Chapter 18
Fast Imaging in the Steady State

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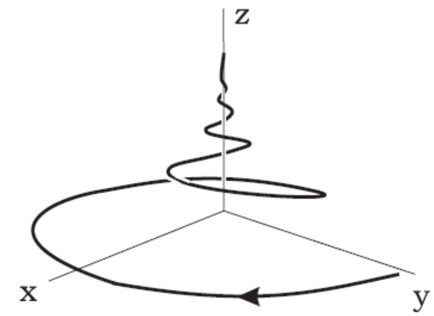
- **Previous classes:**
  - MR Signal detection (chap.8)
  - T1, T2 and T2*, GE and SE (chap.8)
  - T1 weighted contrast (chap. 15)
- **Today's content**
  - Short-TR, Spoiled, Gradient Echo Imaging
  - Short-TR, Coherent, Gradient Echo Imaging
  - Understanding Spoiling Mechanisms

Review

- MR signal recovery - T1
- MR signal decay - T2(*)
- When thinking of T1 and T2(*)
  - T1 is independent of T2(*)
  - B0-parallel M component described by T1
  - B0-perpendicular M components described by T2(*)



(Fig. 4.3)

$$M_z(t) = M_0(1 - e^{-t/T1})$$

Review

- MRI data acquisition
  - K-space filling (Cartesian/radial/spiral/…)
- Why fast imaging?
  - Shorter scan time, reduce artifacts/discomfort/costs
  - Specific image contrast
- How to achieve fast imaging?
  - TA = TR x Npe x Npar / TurboFactor
- Rapidly repeating excitation will lead to:
  - M_z not fully recovered at the end of TR
  - M_{xy} not fully decayed at the end of TR
  - A steady state of Mz and Mxy before each excitation, different than equilibrium

Steady State Incoherent (SSI)

- SSI: Residual Mxy is destroyed at the end of each TR

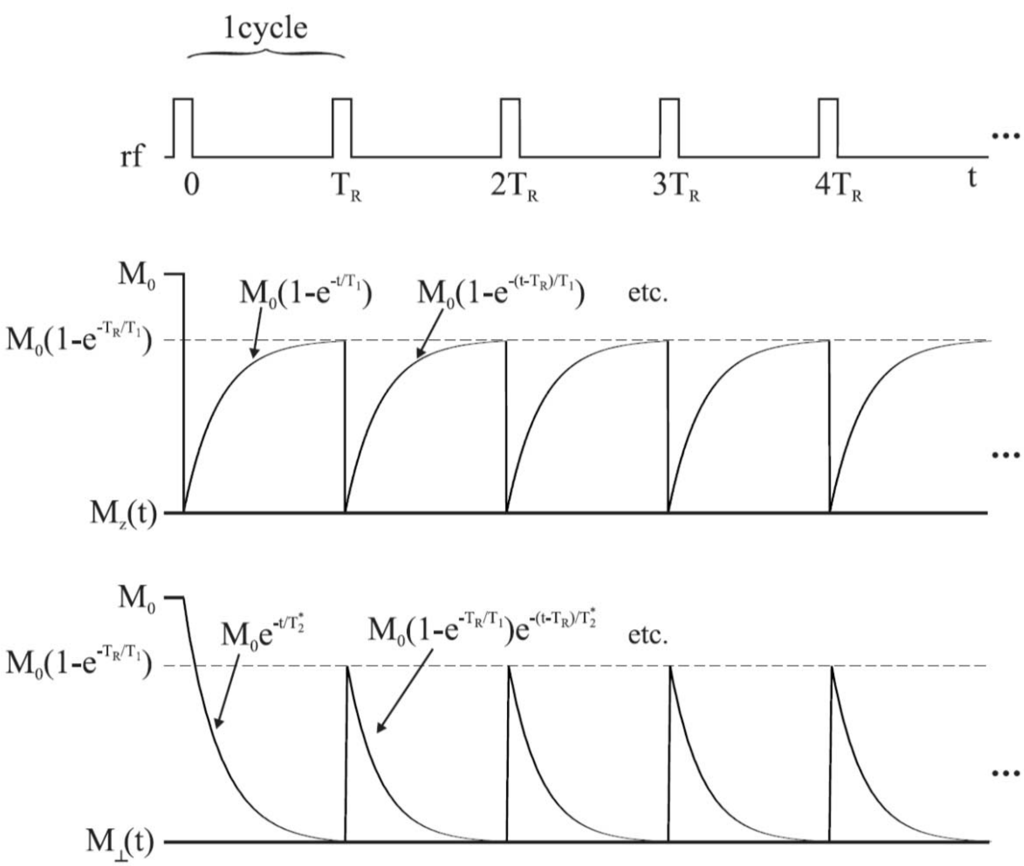


Fig. 8.6 SSI built up for 90° pulses

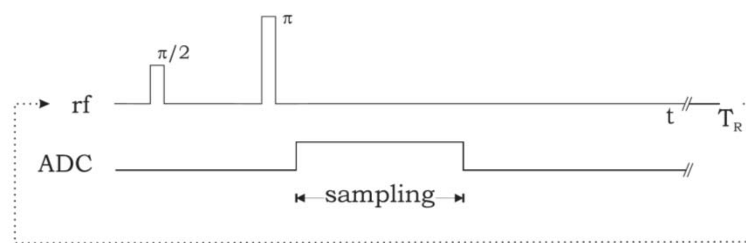


Fig. 8.8 SSI built up for SE

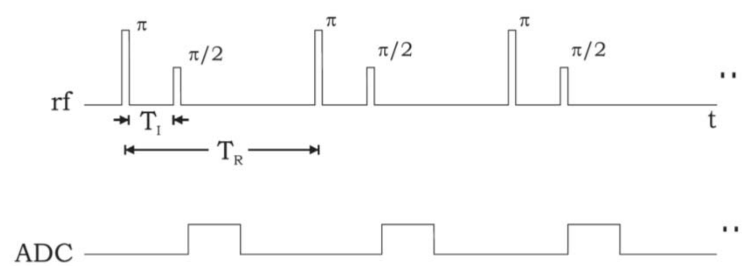


Fig. 8.12 SSI built up for IR FID

Steady State Incoherent (SSI)

- Before n_{th} rf pulse (or TR)
  - $M_{xy}(nTR^-)$=0 and $M_z(nTR^-)$
- After n_{th} rf pulse (flip angle θ)
  - $M_{xy}(nTR^+) = M_z(nTR^-)sin\theta$
  - $M_z(nTR^+) = M_z(nTR^-)cos\theta$
- During n_{th} TR ($t_n \equiv t - nTR$)
  - $M_{xy}(t_n) = M_{xy}(nTR^+)e^{-t_n/T_2}$
  - $M_z(t_n) = M_z(nTR^+)e^{-t_n/T_1} + M_0(1 - e^{-t_n/T_1})$
- When t_n = TR, i.e. before $(n+1)_{th}$ rf pulse
  - $M_{xy}\big((n+1)TR^-\big) = M_{xy}(nTR^+)E2$
  - $M_z\big((n+1)TR^-\big) = M_z(nTR^+)E1 + M_0(1 - E1) = M_z(nTR^-)$

Spoiled to zero!

(E1=e^{-TR/T_1} and E2=e^{-TR/T_2})

Steady State Incoherent (SSI)

- SSI for GRE/FID:

$$M_{ze} = \frac{M_0(1 - E1)}{(1 - E1cos\theta)}$$

- Question
  - SSI for SE? for IR?

- SSI echo signal:

$$M_{xy}(\theta, t_n) = M_{ze} sin\theta e^{-TE/T_2*}$$

- Popular sequence
  - FLASH (Fast Low Angle Shot)
  - GRE

Steady State Incoherent (SSI)

$$M_{xy}(\theta) = \frac{M_0(1 - E1)}{(1 - E1cos\theta)} sin\theta$$

- When TR<<T1 & θ<< θ_E (PD-W)
  - $E1 \approx 1 - \frac{TR}{T_1}, sin\theta \approx \theta, cos\theta \approx 1 - \frac{\theta^2}{2}$

$$=> \quad M_{xy}(\theta) \approx \frac{M_0 \cdot \frac{TR}{T1} \cdot \theta}{1 - \left(1 - \frac{TR}{T1}\right)\left(1 - \frac{\theta^2}{2}\right)} \approx \frac{M_0 \theta}{1 + (\frac{\theta}{\theta_E})^2}$$

  - Empirical: θ is considered small if θ< $\theta_E/3$

- When TR<<T1 & θ=90° (T1-W)
  - $M_{xy}(90°) \approx M_0 \frac{TR}{T_1}$

Steady State Incoherent (SSI)

- Ernst angle
  - Flip angle for maximal signal with certain TR and T1
  - $\theta_E \equiv \cos^{-1}(E1) \approx \sqrt{\frac{2TR}{T_1}}$
  - Relative constant contrast for $\theta > \theta_E$

Tissue	ρ_0	T_1 (ms)	T_2 (ms)
CSF	1.0	4500	2200
WM	0.65	600	80
GM	0.8	950	100
fatty tissue	0.9	250	60

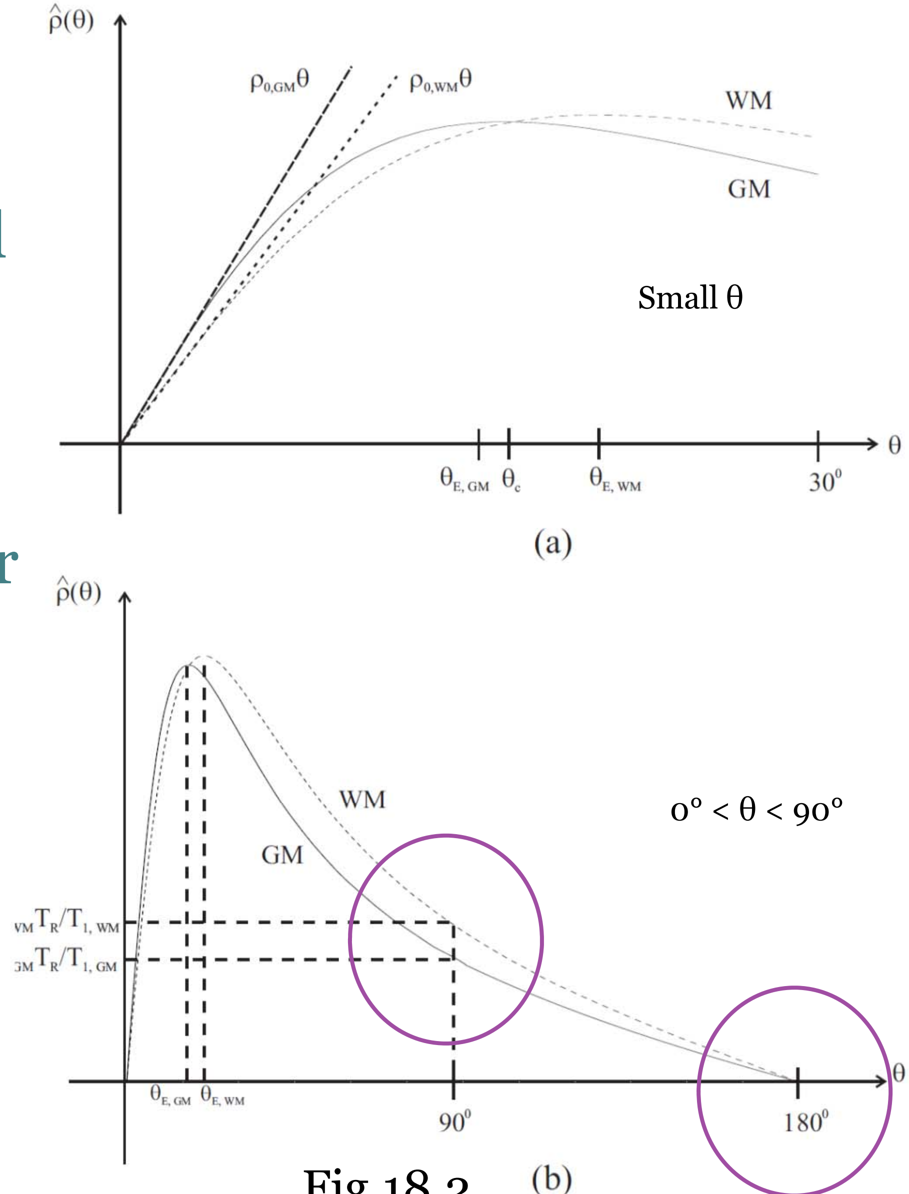


Fig.18.2

Steady State Incoherent (SSI)

- CNR of SSI signal

$$CNR(\theta) = \frac{\rho(\theta, T_1) - \rho(\theta, T_1 \pm \delta T_1)}{\sigma_0}$$

$$\Big\downarrow \; \delta T_1 << T_1$$

$$CNR(\theta) = \frac{\rho_0 E_1 \delta T_1 TR \sin\theta (1 - \cos\theta)}{\sigma_0 T_1^2 (1 - E_1 \cos\theta)^2}$$

$$\Big\downarrow \; \frac{dCNR(\theta)}{d\theta} = 0$$

$$cos\theta_c = \frac{2E_1 - 1}{2 - E_1} \quad \xrightarrow[\text{TR} << T_1]{} \quad cos\theta_c \approx \sqrt{3}\theta_E$$

Steady State Incoherent (SSI)

- CNR of SSI signal

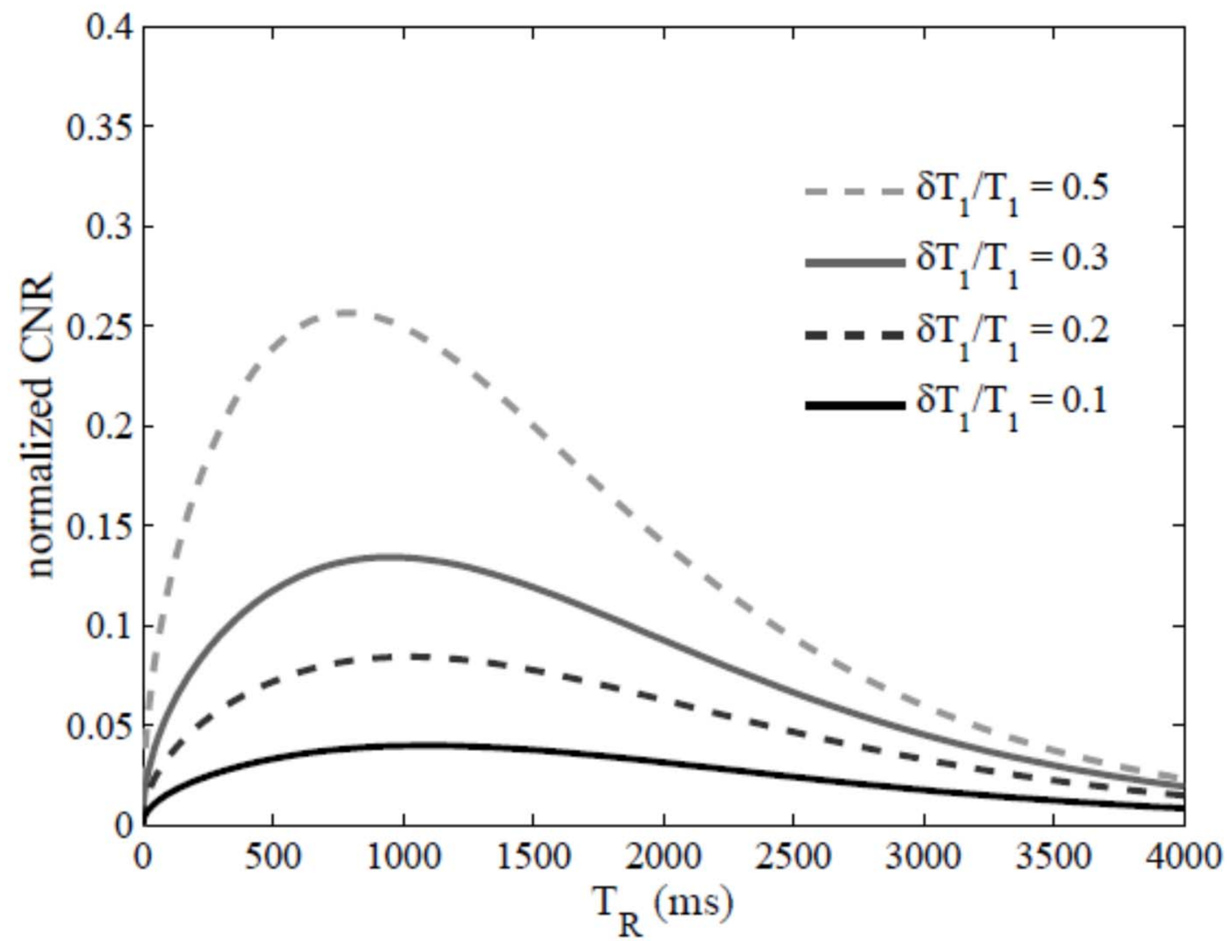
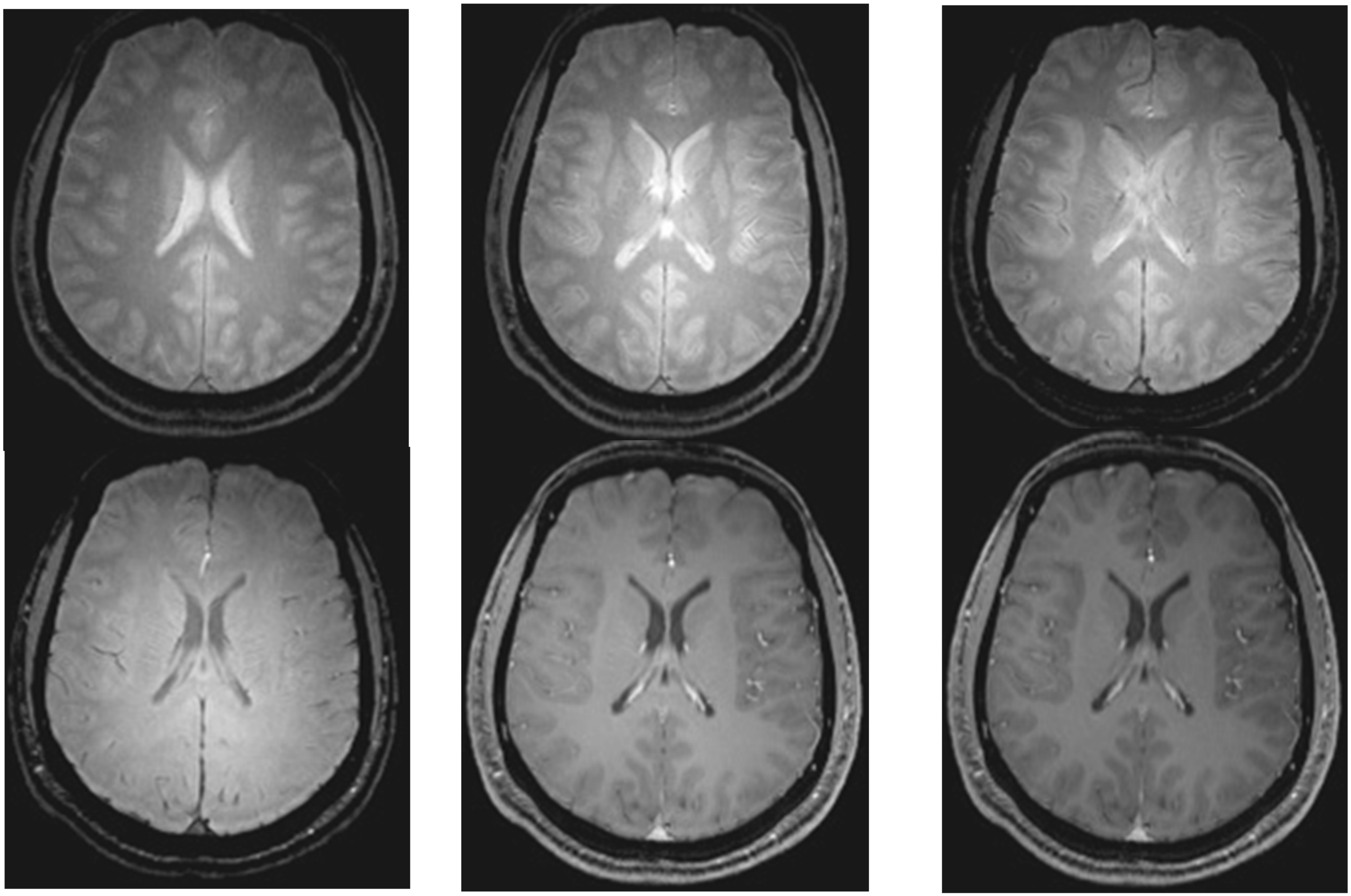


Fig. 18.4

TR=20msec @ 4T field strength

FA = 1 FA = 2 FA = 4



FA = 8 FA = 15 FA = 20

Data from Dr. Neelavalli

Steady State Incoherent (SSI)

- Building up SSI from equilibrium
  - The number of rf pulses needed to reach SSI at θ_E

$$n_\alpha = [-\frac{T_1}{2TR} ln\alpha - \frac{1}{2}]$$

(α is the target relative error)

  - $\theta = 0°, then\ n_\alpha = \infty$
  - $\theta = 90°, then\ n_\alpha = 1$

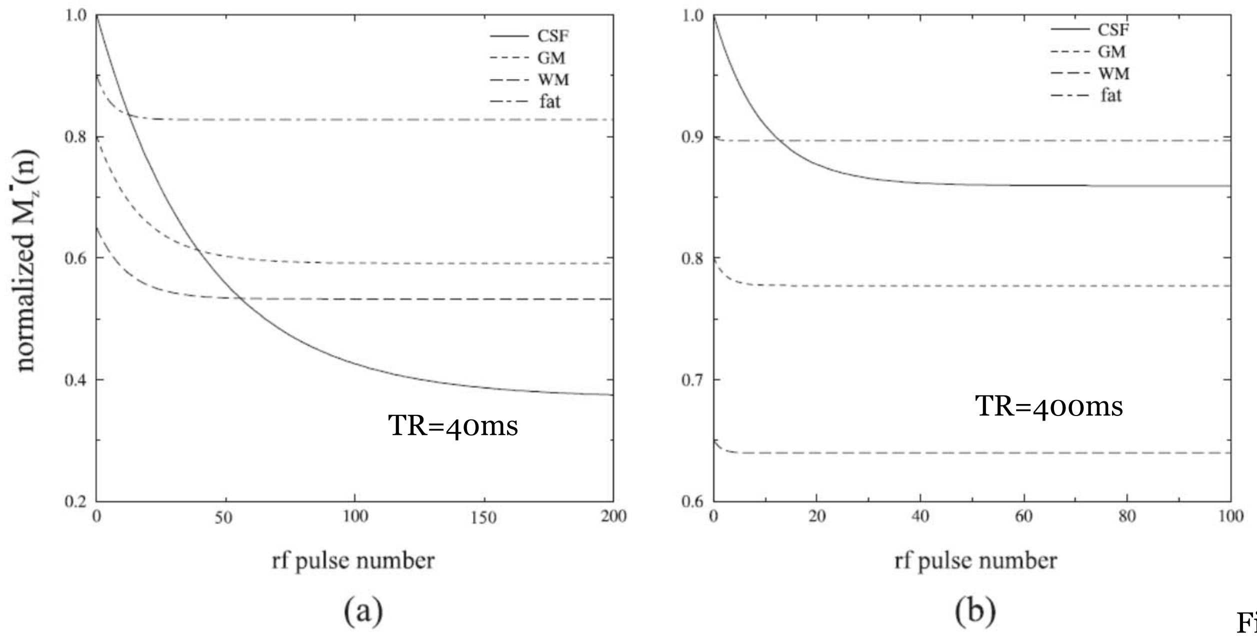
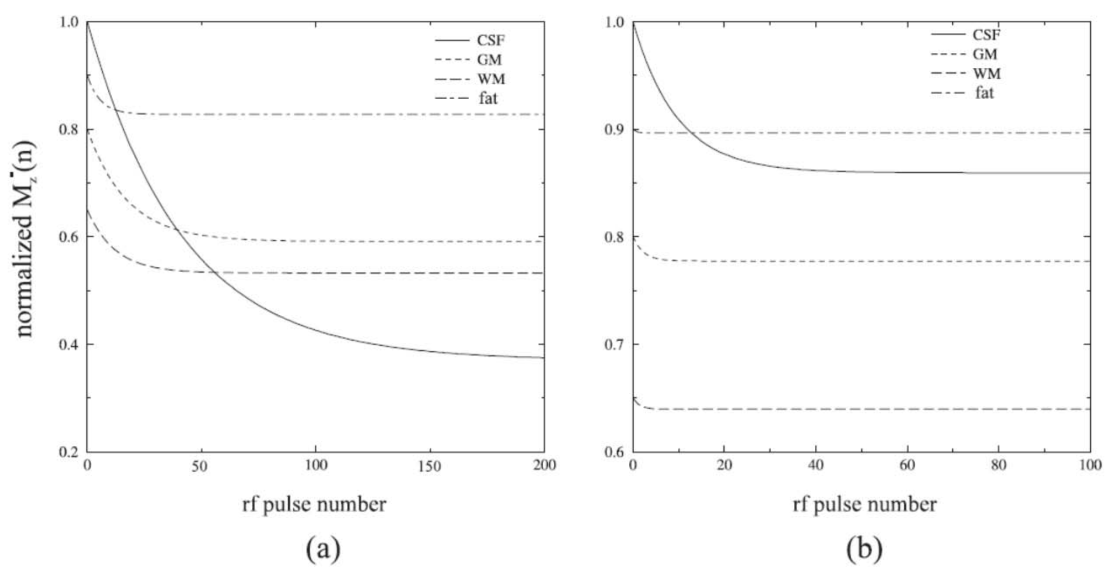


Fig. 18.5

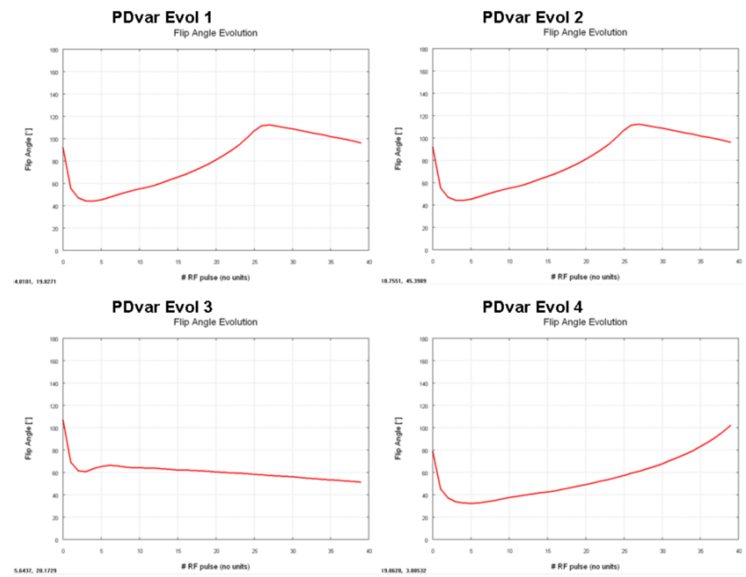
Steady State Incoherent (SSI)

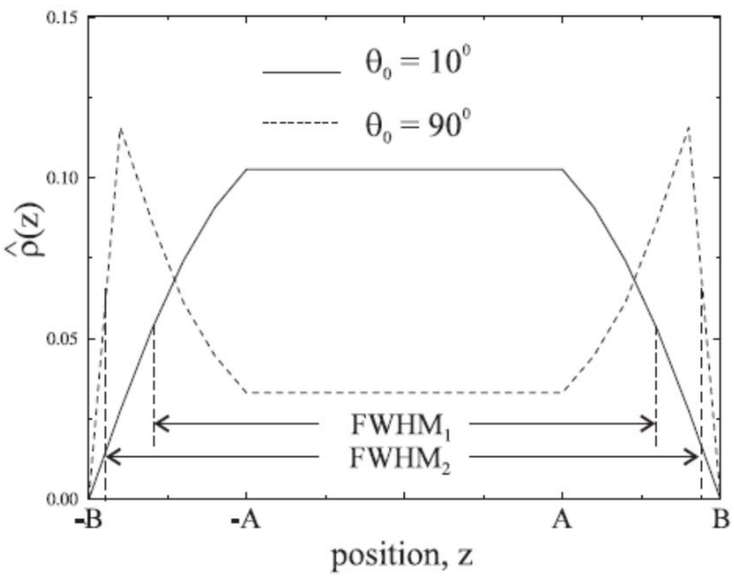
- Collecting signal before SSI is reached
  - 2D vs. 3D
  - May cause filtering effects in k-space
  - May cause T1 shrine through effects
  - May help enhance edge information for high resolution imaging
  - Quicker scan



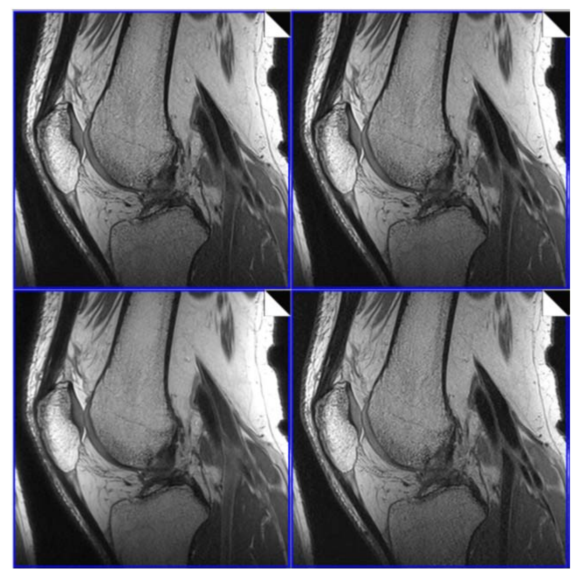
Steady State Incoherent (SSI)

- Other considerations
  - Forced constant M_{xy}
  - Non-ideal 2D Slice Profile





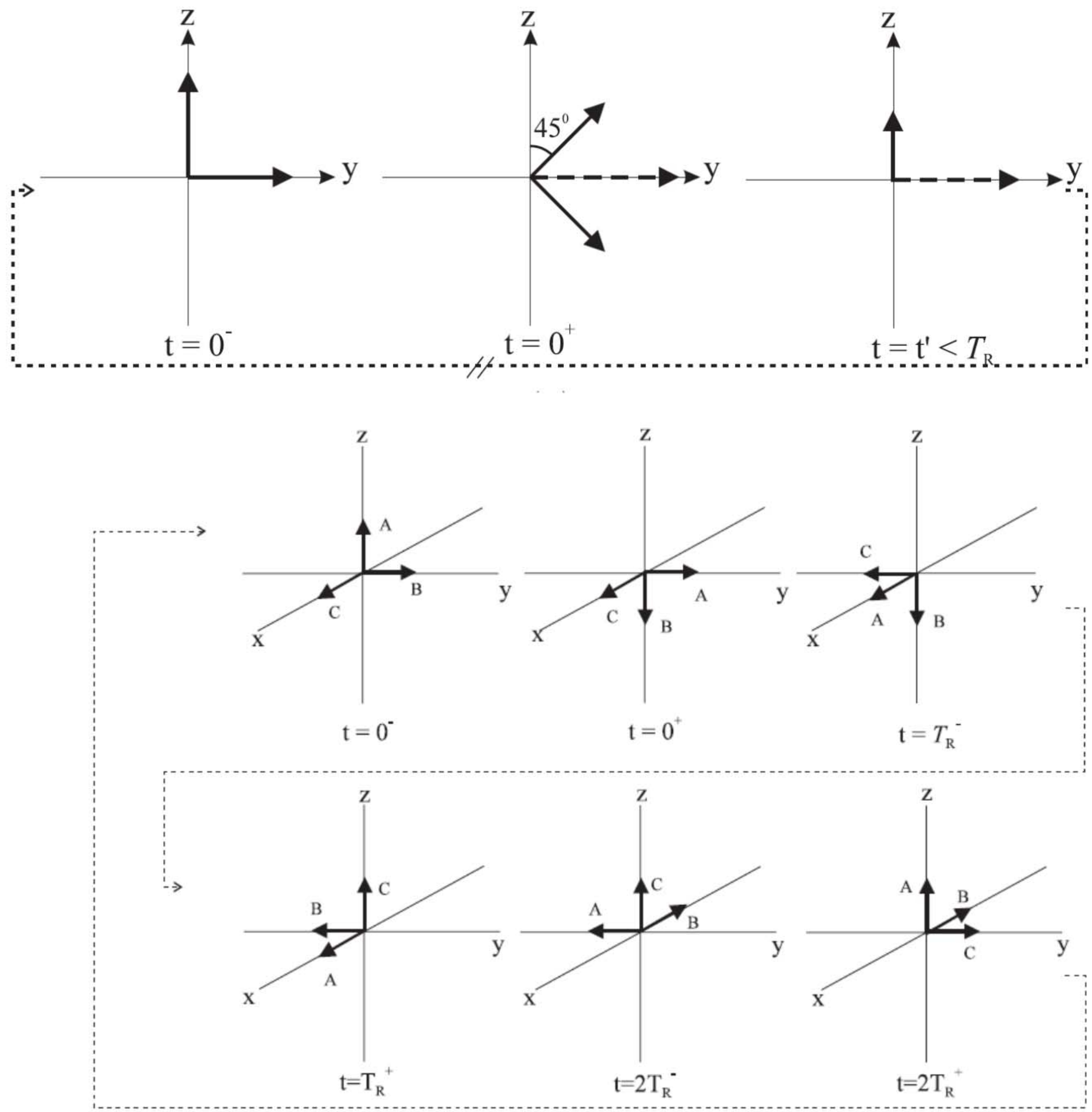
Example:
SPACE
(TSE w/ Variable flip angle, Siemens)



Steady State Coherent (SSC)

- Residual M_{xy} is preserved at the end of each TR, and may contribute to the signal detected in the subsequent TRs

- Multiple schemes for coherent built up
  - RF pulse (freq, phase, B1)
  - Gradient (balanced/ imbalanced)
  - Timing



Steady State Coherent (SSC)

- SSC signal is determined by the total precession angle of the transverse magnetization components during each TR

$$\beta_{total}(TR) = \gamma \Delta B TR + \gamma \vec{r} \int_0^{TR} \vec{G}\,(t)dt$$

Resonance Offset Angle

- Field inhomogeneity
- RF frequency offset
- Chemical shift

Gradient
(Term should be zero for SSFP)

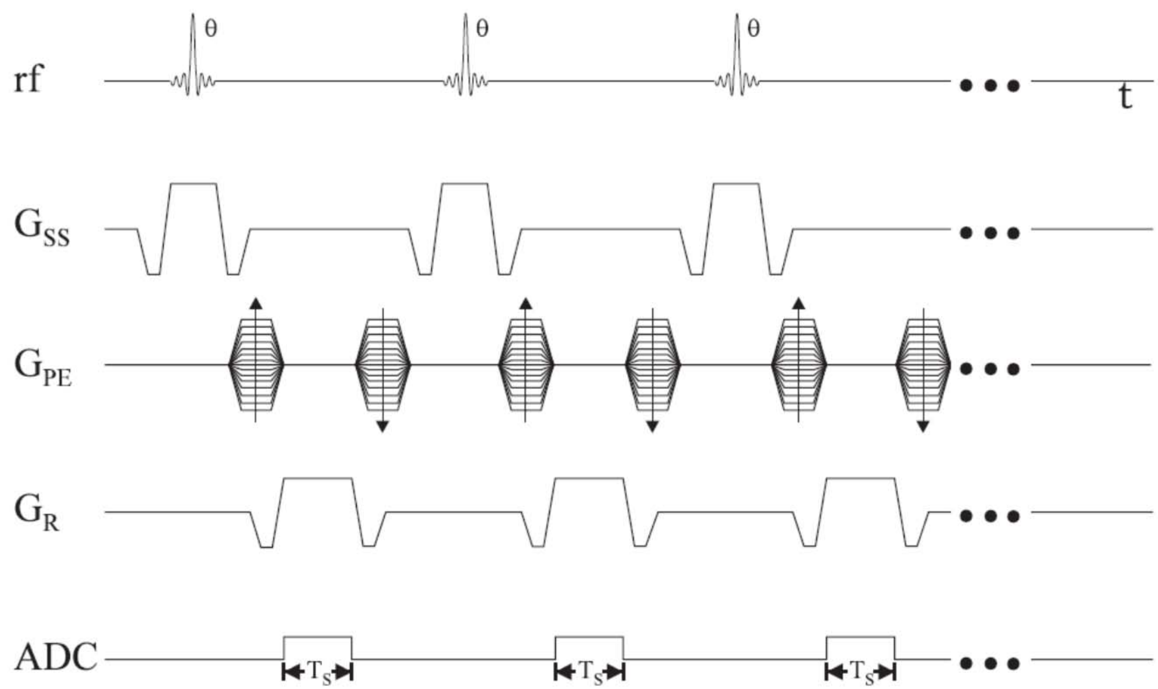
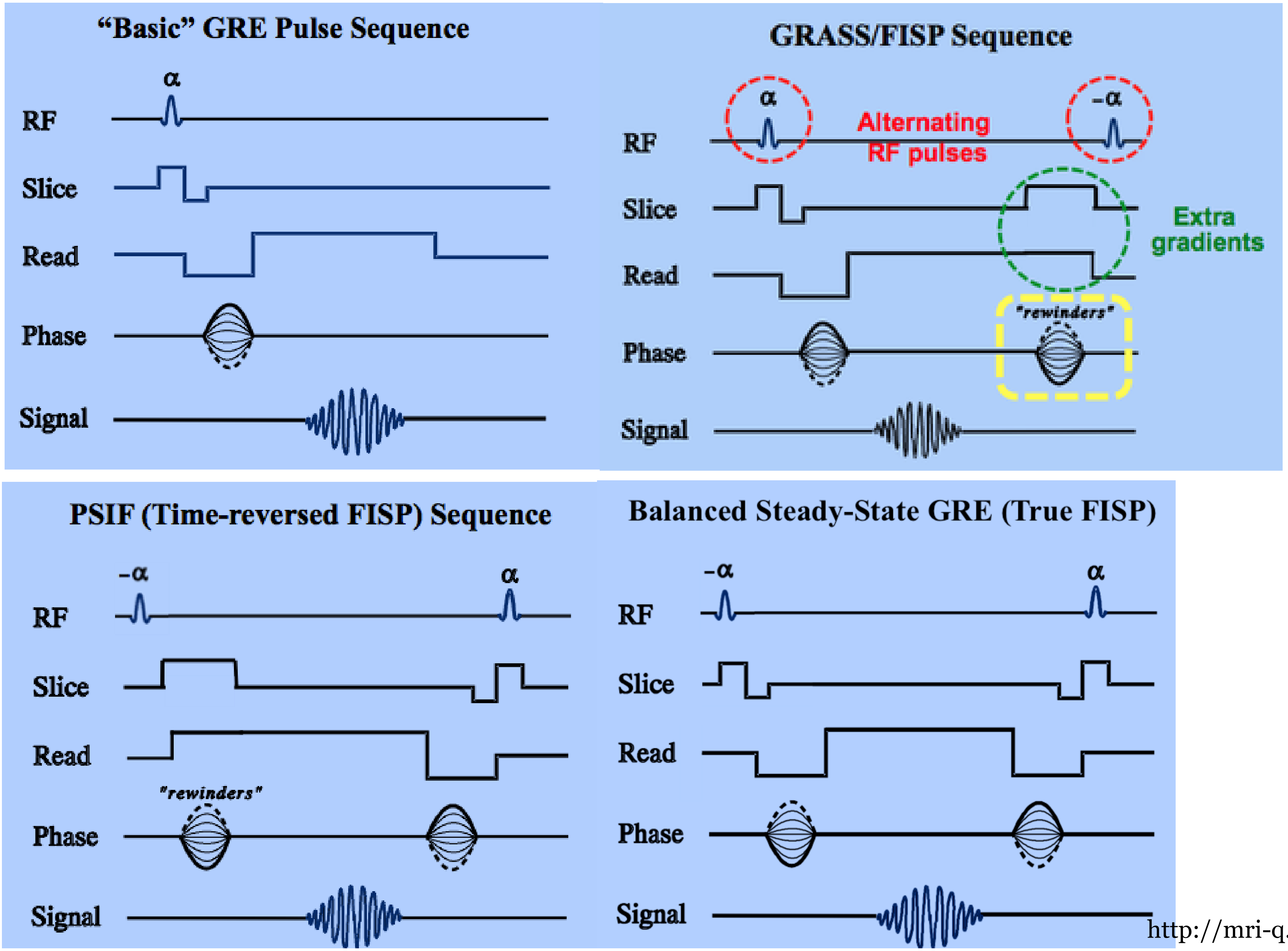


Fig. 18.12

GRE, SSFP, FISP, PSIF



http://mri-q.com/

SSFP

$$M_x^-(\infty) = M_0(1-E_1)\frac{E_2 \sin\theta \sin\beta}{d} \tag{18.64}$$

$$M_y^-(\infty) = M_0(1-E_1)\frac{E_2 \sin\theta(\cos\beta - E_2)}{d} \tag{18.65}$$

$$M_z^-(\infty) = M_0(1-E_1)\frac{[(1-E_2\cos\beta) - E_2\cos\theta(\cos\beta - E_2)]}{d} \tag{18.66}$$

and

$$M_x^+(\infty) = M_x^-(\infty)\,* \tag{18.67}$$

$$M_y^+(\infty) = M_0(1-E_1)\frac{\sin\theta(1-E_2\cos\beta)}{d} \tag{18.68}$$

$$M_z^+(\infty) = M_0(1-E_1)\frac{[E_2(E_2-\cos\beta) + (1-E_2\cos\beta)\cos\theta]}{d} \tag{18.69}$$

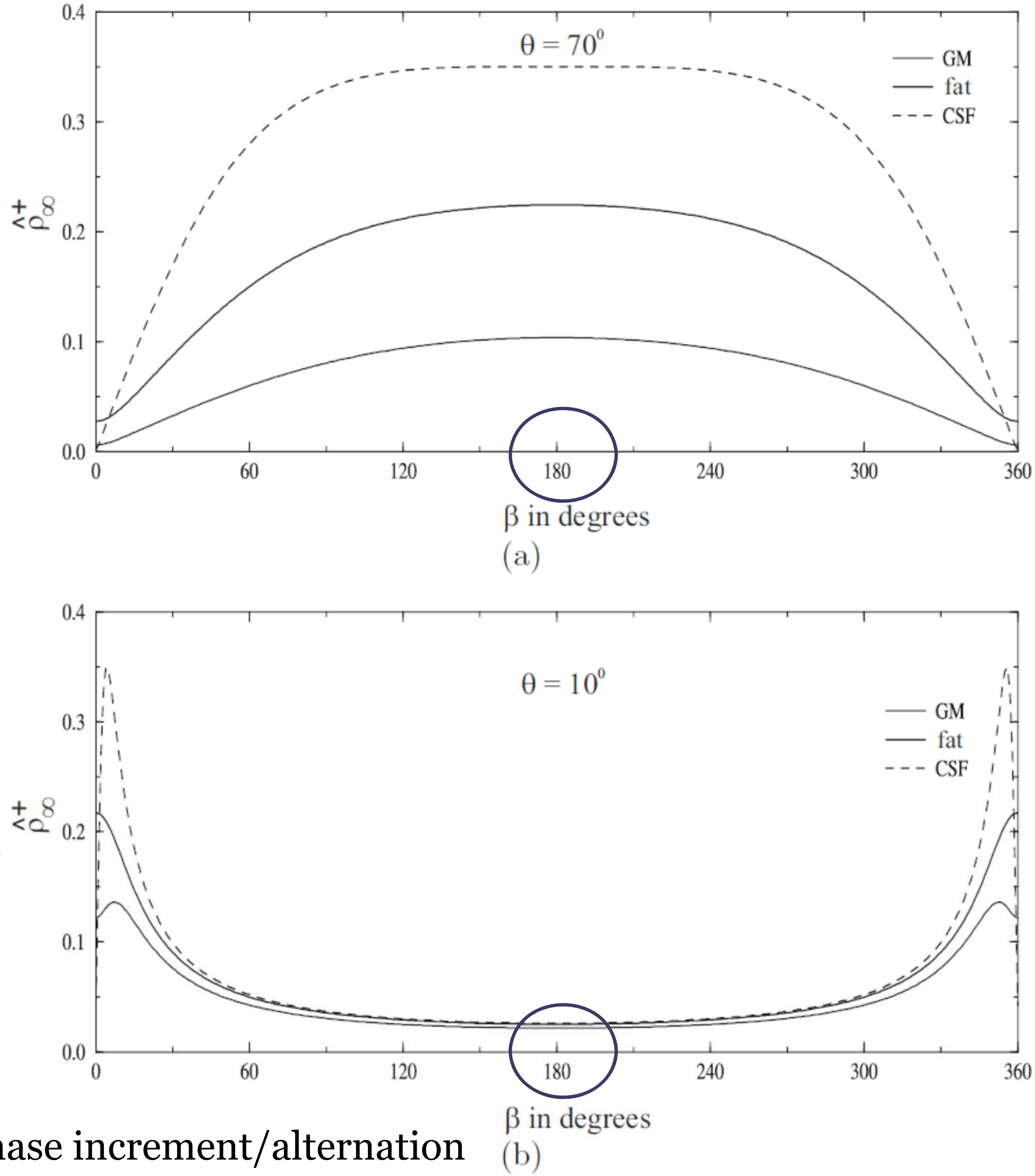
where $E_2 \equiv e^{-T_R/T_2}$ and

$$d = (1-E_1\cos\theta)(1-E_2\cos\beta) - E_2(E_1-\cos\theta)(E_2-\cos\beta) \tag{18.70}$$

* RF along x axis, or no RF phase increment/alternation

SSFP

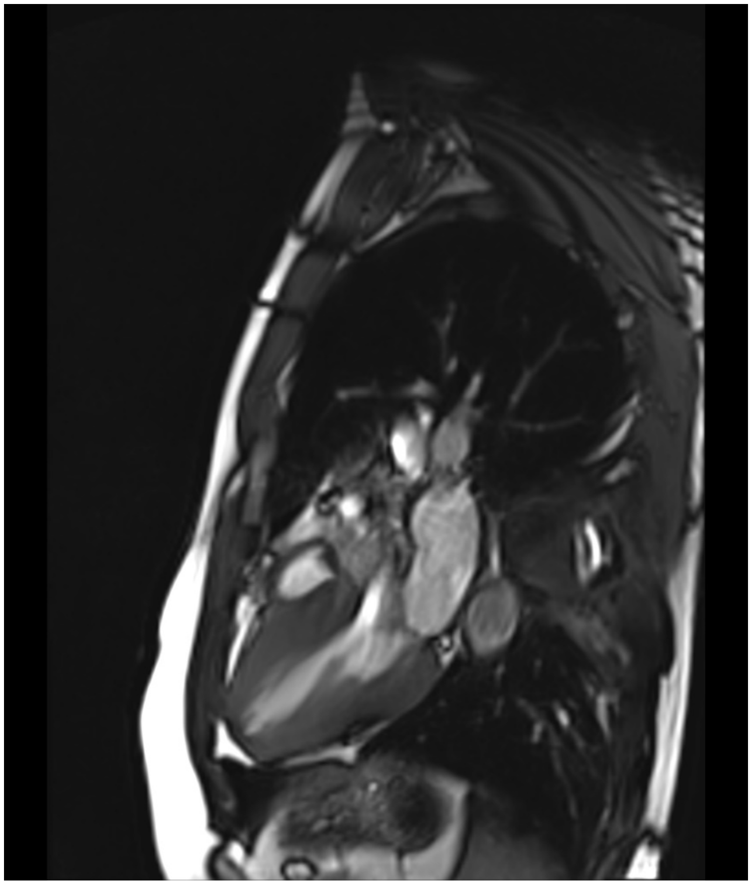
- Large FA
  - Uniform platform (passband)
  - Stopbands at 2nπ resonance offset angle
- Small FA
  - Uniform platform (stopband)
  - Passbands close to 2nπ resonance offset angle
  - Possible nulling point at 2nπ resonance offset angle
- The bandwidth of the platform?

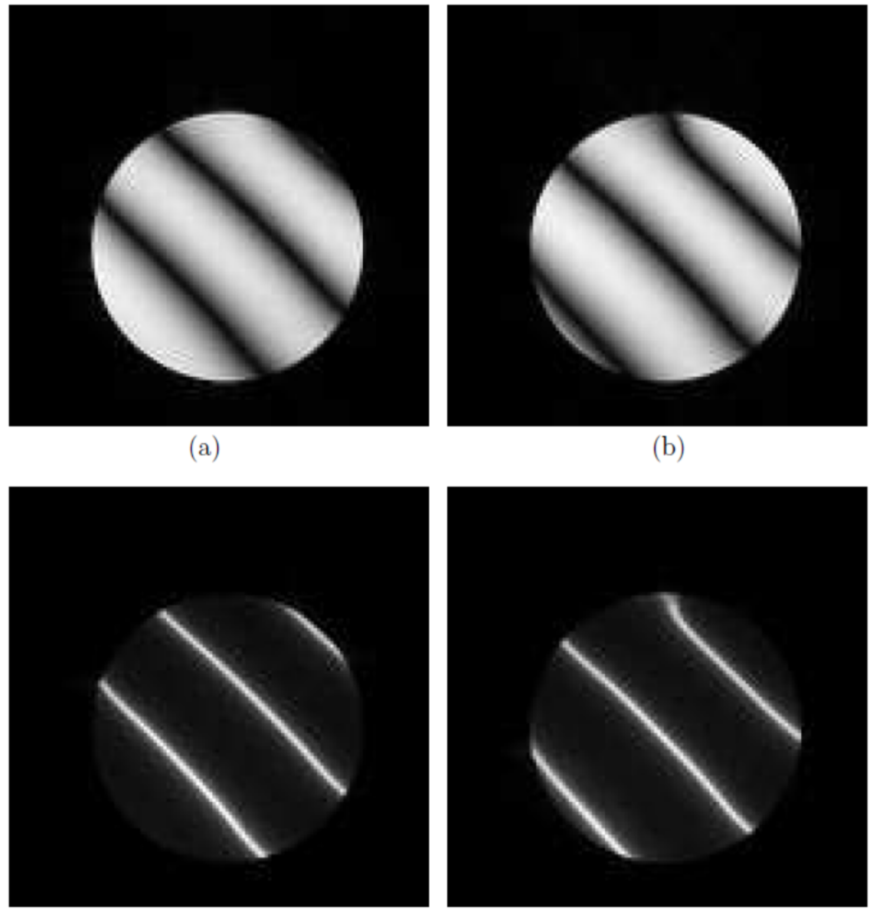


* No RF phase increment/alternation

SSFP

- Shifting Resonance Offset Angle via RF pulse (β_{rf})
  - $\beta_{total}(TR) = \gamma \Delta B TR + \gamma \vec{r} \int_0^{TR} \vec{G}(t)dt + \beta_{rf}$





(a)

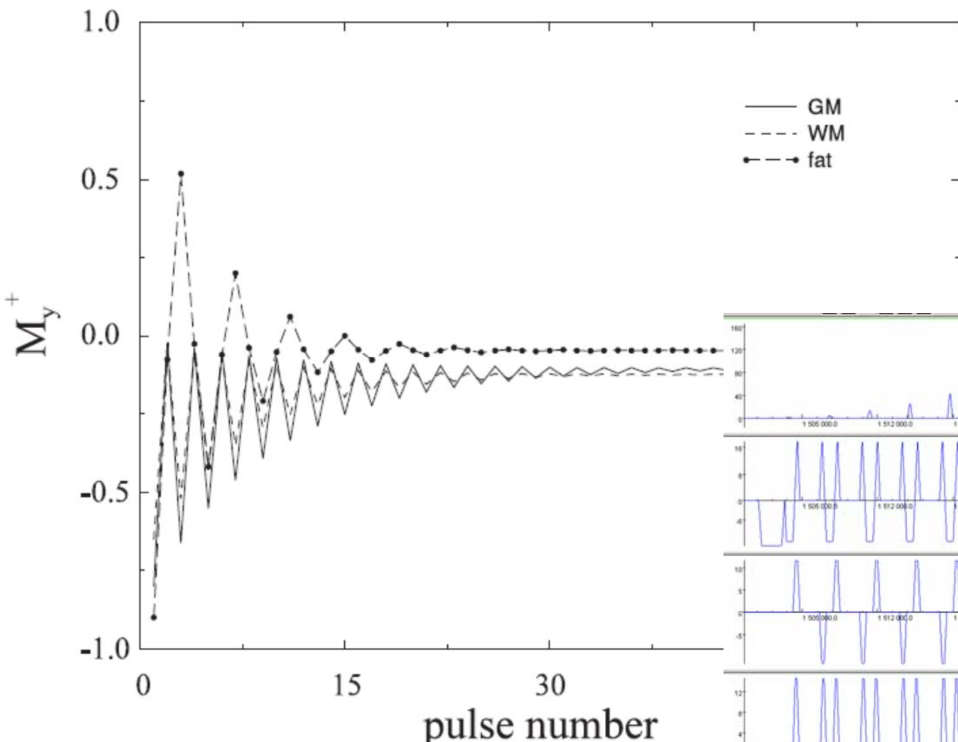
(b)

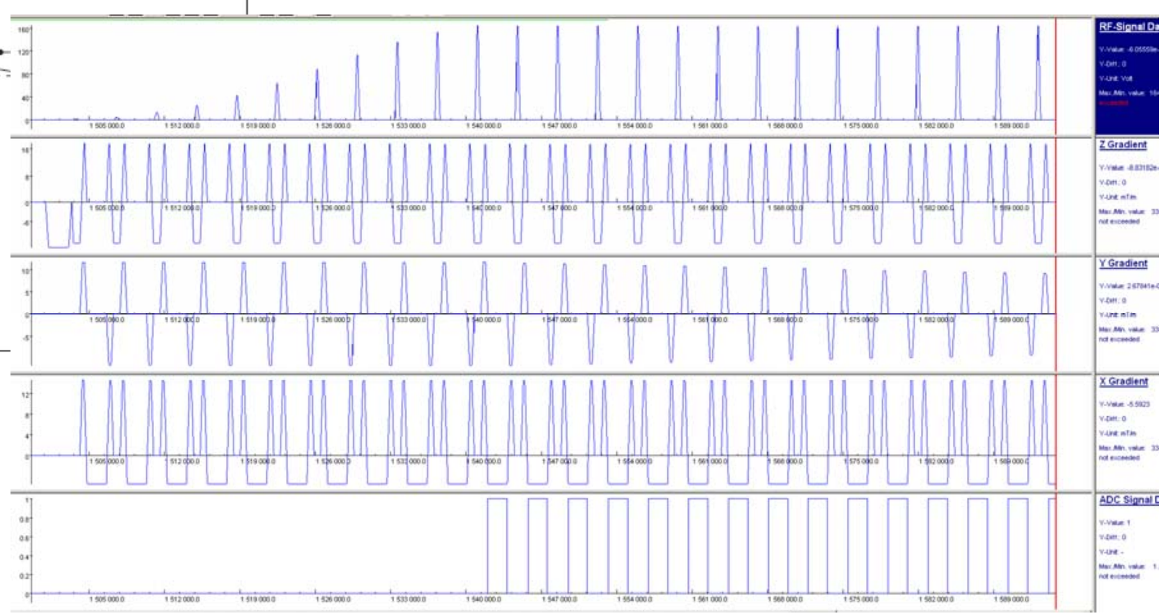
(c)

(d)

SSFP

- Reaching Steady State Coherent





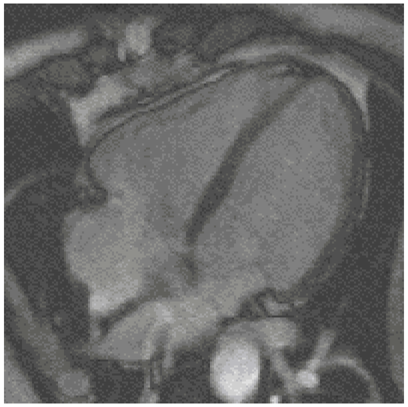
SSFP image contrast

- TR<<T2, T1

$$M_y^+(\infty) = \frac{M_0(1-E_1)\sin\theta}{(1-E_1\cos\theta)-E_2(E_1-\cos\theta)}$$

$$\simeq \frac{M_0\sin\theta}{\left(\frac{T_1}{T_2}+1\right)-\cos\theta\left(\frac{T_1}{T_2}-1\right)}$$

$$M_y^+(\infty)|_{\theta=\theta_{opt}} \simeq \frac{1}{2}M_0\sqrt{\frac{T_2}{T_1}}$$

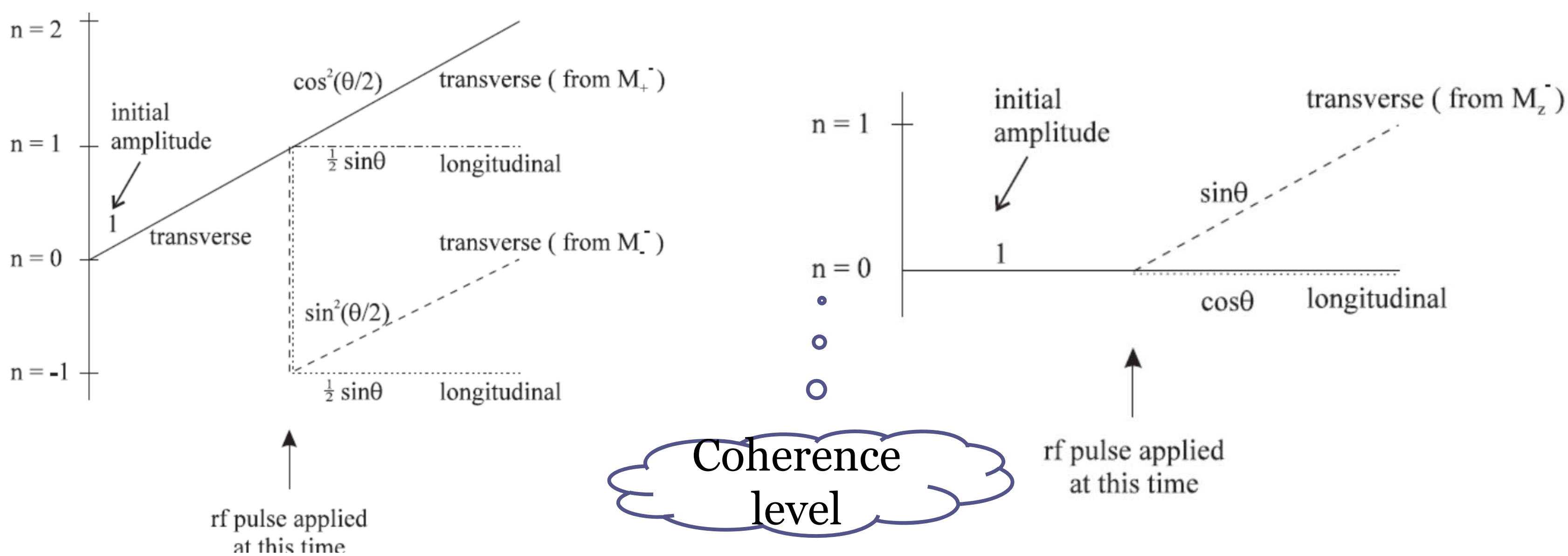


CSF and blood have high T2/T1 ratio:
Flow independent MRA

Spin phase pathways

- A single rf pulse's effect

Flip angle	Effective amplitude	Effect on prior transverse magnetization	Effect on prior longitudinal magnetization
0°	$\cos^2(\theta/2)$	stays as transverse magnetization; continues to evolve later	stays as longitudinal magnetization; continues regrowth towards M_0
90°	$\sin\theta$	tipped to longitudinal axis; storage of accumulated phase and inverted phase in equal numbers ($\frac{1}{2}\sin\theta$) during the following free precession period	tipping of fresh and stored magnetization to transverse plane
180°	$\sin^2(\theta/2)$	phase inverted; rephased later	magnetization inversion



Spin phase pathways

- Transverse pathway number: $T_n \equiv 3^{n-1}$
- Maximum echo number after the nth RF pulse:

$$E_n = \frac{T_n - 1}{2}$$

- Echo condition: coherence level back to zero

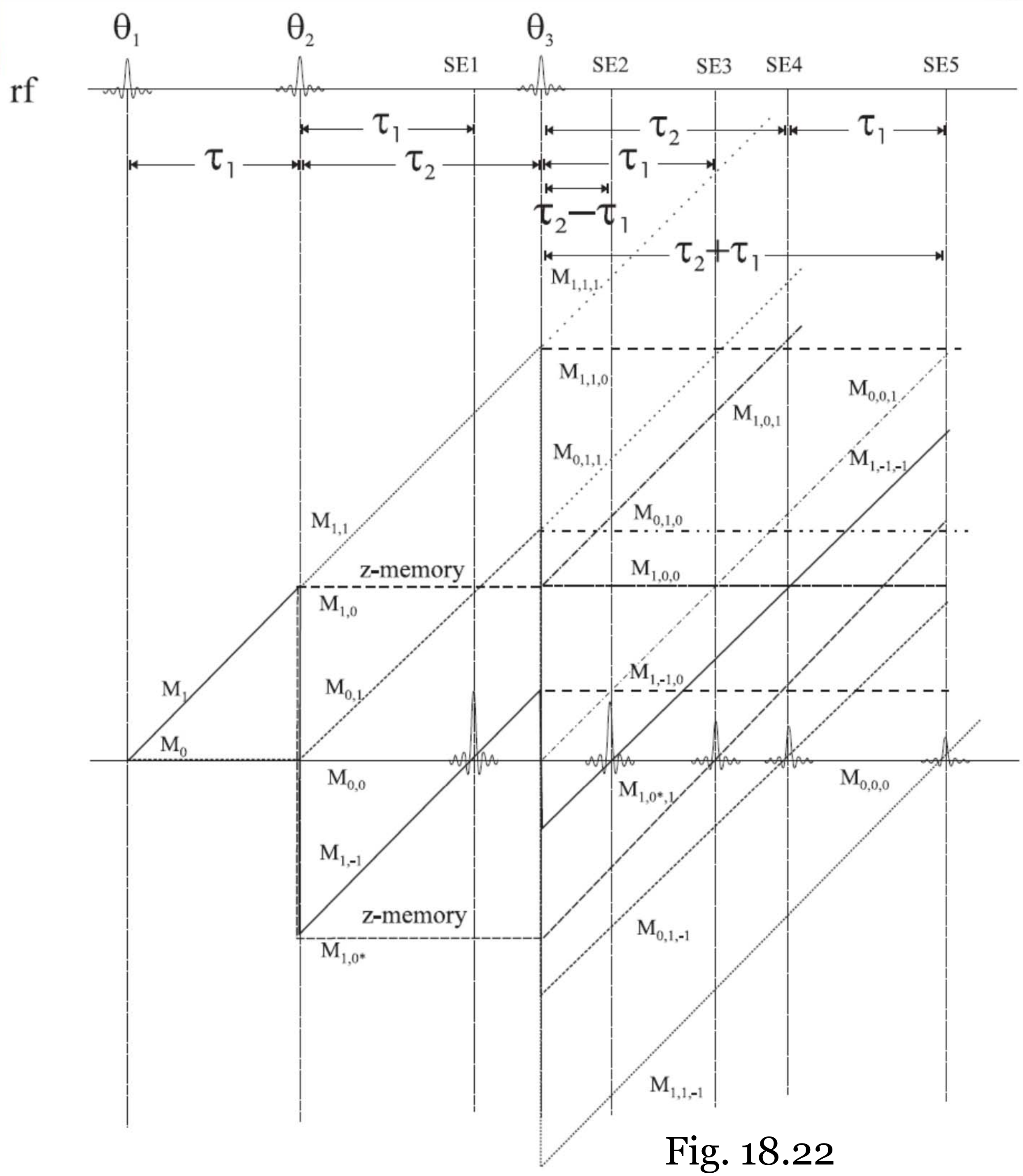
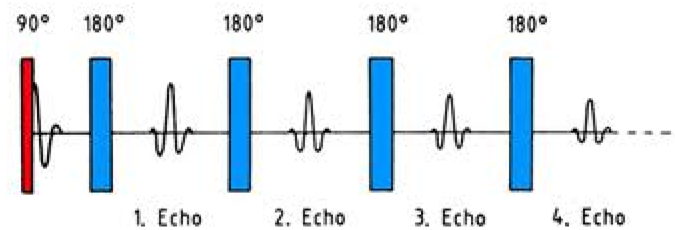
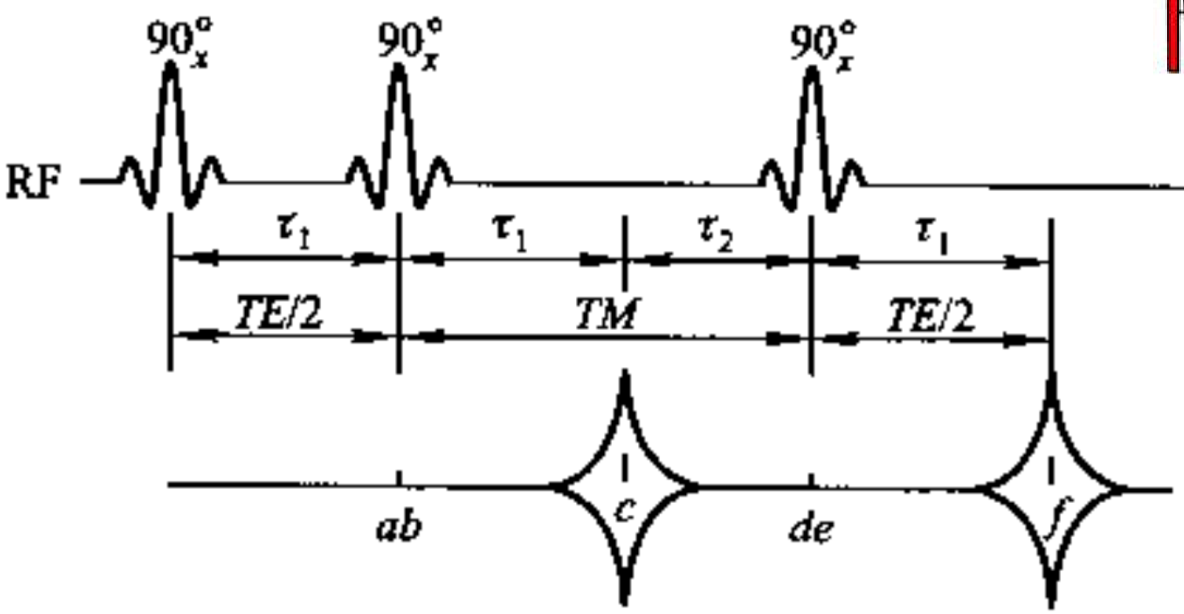


Fig. 18.22

Spin phase pathways

- Implications/application
  - Hahn's echo: use the 180° comp to 'refocus' signal phase
  - STEAM: use the 90° comp to store the signal phase
  - FSE: crush the 90° comp of refocusing pulses
  - SSFP: mixture of pathways





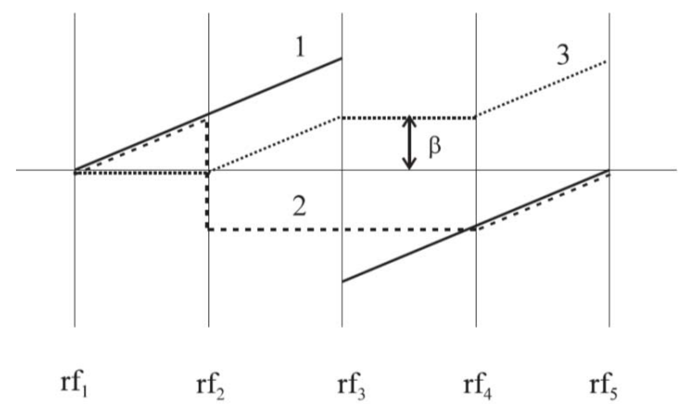


Fig. 18.25

SSFP summary

- Very fast sequences scanning sequences (typical TR 5-10ms), widely used in cardiac/abdomen imaging and MR angiography
- T2/T1 weighted
- SE or GE?
- High SAR with high FA
- Several derivative sequences

Generic Name	Refocused Signal(s)	Common Acronyms
SSFP-FID	FID (S+) alone	FISP, GRASS, FFE
SSFP-Echo	SE/STE (S−) alone	PSIF, SSFP, T2-FFE
SSFP-Double	FID and SE/STE acquired separately, then combined	DESS, MENSA
SSFP-Balanced	FID and SE/STE together	TrueFISP, FIESTA, Balanced-FFE

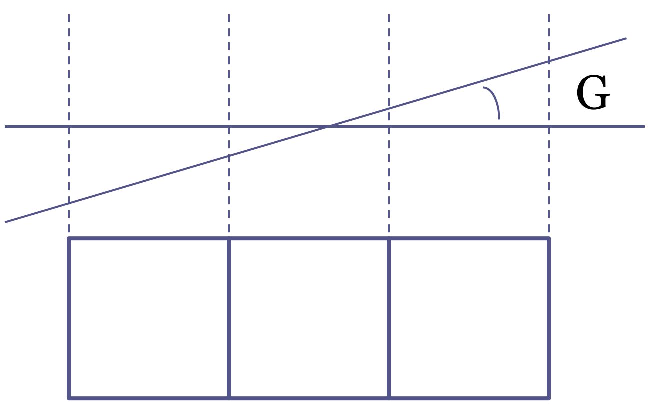
Signal spoiling mechanism

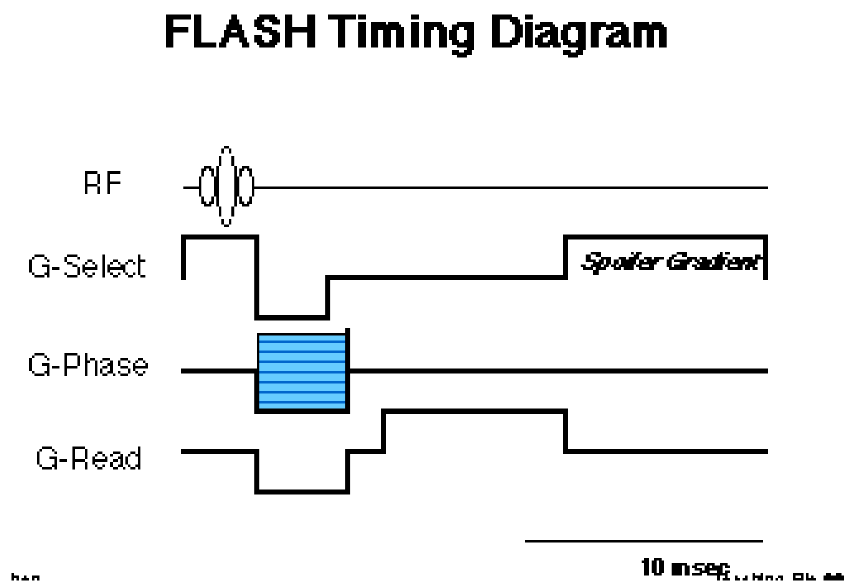
- Microscopically, M_{xy} from each spin cannot be forced to zero except due to T2 decay: ‘natural’ spoiling
- Macroscopically, M_{xy} from spins with different phase or from different spin phase pathways can cancel each other
- Means of signal spoiling: gradient or RF pulse

Gradient dephasing

- Introduce extra T2’ term
- For complete dephasing for each voxel:

$$\gamma \int dr^3 \int_0^{TR} dt \vec{r} \cdot \vec{G}(t) = 2\pi$$





RF spoiling

- Varying the phase of the rf pulse, $\varphi_{rf}(n)$, as a function of rf pulse number to create effective SSI signal

$$\varphi_{\mathrm{rf}}(n) \equiv n\epsilon_1 + \epsilon_0$$

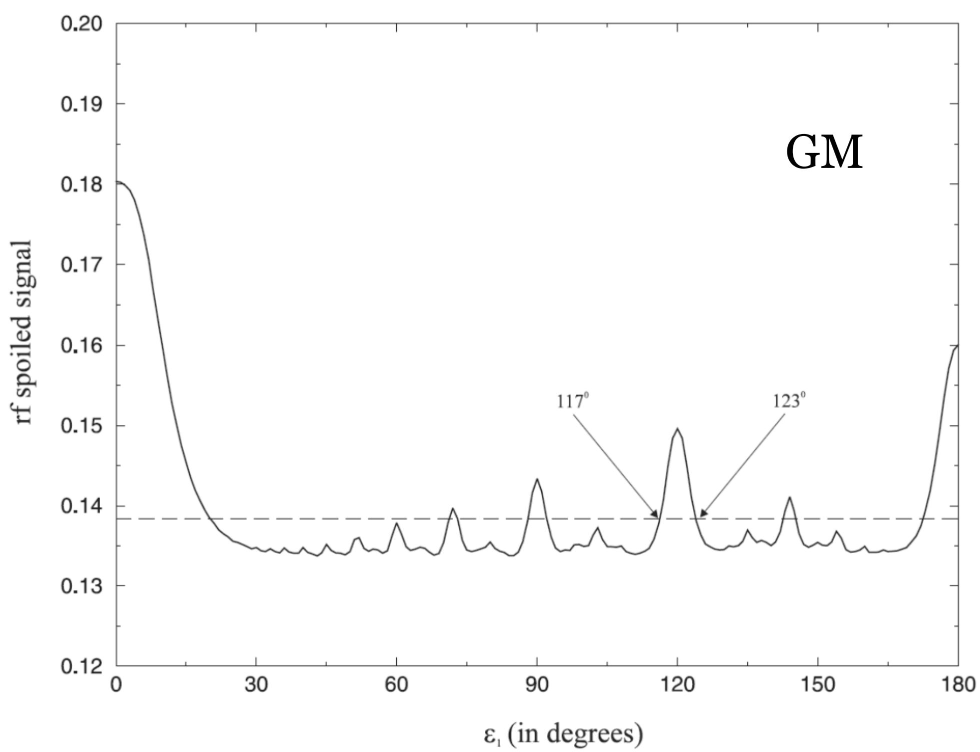


Fig. 18.29

RF+gradient spoiling

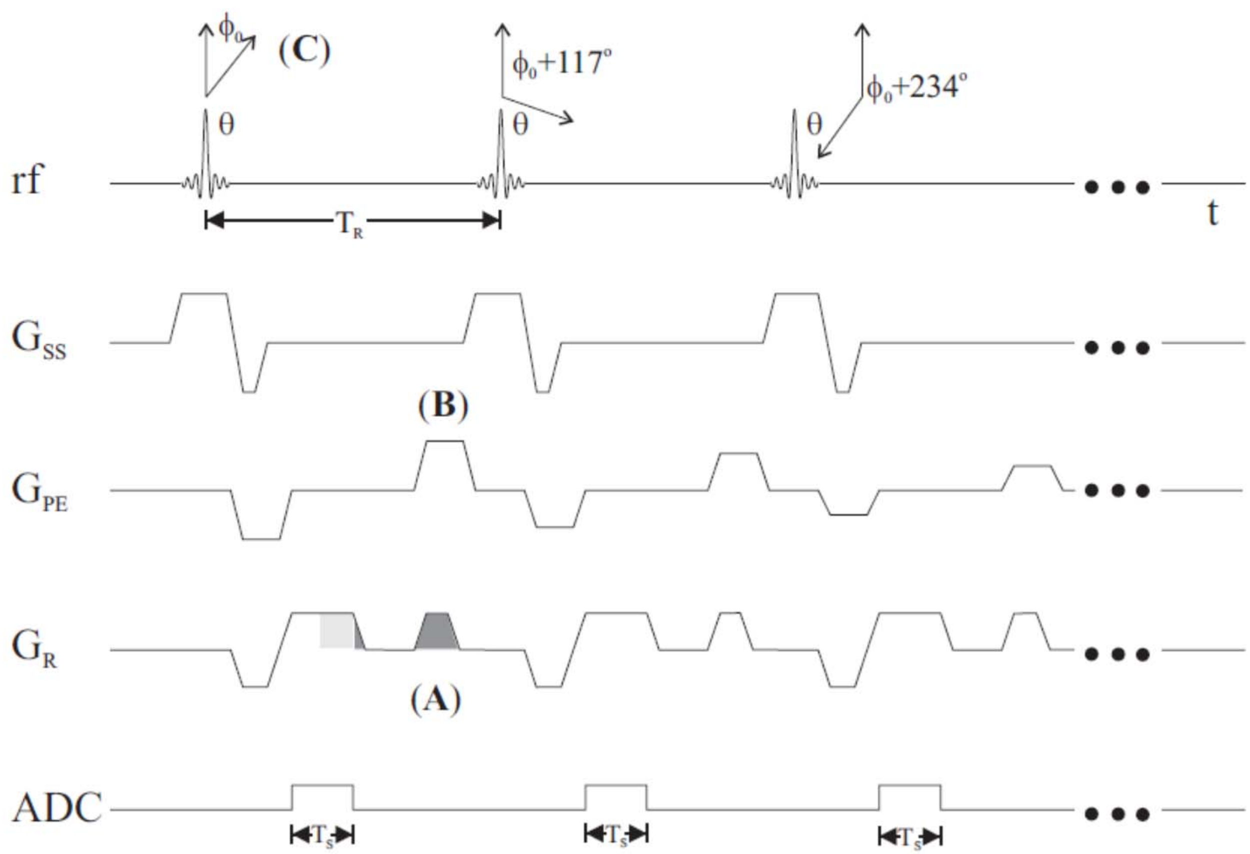


Fig. 18.31

Homework

18.1, 18.2, 18.6, 18.8

Just for fun: Deduct the SSI signal for IR-FID

Next Session

Chap 19. 1-5 & 7, intro for 19.6 & 8