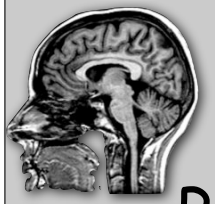
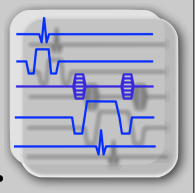




Principles of MRI

EE225E / BIO265

Lecture 18

Instructor: Miki Lustig
UC Berkeley, EECS

IMAGE CONTRAST

SO FAR ASSUMED

$\vec{M}(0) = [0, 0, M_0]^T$

SAMPLE IS FULLY RELAXED $TR \gg 3T_1$

IN PRACTICE THIS IS SELDOM TRUE

- $I(x,y) = f(\rho, T_1, T_2, \Theta, TR, TE)$

$I(x,y)$: IMAGE

ρ, T_1, T_2: PHYSICAL PARAMETERS

Θ, TR, TE: INSTRUMENTAL PARAMETERS

TISSUE HAS INHERENT VARIABILITY IN T_1, T_2, ρ

WANT TO EMPHASIZE IT

Question

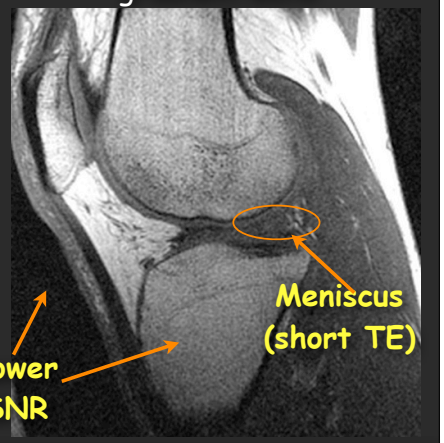
- What is the difference between the images?

Answer

- Both T1-weighted

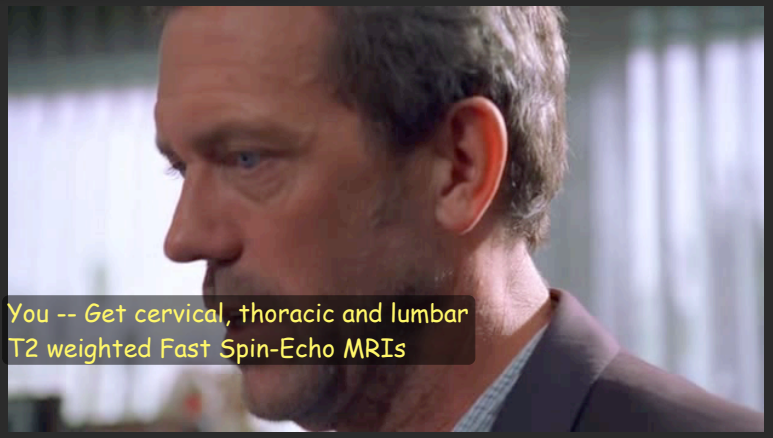
spin-echo

gradient-echo



Spin-Echo Properties

- Robust to off-resonance effects
- Excellent Contrast



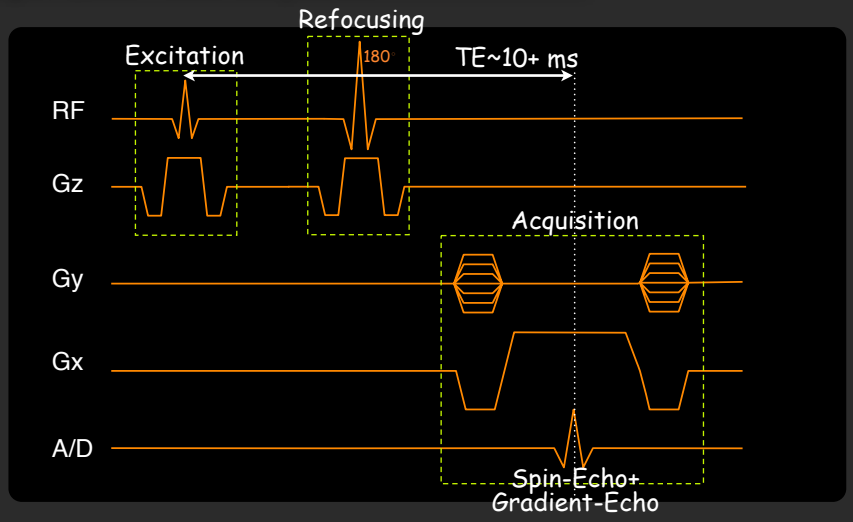
Spin-Echo Properties

- Robust to off-resonance effects
- Excellent Contrast

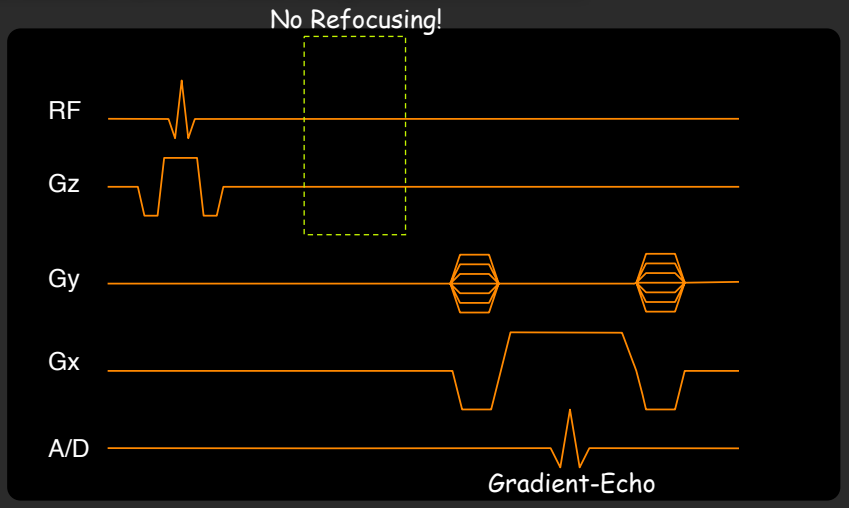
  but...
- SAR limitations (high-power RF)
- Long scan times, and long echo-time
- Mostly multi-slice 2D
- Artifacts/long scan-time in 3D

Gradient-echo: Fast, short TE, often 3D

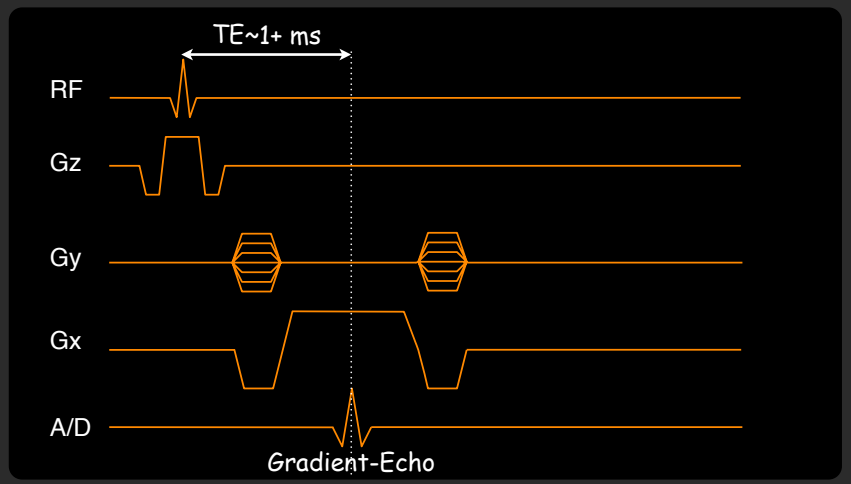
Spin-Echo Pulse Sequence



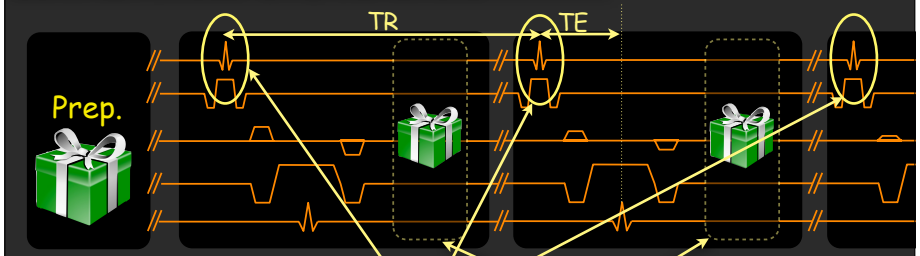
Gradient-Echo Pulse Sequence



Gradient-Echo Pulse Sequence



Contrast Knobs: GRE Variations



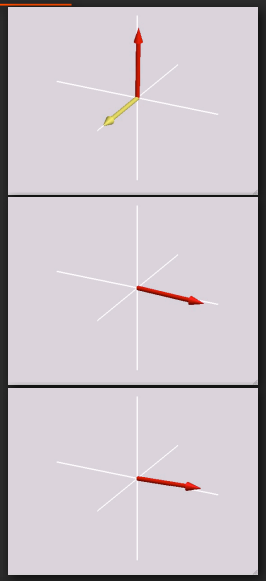
- Spoiling (sequence)
- RF: Flip / Phase
- Timing (TR, TE)
- Preparation Sequence

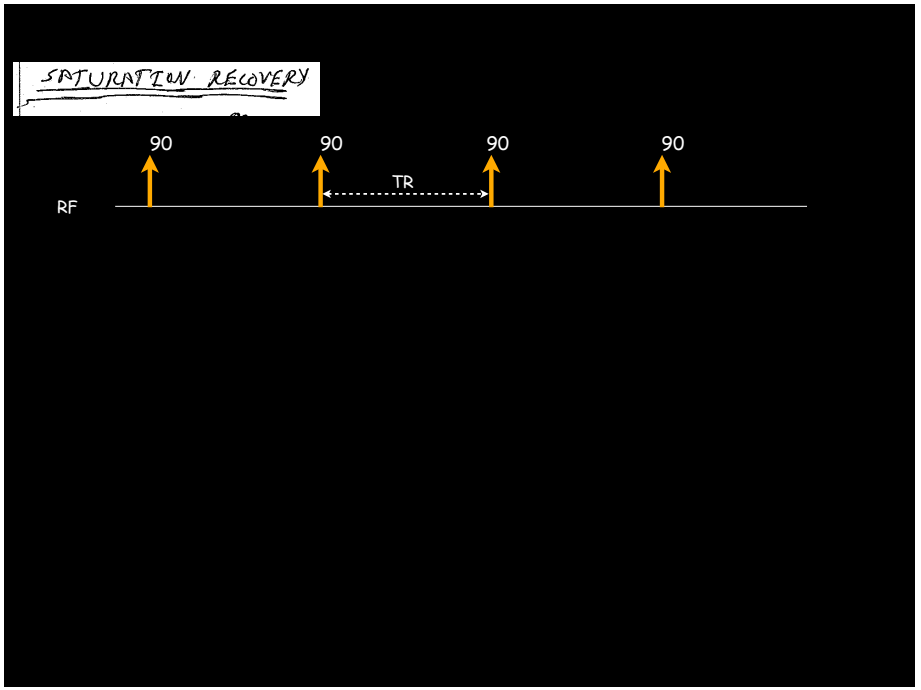
Assumptions

- m(x,y,t) is a function of time
- Approximation:
  - when analyzing I(x,y), assume m(x,y,t=TE)
- Consider:
  - T1 > TR > 3T2
  - Later : TR < 3T2

Review Magnetization Dynamics

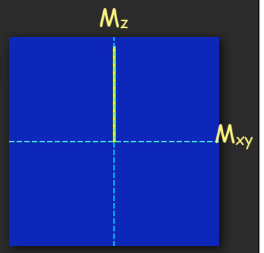
- RF Excitation
- Free-precession/ (gradient induced)
- Relaxation



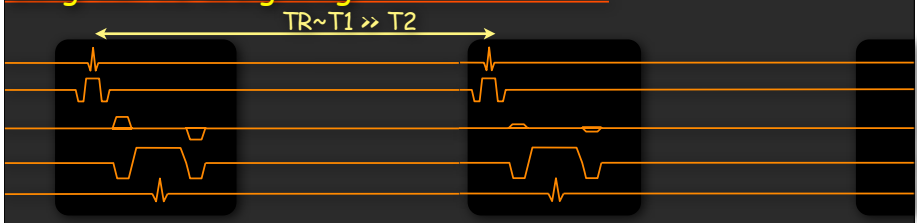


Very Long TR: Full Relaxation

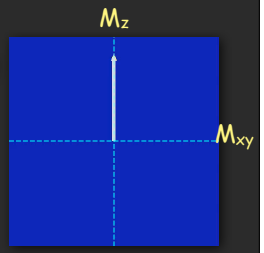
- Mxy decays completely before next RF
- Mz recovers fully before next RF
- Full signal after RF



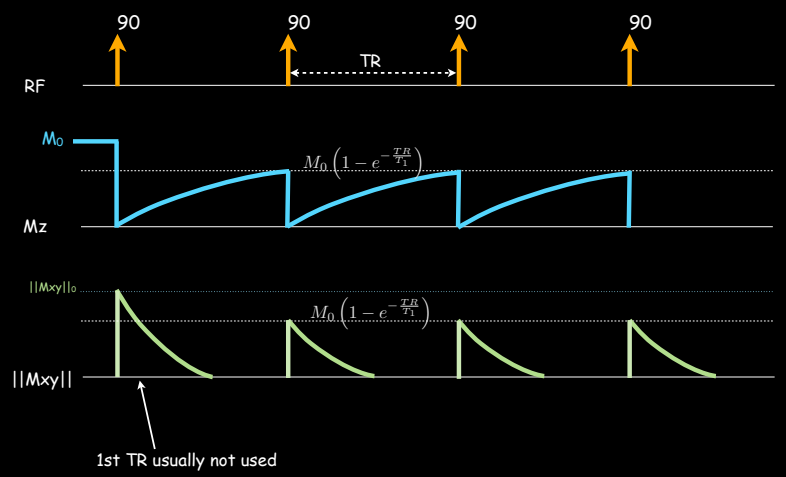
Long TR: T1-Weighting



- Mxy decays completely before next RF
- Mz partially recovers before next RF
- T1-weighted signal after RF



SATURATION RECOVERY



STEADY-STATE SIGNAL: $M_0(1-e^{-\frac{TR}{T_1}})$

IMAGE IS: GAIN CONSTANT

$TE \approx 0$ $\quad I(x,y) = k\,\rho(x,y)\left[1-e^{-\frac{TR}{T_1(x,y)}}\right]$

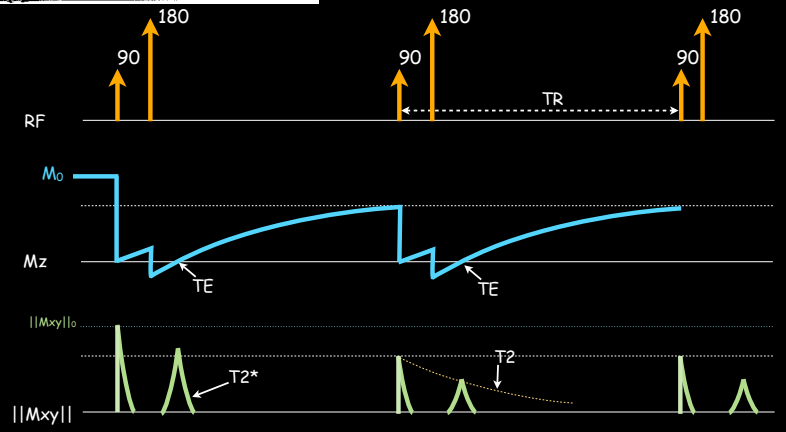
ρ: spin density; T_1 WEIGHTING

$TR \ll T_1$ $\quad I(x,y) \cong k\,\rho(x,y)\left(\frac{TR}{T_1(x,y)}\right)$ SHORT T_1 BRIGHT, LONG T_1 DARK

$TE \neq 0$

$$I(x,y) = k\rho(x,y)\left[1-e^{-\frac{TR}{T_1(x,y)}}\right]e^{-TE/T_2}$$

SPIN-ECHO VERSION



IF $TE \ll TR$

$$I(x,y) = k\rho(x,y)\left[1-e^{-\frac{TR}{T_1(x,y)}}\right]e^{-\frac{TE}{T_2(x,y)}}$$

PROTON DENSITY: TE SHORT $\ll T_2$, TR LONG $\gg T_1$ $\Rightarrow I \cong k\rho(x,y)$

T_1 WEIGHTING: TE SHORT $\ll T_2$, $TR \sim T_1$ $\Rightarrow I \cong k\rho\left(1-e^{-\frac{TR}{T_1}}\right)$

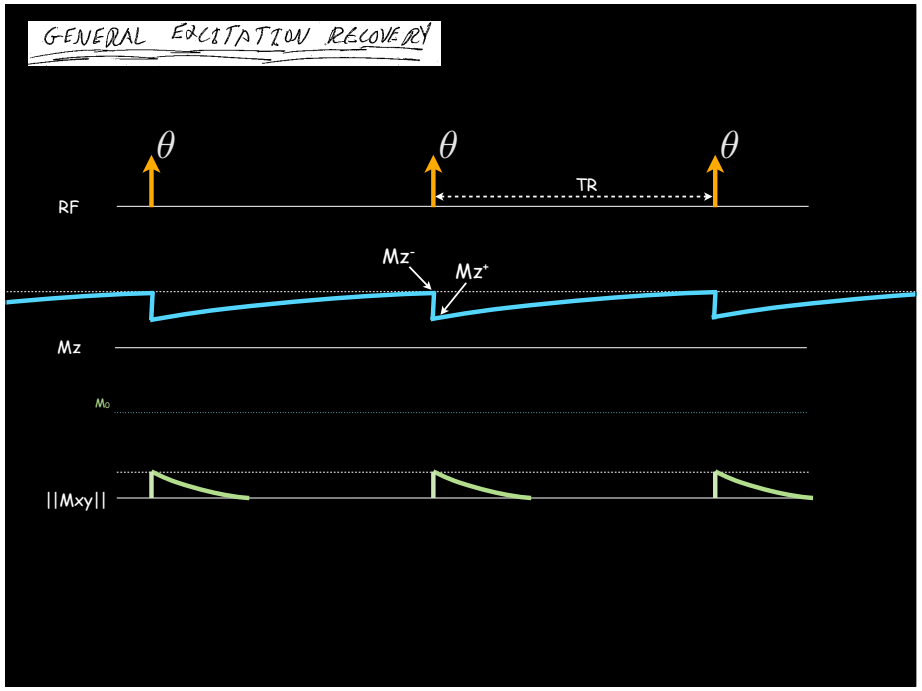
(TR = 400ms, TE = 15ms @ 1.5T BRAIN)

T_2 WEIGHTING: TR LONG $\gg T_1$, $TE \sim T_2$ $\Rightarrow I \cong k\rho e^{-\frac{TE}{T_2}}$

(TR = 2500ms, TE = 80ms BRAIN @ 1.5T)

T_1 – ANATOMY

T_2 – LESION SENSITIVE



LET $E_1 = e^{-\frac{TR}{T_1}}$

$$M_z^- = M_z^+ e^{-\frac{TR}{T_1}} + (1 - e^{-\frac{TR}{T_1}}) M_0$$

$$M_z^- = M_z^+ E_1 + M_0(1-E_1)$$

$TR=0 \Rightarrow M_z^+$

$TR=\infty \Rightarrow M_0$

AND

$$M_z^+ = M_z^- \cos\Theta$$

IN STEADY-STATE

$$M_z^- = M_z^- \cos\Theta E_1 + M_0(1-E_1)$$

$$M_z^-(1-\cos\Theta E_1) = M_0(1-E_1)$$

$$M_z^- = \frac{M_0(1-E_1)}{1-\cos\Theta E_1}$$

$$M_{xy}^+ = \frac{M_0(1-E_1)\sin\Theta}{1-\cos\Theta E_1}$$

AT TE

$$I(x,y) = k\rho(x,y)\frac{(1-E_1(x,y))\sin\Theta}{1-\cos\Theta E_1(x,y)} e^{-\frac{TE}{T_2(x,y)}}$$

WHAT IS Θ^* THAT MAX SIGNAL

Θ SMALL, $\sin\Theta$ SMALL, NO SIGNAL

Θ LARGE, M_z SMALL, NO SIGNAL

OPTIMUM:

$$\Theta_E = \cos^{-1} E_1 = \cos^{-1}(e^{-\frac{TR}{T_1}})$$

ERNST ANGLE

EXAMPLE:

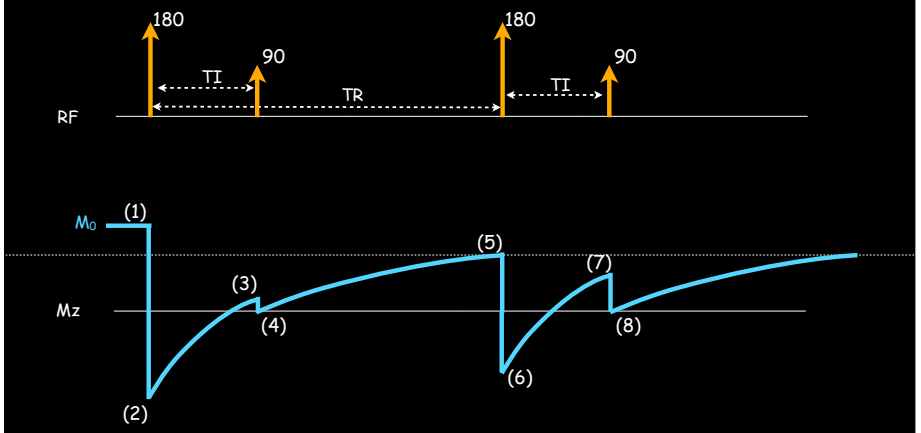
$TR = T1$, $\Theta_E = 68.4°$

OPTIMUM M_{xy}^+

$$M_{xy}^{+*} = M_0\sqrt{\frac{1-E_1}{1+E_1}}$$

OPTIMUM SIGNAL NOT CONTRAST

INVERSION RECOVERY



AFTER 90, $M_z = 0$

AT ⑤

$$M_z = \left(1 - e^{-\frac{(TR-TI)}{T_1}}\right) M_0$$

AT ⑥

$$M_z = -M_0 \left(1 - e^{-\frac{(TR-TI)}{T_1}}\right)$$

AT ⑦

$$M_z = -M_0 \left(1 - e^{-\frac{(TR-TI)}{T_1}}\right) e^{-\frac{TI}{T_1}} + \left(1 - e^{-\frac{TI}{T_1}}\right) M_0 =$$

$$= -M_0 e^{-\frac{TI}{T_1}} + M_0 e^{-\frac{TR}{T_1}} + M_0 + M_0 e^{-\frac{TI}{T_1}}$$

$$M_z = M_0 \left(1 - 2e^{-\frac{TI}{T_1}} + e^{-\frac{TR}{T_1}}\right)$$

IMAGE IS @ TE

$$I(x,y) = k\rho(x,y)\left[1 - 2e^{-\frac{TI}{T_1(x,y)}} + e^{-\frac{TR}{T_1(x,y)}}\right] e^{-\frac{TE}{T_2^*(x,y)}}$$

IR GIVES

a) GREATER T_1 CONTRAST (ALMOST TWICE)

b) NULL SPECIFIC TISSUE

FAT ⇒ STIR $TI \sim 150$ ms

CSF ⇒ FLAIR $TI = 2000$ ms

NULL TIME:

$$1 - 2e^{-\frac{TI}{T_1}} + e^{-\frac{TR}{T_1}} = 0$$

$$TI = -T_1 \log\left[\frac{1 + e^{-\frac{TR}{T_1}}}{2}\right]$$

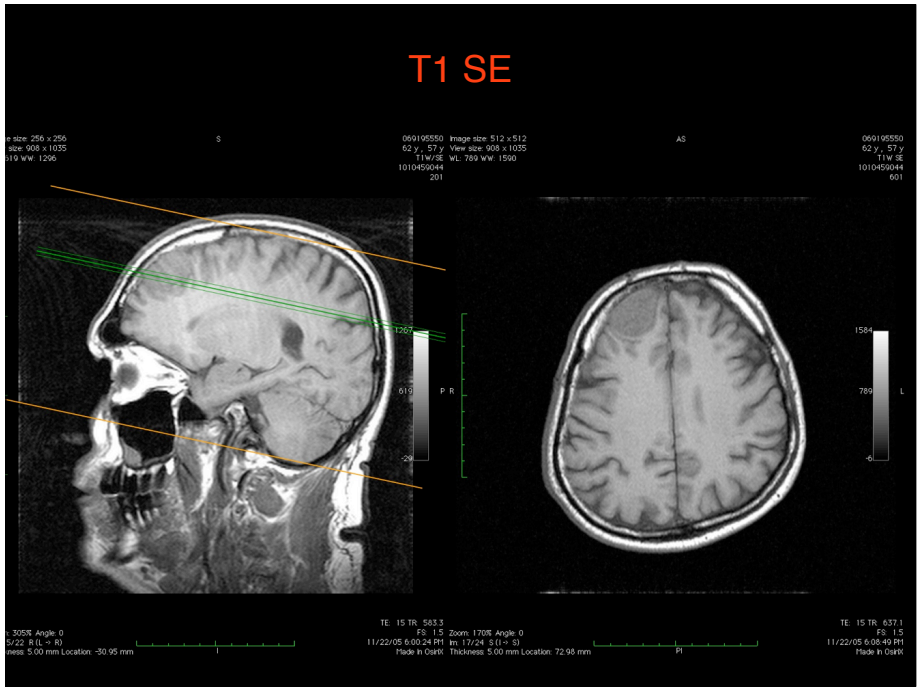
$TR \gg T_1$

$$TI \approx -T_1 \log\frac{1}{2} = 0.693\, T_1$$

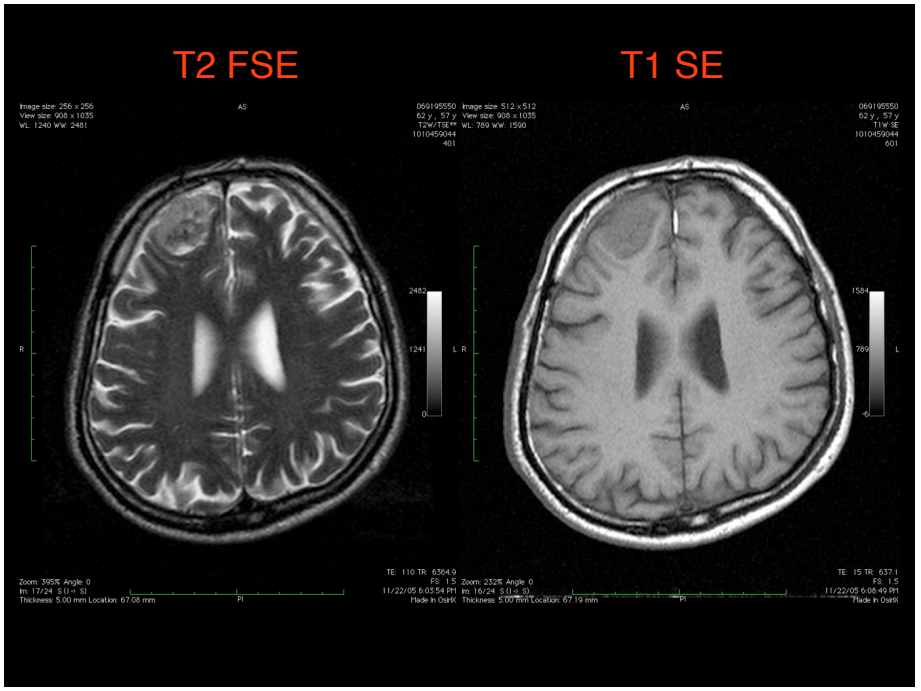
EXAMPLE: FAT NULLING

T_1 of FAT ~ 260 ms, $TR = 900$

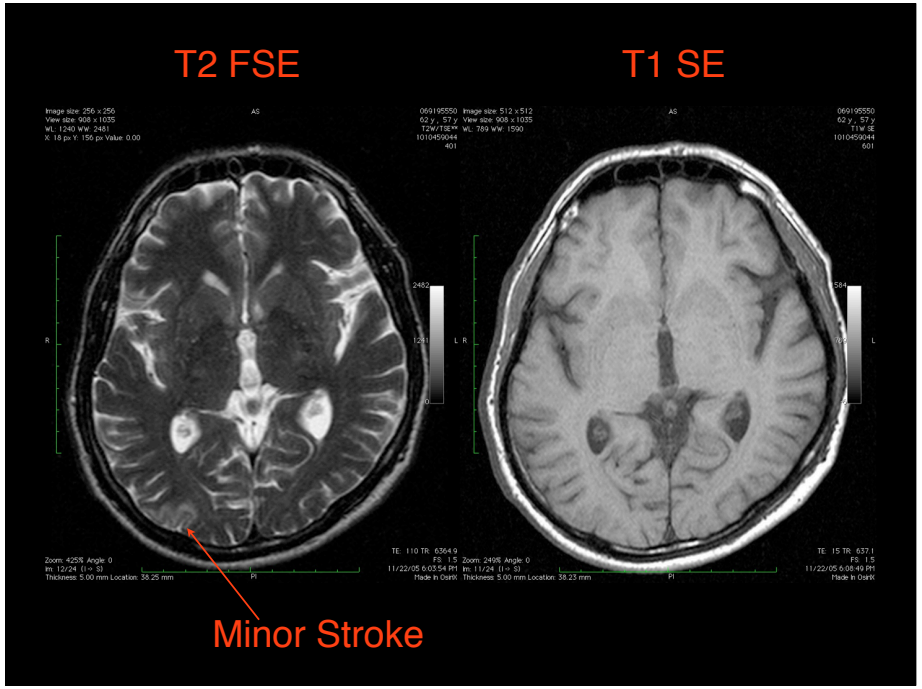
$$TI = -260 \log\left(\frac{1 + e^{-\frac{900}{260}}}{2}\right) \simeq 168 \text{ ms}$$


T1 SE

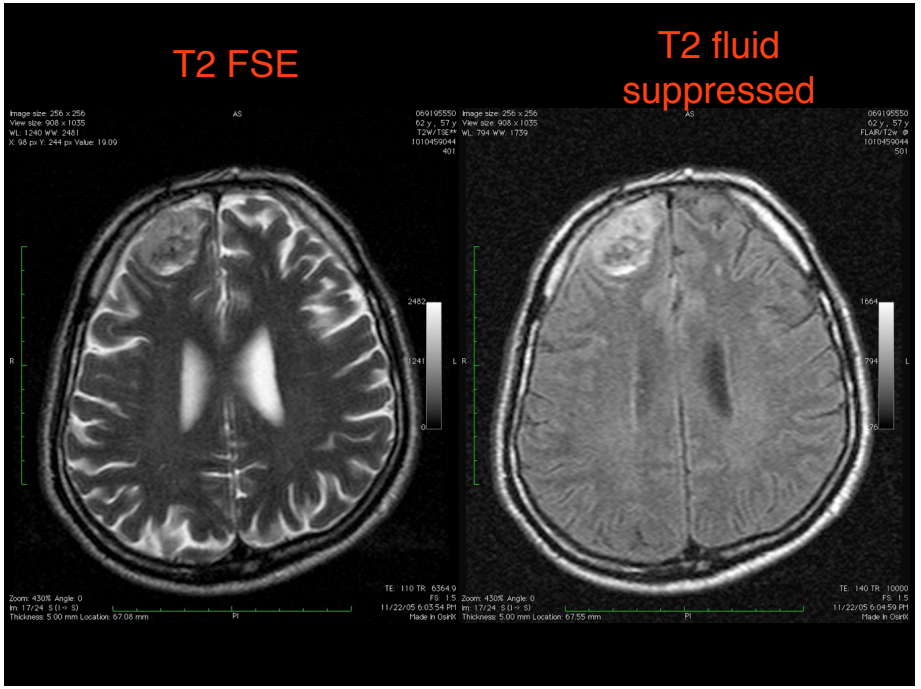
29


T2 FSE
T1 SE

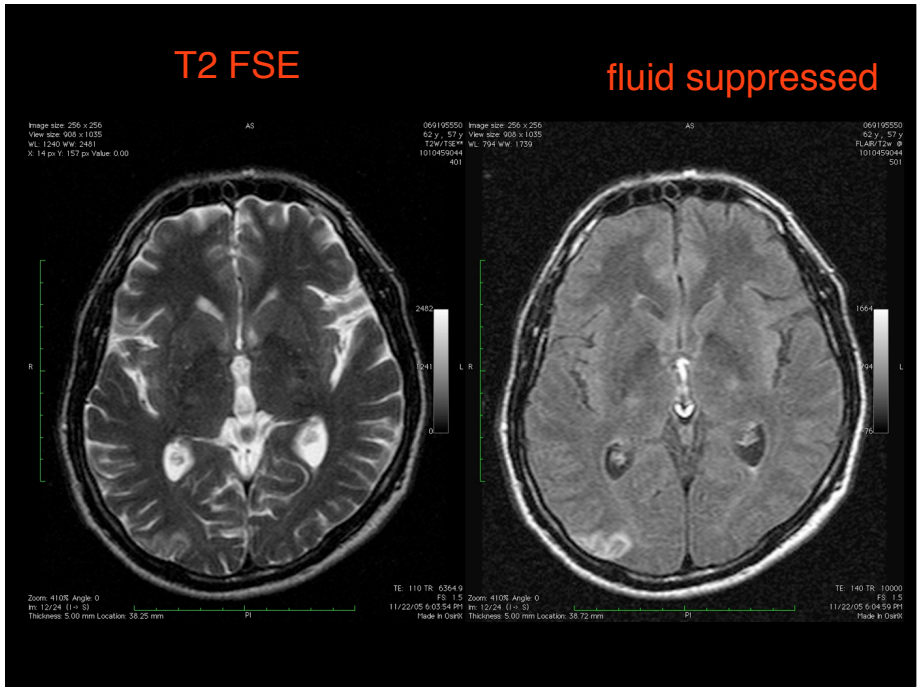
30


T2 FSE
T1 SE
Minor Stroke

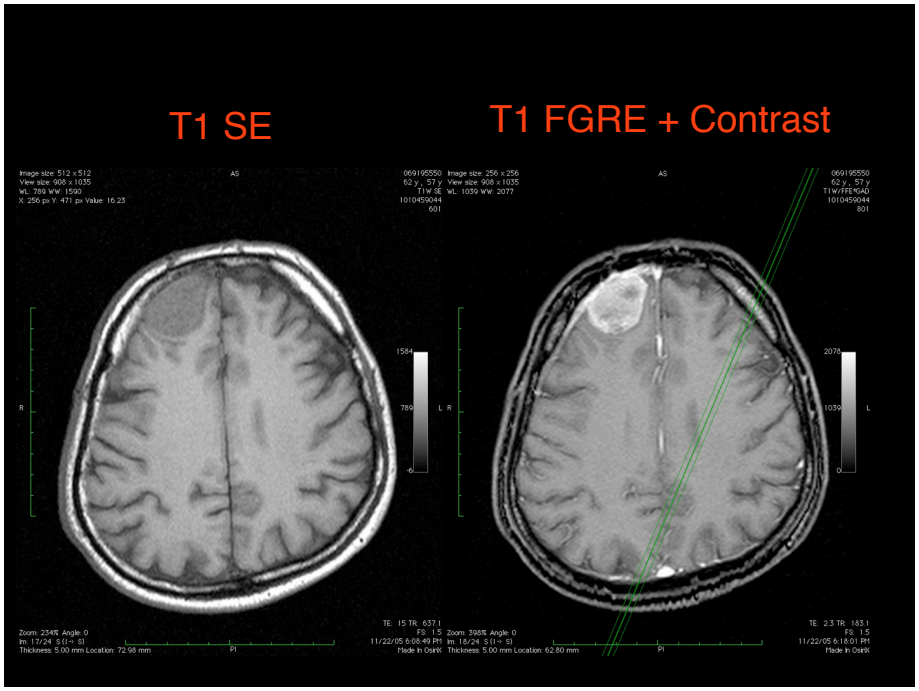
31


T2 FSE
T2 fluid suppressed

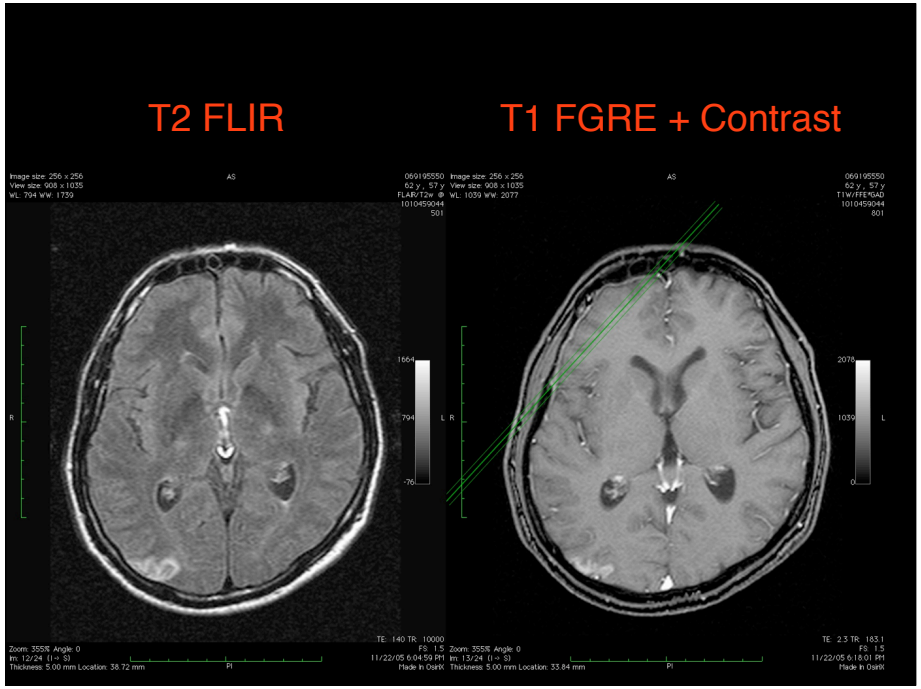
32



33



34



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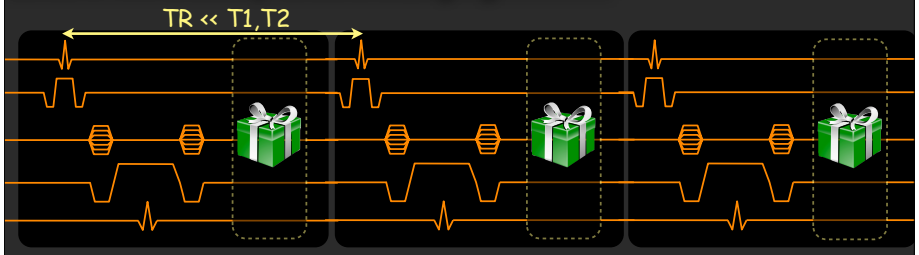
Short TR Steady-State Imaging



- Mxy persists before next RF
- May have shifted in phase
- Adds/Subtracts from next signal
- makes a HUGE difference on image contrast

M. Lustig, EECS UC Berkeley

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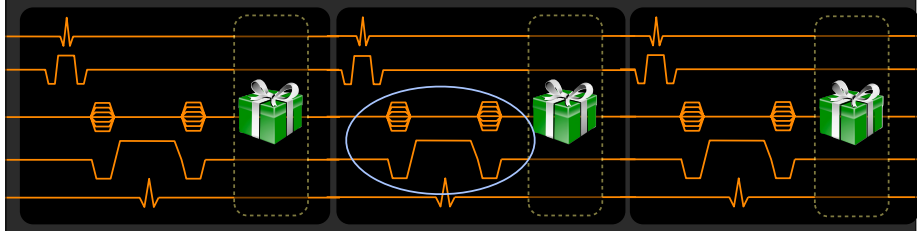
Balanced SSFP

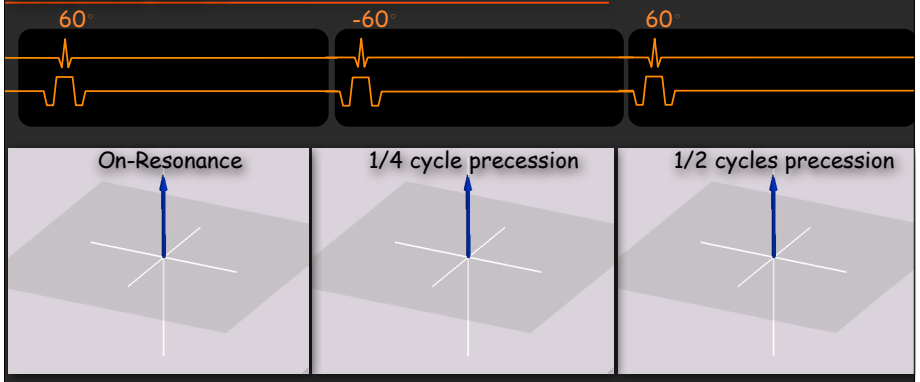


True-FISP, FIESTA, balanced FFE, BASG

- Do nothing at the end
- Balanced Gradients

Oppelt 1986, Duerk 1997

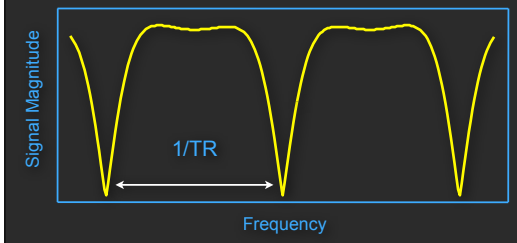
Balanced SSFP



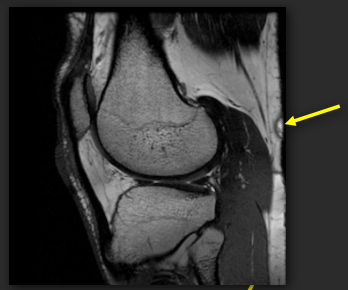
- High steady-state signal
- T2/T1 mixed contrast
- Sensitive to off-resonance

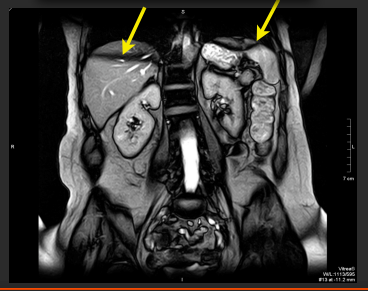
Balanced-SSFP Dark Bands

- Must limit precession
  - Short TR
- Limits resolution



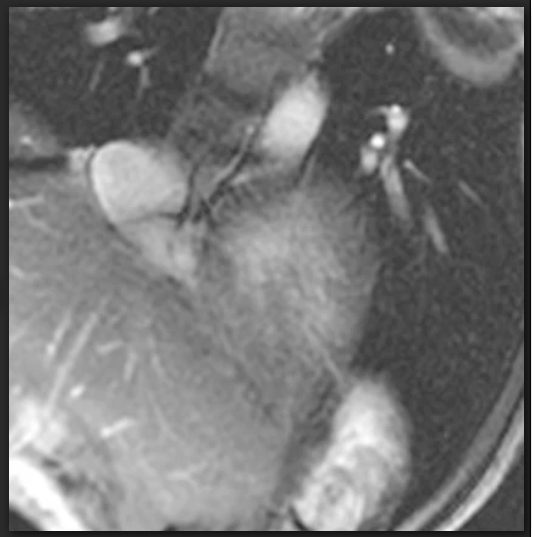
Freeman 1971





Balanced-SSFP Cardiac Imaging

- Fast (TR=2-5ms)
- Good contrast
- Flow-compensated

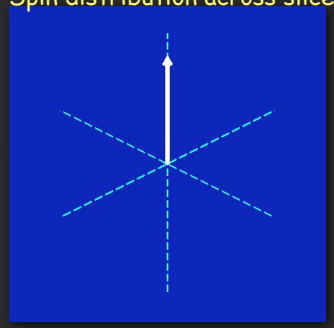


Gradient Spoiling

FFE, FISP, GRASS, GRE, FAST, Field Echo

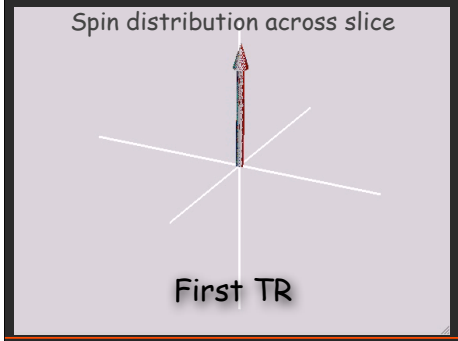
- Reduce sensitivity to off-resonance by Spoiling Mxy before next RF

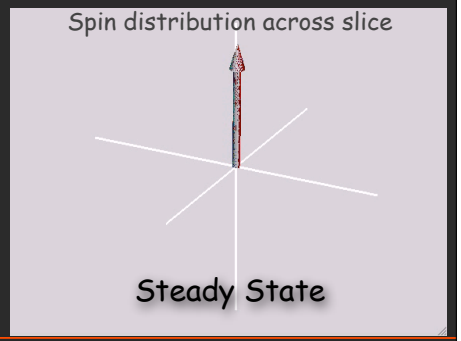
Spin distribution across slice



Question

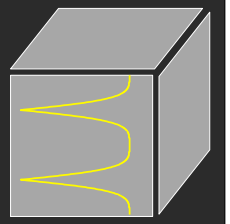
- Does gradient spoiling eliminates transverse signal at the end of TR?





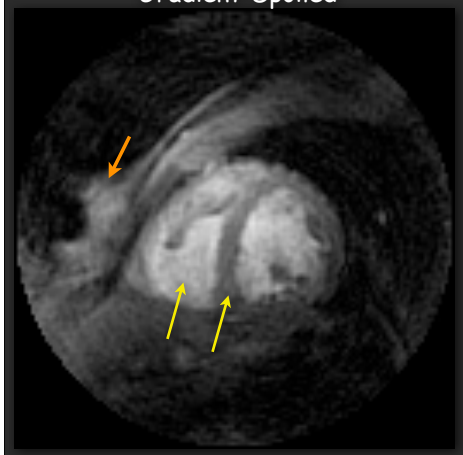
Answer

- No, its an average of balanced-SSFP but....
- No dark bands
- Lower signal than balanced-SSFP
- Reduced contrast

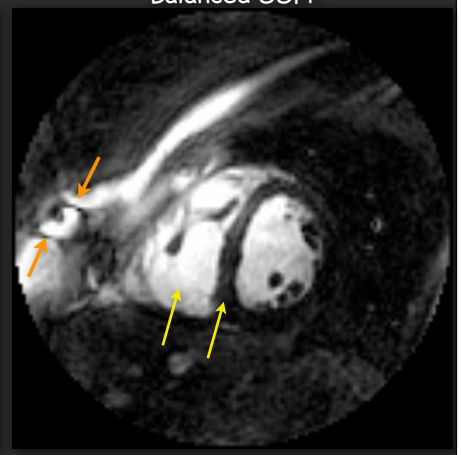


Gradient Spoiled vs Balanced SSFP

Gradient-Spoiled



Balanced SSFP



(Courtesy of Krishna Nayak, USC Electrical Engineering)

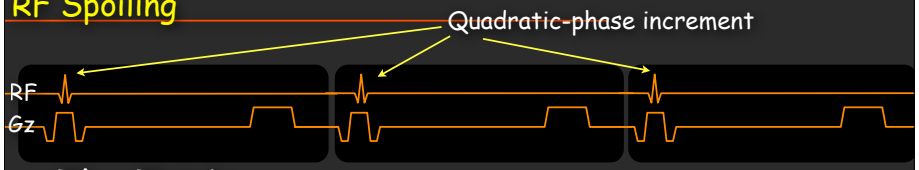
RF Spoiled Imaging

- Goal: Pure T1 contrast with short TR
- Fast, 3D T1-Weighted imaging
- Need to "Zero" Mxy at the end of TR

SPGR, FLASH, T1-FFE, RF-spoiled FAST

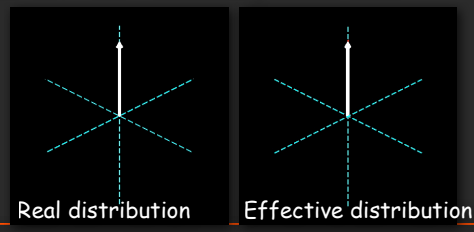
Frahm 1987, Zur 1991

RF Spoiling



- The Trick:
  - Quadratic Phase Increment of RF
  - Effectively "Random" angle RF every TR
  - Spoiled magnetization has random phase and does not add

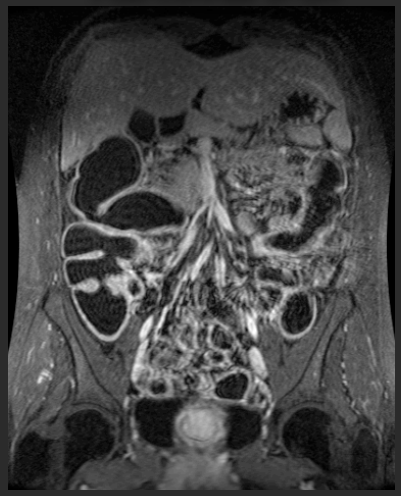
- Low SNR!



RF Spoiled Contrast Enhanced MR

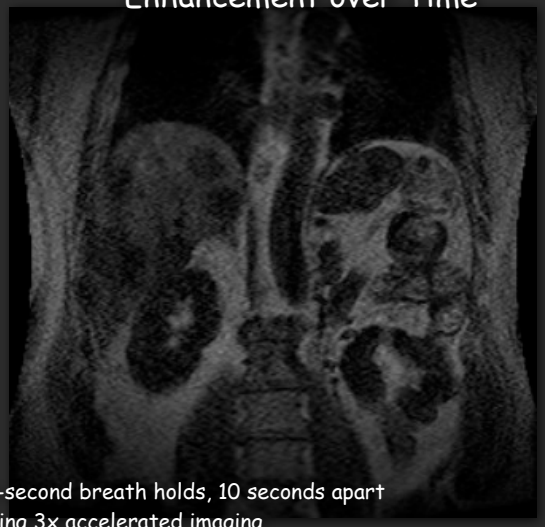
Pre-Contrast SPGR

Post-Contrast SPGR



RF Spoiled Dynamic Contrast MR

Enhancement over Time



Repeated 6-second breath holds, 10 seconds apart
32 slices using 3x accelerated imaging

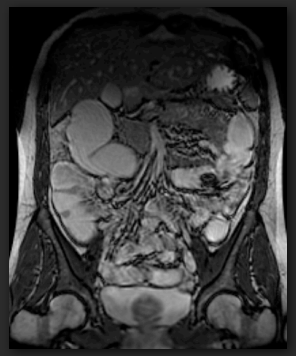
Gradient Echo Sequence Comparison

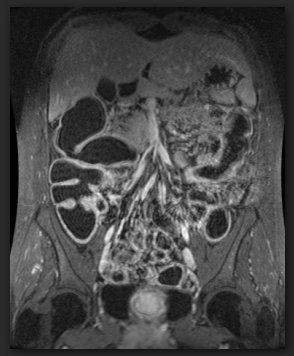
Sequence	Balanced SSFP	Gradient Echo	RF-Spoiled
Spoiling	None	Gradient	RF + Gradient
Transverse Magnetization	Retained	Averaged	Cancelled
Contrast	T_2/T_1	T_2/T_1	T_1
SNR	High (but Banding)	Moderate	Lower

Quiz I

Here are a balanced SSFP and RF-Spoiled post-contrast image. Which is the image on the left?

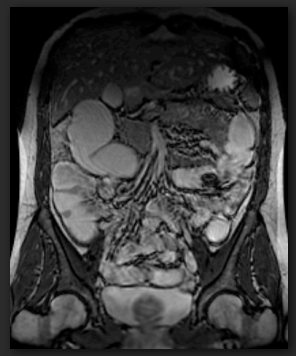
1) RF-Spoiled Post Gd
2) Balanced SSFP





Quiz I

2) Balanced SSFP
Bright Fluid (T2-like)



1) RF Spoiled post Gd
T1 contrast, enhanced wall

Image Comparison

Identify the images shown (Same TR, TE, Flip)

1)	RF Spoiled	Balanced SSFP	Gradient Spoiled
2)	Gradient Spoiled	RF Spoiled	Balanced SSFP
3)	RF Spoiled	Gradient Spoiled	Balanced SSFP

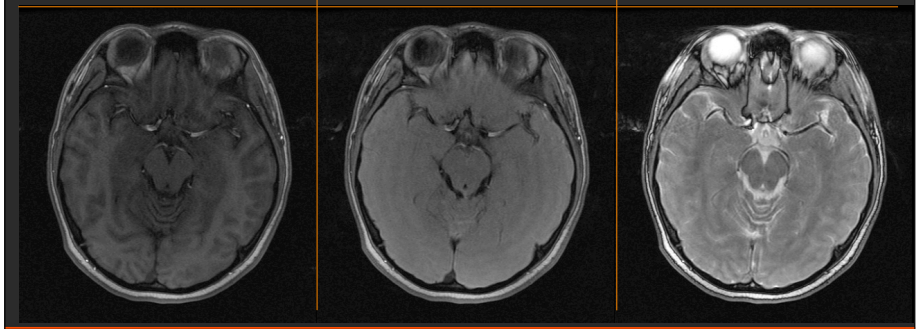
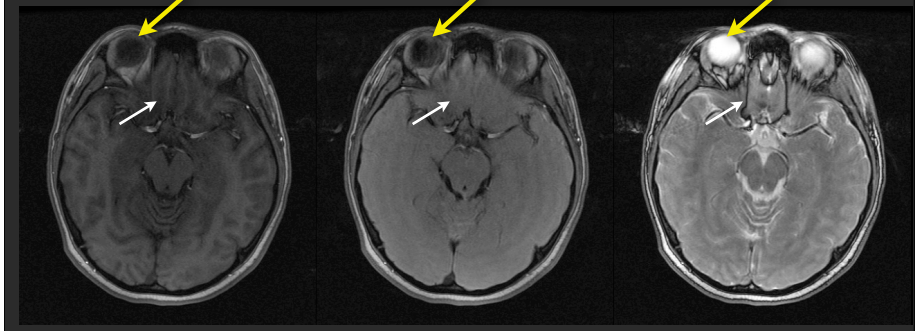


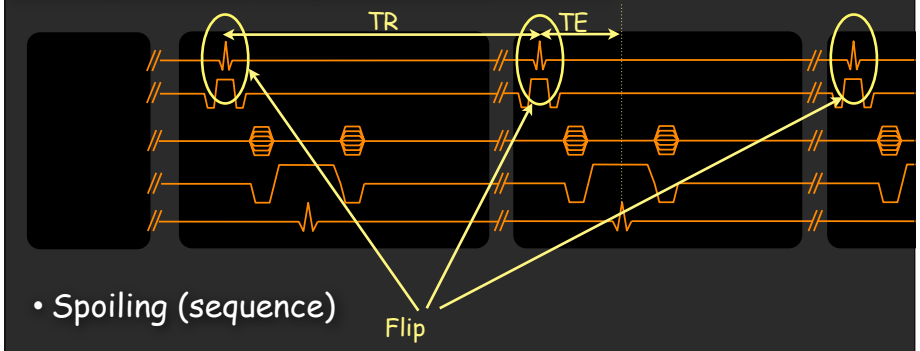
Image Comparison

- Same TR, TE, flip angle
- Differences: Signal, Contrast, Dark-Bands

3) RF Spoiled Gradient Spoiled Balanced SSFP



Contrast Knobs: GRE Variations



- Spoiling (sequence)
- RF: Flip
- Timing (TR, TE)
- Preparation Sequence

Flip Angle in Gradient Echo Sequences

Does increasing the flip angle increase signal?

1) Yes: Signal always increases with flip angle.
2) No: Signal decreases as flip angle increases
3) Sometimes: The signal peaks at a specific flip angle

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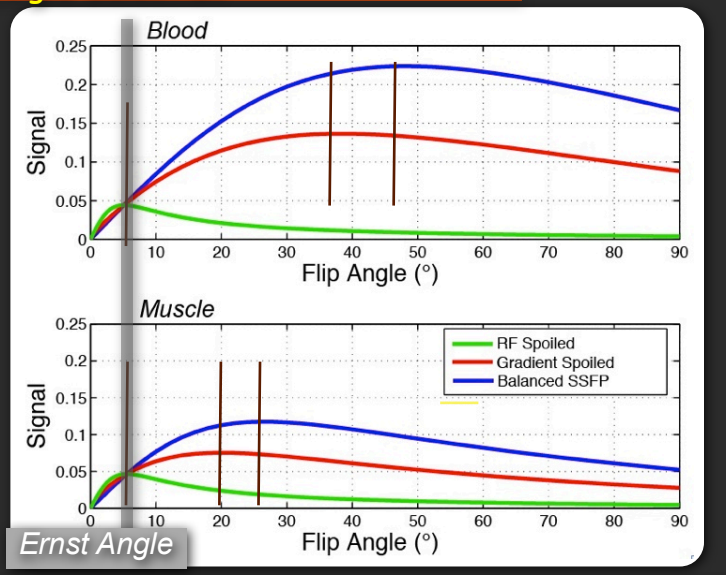
Flip Angle Selection



Buxton 1990

Flip Angle Selection?

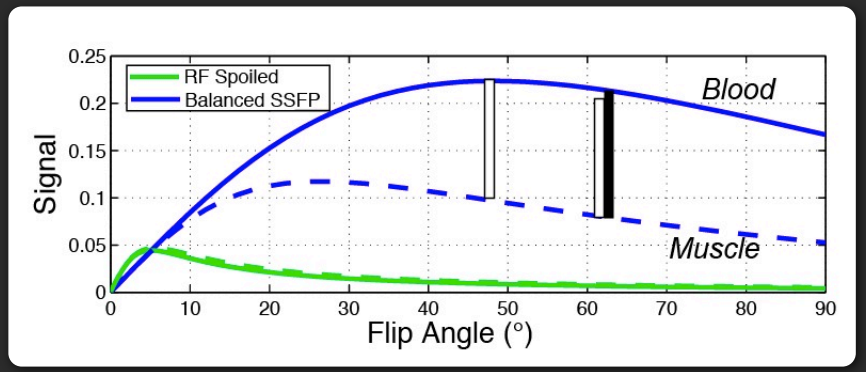
The best flip angle to use is found by:

1) Maximizing the image SNR
2) Maximizing contrast between certain tissues
3) Both 1 and 2

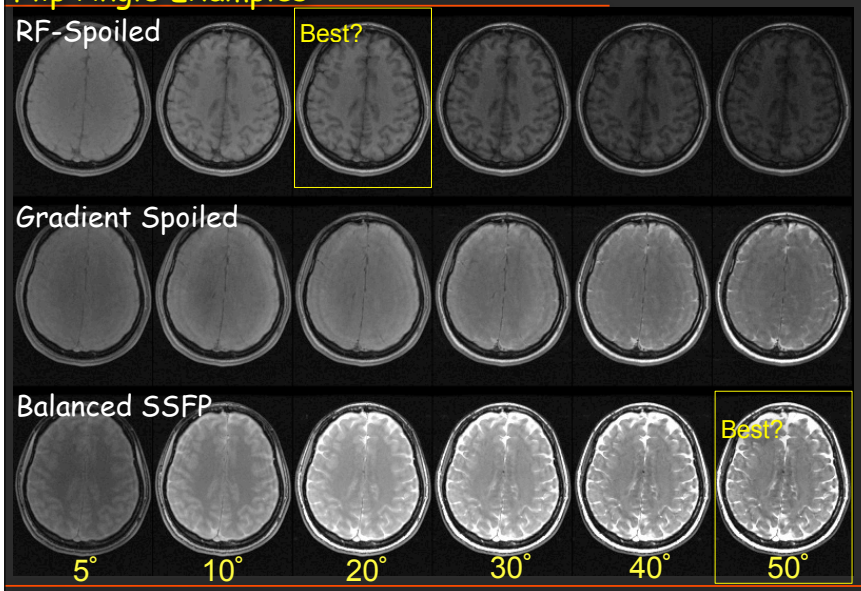
Flip Angle Selection?

The best flip angle to use is found by:

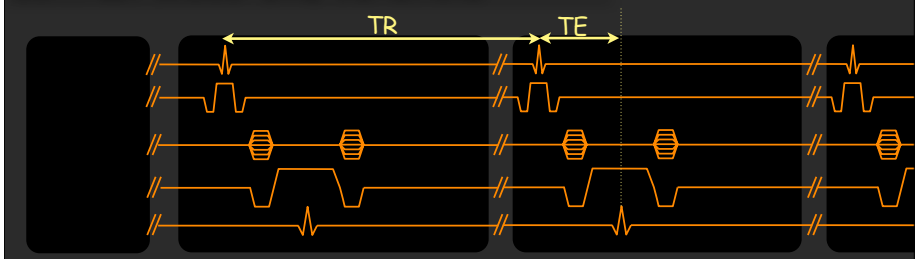
3) Both 1 and 2: maximizing SNR and contrast (CNR)



Flip Angle Examples



Contrast Knobs: GRE Variations

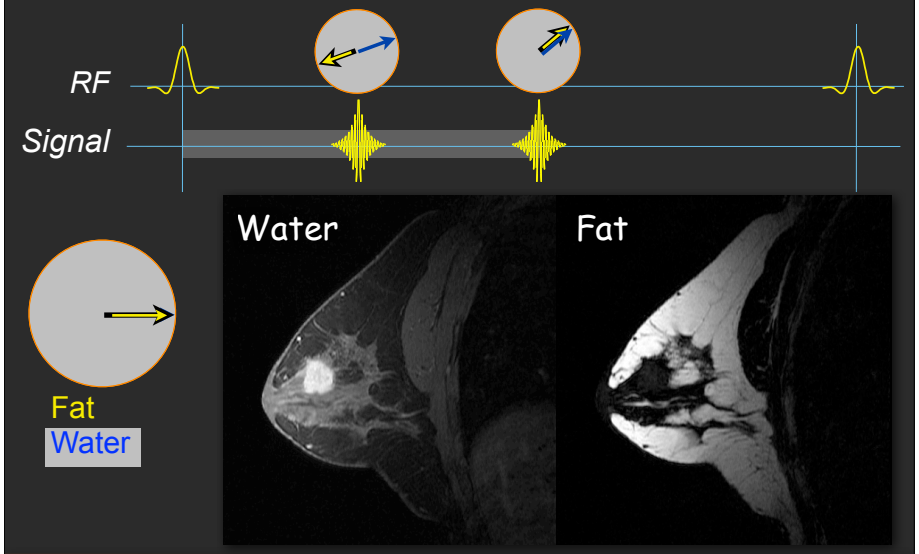


- Spoiling (sequence)
- RF: Flip / Phase
- Timing (TR, TE)
- Preparation Sequence

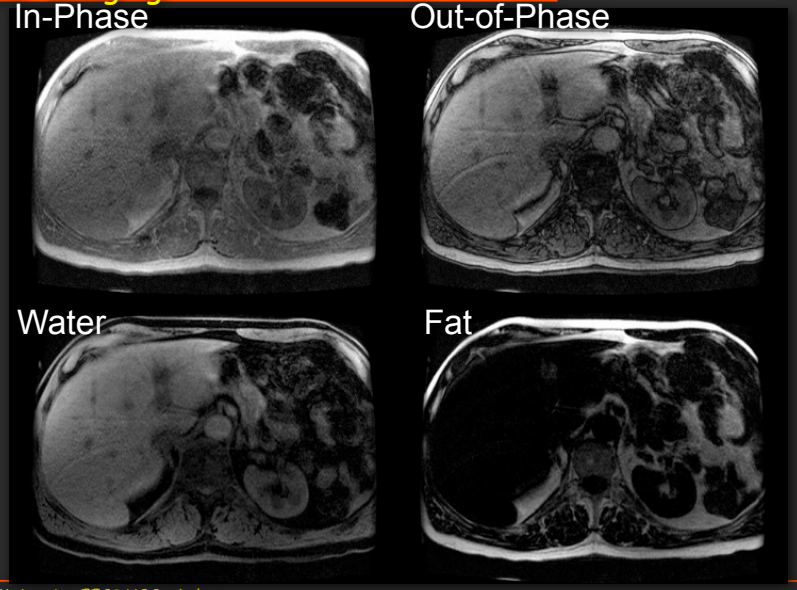
Echo Time (TE) Considerations

- Longer TE: T2* weighting (BOLD, Perfusion)
  - BOLD Imaging for fMRI
  - T2*-weighted perfusion
- Short TE
  - Reduced flow/motion sensitivity
  - Reduced T2* weighting
- In-phase and Out-of-phase TE
  - Water/Fat cancellation, Dixon Imaging

Dixon-Based Imaging



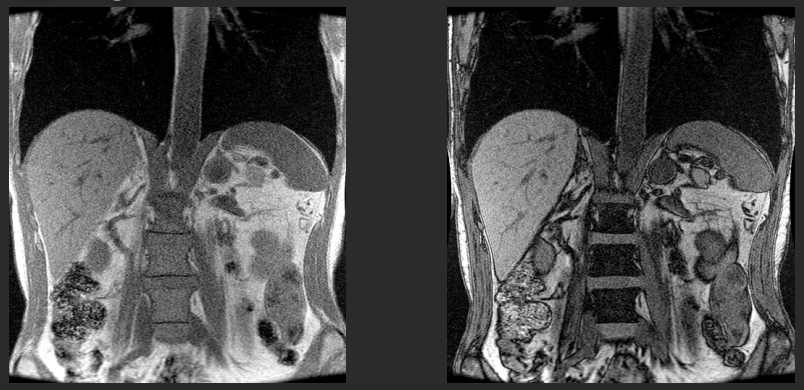
Liver Imaging



Question

Gradient spoiled images - which is opposed phase?

1) Left
2) Right

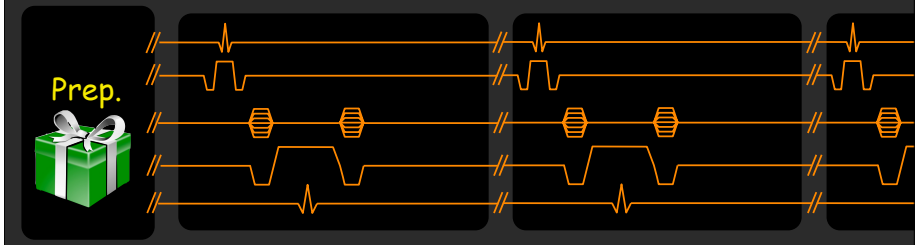


Gradient Spoiling: TE Effects

2) Right

Left adrenal lesion with signal loss on opposed phase imaging – Diagnosis Benign Adenoma

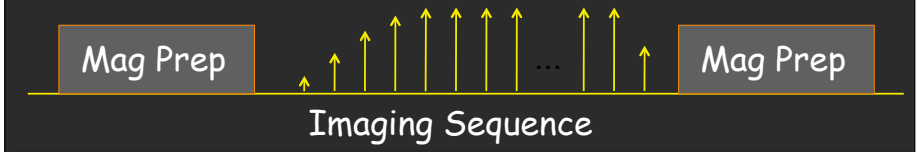
Contrast Knobs: GRE Variations



- Spoiling (sequence)
- RF: Flip / Phase
- Timing (TR, TE)
- Preparation Sequence

Preparation Options

- Fat Saturation
- Inversion - Recovery
- Myocardial Tagging
- T2-prep
- Magnetization Transfer

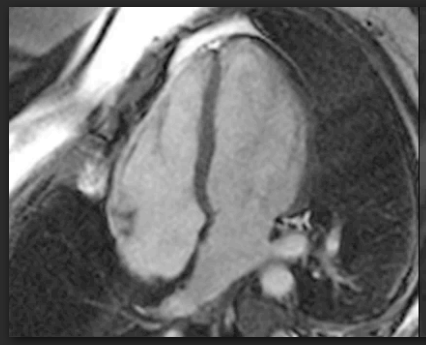


Fat Saturation Example

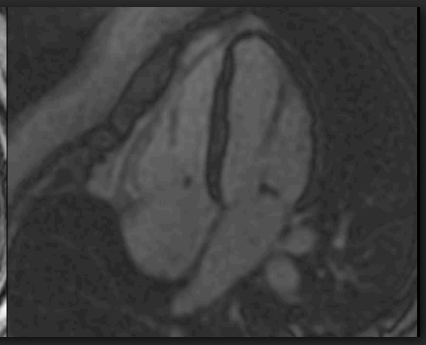
Not Fat-Sat RF-Spoiled

Fat Sat RF-Spoiled

Cardiac: bSSFP and IR-RF-Spoiled

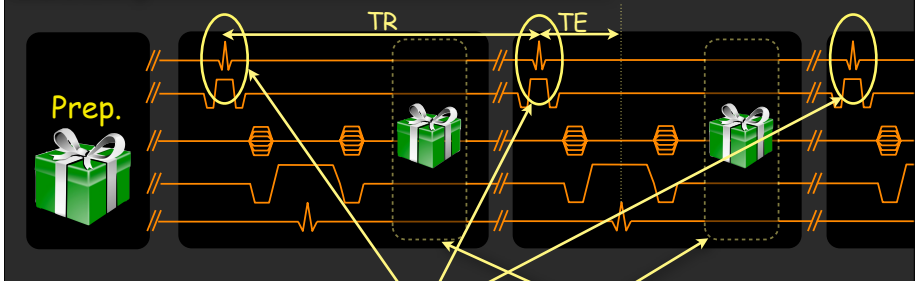


Balanced SSFP



IR-Prep RF-Spoiled

Summary



- Spoiling (sequence)
- RF: Flip / Phase
- Timing (TR, TE)
- Preparation Sequence

Summary and Acronyms

- RF spoiled
  - SPGR, FLASH, T1-FFE, RF-spoiled FAST
- Balanced SSFP
  - True-FISP, FIESTA, balanced FFE, BASG
- Gradient spoiled
  - FFE, FISP, GRASS, GRE, FAST, Field Echo
- Vendor acronyms are confusing -- Demand that they tell you what it really is...!
- Acronym source: mr-tip.com

Slide Acknowledgements

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