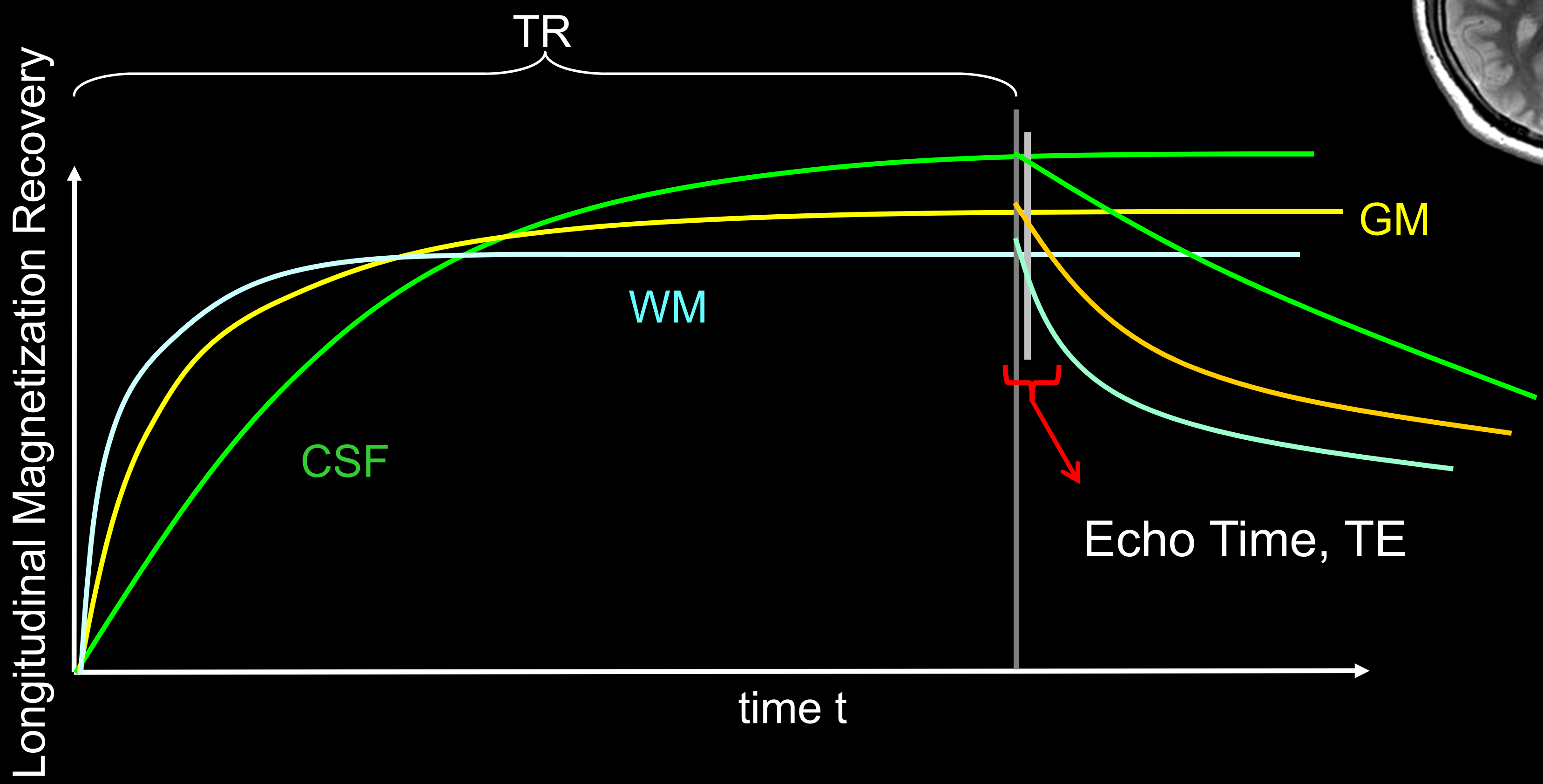
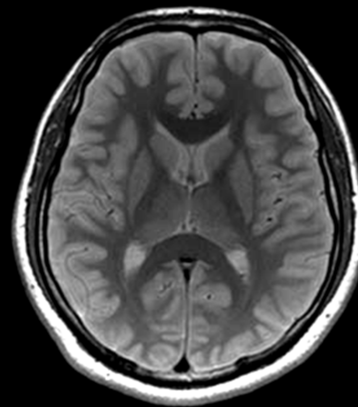
Chapter 17 – Chemical Shift Imaging and Water/Fat separation

Jaladhar Neelavalli, Ph.D.
Assistant Professor,
WSU SOM - Dept. of Radiology

Contrast…ρ_0 weighting

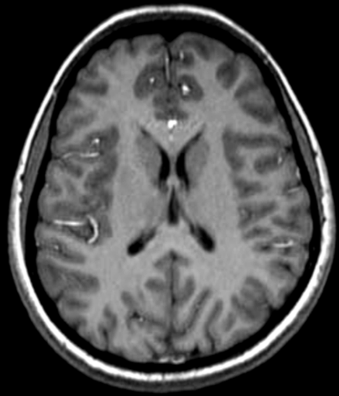
Long repetition time -TR
Short echo time - TE

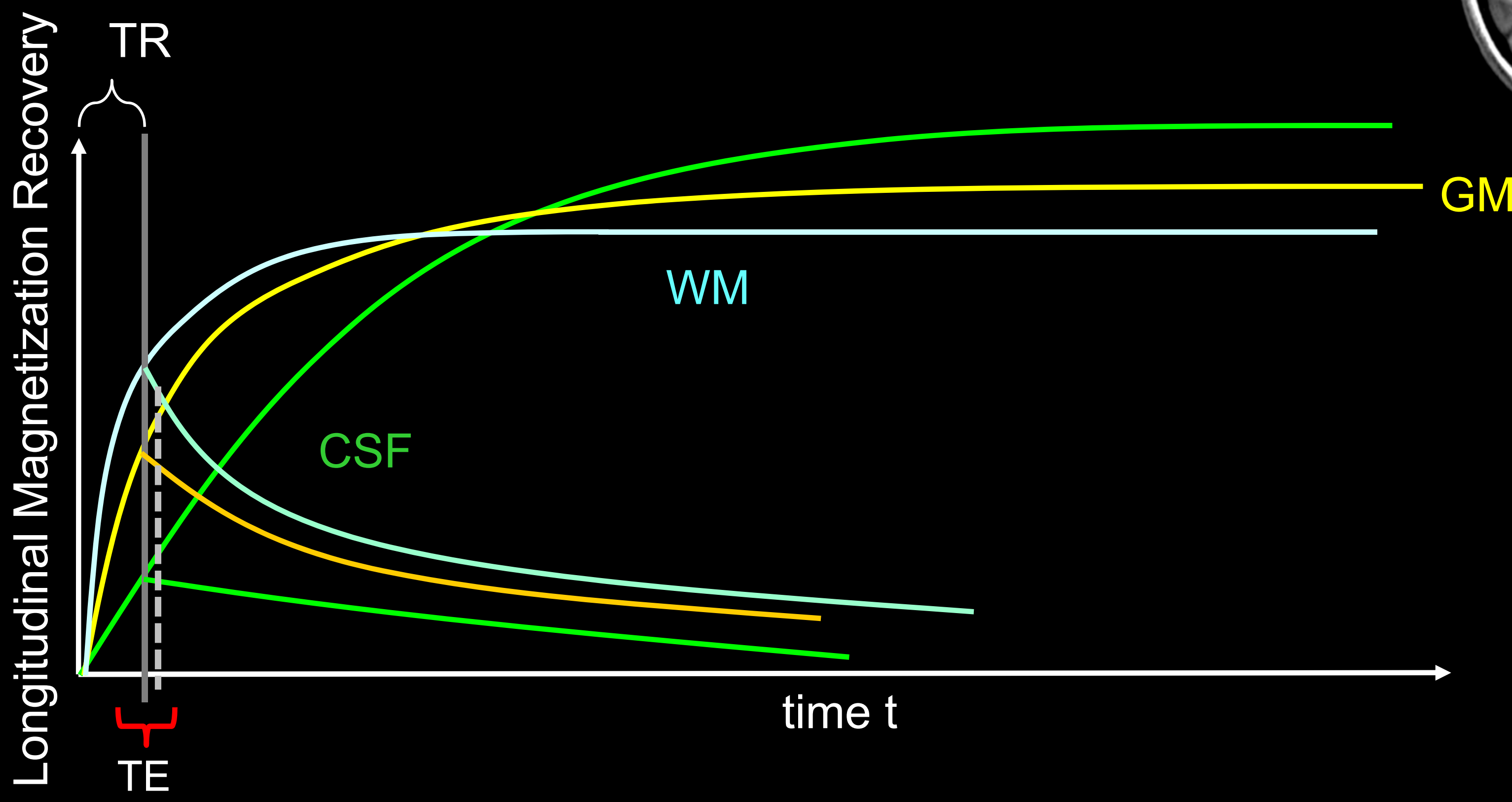




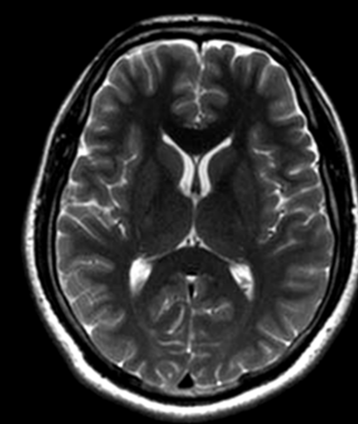
Contrast…T_1 weighting

Short repetition time -TR
Short echo time - TE

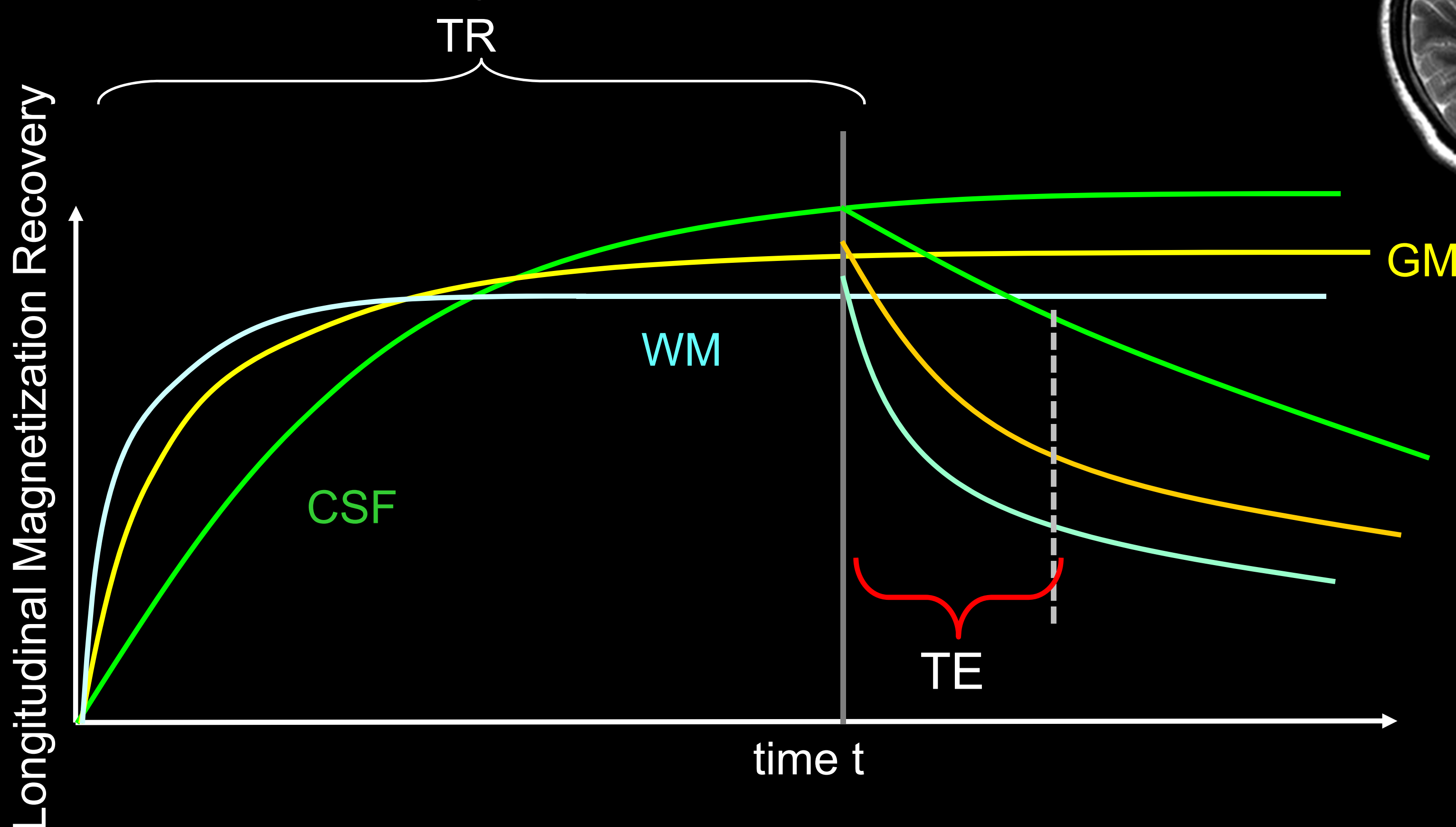




Contrast…T_2 weighting



Long repeat time - TR
Long Echo time - TE



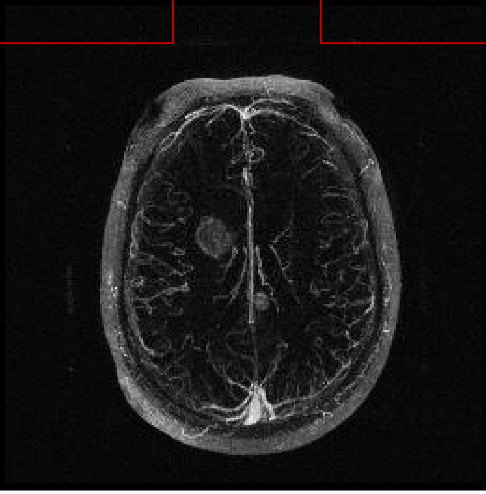
Contrast enhancement with T1-shortening agents (Gd)

- **With T1 (T2) shortened , target tissue will have increased signal in short TR GE images**

- **T1 (T2) shortening effect proportional to agent concentration**

$$\frac{1}{T_{1eff}} = \frac{1}{T_1} + \alpha_1[c]$$

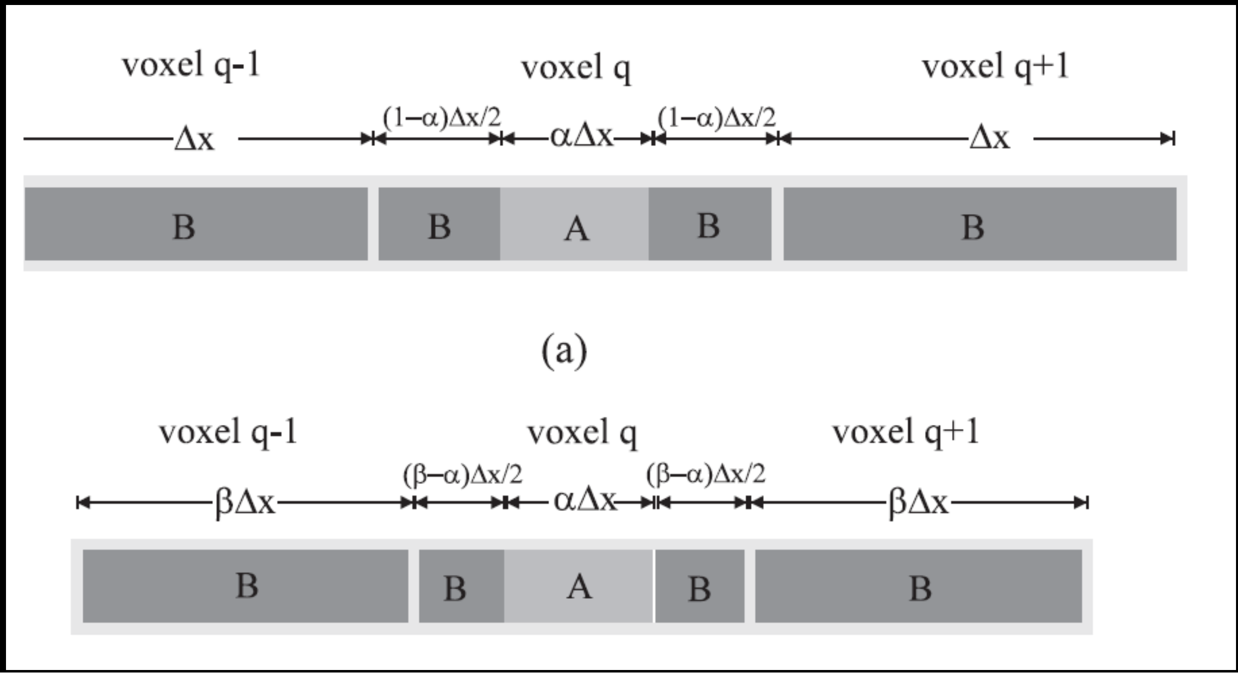
$$\frac{1}{T_{2eff}} = \frac{1}{T_2} + \alpha_2[c]$$



CNR, partial volume and resolution

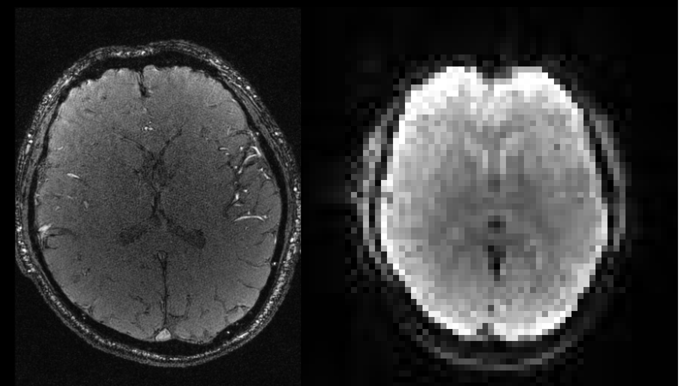
- **Size of A: $\alpha\Delta x$, (α<1)**
- **Size of B: Δx or $\beta\Delta x$, (β<1)**
- **In both scenarios: $C_{AB} = \alpha(S_A - S_B)$**
- **Noise σ:** $\sigma(\beta) = \sigma_0$, **(βL_x, N)**

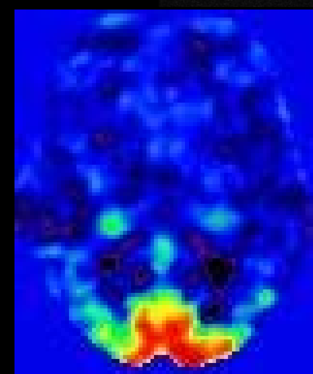
$$\sigma(\beta) = \sqrt{\beta} \cdot \sigma_0, \quad (L_x, N/\beta)$$

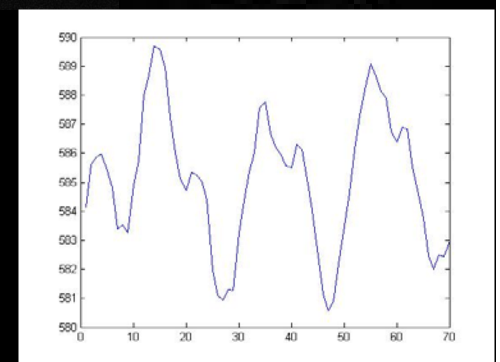


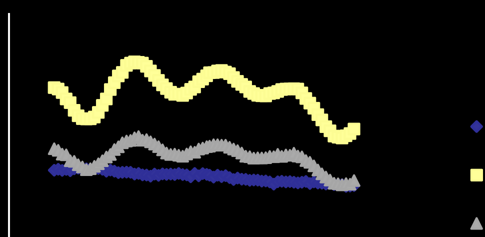
How PV affects the image?

- **Blurring**
- **Signal dephase (T2'/T2*, BOLD imaging, chap 25)**
- **Double/multiple T2/T2* exponential decay**
- **Signal cancellation (water/fat)**

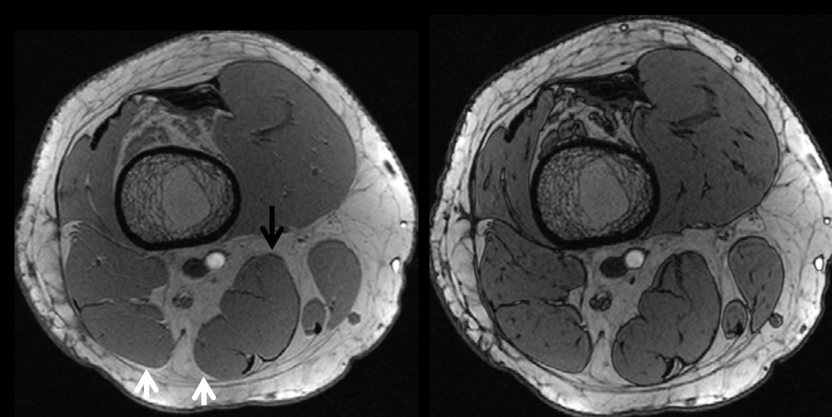








Note the similarity with Fig. 17.8
Courtesy of Dr. Manju Liu



This class - Key points

- Chemical Shift property
- Chemical Shift imaging
- Fat-shift
- Imaging Fat/Water fraction

Spectroscopy and Chemical Shift (CS)

- **Revisit FID signal (w/o spatial encoding)**

$$S_j(t) \propto S_{0,j} e^{i(\Omega - \omega_{0,j})t}, \ \omega_{0,j} = \gamma_j B_0$$

$$S_{FID} \propto \sum S_j(t)$$

- **γ_j is determined by nucleus types (e.g. ^1H(42.58), $^{23}N_a$(11.27),^{31}P(17.25)), micro chemical/ molecular environment (e.g. H_2O/CH_2+CH_3, thus the term chemical shift)**

- **B_0 inhomogeneity also affects FID frequency component, thus highly uniform B_0 is required for MRS**

Spectroscopy and Chemical Shift (CS)

- CS implies frequency shift, can be described by the shielding constant σ

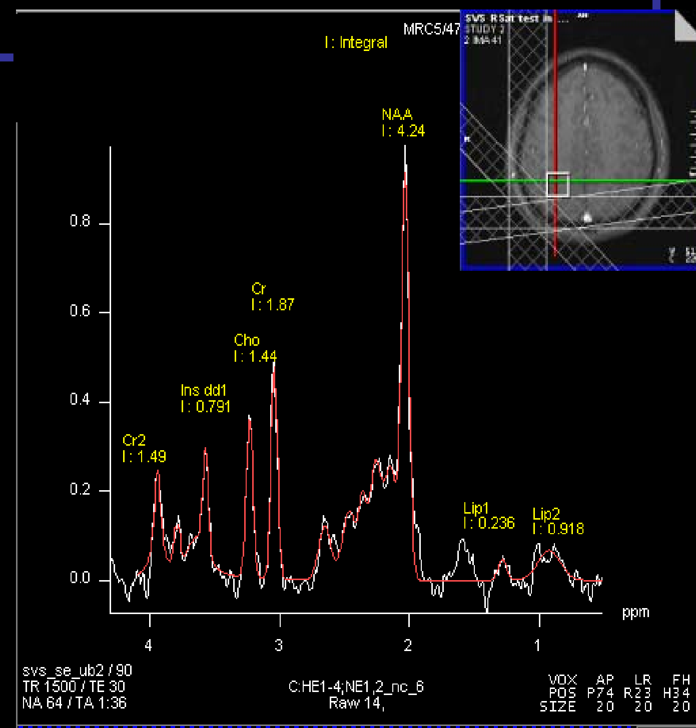
$$B_{shifted}(j) = (1 - \sigma_j)B_0$$

- CS is practically expressed in ppm unit, taking Larmor frequency as reference (e.g. $CS_{water/fat}$ = 3.35ppm)
- MR Spectroscopy (MRS) determines the abundance of different molecules spectrally rather than spatially, i.e. non spatial selective
- MR Spectroscopy Imaging (MRSI) incorporates limited spatial selection

MRS

- **Collects FID w/o spatial encoding, then directly do 1D FT**
- **Practically, excitation is spatial selective**
- **Multiple acquisition is needed for sufficient SNR**

$$\sigma = \sigma_m / \sqrt{N_{acq}}$$



- **Tissue and molecular of interest**
  - **Water/fat, choline(Cho), creatine (Cr/Cr2), n-acetyl aspartate (NAA), lactate, acetate**

Chemical shift imaging (CSI)

- CSI selectively image one nuclei (usually ^{1}H) with different chemical shift/frequency/ magnetic shielding
- CSI methodologies
  - Additional CS dimension (MRSI)
  - Selective excitation/suppression
  - Selective saturation of water and fat
  - Multi-point (in-/oppose-phase) acquisition

MRSI

- **CS dimension definition**

$$\sigma = -\Delta\omega/\omega_0$$ **, in ppm**

- **4D (x,y,z, CS) signal**

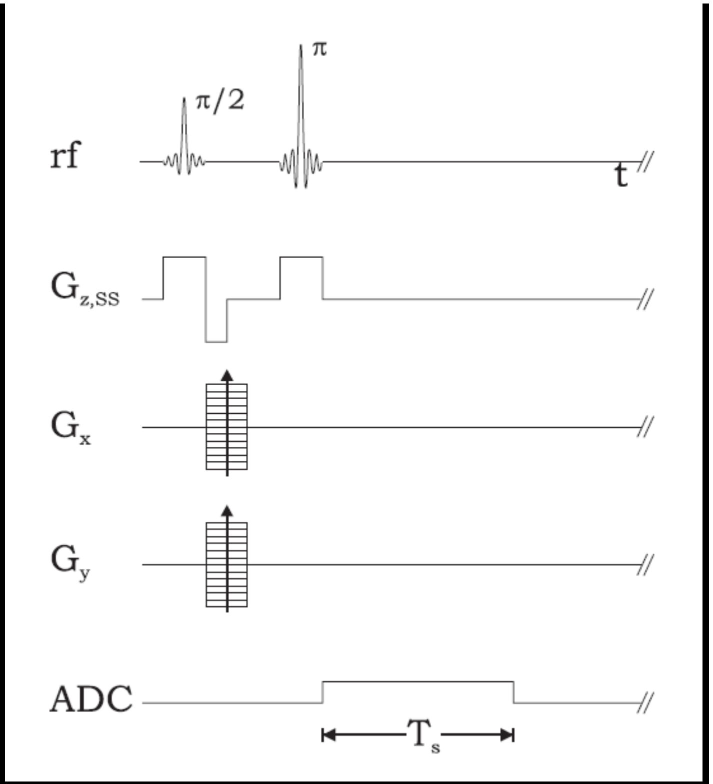
$$s\left(\vec{k}, t\right) = \int d^3 d\sigma \rho(\vec{r}, \sigma) e^{-i2\pi(\vec{k}\cdot\vec{r} - \sigma f_0 t)}$$

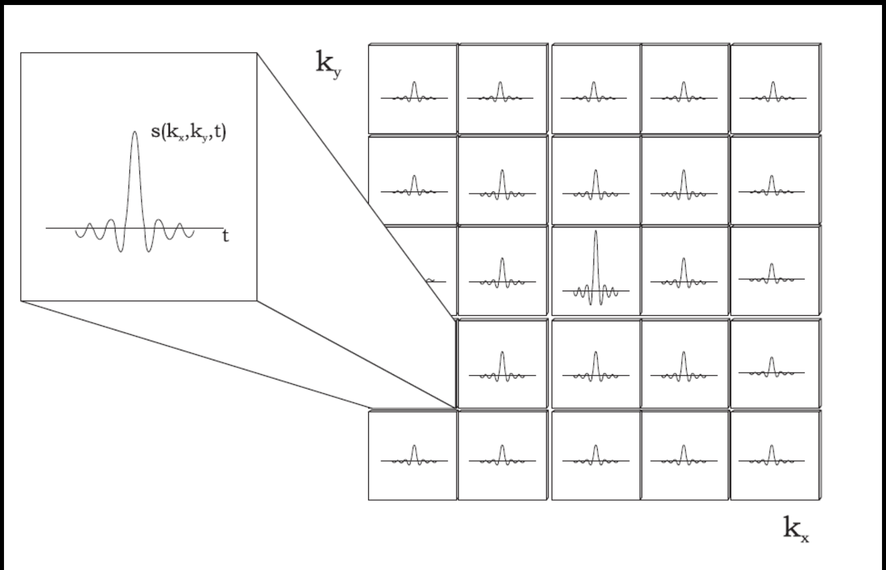
- **Fourier pairs: k-r and f-t**

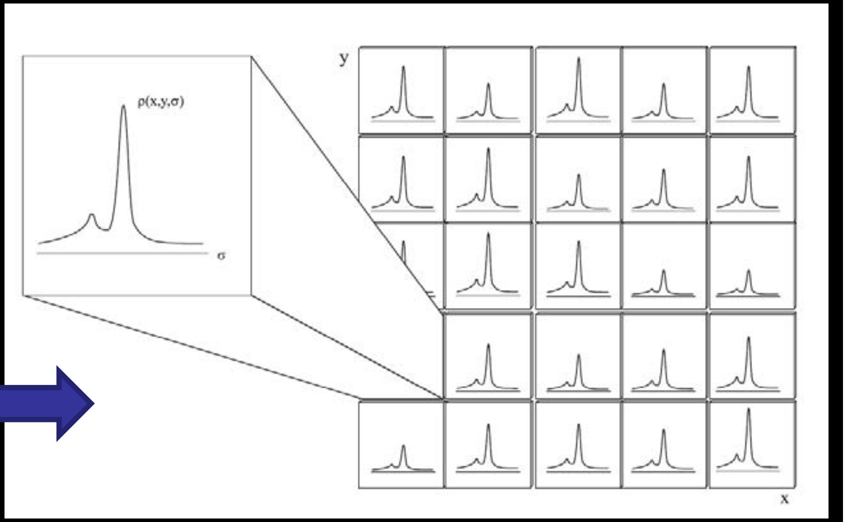
- **CS dimension, instead of the frequency encoding dimension as in 3D imaging, becomes the new 'Read' dimension, while all 3 spatial dimensions act as 'phase encode'**

2D+CS sequence

- Looks like 3D diagram, but
  - Still 2D slice selection
  - No gradient during readout
  - PE steps along x/y instead of y/z
  - MRS analysis for each voxel
  - Or multiple images, each represent the spin density at any CS



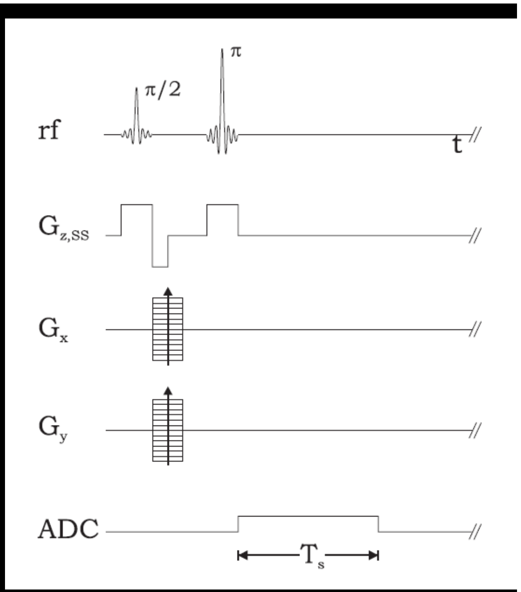


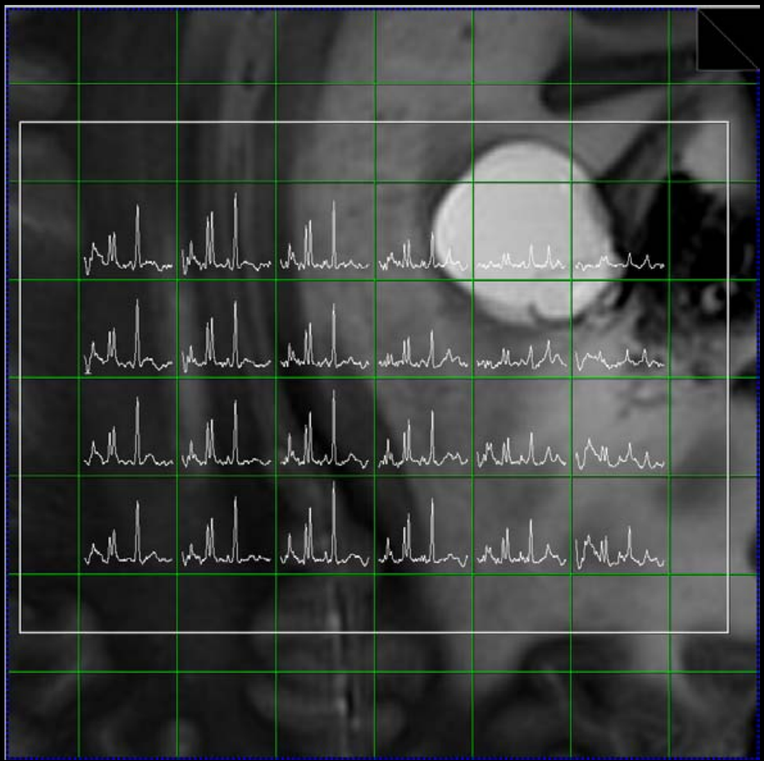


2D MRSI (2D+CS)

- Considerations
  - $T_{acq}=N_{acq}N_xN_yTR$
  - Minimal receiver bandwidth
  - Reduce N_xN_y (fixed L_x/L_y) for high SNR (8x8~32x32)
  - Increase N_{acq} for high SNR (>64)
  - Long TR to reduce T1W (1-2s)
  - Require very high field homogeneity

Fig. 10.21





3D MRSI (3D+CS)

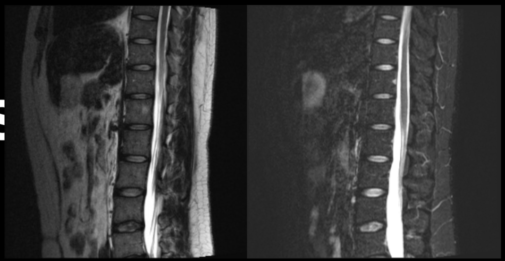
- Similar to 2D+CS, only that slice selection replaced by another phase encoding
- $T_{acq}=N_{acq}N_xN_yN_zTR$
- More stringent requirement on field homogeneity
- Usually too long to be applicable

Why separating water and fat?

- Fat shift artifacts:
  both partial volumed and non-partial volumed voxels

- Signal contamination (beat pattern as function of TE), introducing false contrast: Partial volumed voxels only

- Fat signal is bright in T2W images



T2W Fat nulling,T2W

Fat shift artifact

- $CS_{fw} \rightarrow$ **3.35ppm** $\rightarrow \Delta f_{fw} \rightarrow$ **214Hz@1.5T**

- **Along any direction, the fractional number of voxel the fat is shifted is**

$$N_{shift} = \Delta f_{fw} / \Delta f_{voxel}$$

- **In Read direction**

$$\Delta f_{voxel,x} = \gamma G_x \Delta x = 1/T_s$$

- **In in-plane PE direction (EPI)**

$$\Delta f_{voxel,y} \cong 1/N_y T_s$$

$$\Delta f_{voxel,y} \approx \Delta f_{voxel,x} / N_y$$

Fat shift artifact

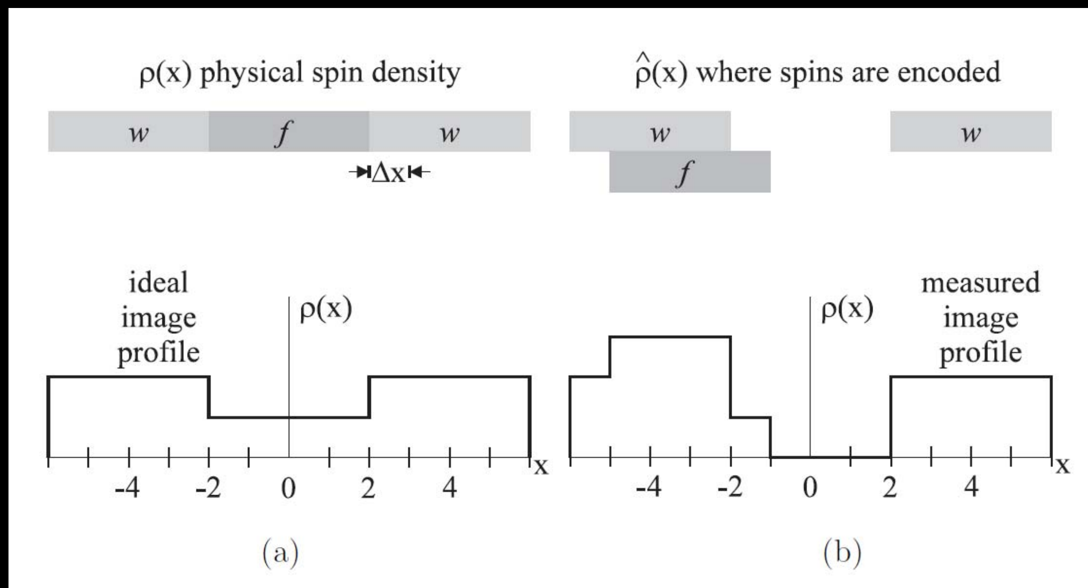
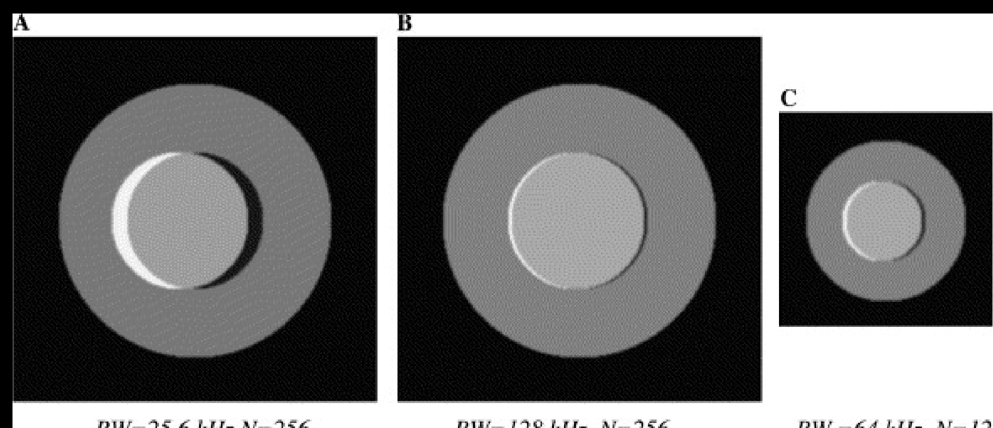


Fig. 17.3

$$\omega_f = -\gamma G x + \Delta\omega_{fw}$$
$$= -\gamma G(x - \Delta\omega_{fw}/\gamma G)$$
$$= -\gamma G x'$$

$$\Delta x_f = \Delta f_{fw}/\gamma G$$
$$= \Delta x \cdot \Delta f_{fw}/\text{BWpx}$$



Benoit-Cattin, JMR, 2005

Signal with beat pattern as a function of TE

- **In a water-fat partial volumed voxel**

$$\hat{\rho}(TE) = \hat{\rho}_w(TE) + \hat{\rho}_f(TE)$$

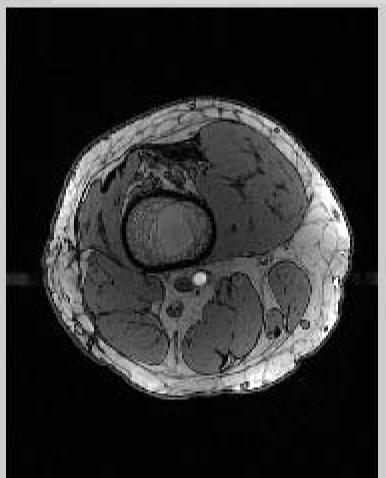
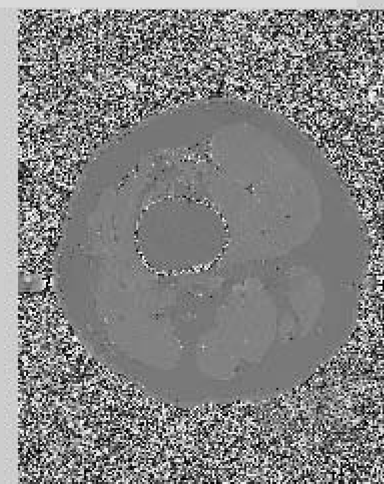
- **Assume water has a zero phase, then**

$$\hat{\rho}(TE) = \hat{\rho}_{w,m} + \hat{\rho}_{f,m} e^{-i2\pi\Delta f_{fw} TE}$$

- **In-phase and oppose-phase scenarios**

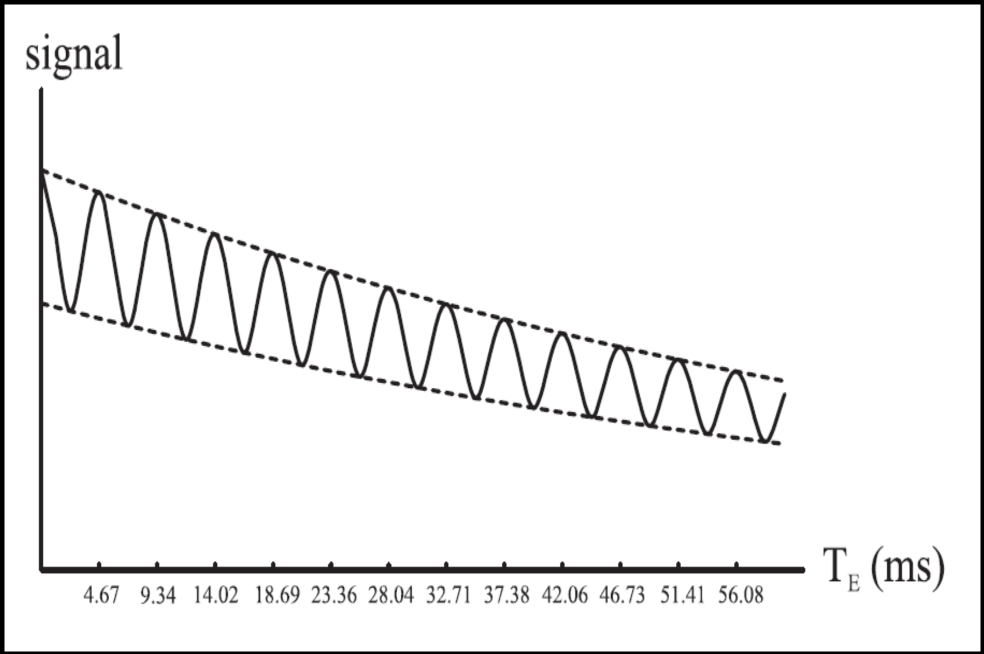
$$-i2\pi\Delta f_{fw} TE_{in}(n) = 2n\pi$$
$$-i2\pi\Delta f_{fw} TE_{op}(n) = (2n+1)\pi$$

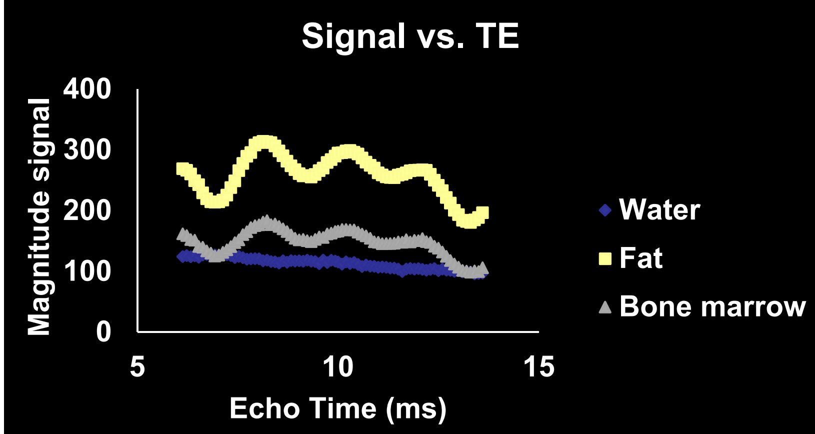
n=0,1,2…

Signal with beat pattern as a function of TE

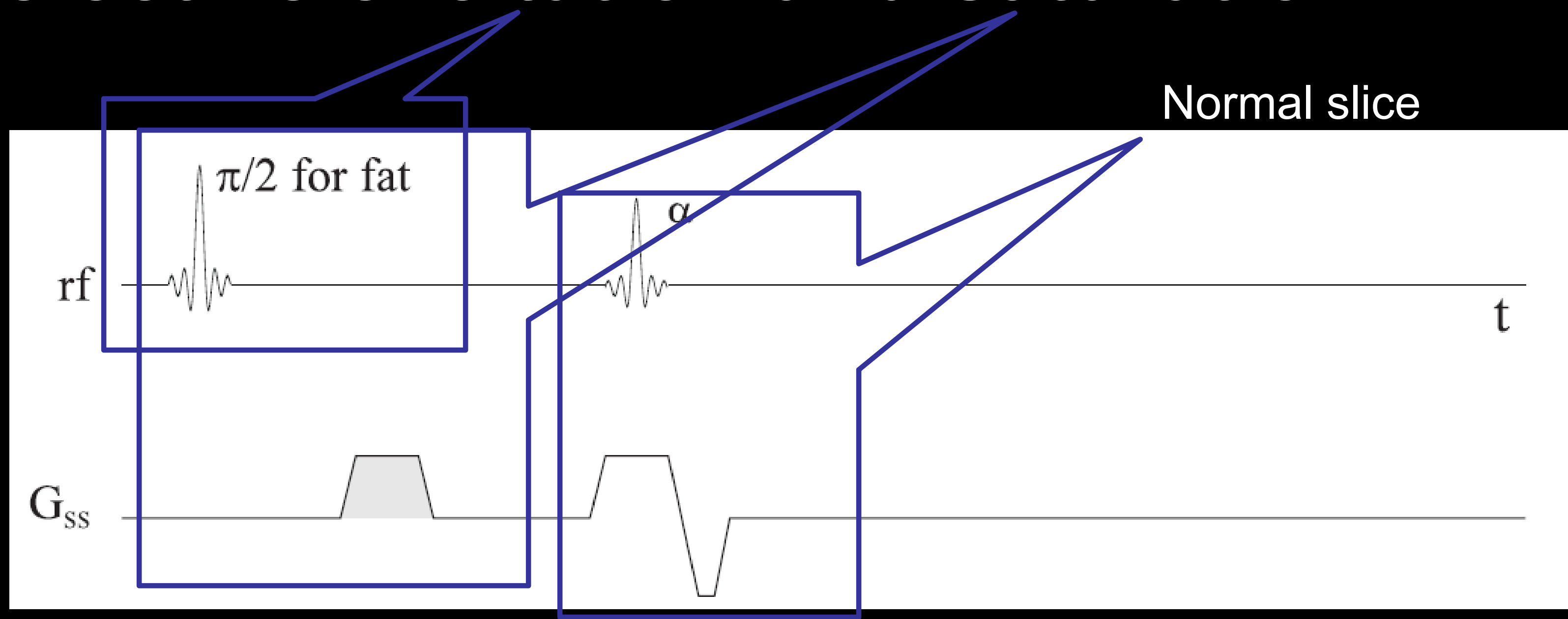
- Edge enhancement/ reduction artifacts
- Inaccuracy in T2* estimation





Separating water and fat

- **Selective excitation and saturation**

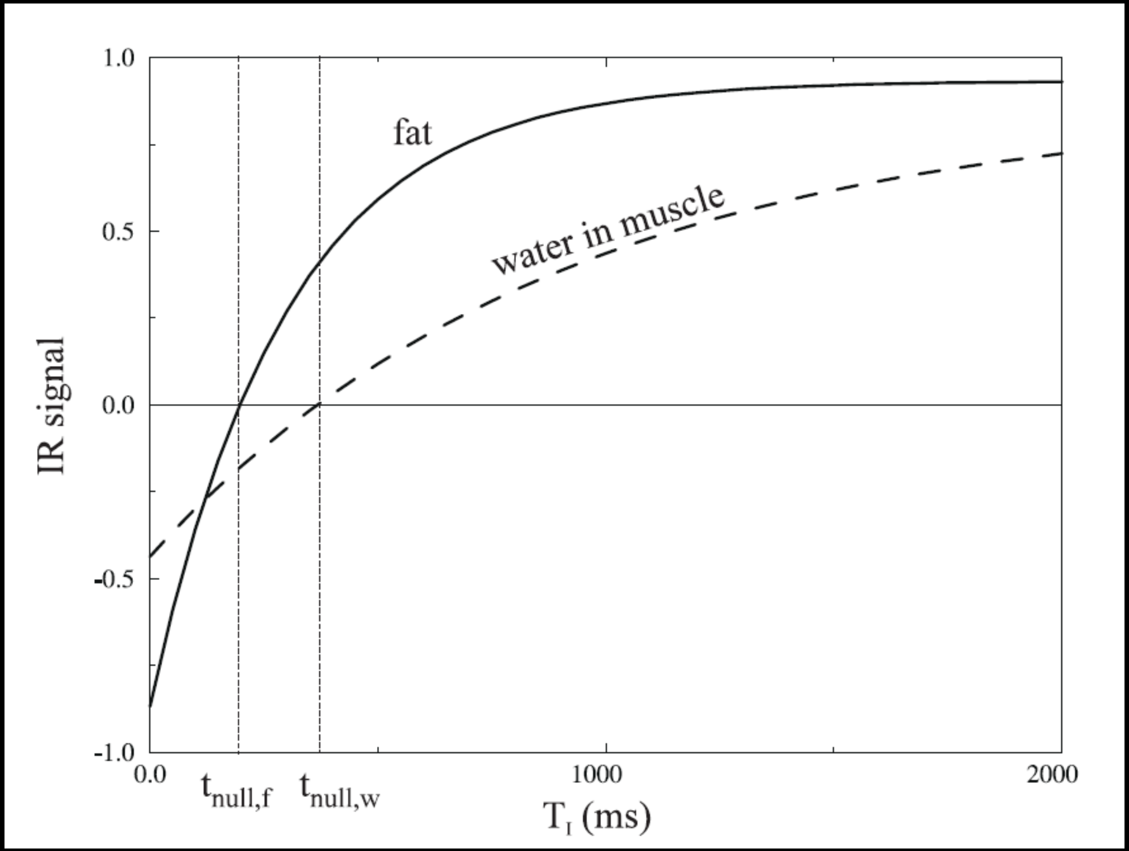


- **Practical issues:**
  - Long RF pulse duration for narrow RF bandwidth
  - Fat selective pulse may also excite water due to field inhomogeneity, or too small Δf_{fw} at low fields
  - Field inhomogeneity also widens fatty peaks

Separating water and fat

- **Inversion recovery**

$$T_{1,fat} < T_{1,GM/WM/muscle}$$

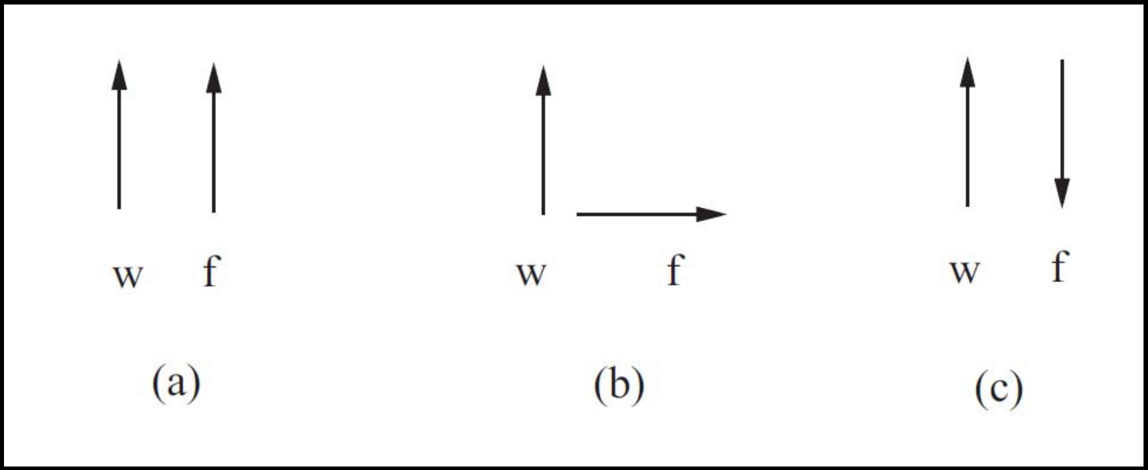


Separating water and fat

- **Multipoint acquisition**
  - Known water/fat chemical shift
  - Adapting a simple partial volume model (Chap. 15)
  - Utilize phase information
- **Methods**
  - Single echo complex separation
  - Two-/three-point Dixon method
  - Multi-point Dixon method (for more accurate results or extra species such as silicon)

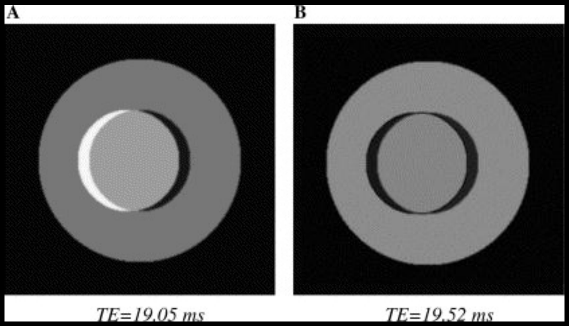
Separating water and fat
Multipoint acquisition (Dixon method)

$$\hat{\rho}(TE) = \hat{\rho}_{w,m} + \hat{\rho}_{f,m} e^{-i2\pi\Delta f_{fw} TE}$$



$TE_{op} = (2n+1)/2\Delta f_{fw}$

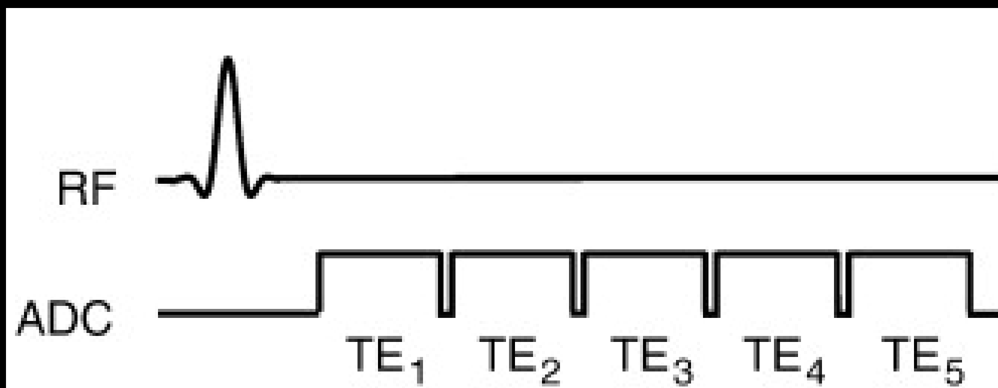
$TE_{in} = n/\Delta f_{fw}$

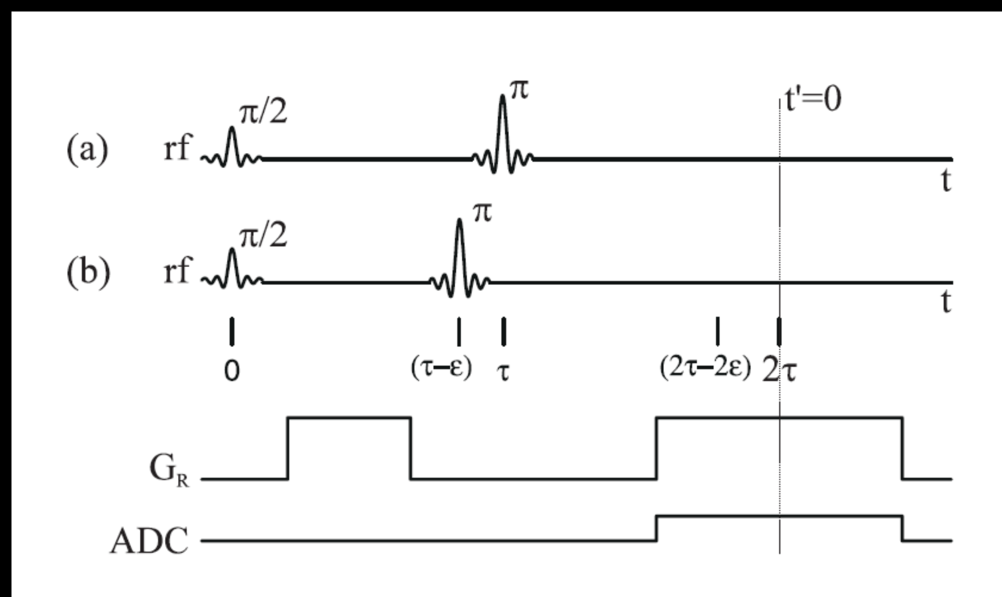


Benoit-Cattin, JMR, 2005

1.5T:
TE_{op} =2.34/7.01/11.69…ms
TE_{in} = 4.67/9.35/14.02…ms
3T:
TE_{op} =1.17/3.51/5.84/8.18…ms
TE_{in} =2.34/4.67/7.01/9.35…ms

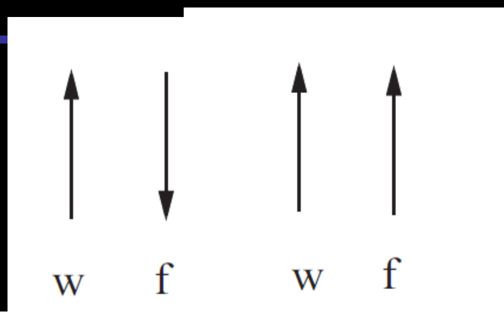
GE and SE


RF
ADC
TE1 TE2 TE3 TE4 TE5


(a) rf
π/2
π
t'=0
t
(b) rf
π/2
π
t
0
(τ−ε)
τ
(2τ−2ε)
2τ
G_R
ADC

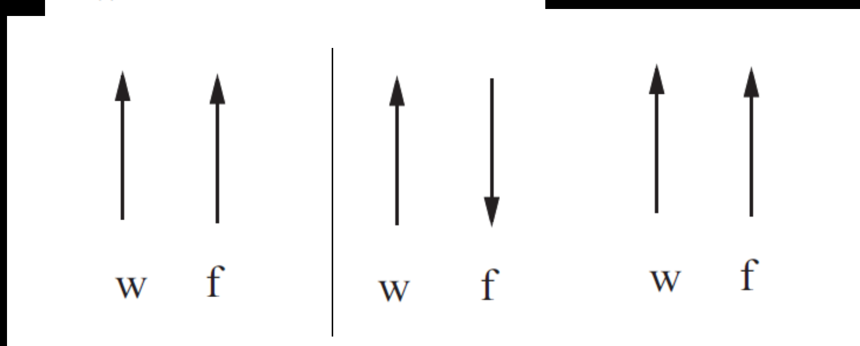
2-/3-/multi-point Dixon

2-point Dixon



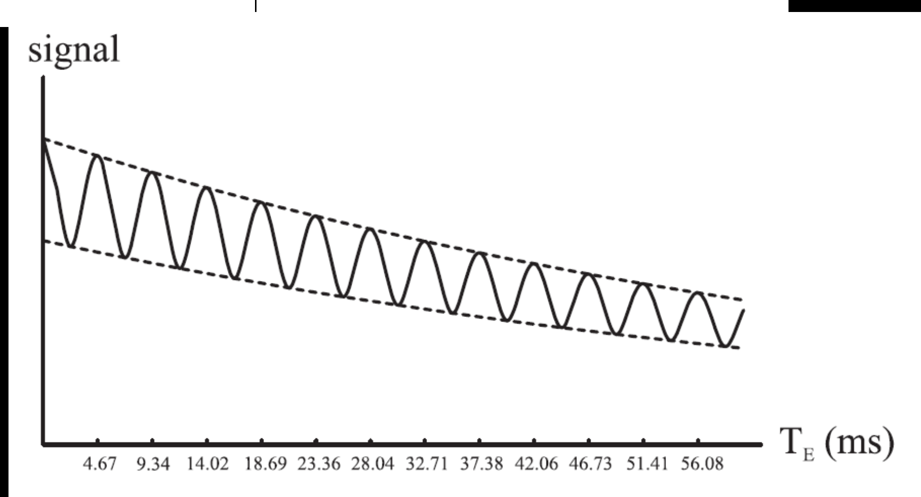
- Easy to understand
- Susceptible to field inhomogeneity

3-point Dixon



- 2 in-phase can determine ΔB

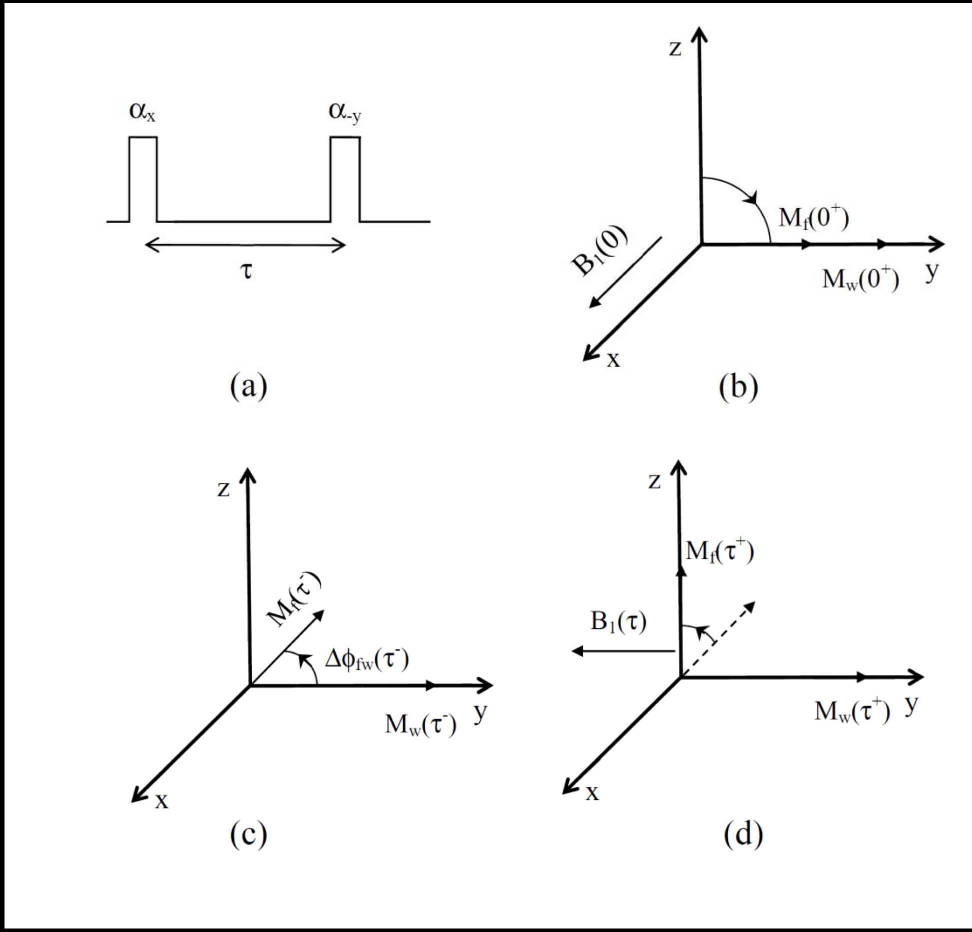
Multi-point Dixon



- Use multi point regression and phase information

Fig.17.8

Separating water and fat
Spatial-Spectral (SPSP) pulses



Homeworks

- Probs 17.1-17.4

Next Class

Chapter 18, by Dr. Yongquan Ye