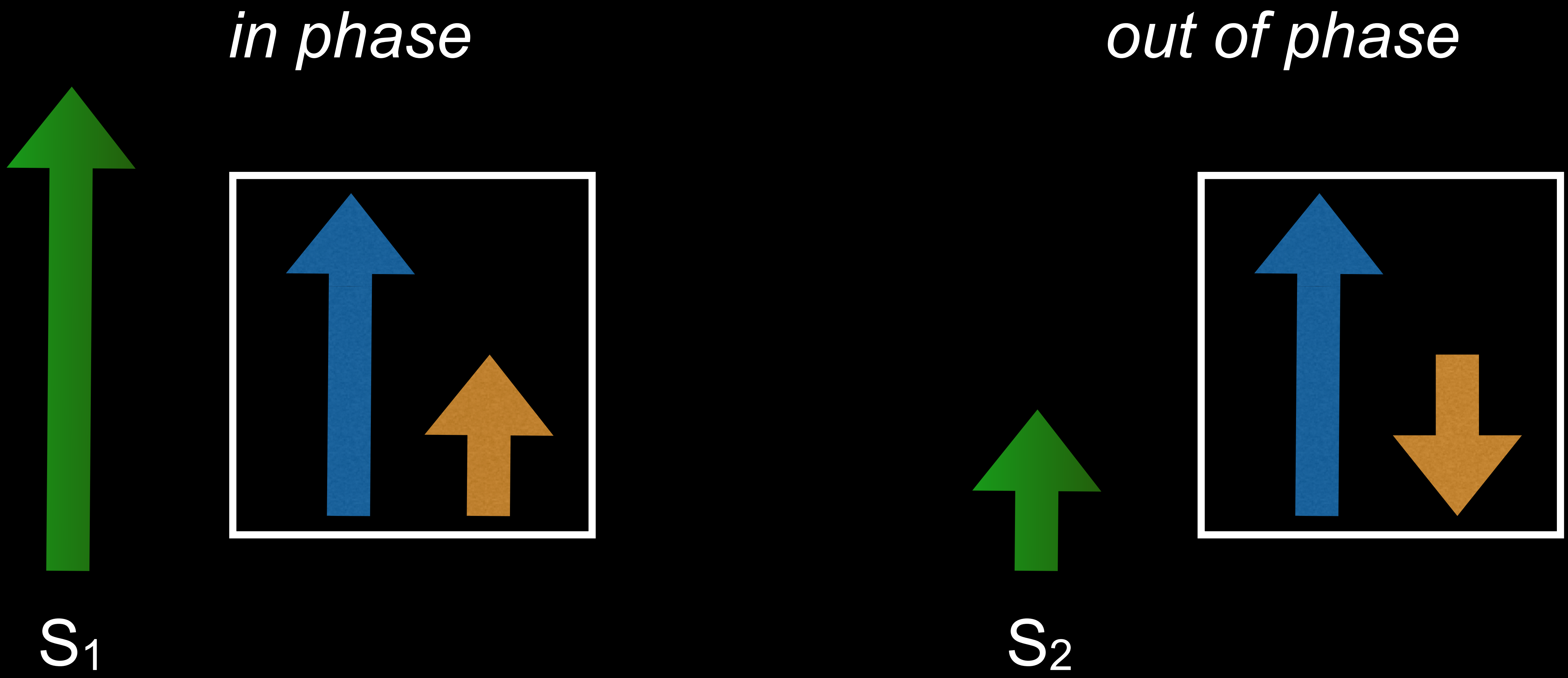
i.e., fat is slightly out-of-sync with water signal



voxel   signal dep. on TE

Fat-Water-Separated MRI

Acquire multiple images with different fat/water sync



in phase

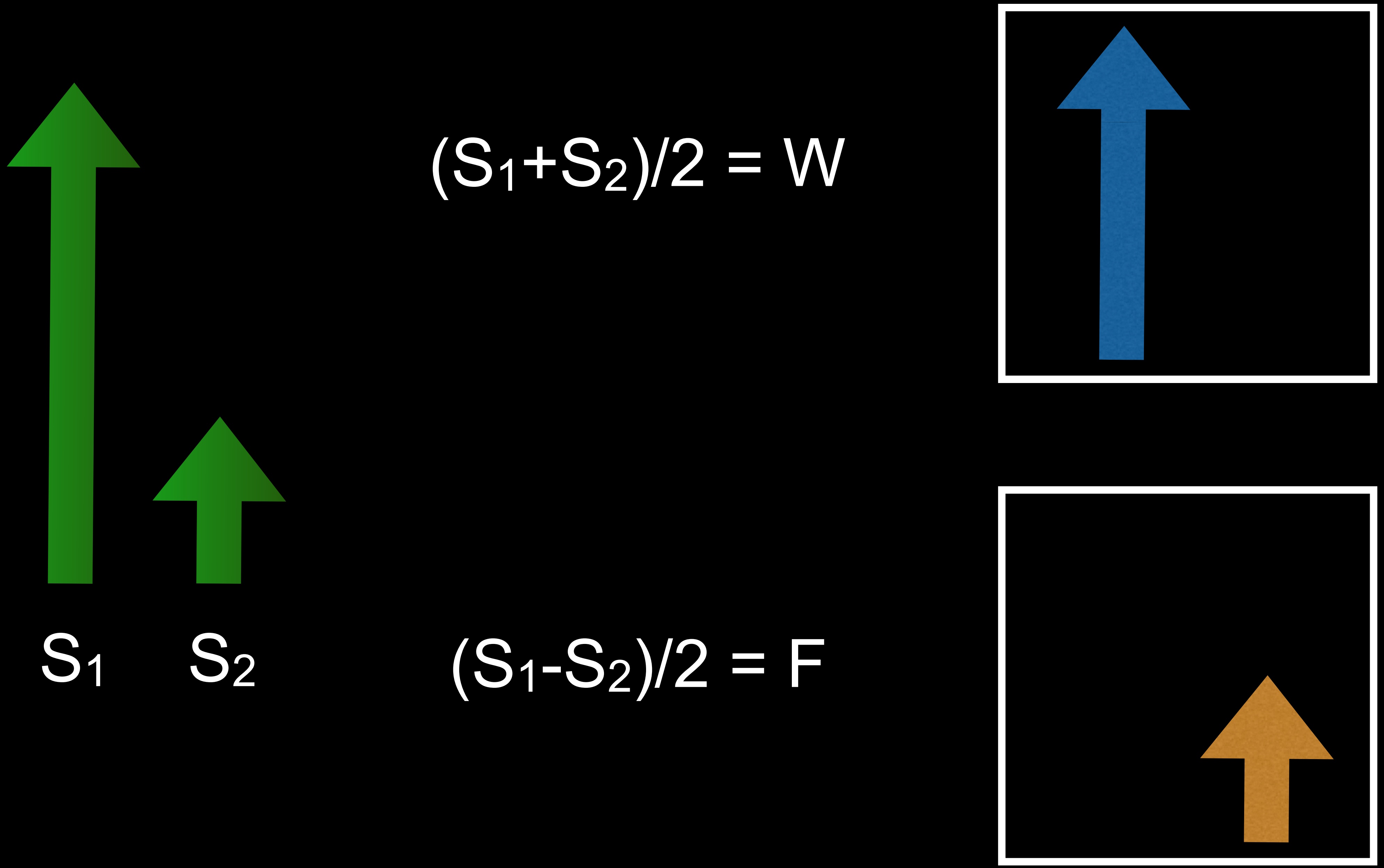
out of phase

S_1

S_2

Fat-Water-Separated MRI

Estimate the water and fat component in each voxel



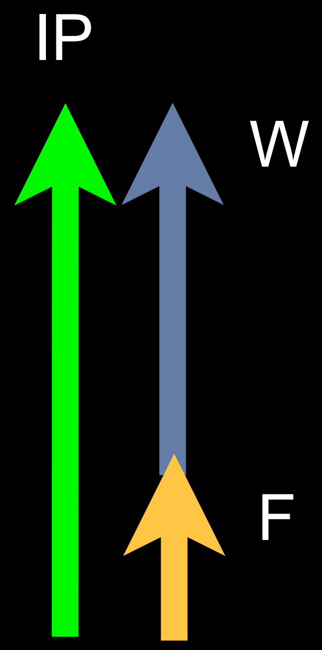
$(S_1+S_2)/2 = W$

S_1 S_2

$(S_1-S_2)/2 = F$

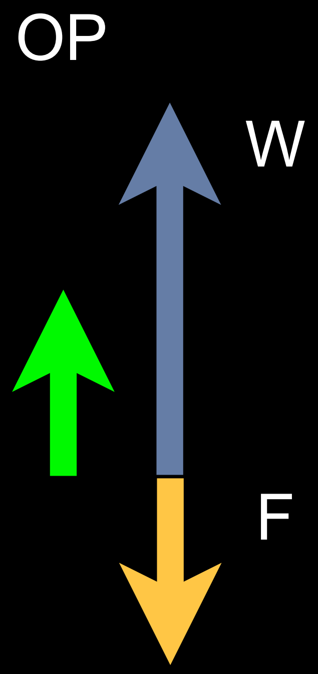
Dixon WT, *Radiology,* 1984; 153: 189-194.

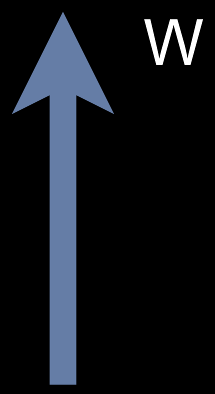
Fat-Water-Separated MRI



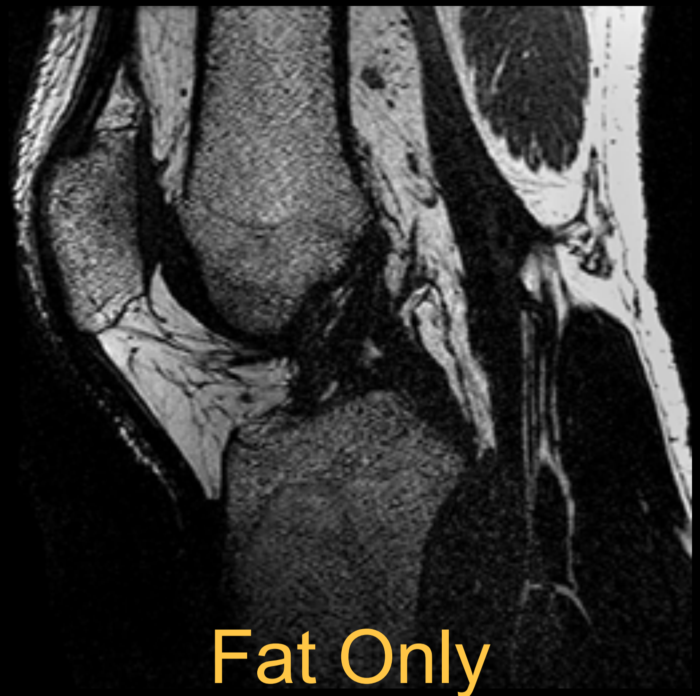

In Phase

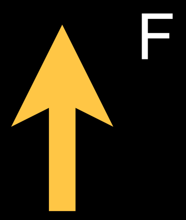

Out of Phase






Water Only


Fat Only



Siepmann D, et al., AJR 2007; 189: 1510-1515

Fat-Water-Separated MRI

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

2-Point Dixon

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

$$s_0 = s(\mathbf{r};\mathrm{TE}_0) = s_W(\mathbf{r}) + s_F(\mathbf{r})e^{-i2\pi\Delta f_{cs}\mathrm{TE}_0} = s_W + s_F$$

$2\pi\Delta f_{cs}\mathrm{TE}_0 = 2n \cdot \pi$ “in-phase” (IP) TE_0

$$s_1 = s(\mathbf{r};\mathrm{TE}_1) = s_W(\mathbf{r}) + s_F(\mathbf{r})e^{-i2\pi\Delta f_{cs}\mathrm{TE}_1} = s_W - s_F$$

$2\pi\Delta f_{cs}\mathrm{TE}_1 = (2n+1)\pi$ “out-of-phase” (OP) TE_1

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

2-Point Dixon

$s_0 = s_W + s_F$ “in-phase” TE_0

$s_1 = s_W - s_F$ “out-of-phase” TE_1

$(0, \pi)$ acquisition

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

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

	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 …

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

2-Point Dixon: Limitations

$$s(\mathbf{r};\mathrm{TE}_n) = [s_W(\mathbf{r}) + s_F(\mathbf{r})e^{-i2\pi\Delta f_{cs}\mathrm{TE}_n}] \cdot \underline{e^{-i\varphi_0}} \cdot \underline{e^{-i2\pi\psi(\mathbf{r})\mathrm{TE}_n}}$$

$$s_0 = (s_W + s_F)e^{-i\phi_0} \qquad \Delta\mathrm{TE} = \mathrm{TE}_1 - \mathrm{TE}_0$$

$$s_1 = (s_W - s_F)e^{-i(\phi_0+\phi)} \qquad \phi = 2\pi\psi(\mathbf{r})\Delta\mathrm{TE}$$

$$\begin{aligned} \hat{s}_W &= \frac{1}{2}(s_0 + s_1) \\ &= \frac{1}{2}e^{-i\phi_0}[s_W\underset{\text{signal loss}}{\underline{(1+e^{-i\phi})}} + \underset{\text{crosstalk}}{\underline{s_F(1-e^{-i\phi})}}] \end{aligned}$$

field map ψ causing a problem …

3-Point Dixon

$$s(\mathbf{r};\mathrm{TE}_n) = [s_W(\mathbf{r}) + s_F(\mathbf{r})e^{-i2\pi\Delta f_{cs}\mathrm{TE}_n}] \cdot e^{-i\varphi_0} \cdot e^{-i2\pi\psi(\mathbf{r})\mathrm{TE}_n}$$

$$s_{-1} = (s_W - s_F)e^{i\phi}$$

$$s_0 = (s_W + s_F)$$

$$s_1 = (s_W - s_F)e^{-i\phi}$$

(-π, 0, π) acquisition e.g., by SE

$$\phi = 2\pi\psi(\mathbf{r})\Delta\mathrm{TE}$$

note: ϕ_0 removed

$$2\hat{\phi} = \angle(s^*_{-1}s_1)$$

estimate and remove field map

calculate s_W and s_F

3-Point Dixon

$$s(\mathbf{r};\mathrm{TE}_n) = [s_W(\mathbf{r}) + s_F(\mathbf{r})e^{-i2\pi\Delta f_{cs}\mathrm{TE}_n}] \cdot e^{-i\varphi_0} \cdot e^{-i2\pi\psi(\mathbf{r})\mathrm{TE}_n}$$

$$s_0 = (s_W + s_F)$$

(0, π, 2π) acquisition

works better!

$$s_1 = (s_W - s_F)e^{-i\phi}$$

$$\phi = 2\pi\psi(\mathbf{r})\Delta\mathrm{TE}$$

$$s_2 = (s_W + s_F)e^{-i2\phi}$$

note: ϕ_0 removed

$$2\hat{\phi} = \angle(s_0^* s_2)$$

estimate and remove field map

$$\hat{s}_W = \frac{1}{2}[s_0 + s_1 e^{i\hat{\phi}}] \qquad \hat{s}_F = \frac{1}{2}[s_0 - s_1 e^{i\hat{\phi}}]$$

$$\hat{s}_W = \frac{1}{4}[s_0 + s_2 e^{i2\hat{\phi}}] + \frac{1}{2} s_1 e^{i\hat{\phi}}$$

better SNR

Glover GH et al., MRM, 1991; 18: 371-383.

3-Point Dixon: Limitations

Field map estimation

$$2\hat{\phi} = \angle(s_0^* s_2)$$

$2\hat{\phi}$ wraps at [-π, π]: $\hat{\phi}$ wraps at [-π/2, π/2]

if $\phi - \hat{\phi} = \pi$ water/fat swap!

phase unwrapping problem … not solved yet

improve with polynomial fitting, region growing

Also have T_2 (T_2*) decay as TE increases

Extended 2-Point Dixon

$$s(\mathbf{r};\mathrm{TE}_n) = \left[s_W(\mathbf{r}) + s_F(\mathbf{r})e^{-i2\pi\Delta f_{cs}\mathrm{TE}_n}\right] \cdot e^{-i\varphi_0} \cdot e^{-i2\pi\psi(\mathbf{r})\mathrm{TE}_n}$$

$$s_0 = (s_W + s_F)e^{-i\phi_0} \qquad \Delta\mathrm{TE} = \mathrm{TE}_1 - \mathrm{TE}_0$$

$$s_1 = (s_W - s_F)e^{-i(\phi_0+\phi)} \qquad \phi = 2\pi\psi(\mathbf{r})\Delta\mathrm{TE}$$

extract ϕ_0 from phase of s_0 and remove from s_1

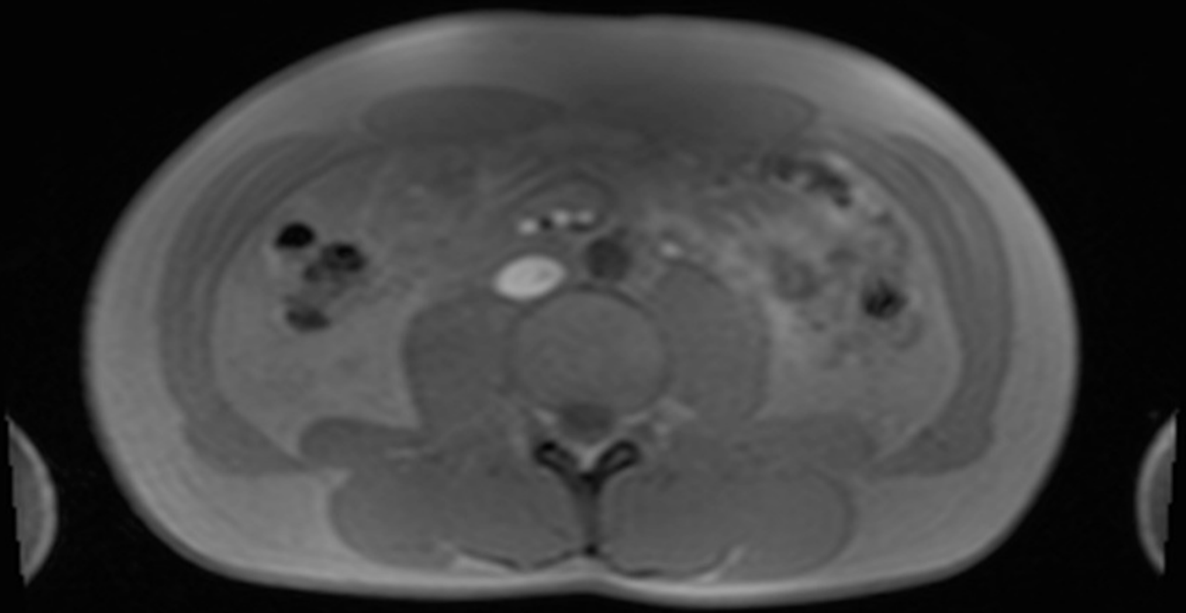
$$s_1' = (s_W - s_F)e^{-i\phi} \qquad (s_1')^2 = |s_W - s_F|^2 e^{-i2\phi}$$

estimate 2ϕ from phase of $(s_1')^2$ and remove ϕ

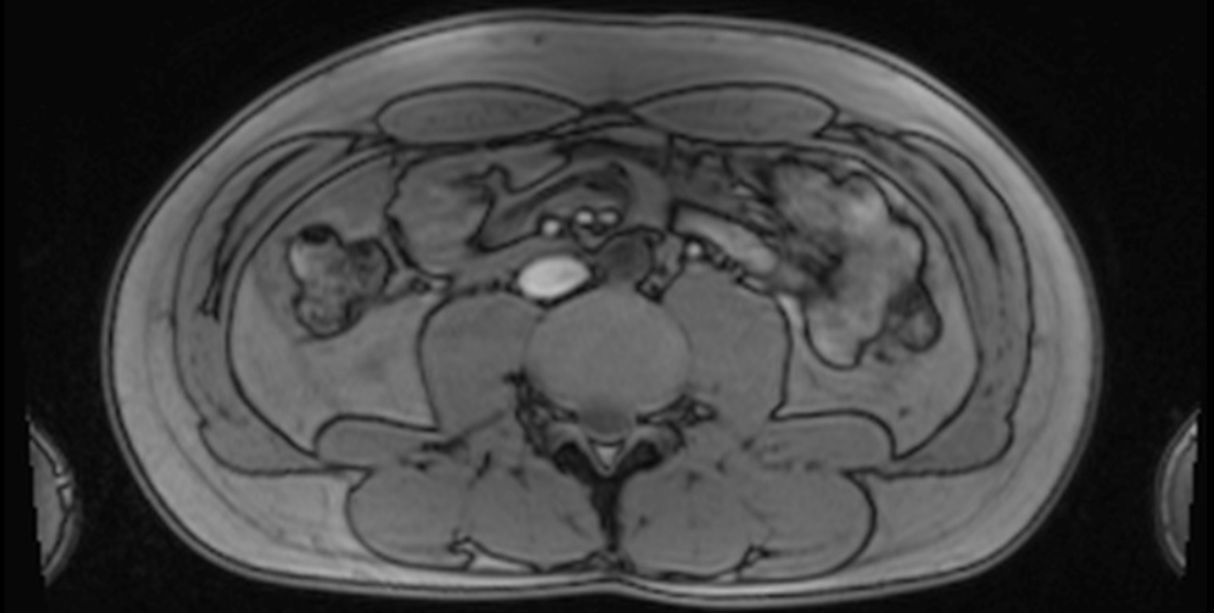
phase unwrapping problem… esp. challenging when $s_W \approx s_F$

Extended 2-Point Dixon

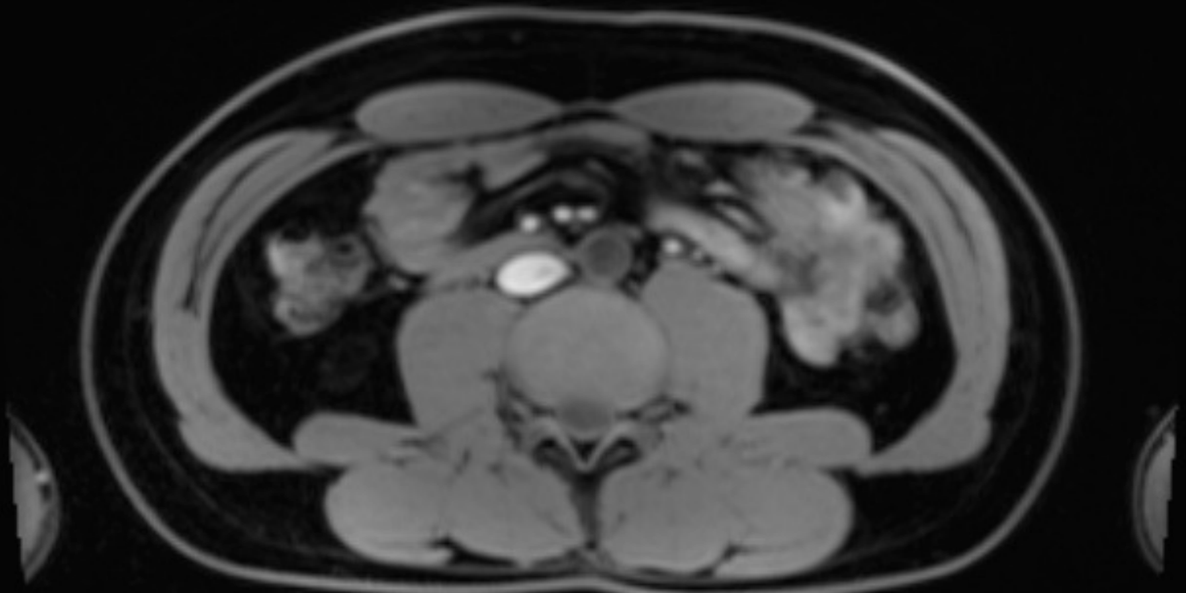
Example: 3 T abdominal scan



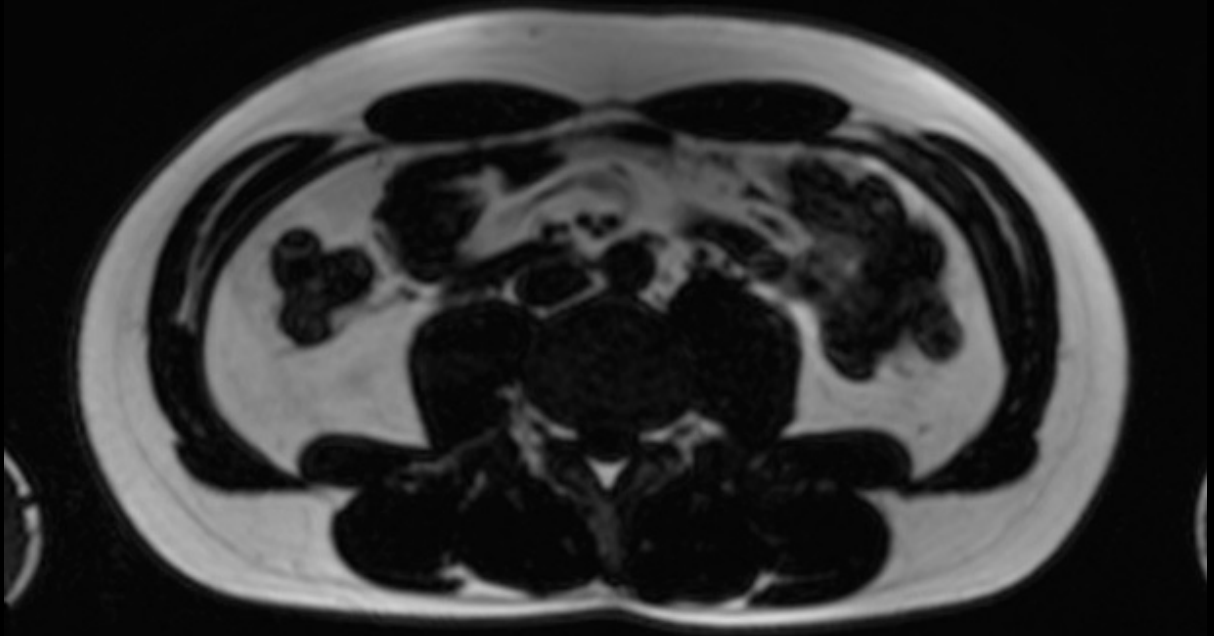
In-phase (3 T), TE = 2.6 ms



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



Water



Fat

F/W MRI Sequence Design

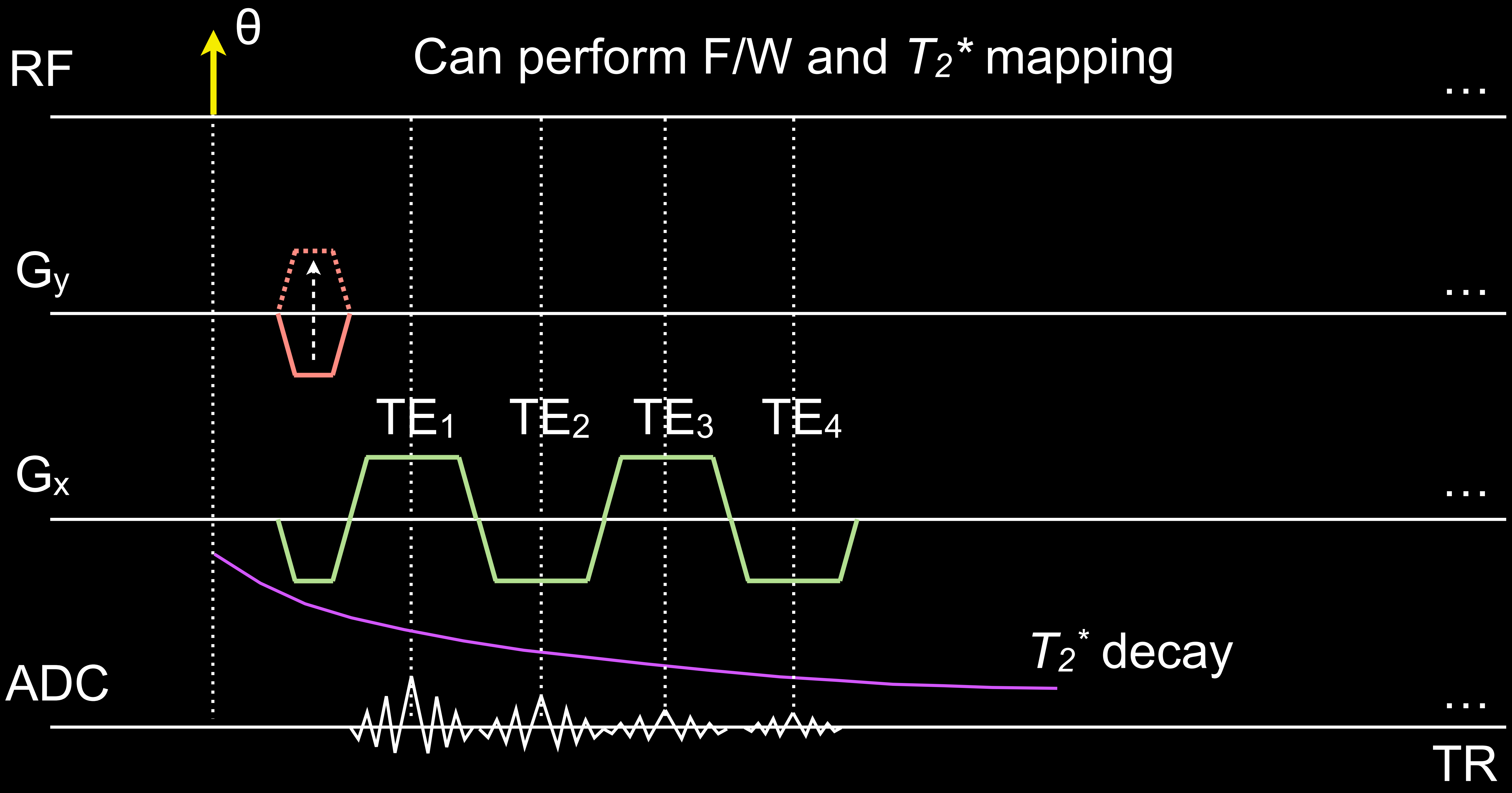
- Can be GRE, bSSFP, SE, FSE, etc.
  - can achieve negative F/W phase angles with SE-type sequences
- Need multiple TE_n's ($n = 1 \ldots N$)
  - repeat scans with different TEs
  - acquire multiple TEs each TR

F/W MRI Sequence Design

Multi-echo Gradient Echo (bipolar)

ΔTE can be non-uniform

Can perform F/W and T_2* mapping



F/W MRI Sequence Design

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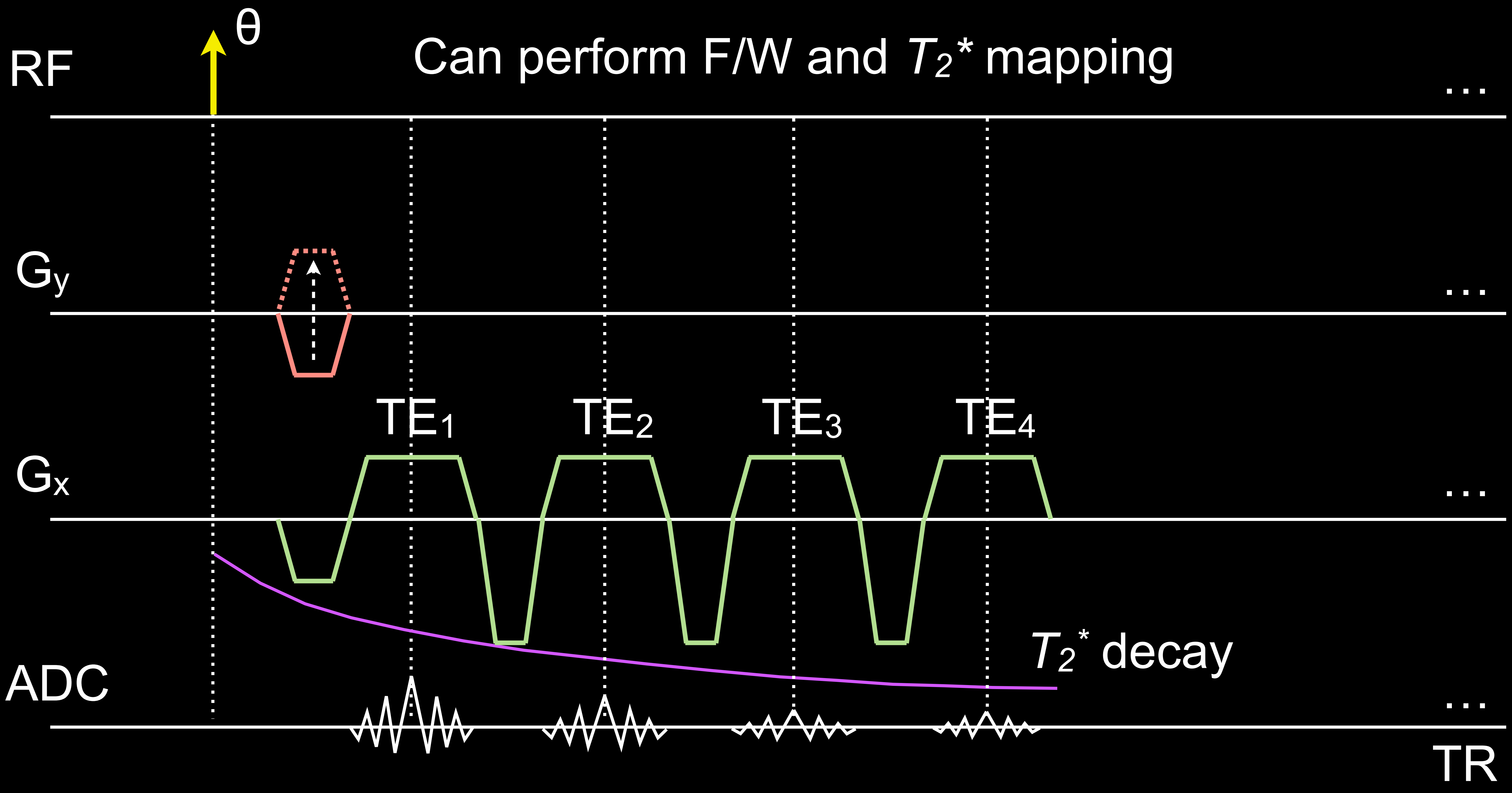


F/W MRI Sequence Design

- ΔTE depends on
  - number of readout points (resolution)
  - readout bandwidth
  - image FOV
  - gradient and slew rate constraints
  - *same as EPI echo spacing*
- Number of TEs (*N*) depends on
  - initial TE
  - ΔTE
  - T_2^* decay
  - TR

Fat-Water-Separated MRI

Signal Equation

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

- $s(\mathbf{r};\mathrm{TE}_n)$: acquired images at TE_n
- known: Δf_{cs} = -3.5 ppm (-210 Hz @ 1.5 T)
- unknown: water s_W, fat s_F, and field map ψ
- non-linear equation due to ψ
- 2PD and 3PD look at special choices of TE_n

To be more flexible … arbitrary choices of TE_n?

Fat-Water-Separated MRI

Signal Equation Revisited

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

- known: Δf_{cs} and TE_n
- unknown: complex s_W, complex s_F, and scalar ψ
- measured: complex s_n ($n = 1 \ldots N$)
- 5 unknowns, need $N = 3$ complex measurements
- solve non-linear equation

Fat-Water-Separated MRI

- Advanced algorithms
  - 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
  - Iterative least squares (e.g., IDEAL)
  - Graph cut
  - Magnitude-based F/W separation
  - *and more!*

  - many are available in the ISMRM Toolbox

F/W MRI using IDEAL

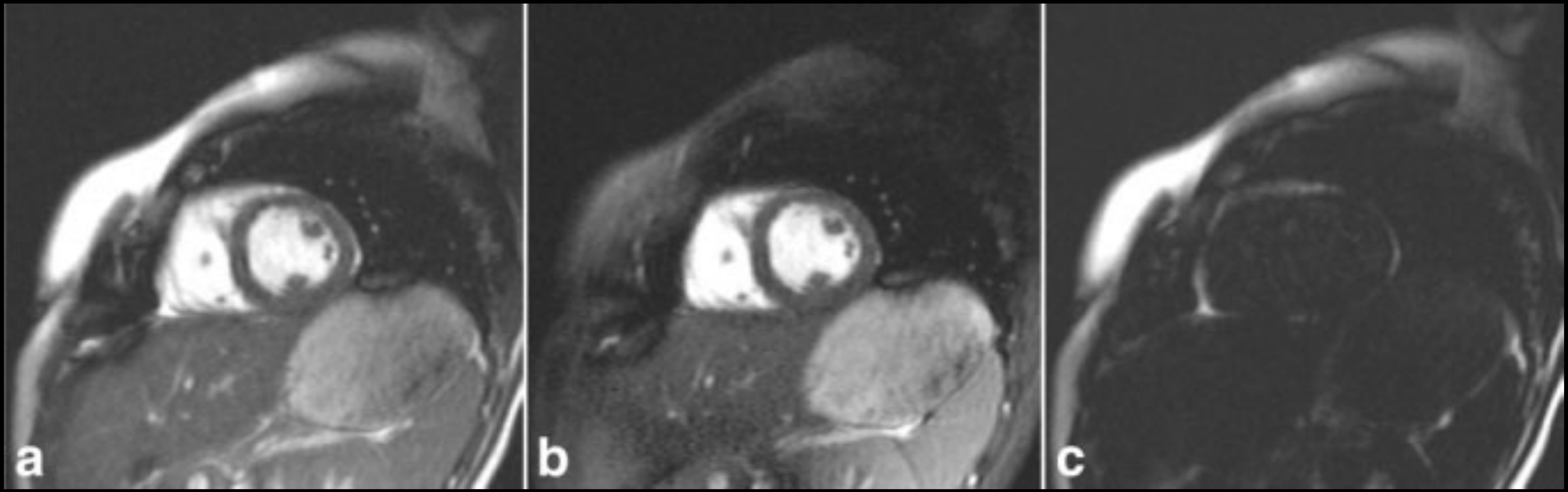
PDw FSE, 1.5 T, TE shifts of (-1, 0, 1) ms

source water fat

Reeder SB et al., MRM, 2004; 51: 35-45

F/W MRI using IDEAL

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



source water fat

Reeder SB et al., MRM, 2004; 51: 35-45

F/W MRI: SNR Performance

Multiple TEs requires longer scan …

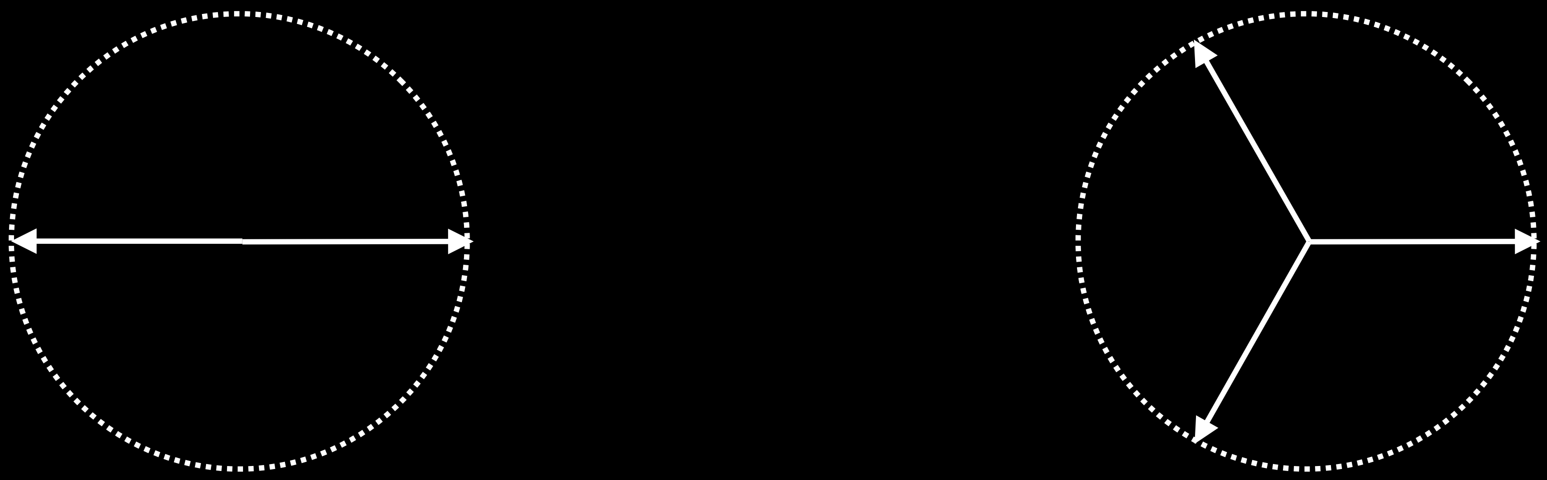
F/W calculation needs to be SNR efficient!

Effective Number of Signal Averages (NSA)

2PD $(0, \pi)$: NSA = 2

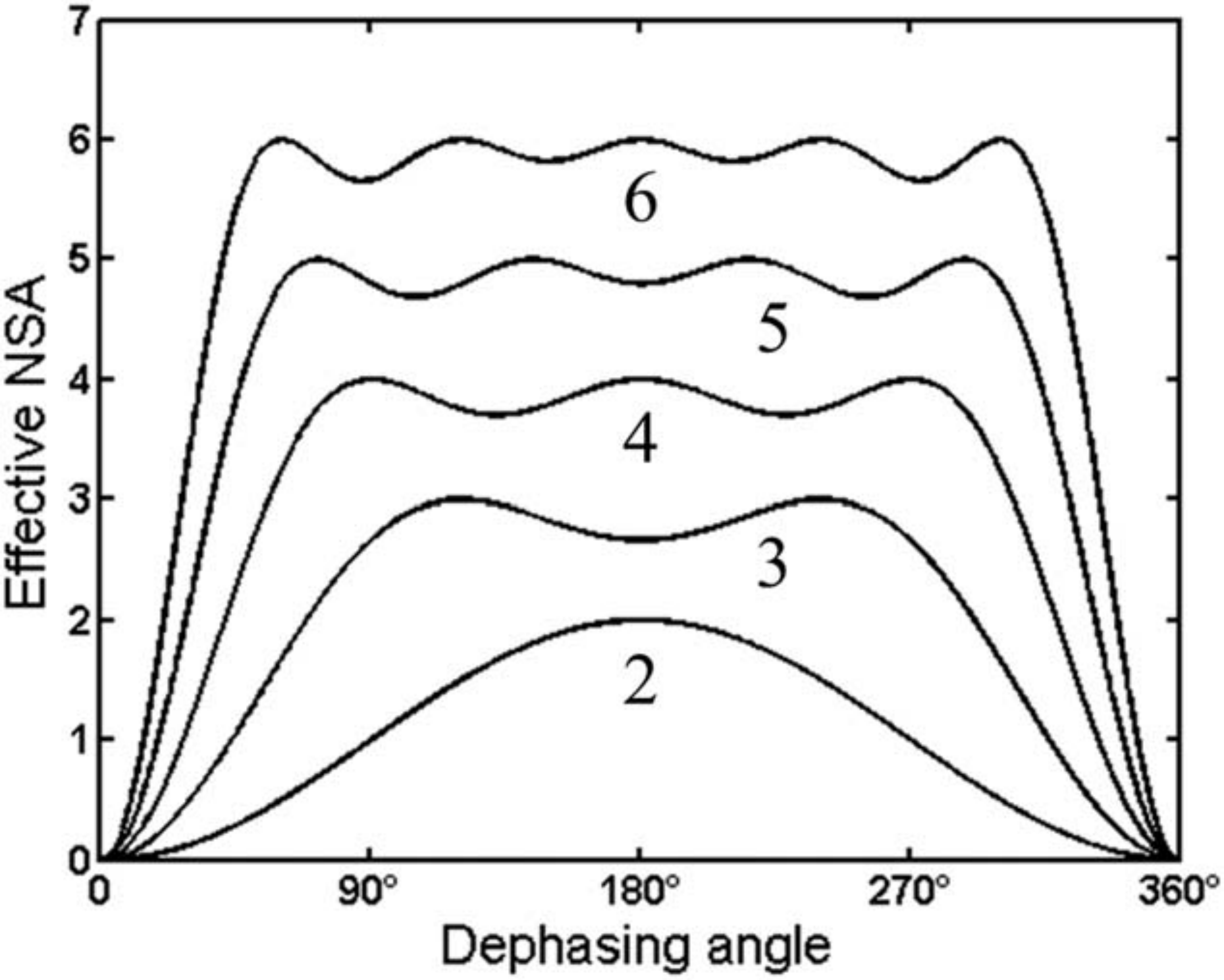
3PD $(0, \pi, 2\pi)$: NSA = 2.67

$(0, 2\pi/3, 4\pi/3)$: NSA = 3



F/W MRI: SNR Performance

In general, want phase angles evenly distributed over 2π
    less critical as number of TEs increases



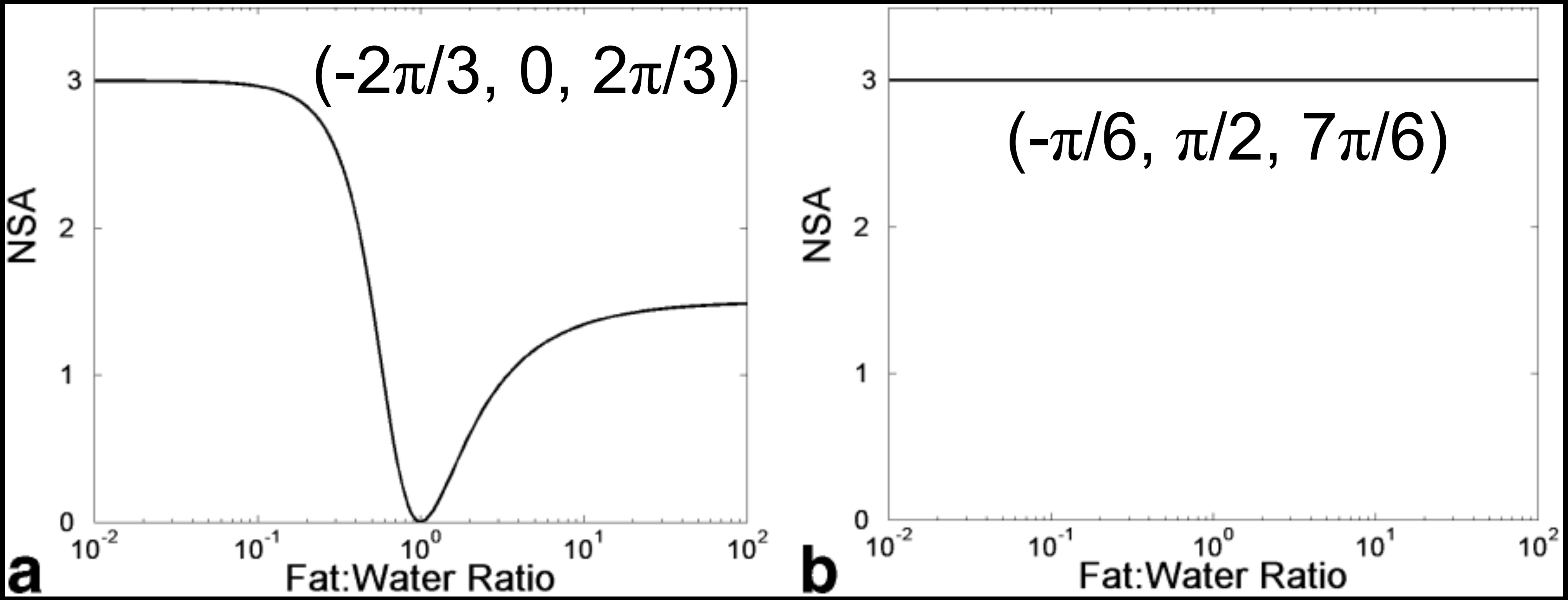
Eggers et al., JMRI 2014; Early View

F/W MRI: SNR Performance

NSA depends on

ΔTE   actual TEs   fat/water ratio in each voxel

Can analyze using Cramer-Rao Bounds, Monte-Carlo sim



Reeder SB et al., MRM, 2005; 54: 636-644

Pineda AR et al., MRM 2005; 54: 625-635

Fat-Water-Separated MRI

Signal Equation (augmented)

$$s(\mathbf{r};\mathrm{TE}_n) = [s_W(\mathbf{r}) e^{-\mathrm{TE}_n/T_{2,W}^*(\mathbf{r})} + \Sigma_{j=1}^{M} s_{F,j}(\mathbf{r}) e^{-i2\pi\Delta f_{cs,j}\mathrm{TE}_n} e^{-\mathrm{TE}_n/T_{2,Fj}^*(\mathbf{r})}] \cdot e^{-i2\pi\psi(\mathbf{r})\mathrm{TE}_n}$$

$$s(\mathbf{r};\mathrm{TE}_n) = [s_W(\mathbf{r}) e^{-\mathrm{TE}_n/T_{2,W}^*(\mathbf{r})} + s_F(\mathbf{r}) \Sigma_{j=1}^{M} \alpha_j e^{-i2\pi\Delta f_{cs,j}\mathrm{TE}_n} e^{-\mathrm{TE}_n/T_{2,Fj}^*(\mathbf{r})}] \cdot e^{-i2\pi\psi(\mathbf{r})\mathrm{TE}_n}$$

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

- T_2* decay as TE_n increases
- fat spectrum has multiple components (peaks)
- 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

- 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

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 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

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

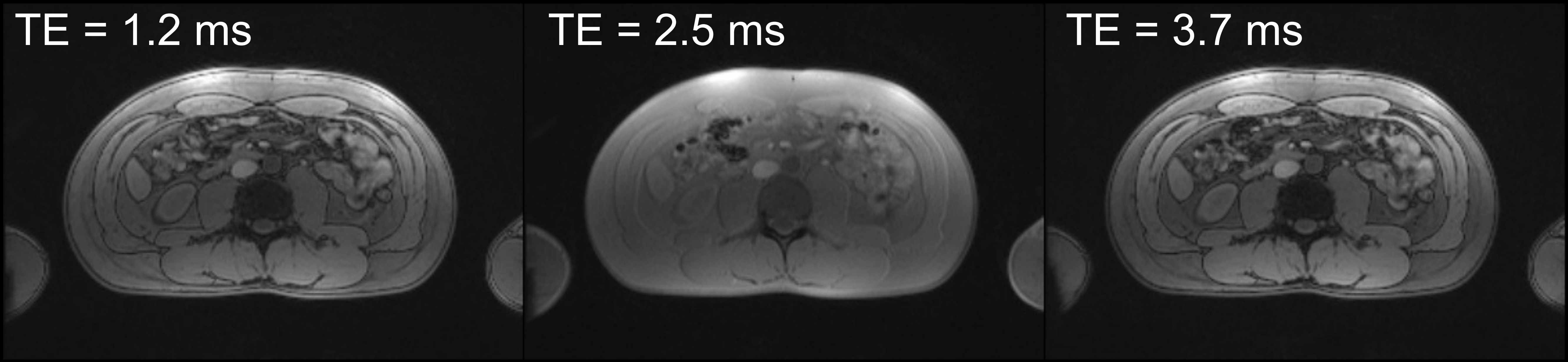
- need to correct for T_1, θ, noise effects
- potential role as an imaging biomarker

Liver Fat Quantification

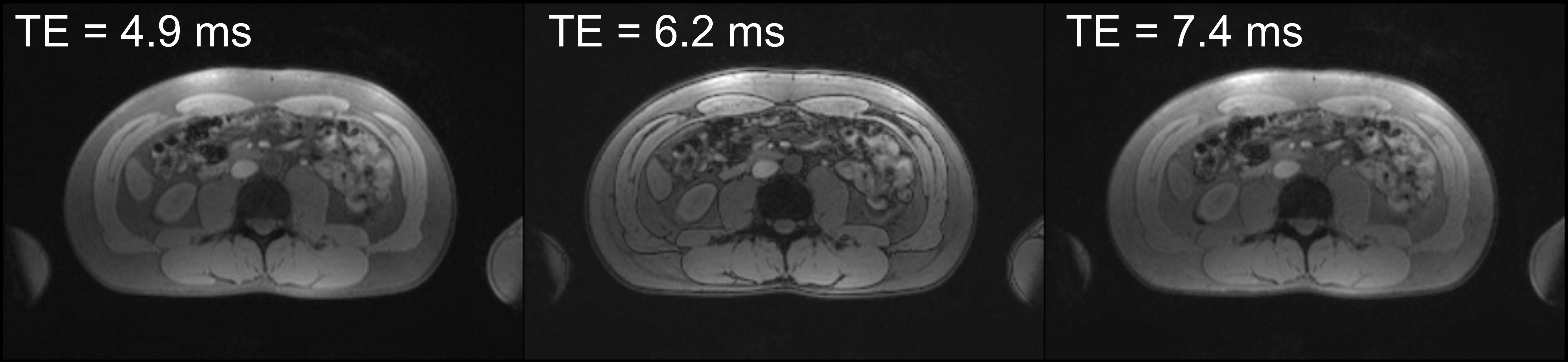
- Non-alcoholic fatty liver disease (NAFLD) is the leading cause of chronic liver disease
- Current gold standard is biopsy
- MRI fat quantification is becoming the new gold standard

Liver Fat Quantification

Example: Multi-echo GRE in liver at 3 T



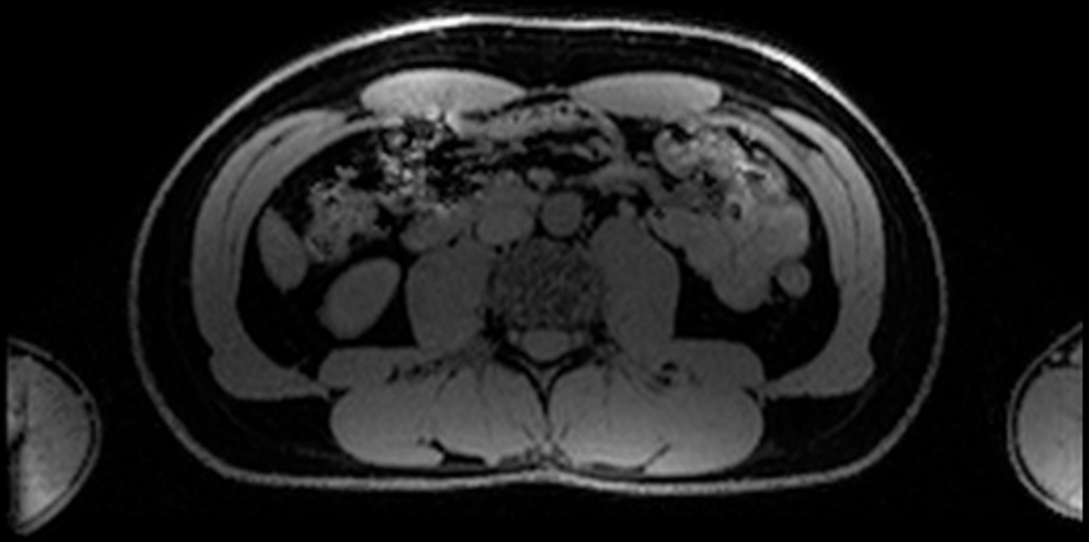
TR = 9.2 ms, θ = 4°, 22 sec BH scan



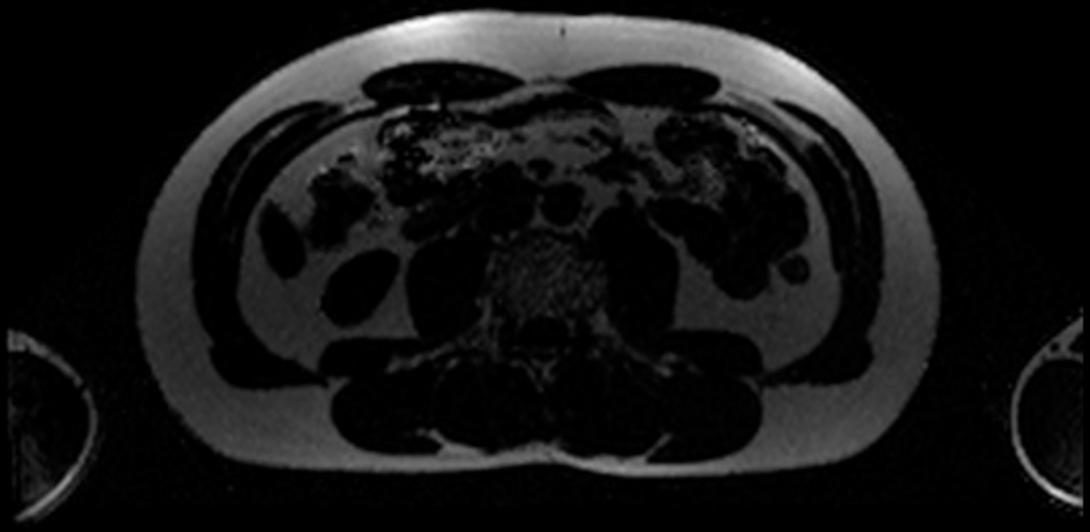
Liver Fat Quantification

Example: Multi-echo GRE in liver at 3 T

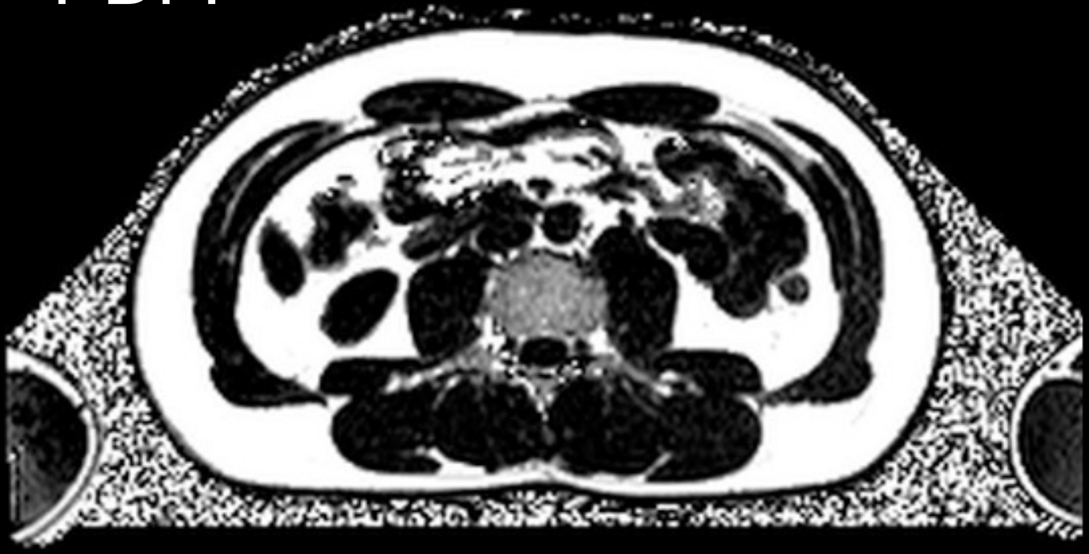
Water



Fat



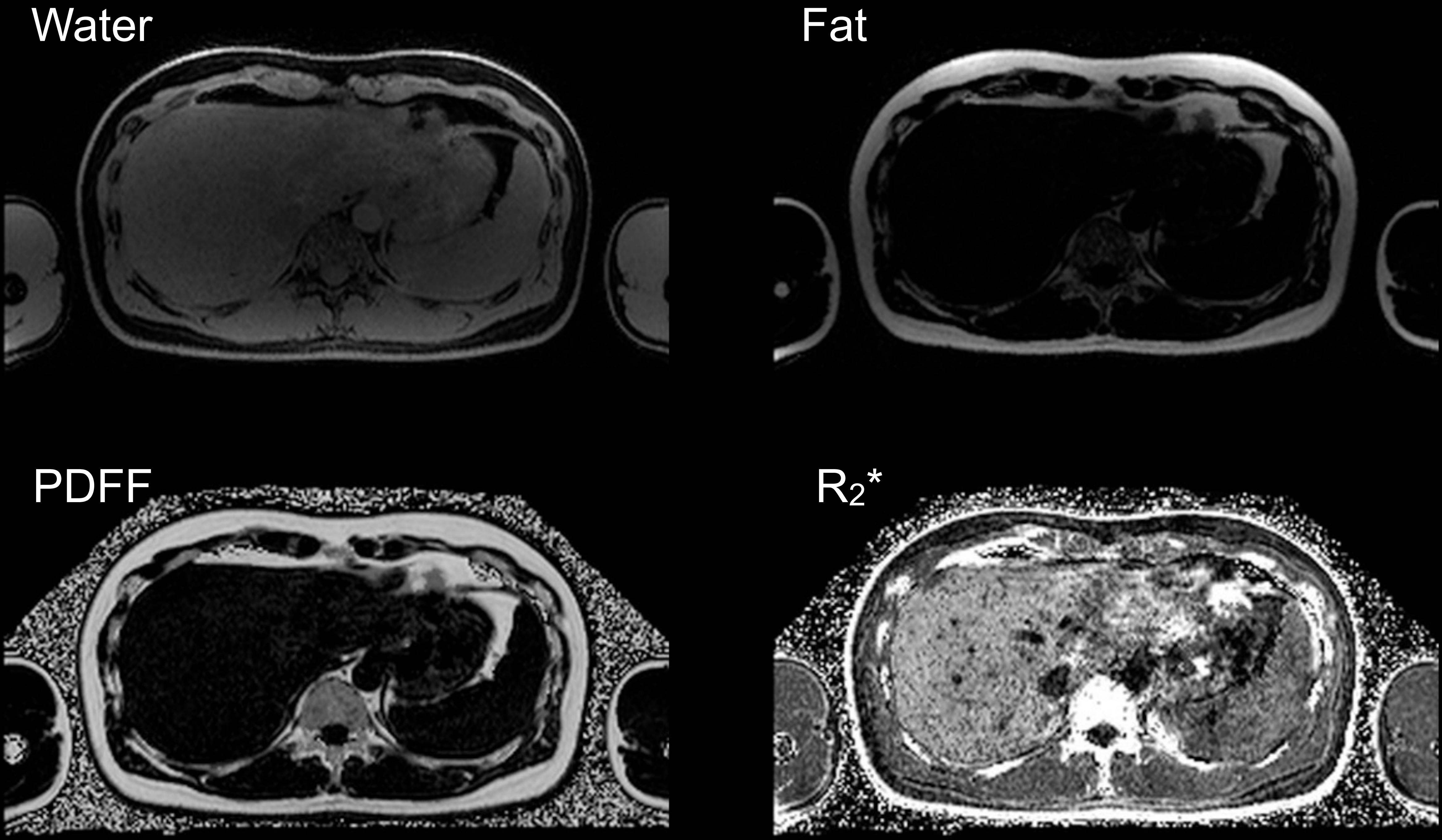
PDFF



R_2^*

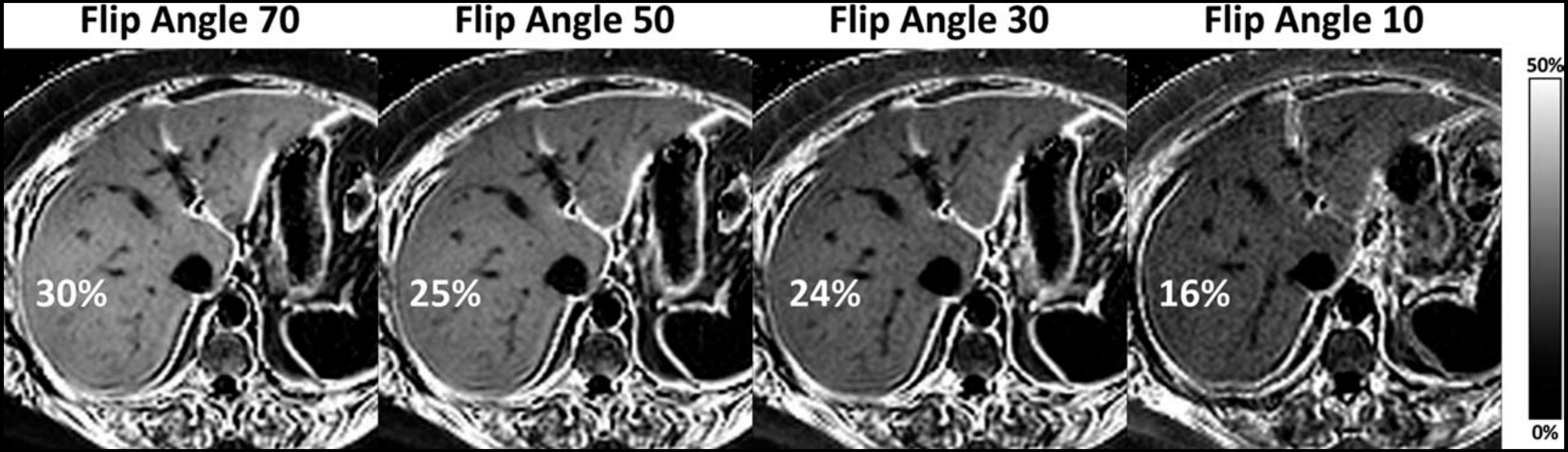
Liver Fat Quantification

Example: Multi-echo GRE in liver at 3 T



Liver Fat Quantification

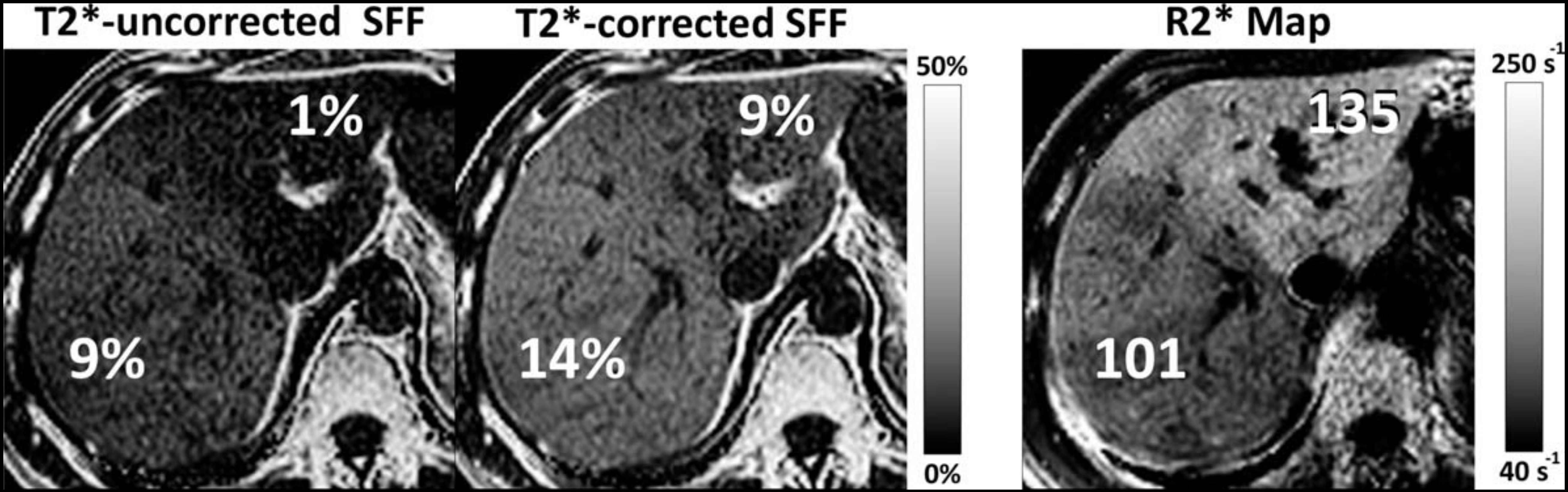
Reduce T_1 bias by using low flip angle



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

Liver Fat Quantification

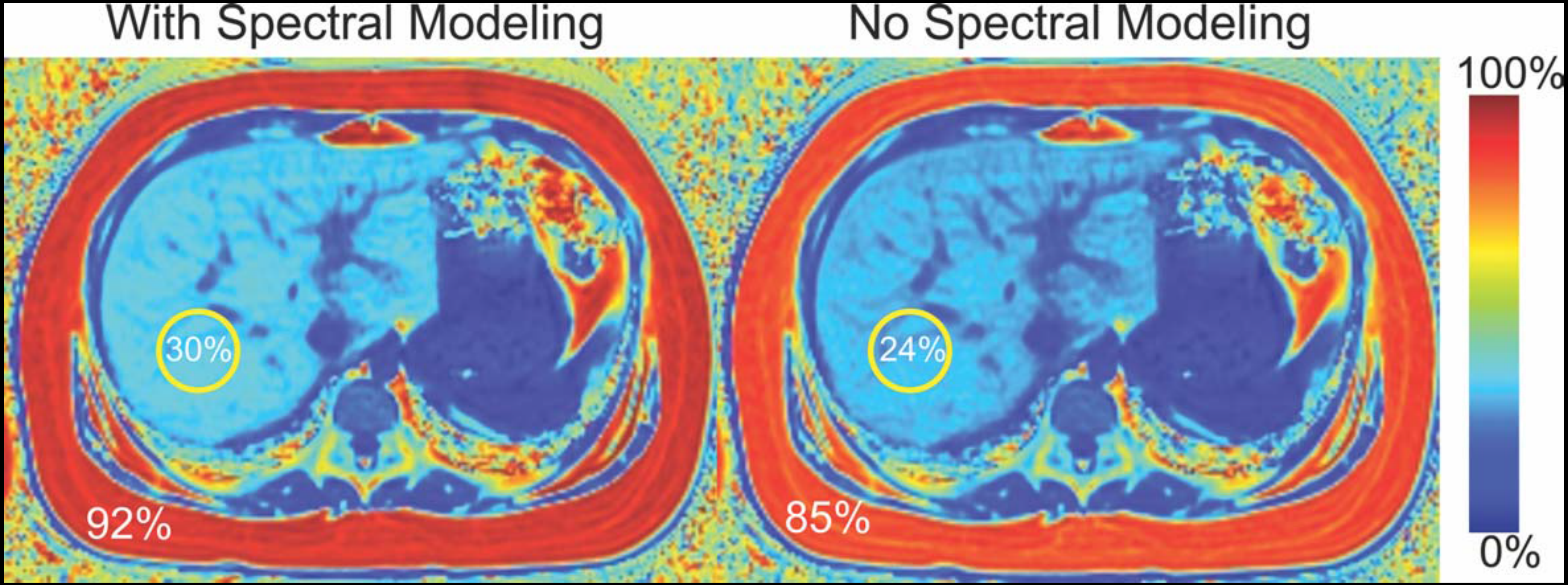
Account for T_2* effects



Reeder SB, et al., JMRI 2011; 34: 729-749, Fig. 7

Liver Fat Quantification

Account for multiple peaks in fat spectrum



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

Reeder SB, et al., JMRI 2011; 34: 729-749, Fig. 8

Liver Fat Quantification

Account for multiple peaks in fat spectrum

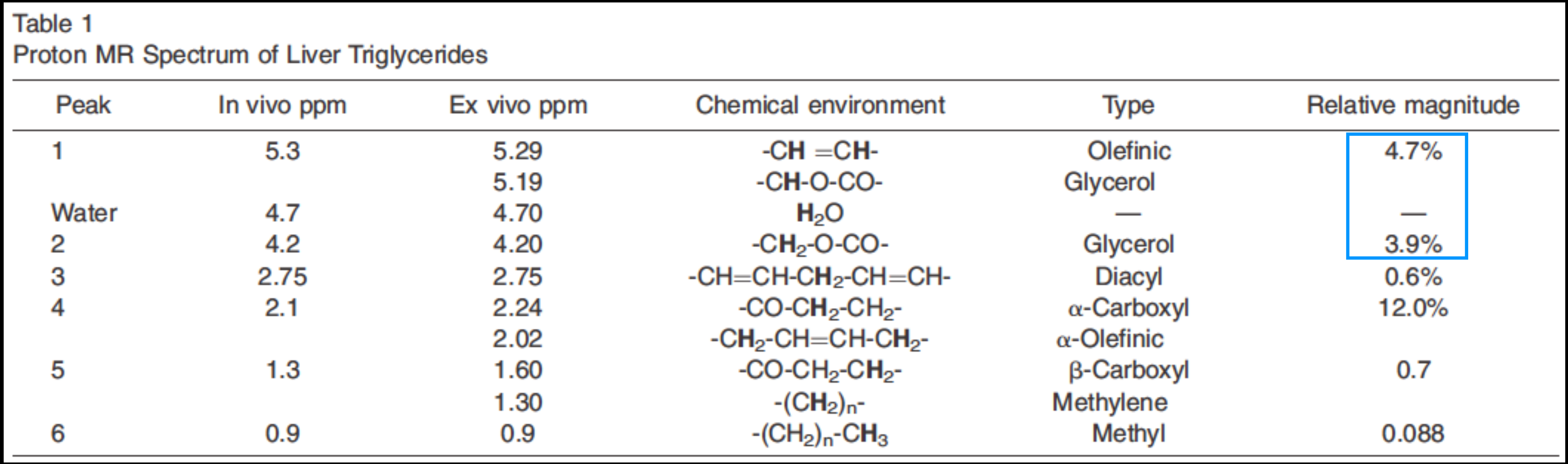


Table 1
Proton MR Spectrum of Liver Triglycerides

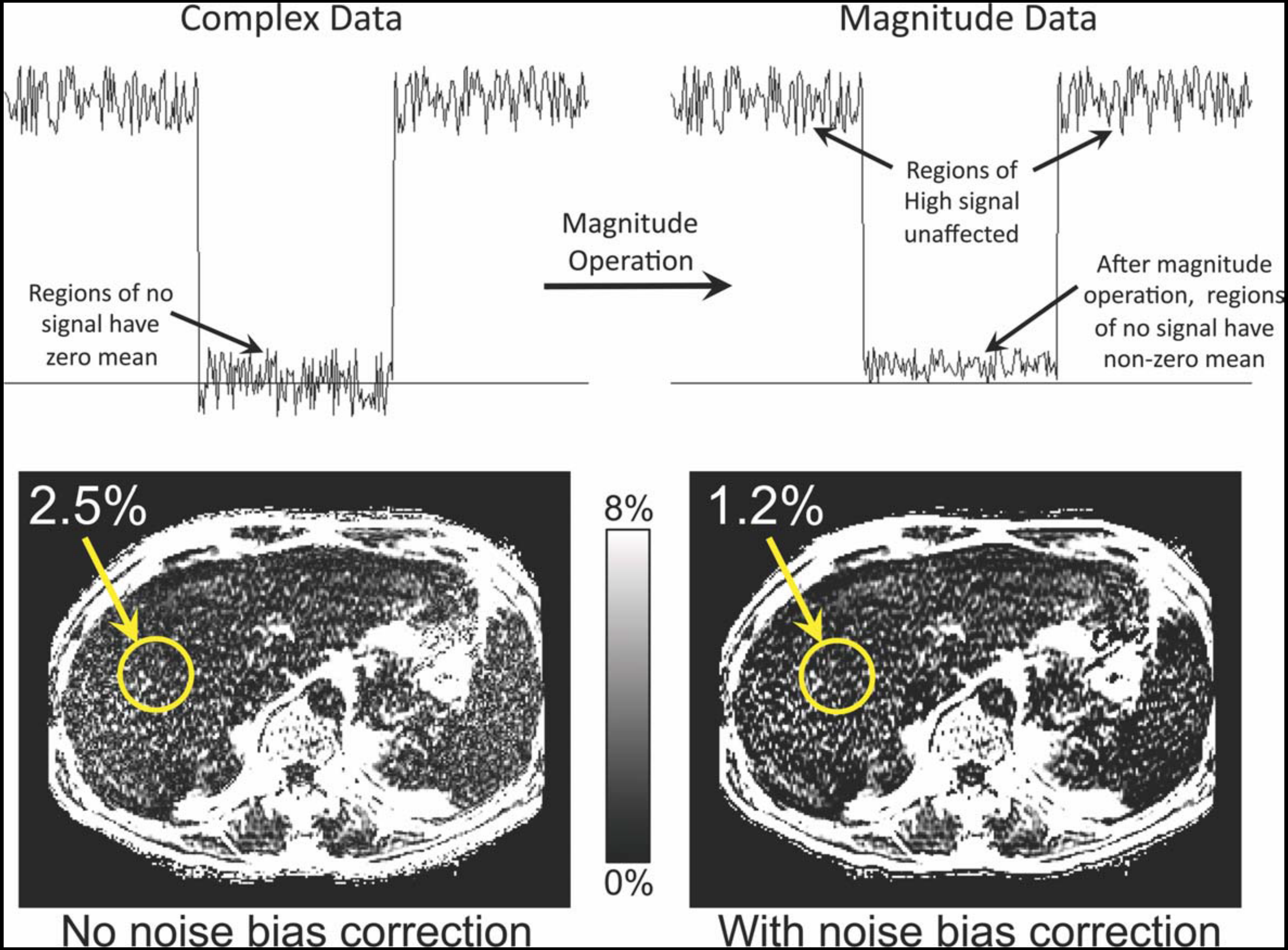
Peak	In vivo ppm	Ex vivo ppm	Chemical environment	Type	Relative magnitude
1	5.3	5.29	$\text{-}\mathbf{CH}=\mathbf{CH}\text{-}$	Olefinic	4.7%
		5.19	$\text{-}\mathbf{CH}\text{-O-CO-}$	Glycerol	
Water	4.7	4.70	$\mathbf{H_2}\text{O}$	—	—
2	4.2	4.20	$\text{-}\mathbf{CH_2}\text{-O-CO-}$	Glycerol	3.9%
3	2.75	2.75	$\text{-CH=CH-}\mathbf{CH_2}\text{-CH=CH-}$	Diacyl	0.6%
4	2.1	2.24	$\text{-CO-}\mathbf{CH_2}\text{-CH}_2\text{-}$	α-Carboxyl	12.0%
		2.02	$\text{-}\mathbf{CH_2}\text{-CH=CH-}\mathbf{CH_2}\text{-}$	α-Olefinic	
5	1.3	1.60	$\text{-CO-CH}_2\text{-}\mathbf{CH_2}\text{-}$	β-Carboxyl	0.7
		1.30	$\text{-(}\mathbf{CH_2}\text{)}_n\text{-}$	Methylene	
6	0.9	0.9	$\text{-(CH}_2\text{)}_n\text{-}\mathbf{CH_3}$	Methyl	0.088

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

Reeder SB, et al., JMRI 2011; 34: 729-749, Table 1

Liver Fat Quantification

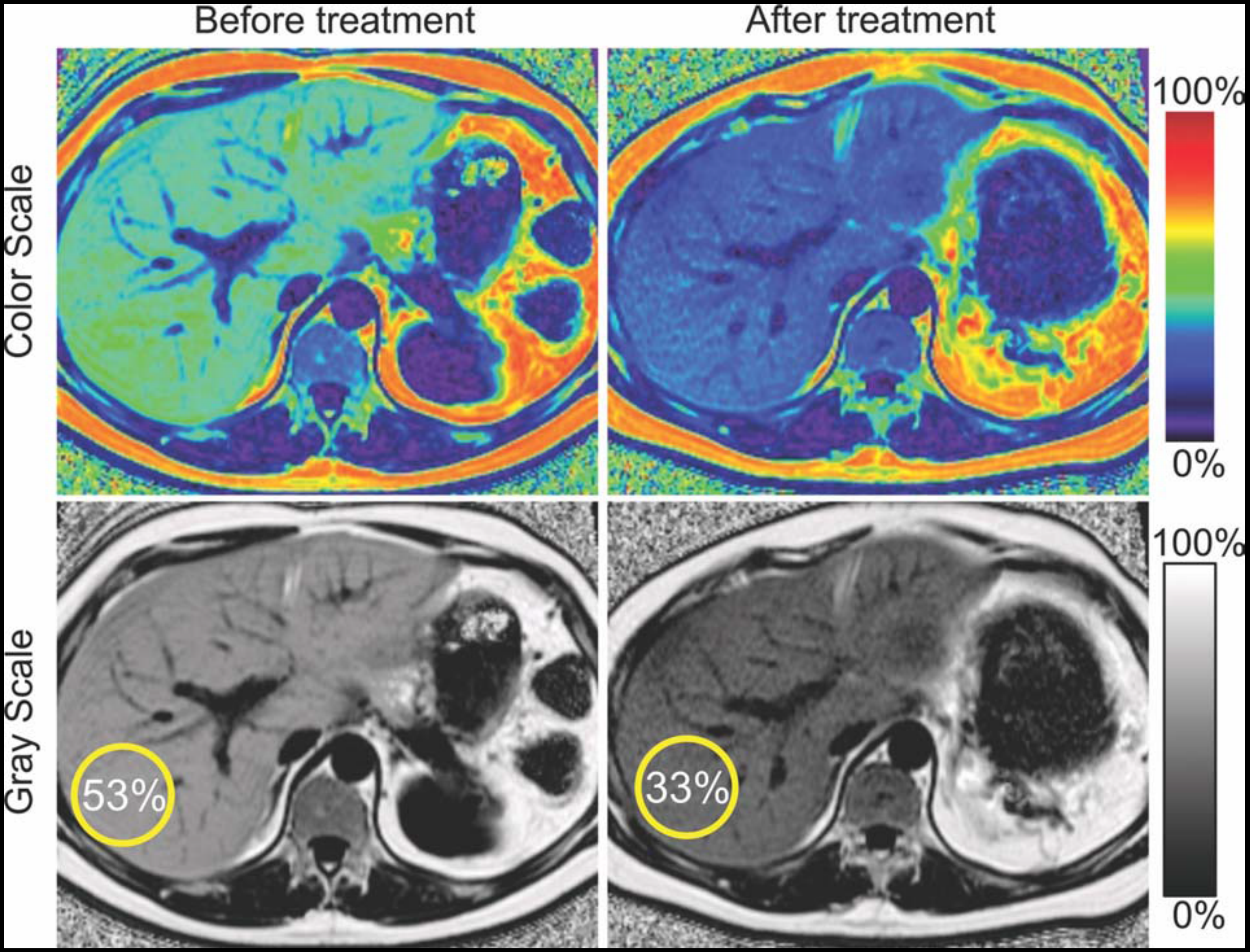
Correct for noise bias



Reeder SB, et al., JMRI 2011; 34: 729-749, Fig. 9

Liver Fat Quantification

Hepatic PDFF as an imaging biomarker



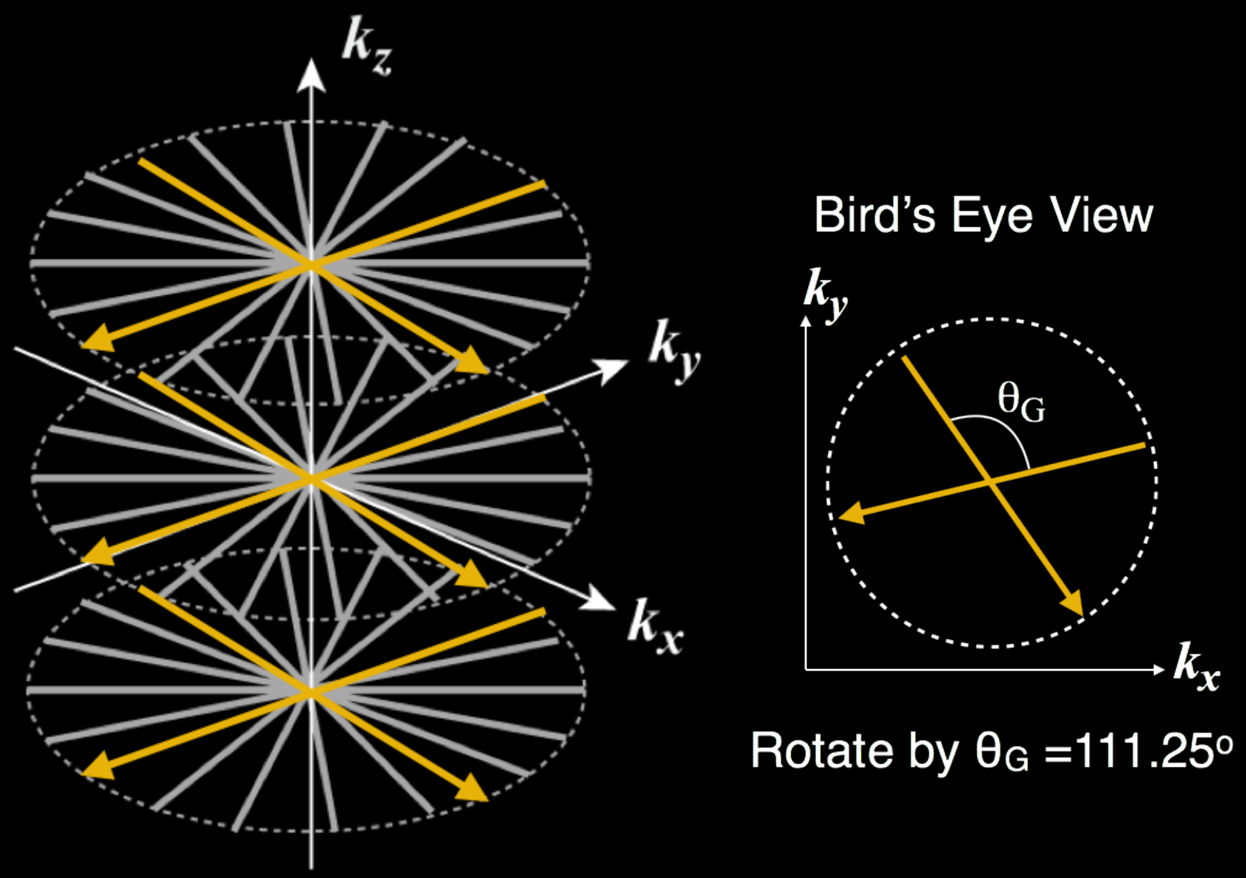
Reeder SB, et al., JMRI 2011; 34: 729-749, Fig. 13

Free-Breathing Fat Quantification

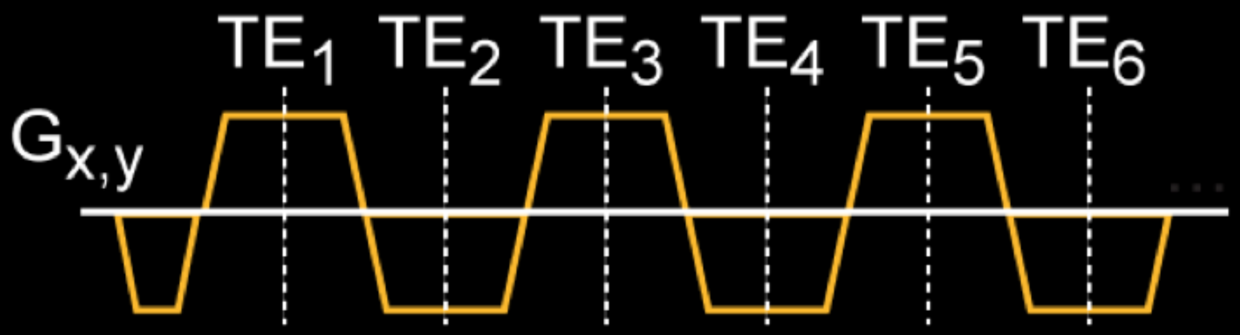
- Cartesian acquisitions limited by motion
  - Breath-hold (BH) imaging, 10-30 sec
- BH imaging limits image quality and fat quantification performance
- Many patients cannot BH

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



Rotate by θ_G =111.25°



Armstrong T, et al., MRM 2017, in press

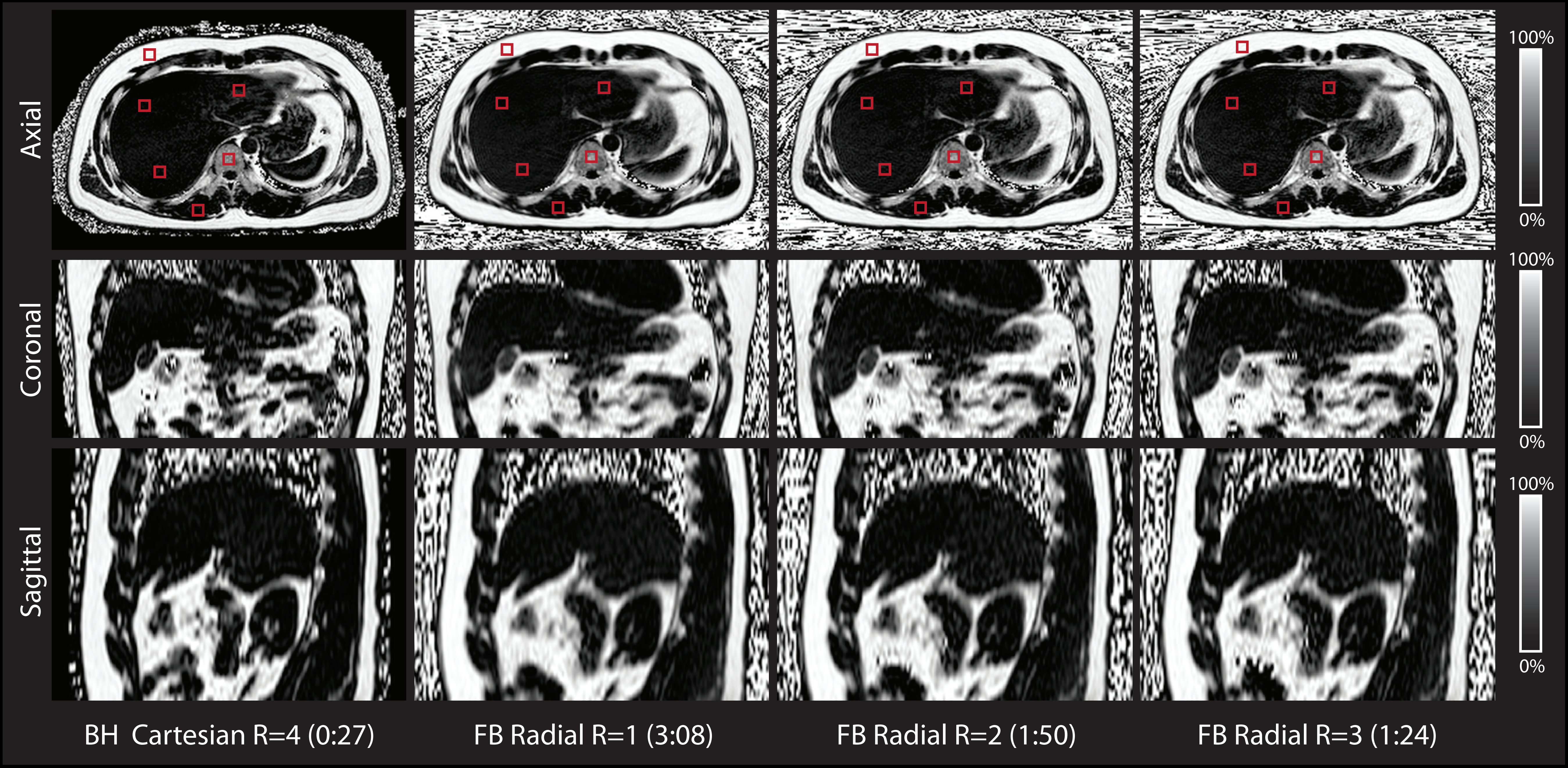
Free-Breathing Fat Quantification

Imaging Parameters (3T)	BH Cartesian	FB Radial
TE (ms)	1.23, 2.46, 3.69, 4.92, 6.15, 7.38	
ΔTE (ms)	1.23	1.23
TR (ms)	8.85	8.85
Matrix (Nx x Ny x Nz)	256 x 256 x 40	256 x 256 x 40
FOV (mm x mm x mm)	400 x 400 x 200	400 x 400 x 200
Slice Thickness (mm)	5	5
Radial Spokes	N/A	403 / 202 / 135
Flip Angle (degrees)	5	5
Bandwidth (Hz/pixel)	1150	1150
Acceleration Factor (R)	4	1 / 2 / 3
Scan Time (min:sec)	0:27	3:08* / 1:50* / 1:24*

** already includes radial gradient calibration*

Armstrong T, et al., MRM 2017, in press

Free-Breathing Fat Quantification

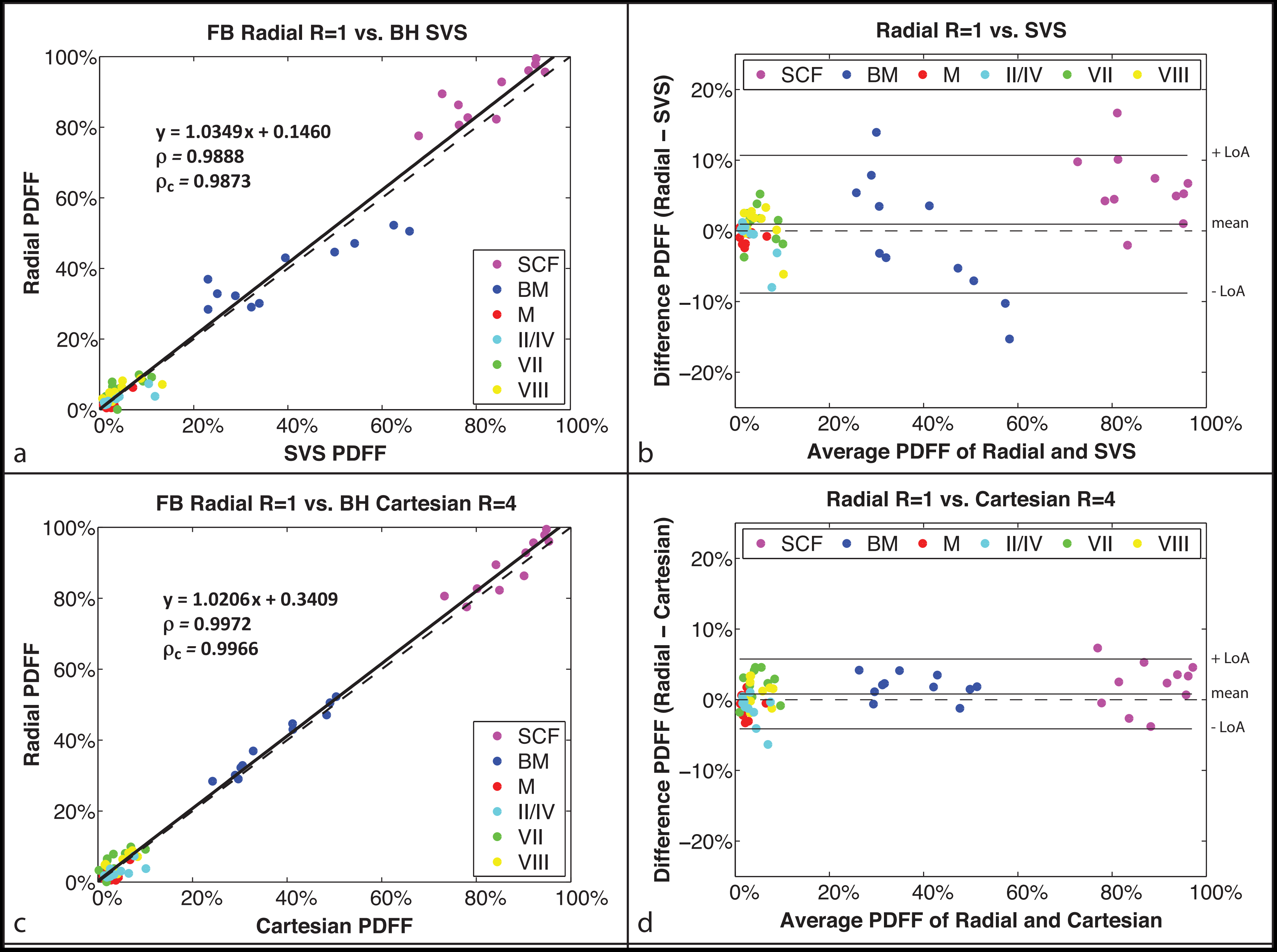


Armstrong T, et al., MRM 2017, in press

Free-Breathing Fat Quantification

N = 11 subjects

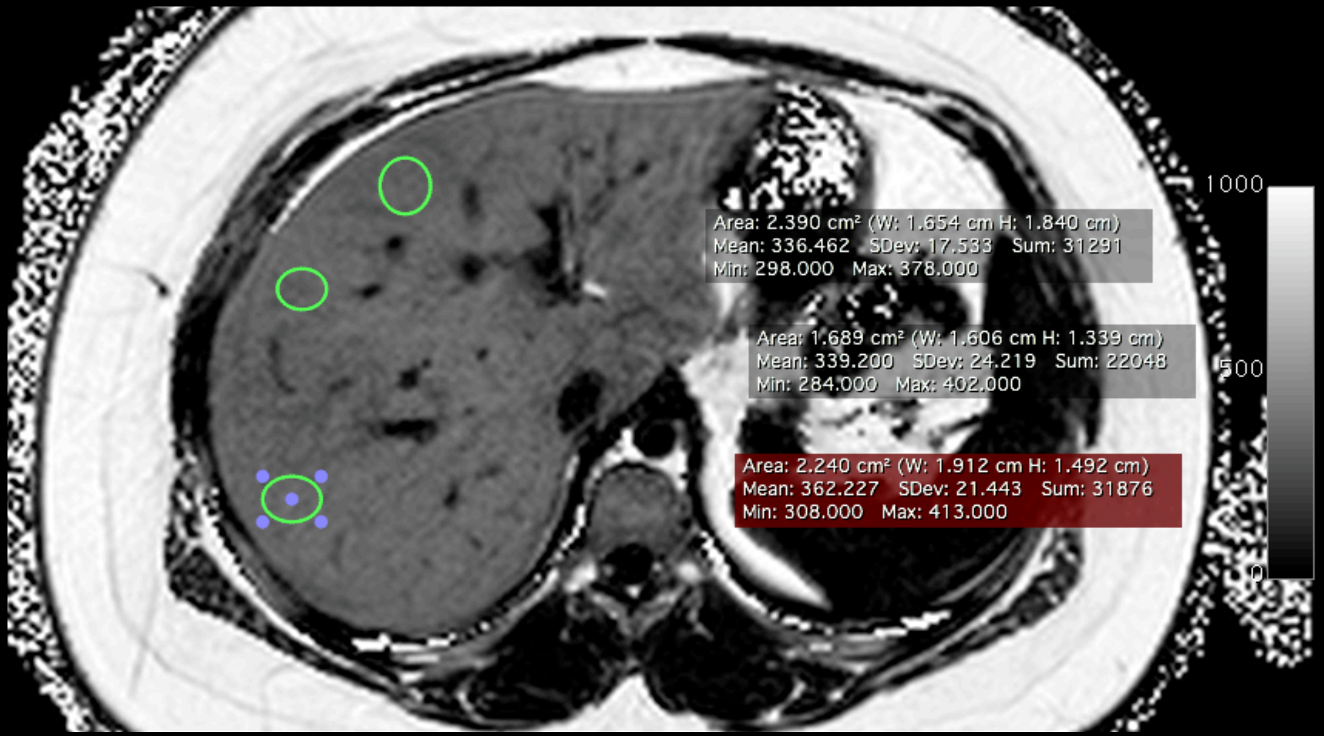
- BH MRS
- BH Cartesian
- FB Radial



Armstrong T, et al., MRM 2017, in press

Free-Breathing Fat Quantification

Pediatric Patient 1



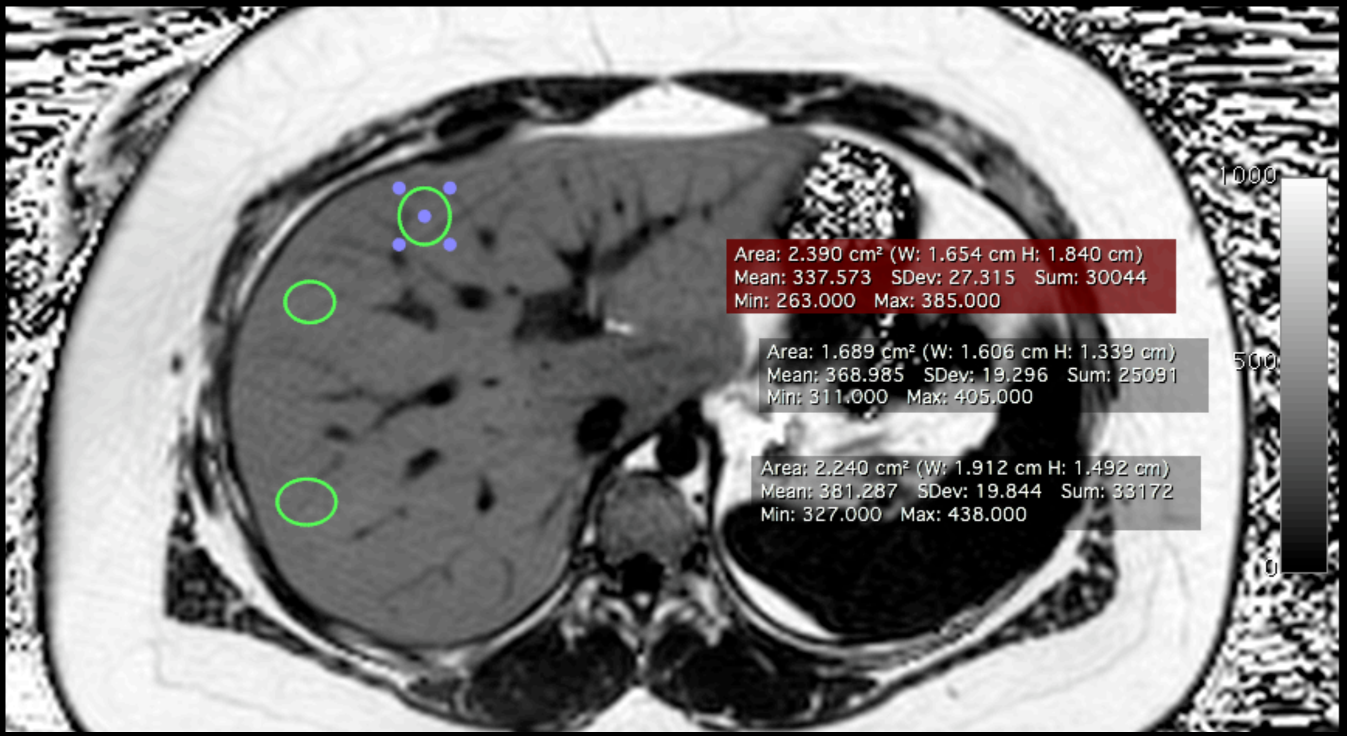
Area: 2.390 cm² (W: 1.654 cm H: 1.840 cm)
Mean: 336.462 SDev: 17.533 Sum: 31291
Min: 298.000 Max: 378.000

Area: 1.689 cm² (W: 1.606 cm H: 1.339 cm)
Mean: 339.200 SDev: 24.219 Sum: 22048
Min: 284.000 Max: 402.000

Area: 2.240 cm² (W: 1.912 cm H: 1.492 cm)
Mean: 362.227 SDev: 21.443 Sum: 31876
Min: 308.000 Max: 413.000

BH Cartesian

mean PDFF = 34.6%



Area: 2.390 cm² (W: 1.654 cm H: 1.840 cm)
Mean: 337.573 SDev: 27.315 Sum: 30044
Min: 263.000 Max: 385.000

Area: 1.689 cm² (W: 1.606 cm H: 1.339 cm)
Mean: 368.985 SDev: 19.296 Sum: 25091
Min: 311.000 Max: 405.000

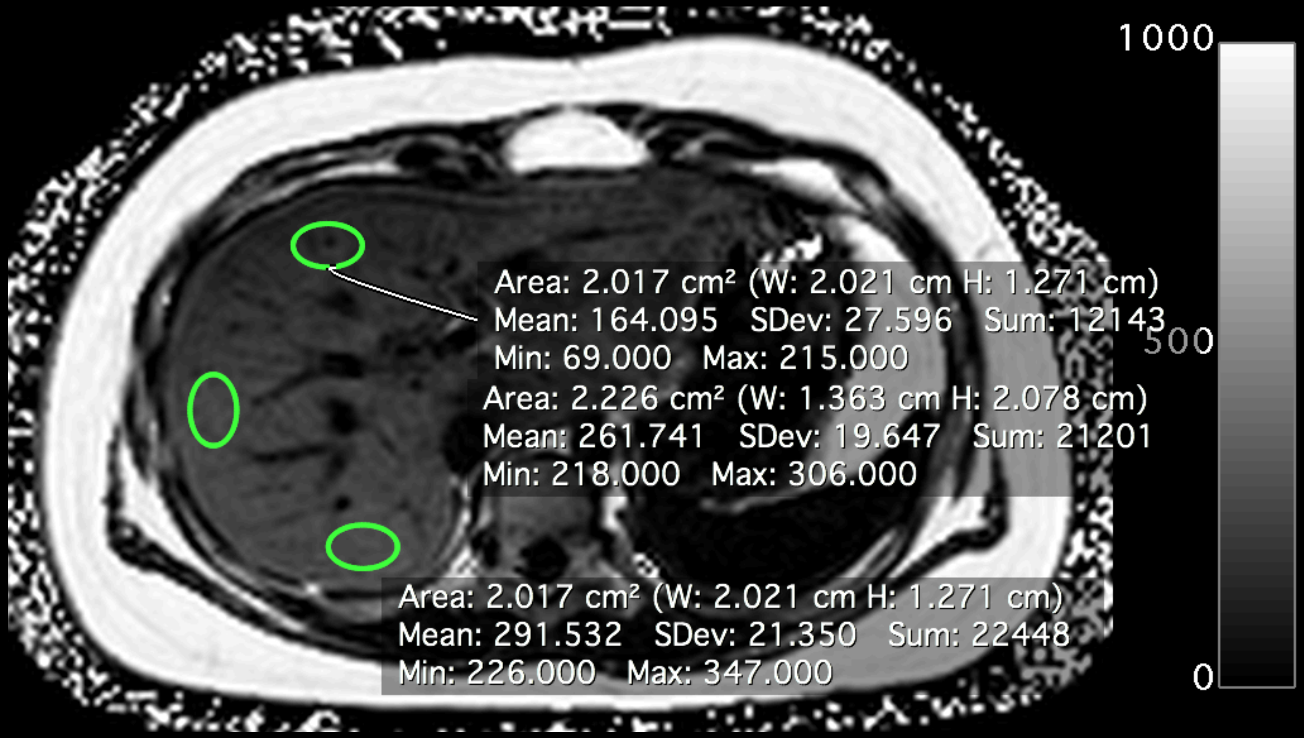
Area: 2.240 cm² (W: 1.912 cm H: 1.492 cm)
Mean: 381.287 SDev: 19.844 Sum: 33172
Min: 327.000 Max: 438.000

FB Radial

mean PDFF = 36.3%

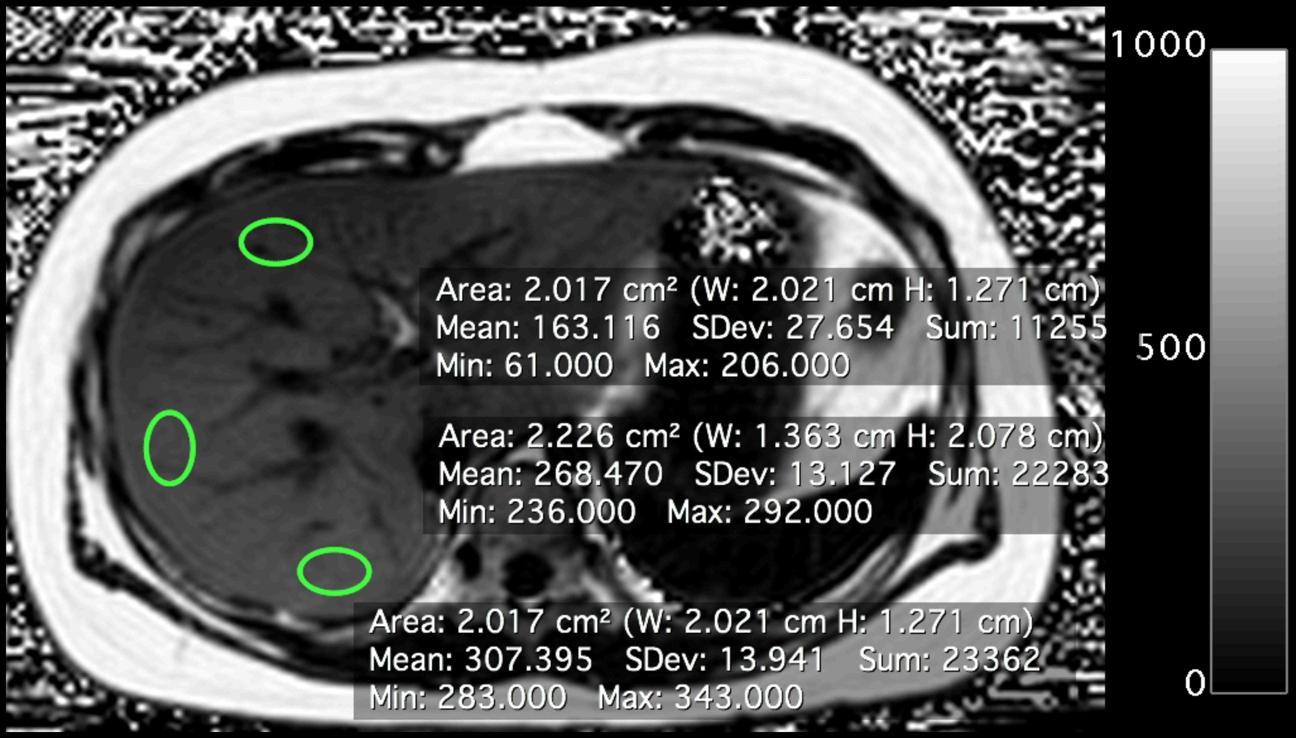
Free-Breathing Fat Quantification

Pediatric Patient 2



BH Cartesian

PDFF = 16.4%, 26.2%, 29.2%



FB Radial

PDFF = 16.3%, 26.8%, 30.7%

Summary: What We Learned

- Fat in MRI
  - chemical shift
- Fat Suppression
- Fat-Water-Separated MRI
  - multi-echo Dixon techniques
- Fat Quantification
  - liver fat quantification
- Free-Breathing Fat Quantification

Summary: Water-Fat MRI Research

Signal Model

Pulse Sequence

Reconstruction

Fat-Water Separation

Registration

Quantitative Analysis

Validation

Application

Thanks!

- Further reading
  - Handbook of MRI Pulse Sequences, Ch17.3
  - references on each slide
  - ISMRM Fat-Water Toolbox (2012)
- PBM229 Advanced Topics in MRI

Holden H. Wu, Ph.D.

HoldenWu@mednet.ucla.edu

http://mrrl.ucla.edu/wulab