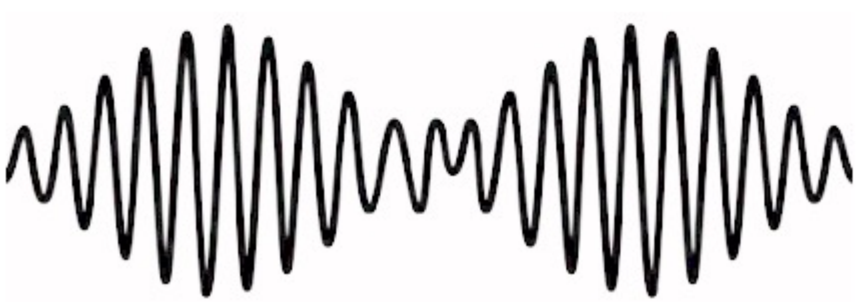
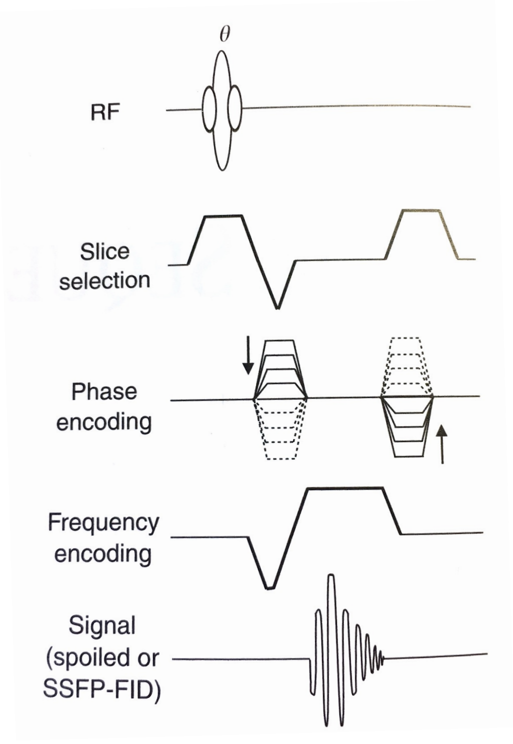
Basic Pulse Sequences

Saturation and Inversion Recovery



Basic Sequences - Gradient Echo (GE or GRE)

- **Class of sequences primarily used for fast scanning (Frahm et al., *Magn Reson Med*, 1986)**
- **GRE used widely for 3D volumetric imaging**
  - **Brain imaging, cardiac/vascular imaging requiring breath-hold, etc.**
- **Also referred to as *Gradient Echoes, Gradient Recalled Echoes, Gradient Refocused Echoes, and Field Echoes***



GRE Advantages

Fast Imaging Applications

Why? *Can use a shorter TE/TR than spin echo.*

When? Breath-held, realtime, & 3D volume imaging

Bright blood signal

Why? Inflowing spins haven't "seen" numerous RF pulses.

When? Cardiovascular & angiographic applications.

Low SAR

Why? Imaging flip angles are small.

When? When heating risks are a concern (devices, high field)

GRE Advantages

Quantitative

Why? Multi-echo acquisition are practical.

When? Flow quantification & Fat/Water mapping

Susceptibility Weighted Imaging

Why? No refocusing pulse.

When? T_2^*-weighted & imaging hemorrhage

Reduced Cross-talk

Why? SE hard to match slice profile of 90° & 180°

When? Little or no slice gap for 2D multi-slice

GRE Disadvantages

Off-resonance sensitivity

Why? Field inhomogeneity, Susceptibility, & Chemical shift

T_2^*-weighted rather than T_2-weighted

Why? No re-focusing pulse

Larger metal artifacts than SE

Why? No refocusing pulse.

GRE Applications

Primarily used for fast scanning

- **Flip angle typically <90°**
  - Only short time needed for T_1 recovery
  - Short TRs (2-50ms)
  - Short TEs (2-10ms)
    - Therefore, weights T1 differences

Varying TE can provide T2* contrast

- Combines field heterogeneity and susceptibility weighting

3D volume imaging

Cardiac/Cardiovascular imaging

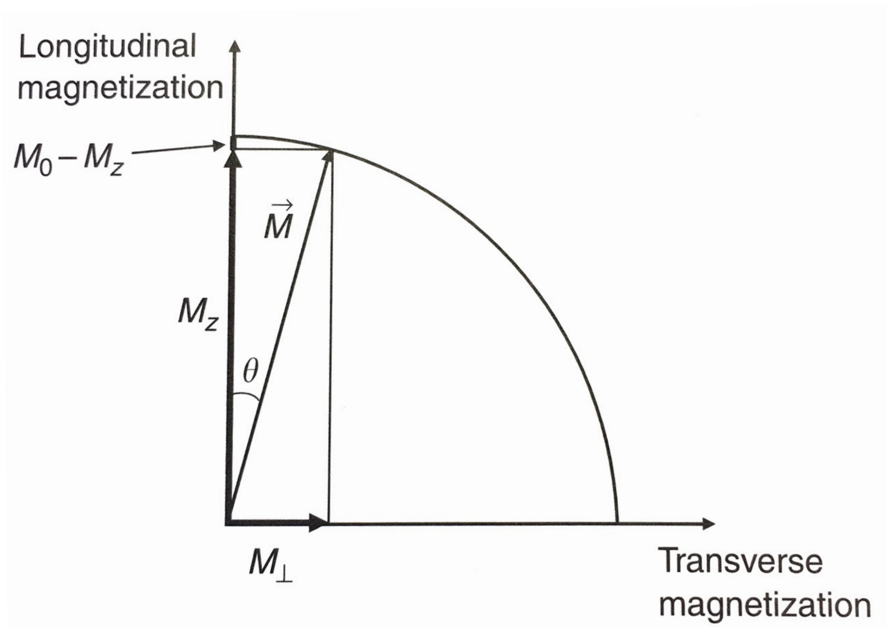
Time-of-flight and phase contrast MRA

Sequence names

- FLASH, FISP/true-FISP, GRASS

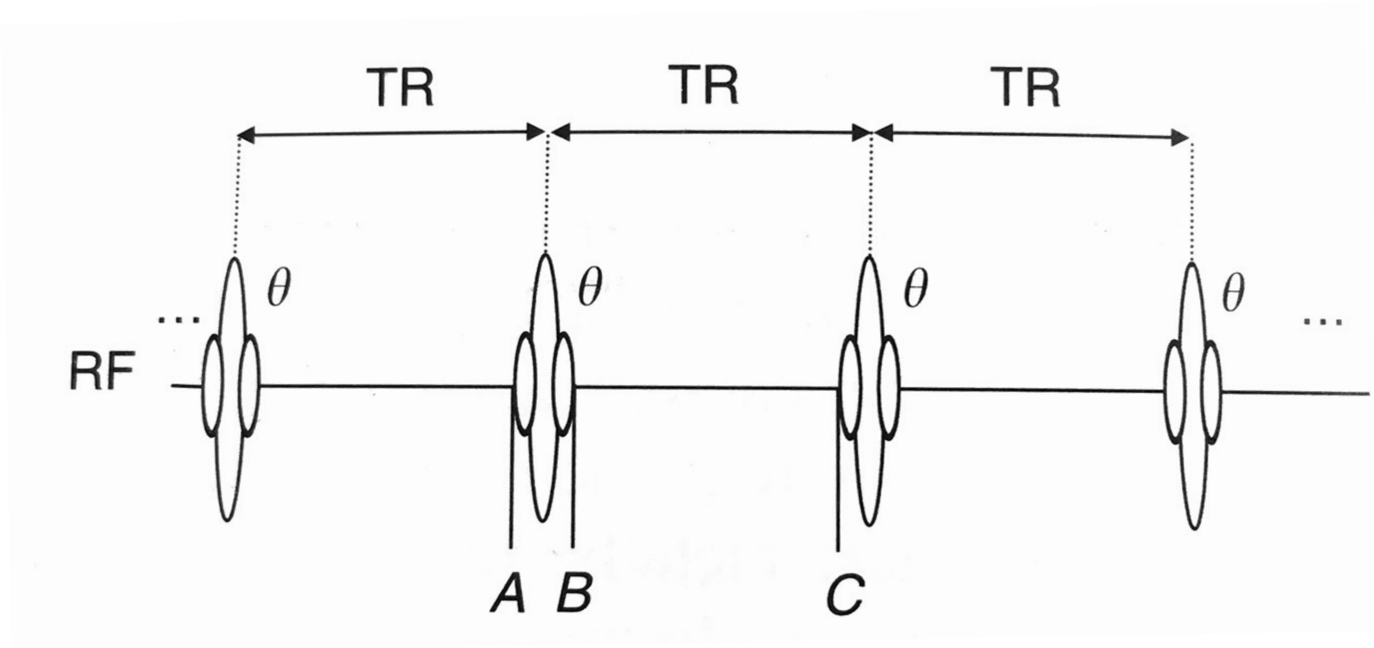
Basic Sequences - Gradient Echo (GE or GRE)

- **GRE acquisitions can be very fast, partially due to using a low flip angle (θ) and short TR**
- **Useful for fast imaging, 3D imaging, time-of-flight (TOF) and phase-contrast angiography, and susceptibility-weighting.**
- **Note that the amount of transverse magnetization created by an RF excitation pulse is much greater than the loss of longitudinal magnetization, resulting in faster acquisition via shorter TR… ($M_\perp$ >> (M_0-M_z))**
- **For values of $\theta << 1$ radian, $\sin\theta \approx \theta >> 1-\cos\theta \approx \theta^2/2$**

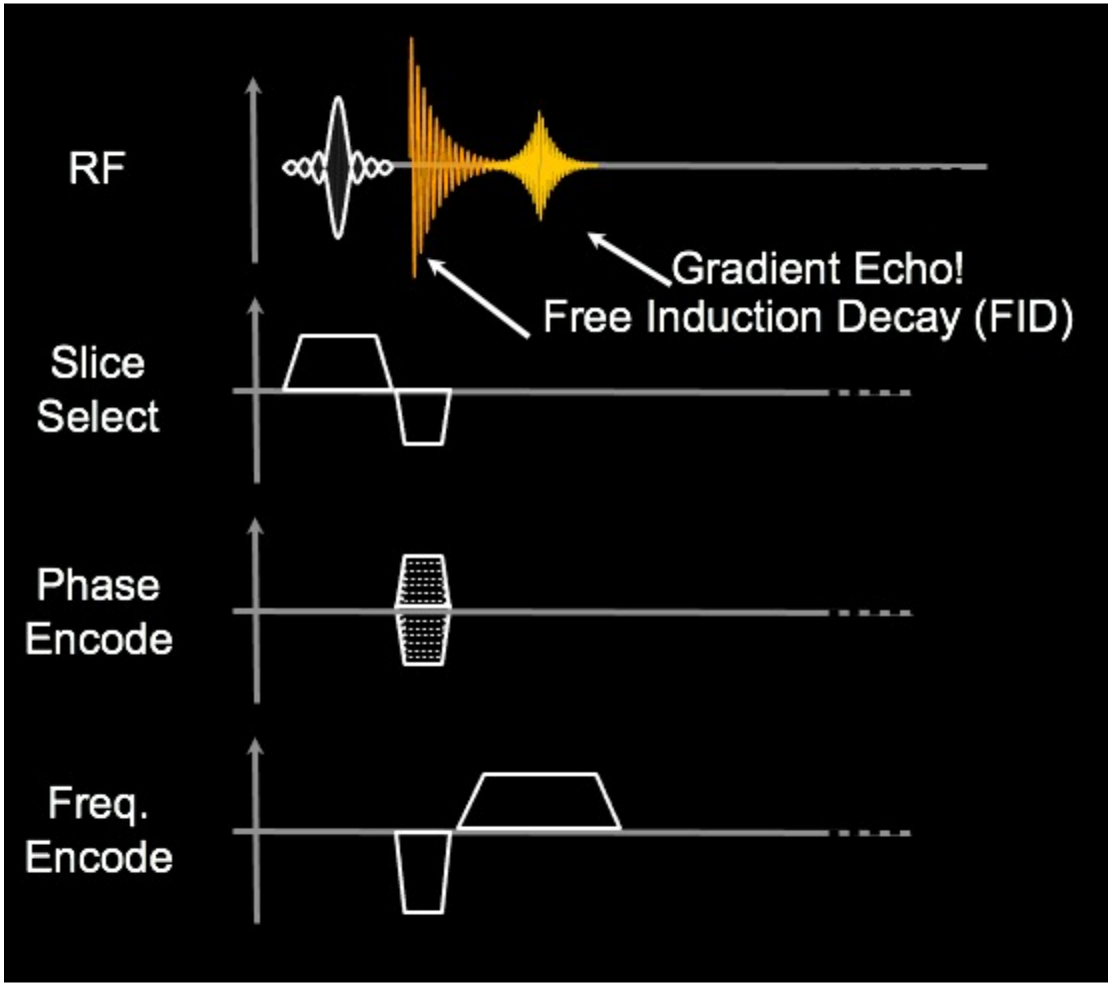


Basic Sequences - Gradient Echo (GE or GRE)

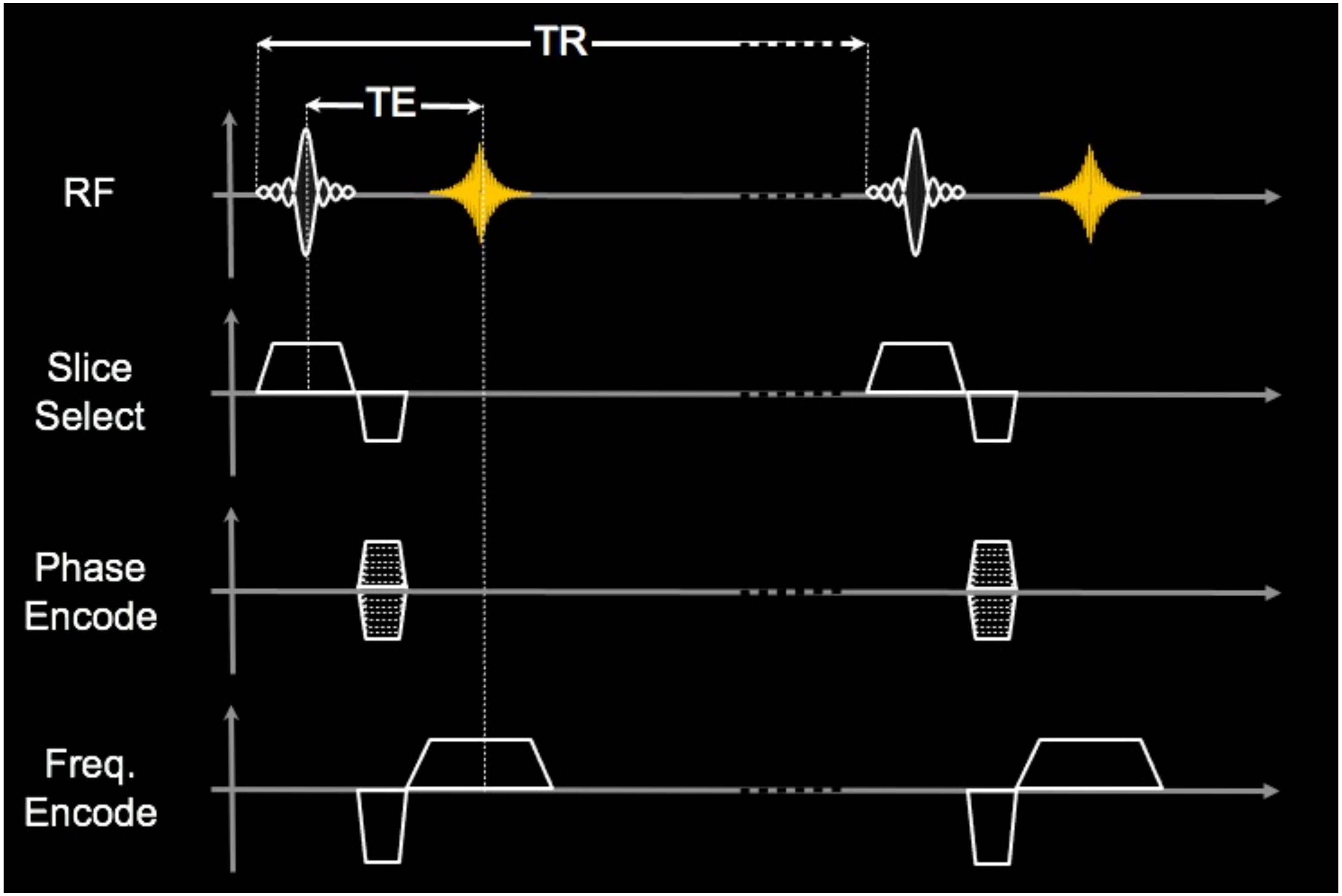
- **Characterized by a series of θ-TR-θ-TR-θ-TR.. pulse sequence**
- ***Dynamic Equilibrium* - When the magnetization vector reaches a "steady state"**
  - **For corresponding time points in adjacent TR intervals, the values of longitudinal magnetization, M_z, will be equal**



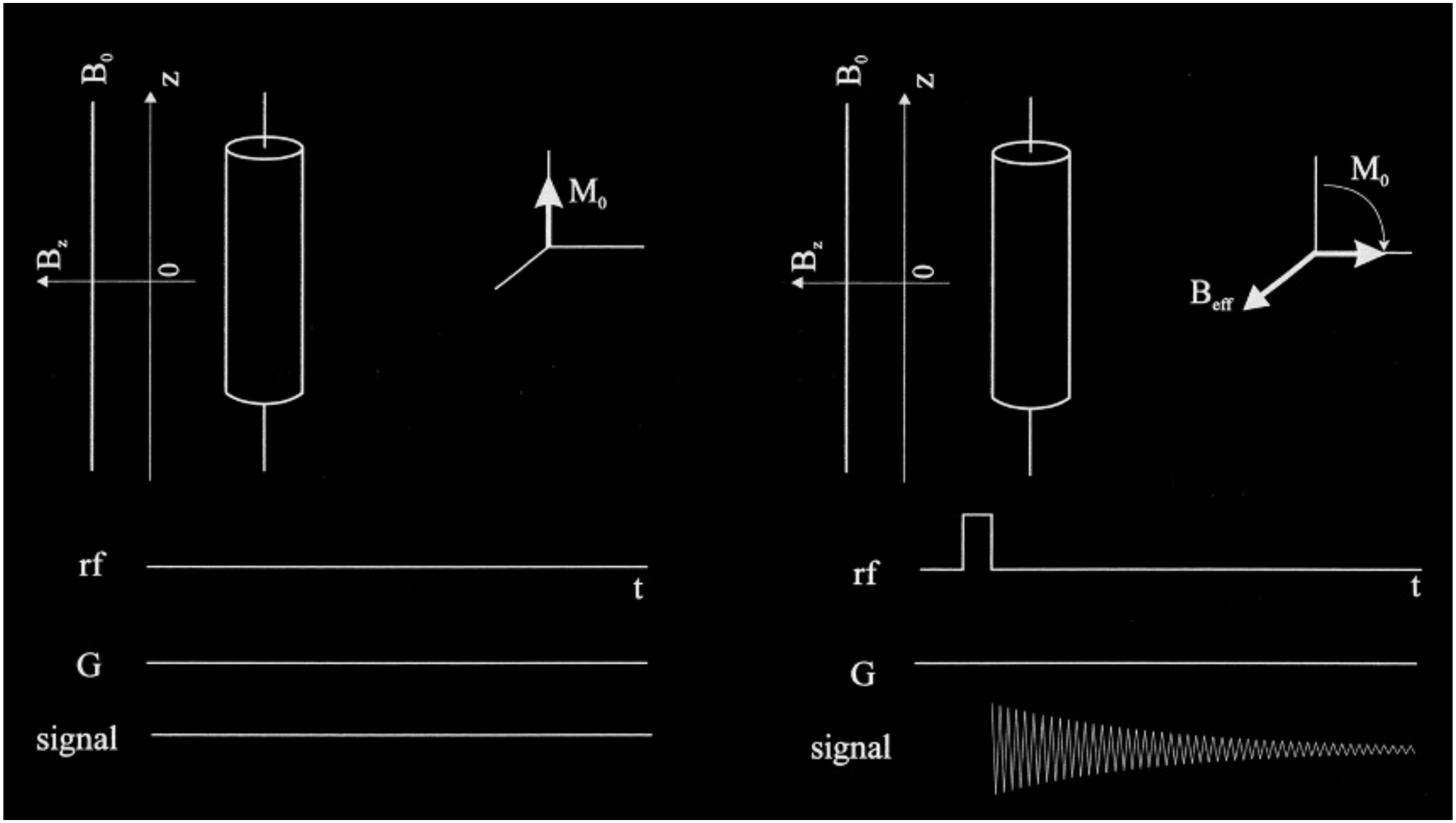
Basic Gradient Echo Pulse Sequence



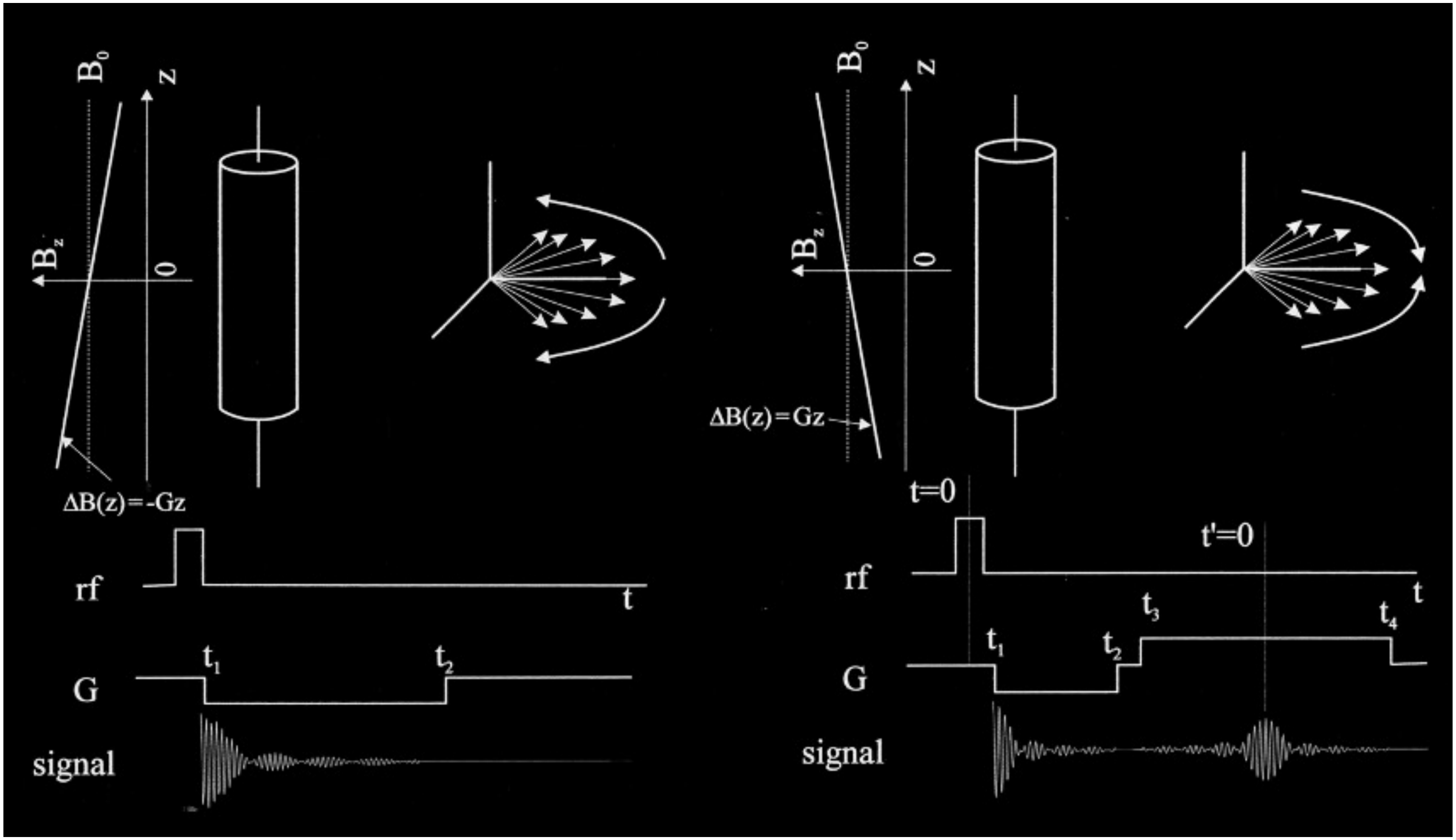
Basic Gradient Echo Pulse Sequence



Basic Gradient Echo Pulse Sequence

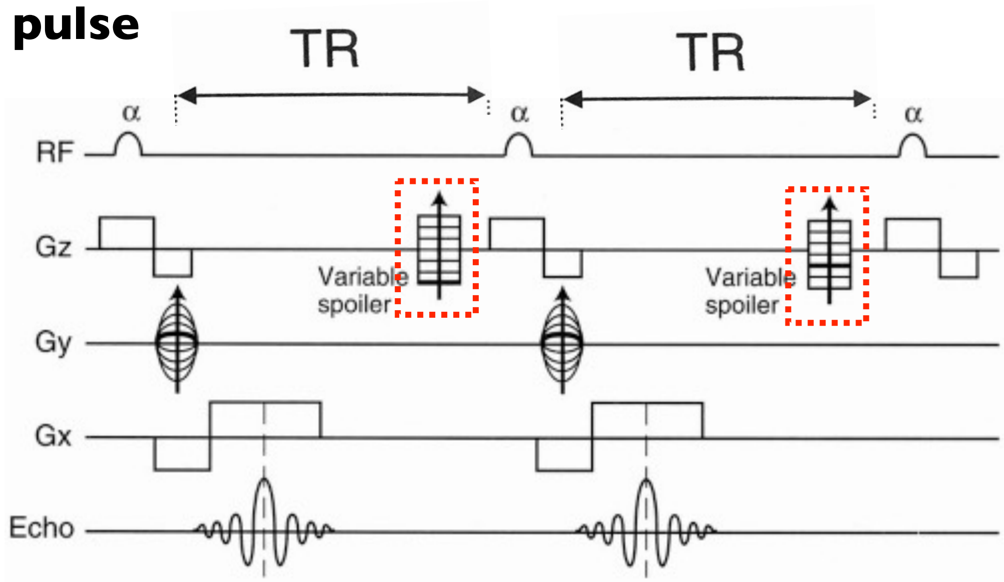


Basic Gradient Echo Pulse Sequence



Basic Sequences - Gradient Echo (GE or GRE)

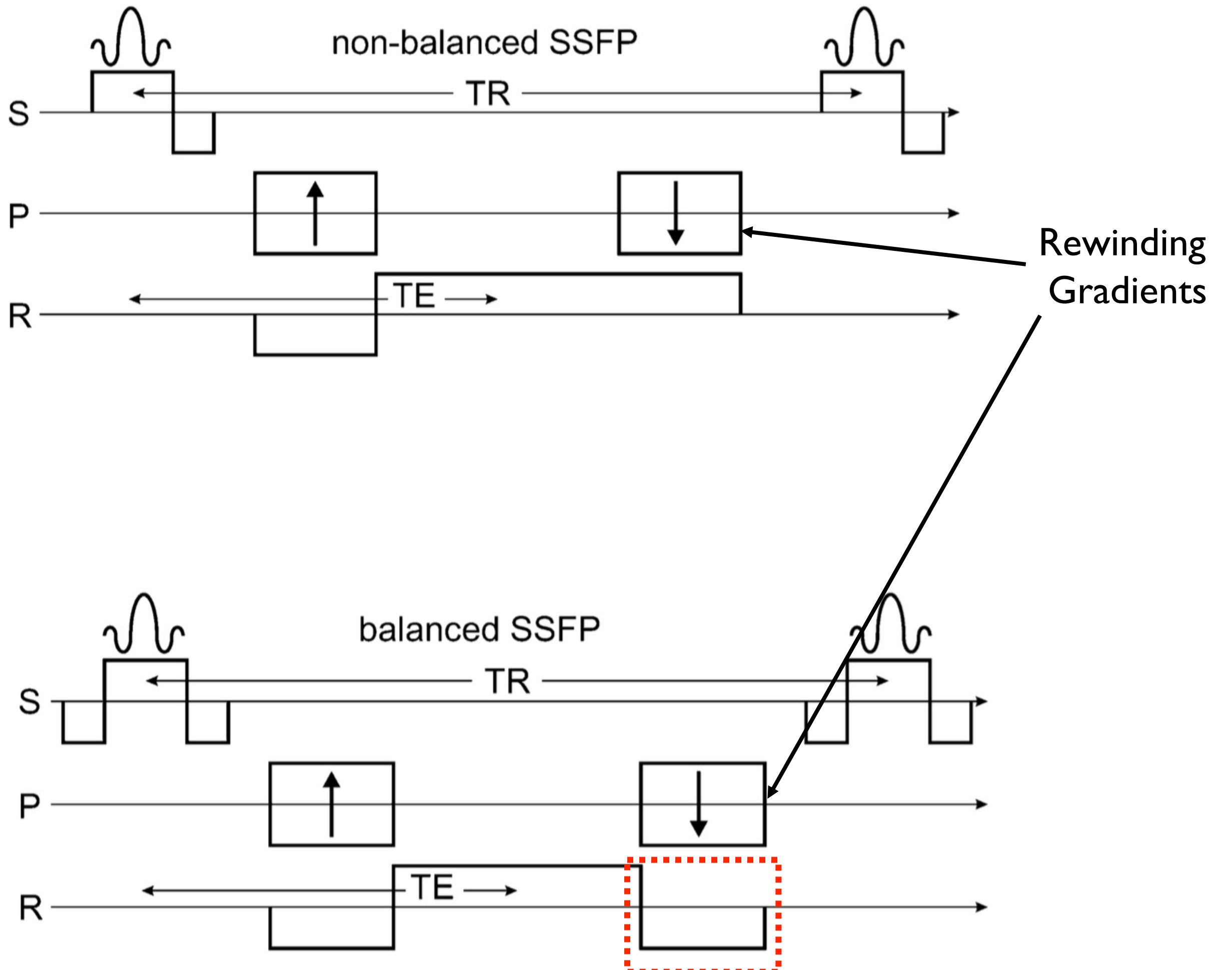
- ***Spoiled GRE* - When transverse magnetization is zero before each excitation pulse**



- ***Steady-State Free Precession (SSFP)* - When transverse magnetization reaches a non-zero steady state just before application of each excitation pulse**

Basic Sequences - Gradient Echo (GE or GRE)

- ***Balanced SSFP*** **- Special type of SSFP sequence where gradient-induced dephasing within each TR is exactly zero.**



Basic Sequences - Gradient Echo (GE or GRE)

- **Comparison across vendors**

Gradient Echo Pulse Sequences					
	Spoiled Gradient Echo		Steady-State Free Precession (SSFP)		
Academic Classification	Ordinary type	Turbo type (Magnetization preparation, extremely low angle shot, short TR)	FID-like	Echo-like	Balanced Steady-State Free Precession (bSSFP)
Siemens	**FLASH** Fast Imaging using Low Angle Shot	**TurboFLASH** Turbo FLASH	**FISP** Fast Imaging with Steady-state Precession	**PSIF** Reversed FISP	**TrueFISP** True FISP
GE	**SPGR** Spoiled GRASS	**FastSPGR** Fast SPGR	**GRASS** Gradient Recall Acquisition using Steady States	**SSFP** Steady State Free Precession	**FIESTA** Fast Imaging Employing Steady-state Acquisition
Philips	**T_1 FFE** T_1-weighted Fast Field Echo	**TFE** Turbo Field Echo	**FFE** Fast Field Echo	**T_2-FFE** T_2-weighted Fast Field Echo	**b-FFE** Balanced Fast Field Echo

Basic Sequences - Gradient Echo (GE or GRE)

- **Comparison across vendors**

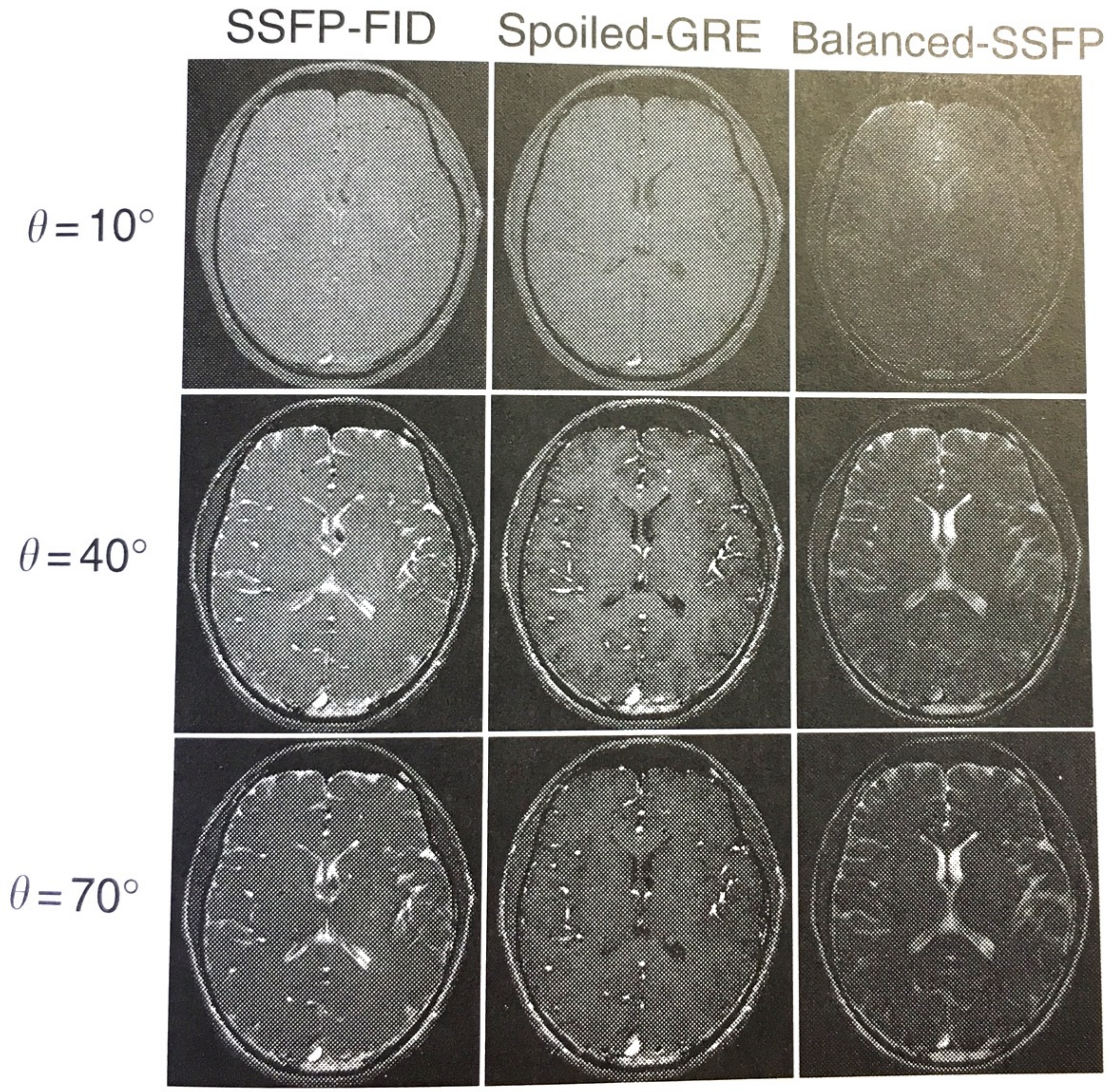
TABLE 14.1
Commercial Names of Common GRE Pulse Sequences Used by a Few MR Equipment Vendors[a]

Vendor	Spoiled Gradient Echo	SSFP-FID or Gradient Echo	SSFP-Echo, or CE-FAST	Balanced SSFP or True FISP	Multiacquisition SSFP or CISS	Dual-Echo SSFP or DESS
General Electric	SPGR	Gradient echo or GRASS	SSFP[b]	FIESTA	FIESTA-C	—
Philips	CE-FFE-T1 or T1-FFE	FFE	CE-FFE-T2 T2-FFE	Balanced FFE	—	—
Siemens	FLASH	FISP	PSIF	TrueFISP	CISS	DESS

[a] CE-FAST, contrast-enhanced Fourier-acquired steady state; CE-FFE, contrast-enhanced fast field echo; CISS, constructive interference in the steady state; DESS, dual-echo steady state; FFE, fast field echo; FID, free-induction decay; FIESTA, fast imaging employing steady-state acquisition; FIESTA-C, fast imaging employing steady-state acquisition with phase cycling; FISP, fast imaging with steady (-state free) precession; FLASH, fast low-angle shot; GRASS, gradient recalled acquisition in the steady state; PSIF, reversed fast imaging with steady (-state free) precession; SPGR, spoiled gradient echo; SSFP, steady-state free precession.
[b] SSFP-Echo pulse sequence not currently offered by General Electric.

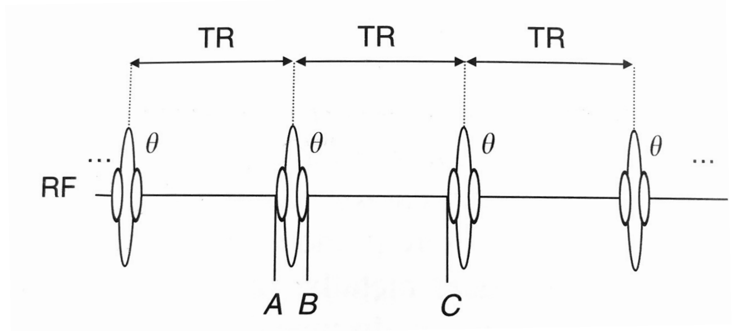
Basic Sequences - Gradient Echo (GE or GRE)

- **Useful for fast imaging, 3D imaging, time-of-flight (TOF) and phase-contrast angiography, susceptibility-weighting, DCE-MRI, and T2* mappi**



Basic Sequences - Gradient Echo (GE or GRE)

- **Steady State of the Longitudinal Magnetization for the Spoiled GRE Sequence:**



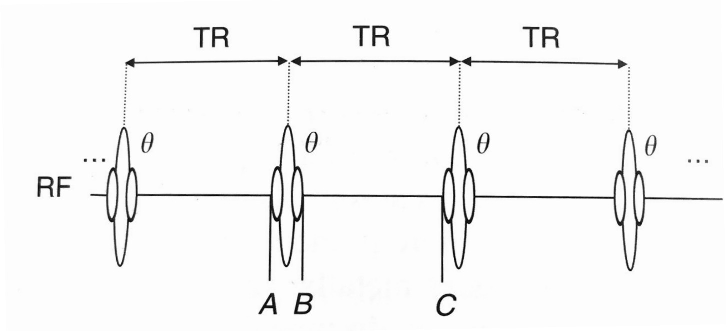
$$M_{zC} = M_{zB} e^{-TR/T_1} + M_0 \left(1 - e^{-TR/T_1}\right) = M_{zA} \cos\theta \cdot E_1 + M_0 \left(1 - E_1\right)$$

$$E_1 = e^{-TR/T_1}$$

- **At steady state, $M_{zA} = M_{zC}$**

Basic Sequences - Gradient Echo (GE or GRE)

- **Steady State of the Longitudinal Magnetization for the Spoiled GRE Sequence:**



$$M_{zC} = M_{zB} e^{-TR/T_1} + M_0\left(1 - e^{-TR/T_1}\right) = M_{zA}\cos\theta \cdot E_1 + M_0\left(1 - E_1\right)$$

$$E_1 = e^{-TR/T_1}$$

- **At steady state, $M_{zA} = M_{zC}$**

$$M_{zA} = M_{zA}\cos\theta \cdot E_1 + M_0\left(1 - E_1\right)$$

$$\frac{M_{zA}}{M_0} = \frac{M_{zA}}{M_0}\cos\theta \cdot E_1 + 1 - E_1$$

$$\frac{M_{zA}}{M_0} - \frac{M_{zA}}{M_0}\cos\theta \cdot E_1 = 1 - E_1$$

$$\frac{M_{zA}}{M_0}\left(1 - \cos\theta \cdot E_1\right) = 1 - E_1$$

$$\frac{M_{zA}}{M_0} = \frac{1 - E_1}{1 - \cos\theta \cdot E_1} \equiv f_{z,ss}$$

Basic Sequences - Gradient Echo (GE or GRE)

- **Signal Intensity of the the Spoiled GRE Sequence:**

$$S_{spoil} = M_{zA} \sin\theta \cdot e^{-TE/T_2^*}$$

Basic Sequences - Gradient Echo (GE or GRE)

- **Signal Intensity of the the Spoiled GRE Sequence:**

$$S_{spoil} = M_{zA} \sin\theta \cdot e^{-TE/T_2^*}$$

$$\frac{M_{zA}}{M_0} = \frac{1 - E_1}{1 - \cos\theta \cdot E_1}$$

$$\frac{S_{spoil}}{M_0 \cdot \sin\theta \cdot e^{-TE/T_2^*}} = \frac{1 - E_1}{1 - \cos\theta \cdot E_1}$$

$$S_{spoil} = \frac{M_0 \cdot \sin\theta \cdot E_2^* (1 - E_1)}{1 - \cos\theta \cdot E_1}$$

Contrast adjusted by changing flip angle, TE and TR.

Gradient Echo Contrast

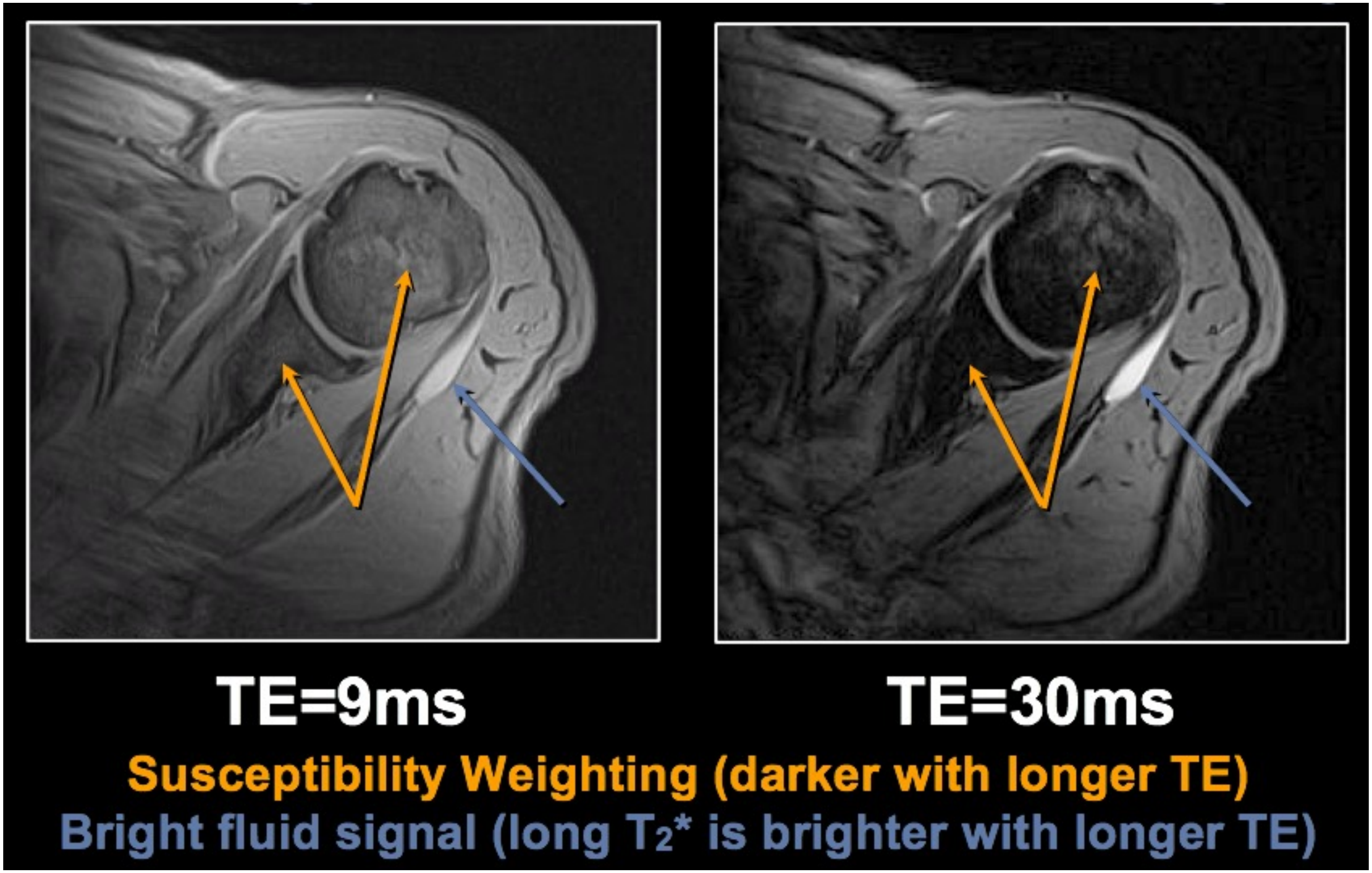
Gradient Echo Parameters

Type of Contrast	TE	TR	Flip Angle
Spin Density	Short	Long	Small
T_1-Weighted	Short	Intermediate	Large
T_2^*-Weighted	Intermediate	Long	Small

Gradient Echo Parameters

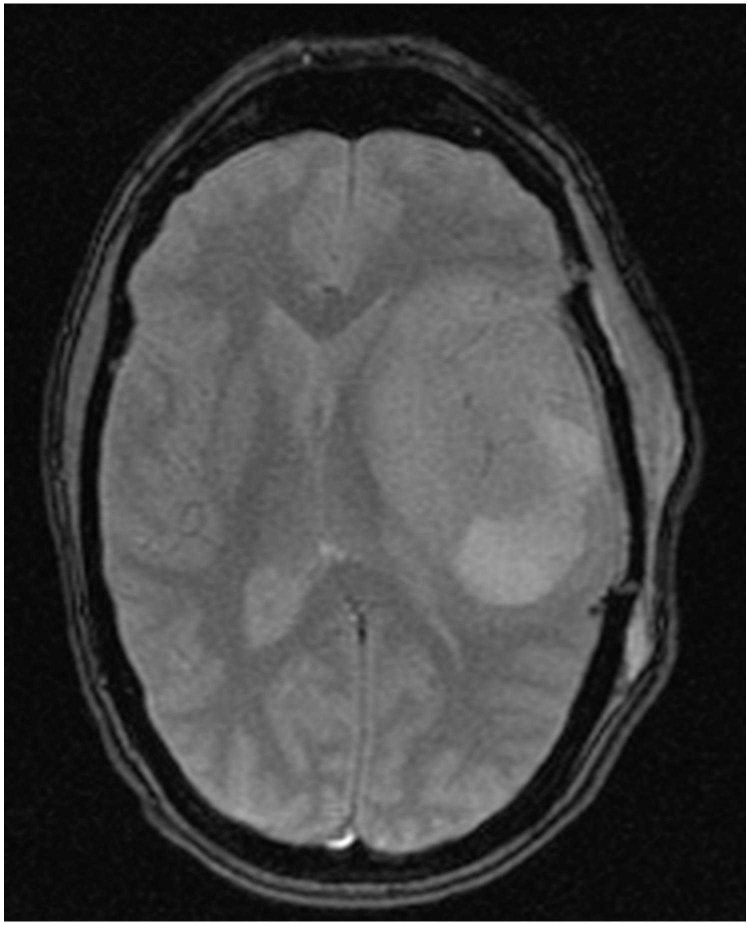
Type of Contrast	TE	TR	Flip Angle
Spin Density	<5ms	>100ms	<10°
T_1-Weighted	<5ms	<50ms	>30°
T_2^*-Weighted	>20ms	>100ms	<10°

T2*-Weighted GRE

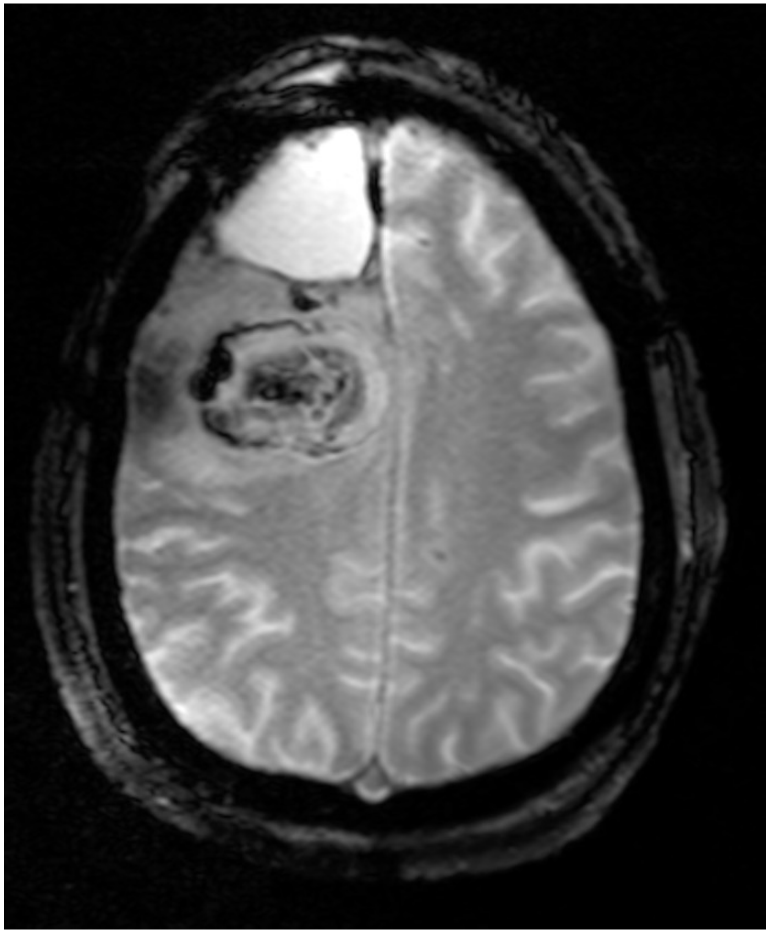


T2*-Weighted GRE

TE=15ms



TE=26ms



Basic Sequences - Gradient Echo (GE or GRE)

- **Ernst Angle - Flip angle that maximizes the spoiled GRE signal**
    - **Setting the first derivative to zero and verifying the 2nd derivative is negative (local maxima) yields:**

Basic Sequences - Gradient Echo (GE or GRE)

- **Ernst Angle - Flip angle that maximizes the spoiled GRE signal**
  - **Setting the first derivative to zero and verifying the 2nd derivative is negative (local maxima) yields:**

$$S_{spoil} = \frac{M_0 \cdot \sin\theta \cdot E_2^*(1-E_1)}{1-\cos\theta \cdot E_1}$$

$$\frac{d}{d\theta}\left(S_{spoil}\right) = \frac{d}{d\theta}\left(\frac{M_0 \cdot \sin\theta \cdot E_2^*(1-E_1)}{1-\cos\theta \cdot E_1}\right) = 0$$

$$\frac{d}{d\theta}\left(S_{spoil}\right) = 0 = \frac{M_0 \cdot \cos\theta \cdot E_2^*(1-E_1)}{1-\cos\theta \cdot E_1} - \frac{M_0 \cdot \cos\theta \cdot E_2^*(1-E_1)E_1 \sin^2\theta}{(1-\cos\theta \cdot E_1)^2}$$

$$\frac{d}{d\theta}\left(S_{spoil}\right) = 0 = \frac{M_0 \cdot E_2^*(1-E_1)}{1-\cos\theta \cdot E_1}\left(\cos\theta - \frac{E_1 \sin^2\theta}{1-\cos\theta \cdot E_1}\right)$$

$$\cos\theta = \frac{E_1 \sin^2\theta}{1-\cos\theta \cdot E_1}$$

$$\cos\theta - \cos^2\theta \cdot E_1 = E_1 \sin^2\theta$$

$$\cos\theta = E_1\left(\sin^2\theta + \cos^2\theta\right)$$

$$\theta = \arccos E_1$$

Basic Sequences - Gradient Echo (GE or GRE)

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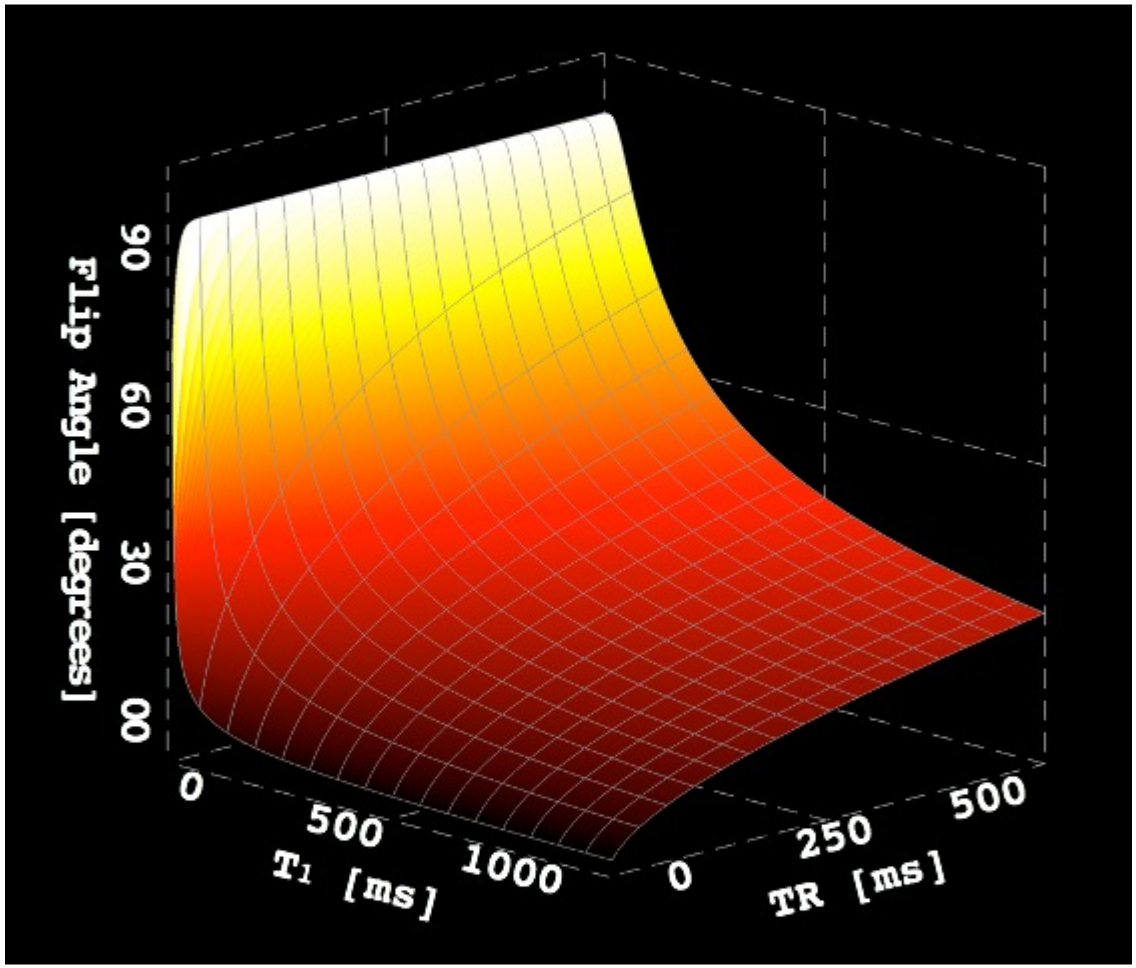

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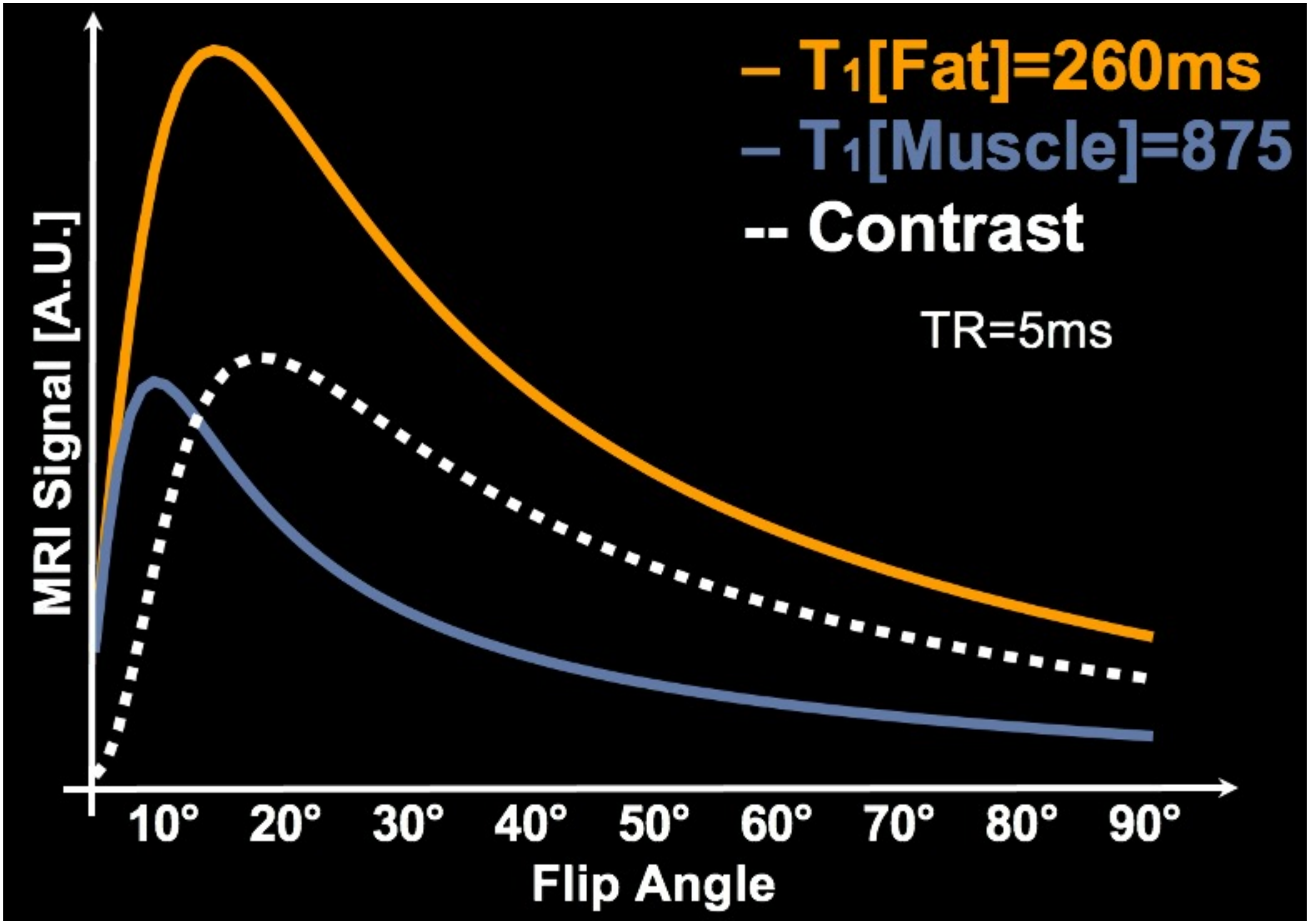

Basic Sequences - Gradient Echo (GE or GRE)

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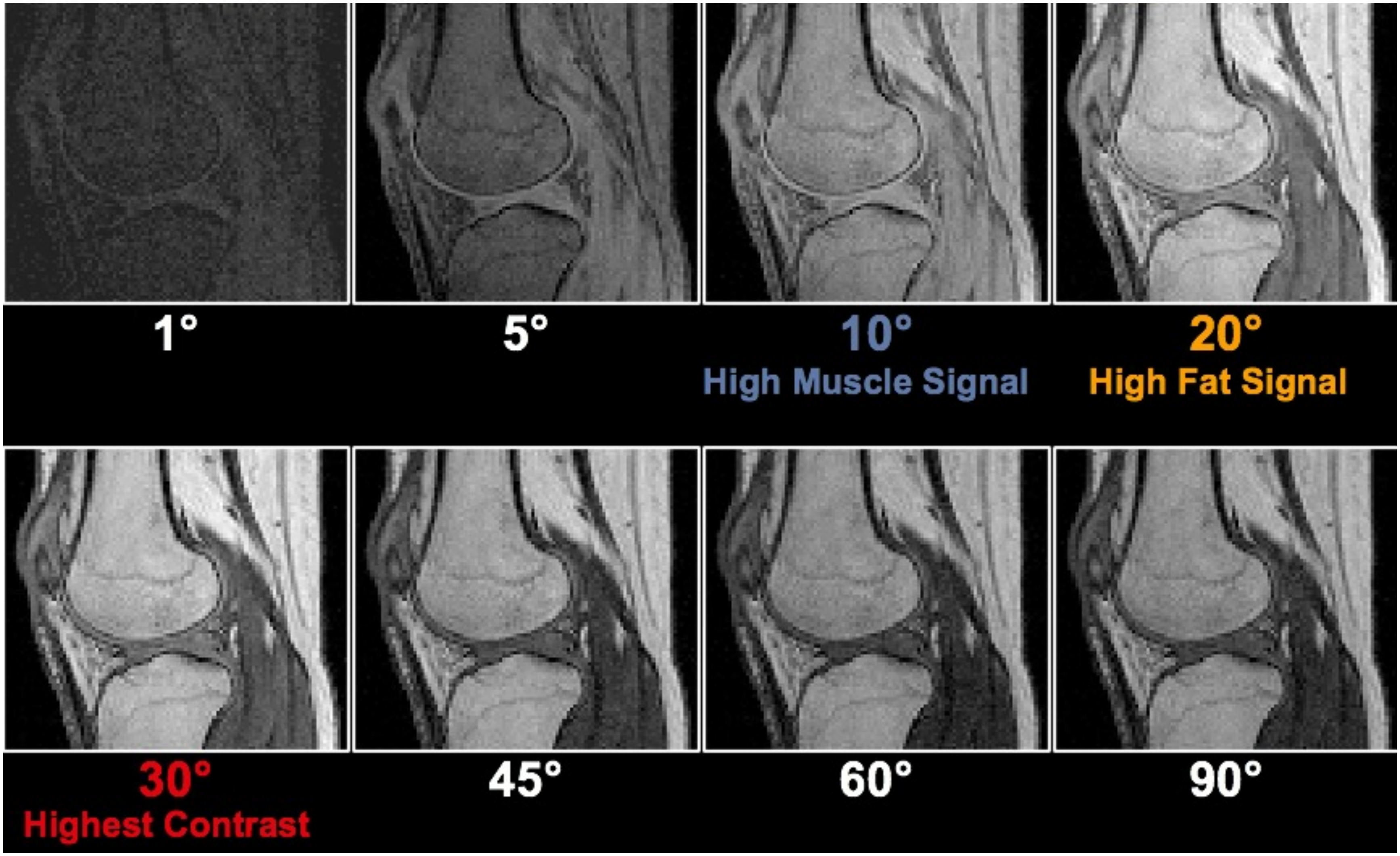


Why Spoiling?

Eliminates M_{xy} at end of each TR

Prevents cumulative errors/artifacts

Shortens the TR

Faster imaging

Enhances T_1 contrast

T_2-dependent signal (M_{xy}) is eliminated

How to Spoil?

Long TR

Choose TR 4-5x T_2*

Can work for interleaved multi-slice

Gradient spoiling

Applied at end of TR

Dephases spins within voxel

Variable gradient area from TR to TR

Spatially non-uniform

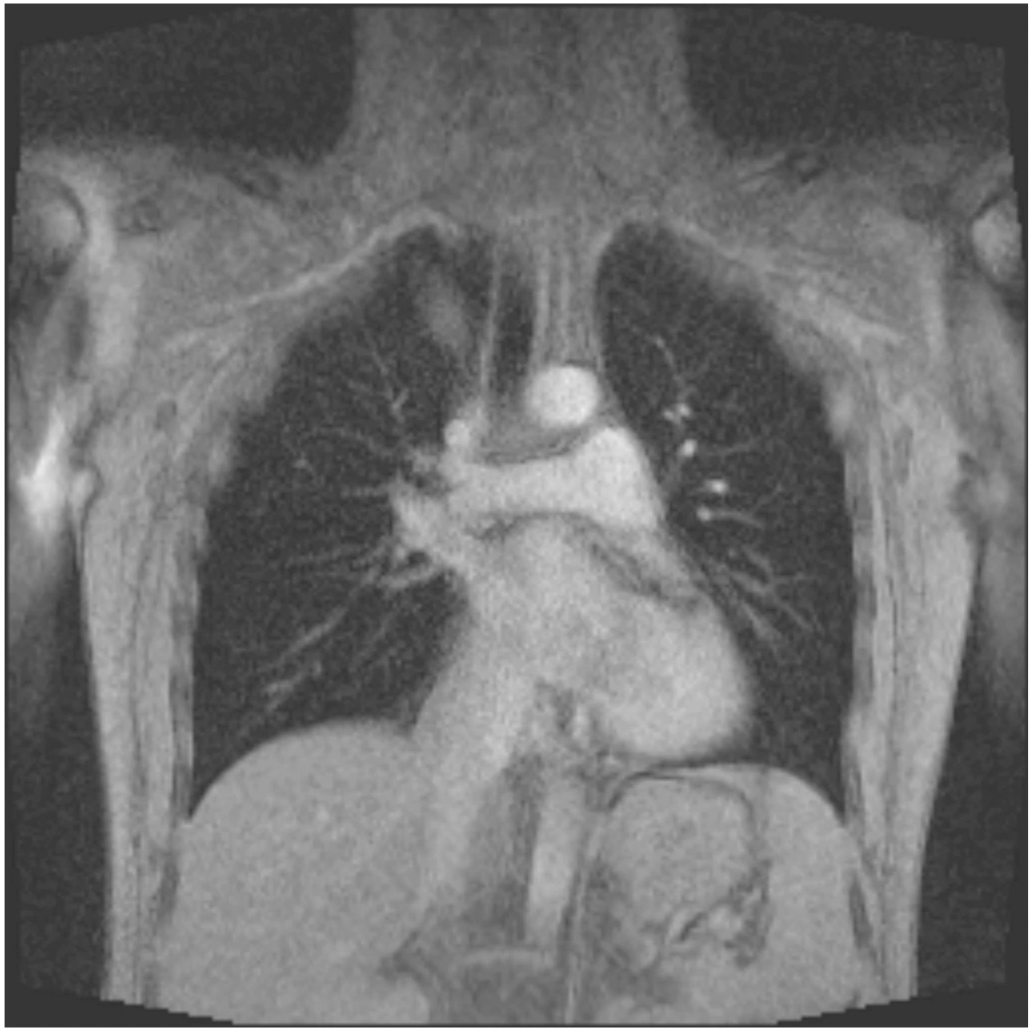
RF spoiling

Cycle the phase of the RF pulse

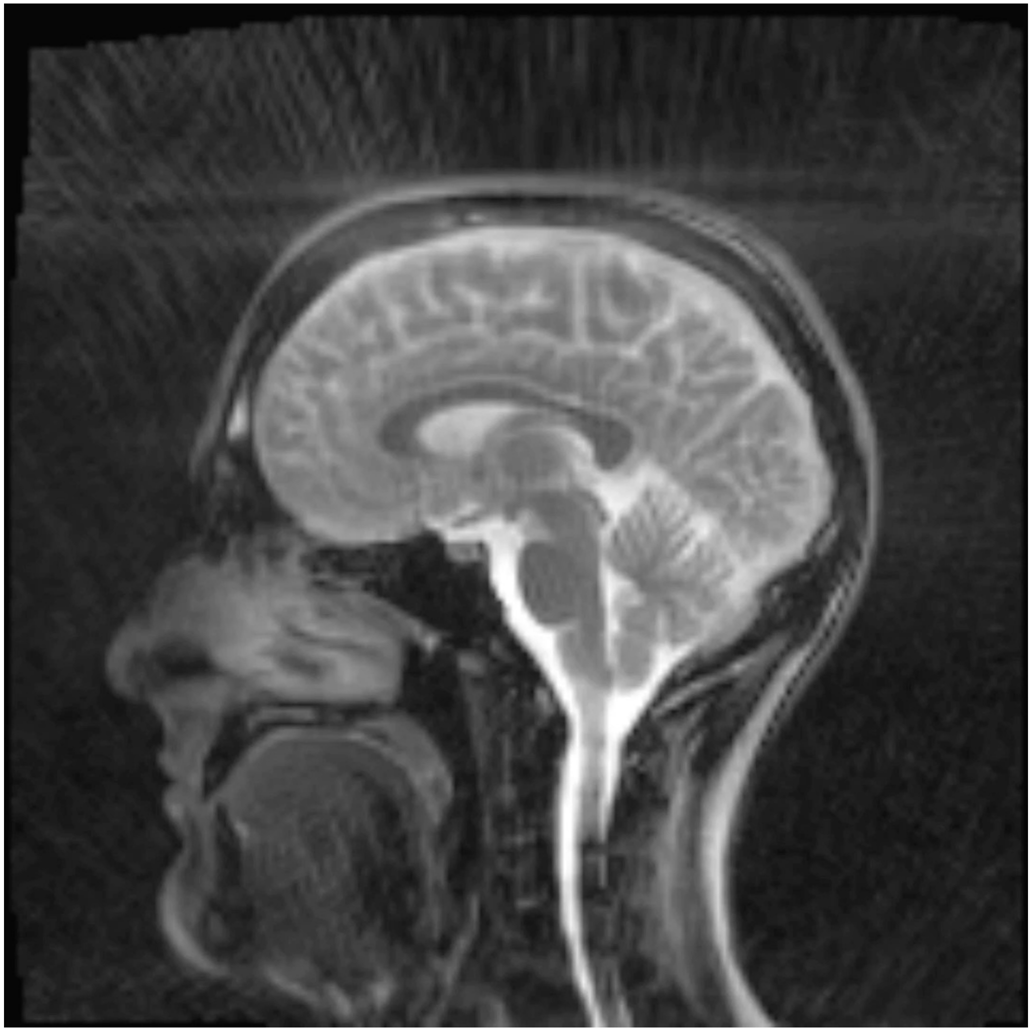
Minimizes coherent signal pathways

Requires a phase encode rewinder

Real-Time Imaging with Gradient Echoes



Real-Time Imaging with Gradient Echoes



Basic Sequences - Gradient Echo (GE or GRE)

- **Balanced SSFP Magnetization at Steady State:**

$$M_{ss} = M_0 \frac{\sqrt{E_2(1-E_1)}\sin\theta}{1-(E_1-E_2)\cos\theta - E_1E_2}$$

- **If TR << T1, T2 (reasonable for biological tissues with TR ~ 3-5ms)**

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

- **Ernst Angle is:**

$$\theta = \arccos\left(\frac{\frac{T_1}{T_2}-1}{\frac{T_1}{T_2}+1}\right)$$

- **With Maximum Signal Intensity of:**

$$M_{ss} = \frac{1}{2} M_0 \sqrt{\frac{T_1}{T_2}}$$

GRE & Fat/Water Phase

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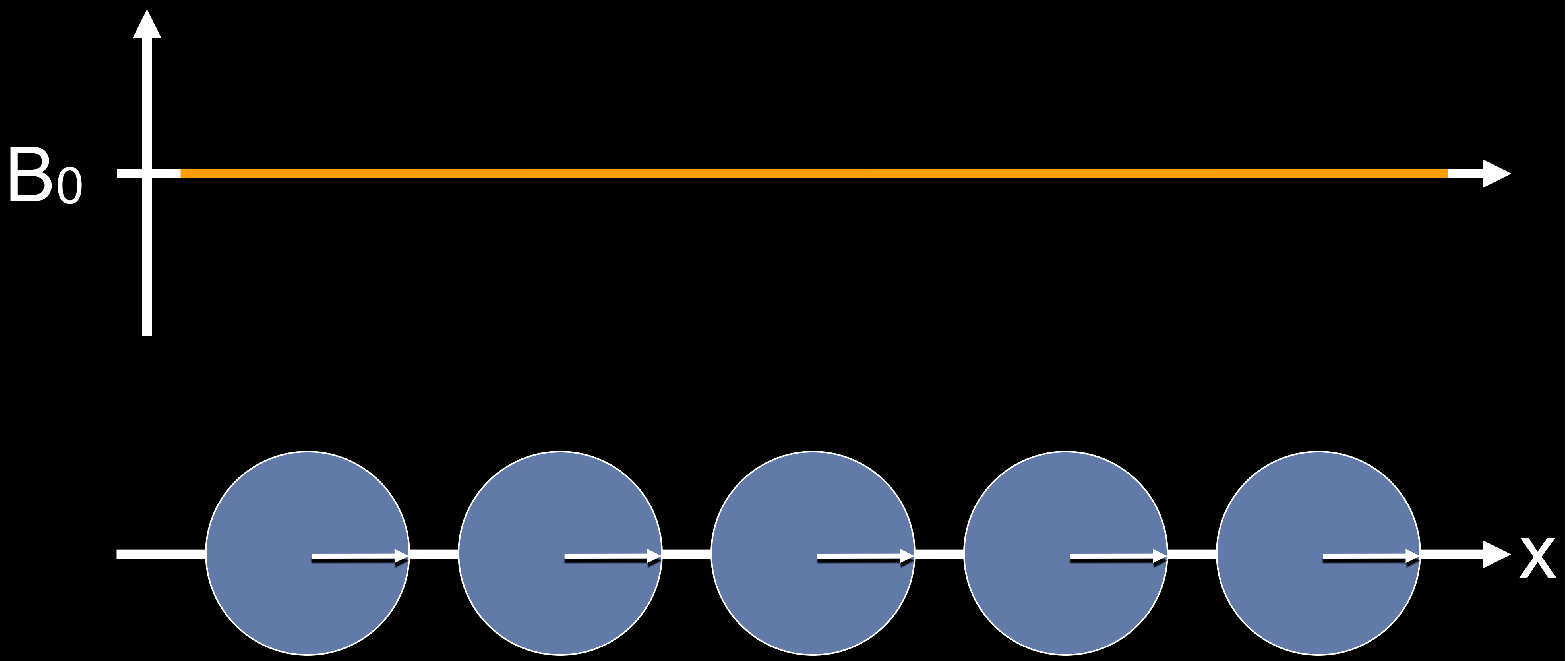
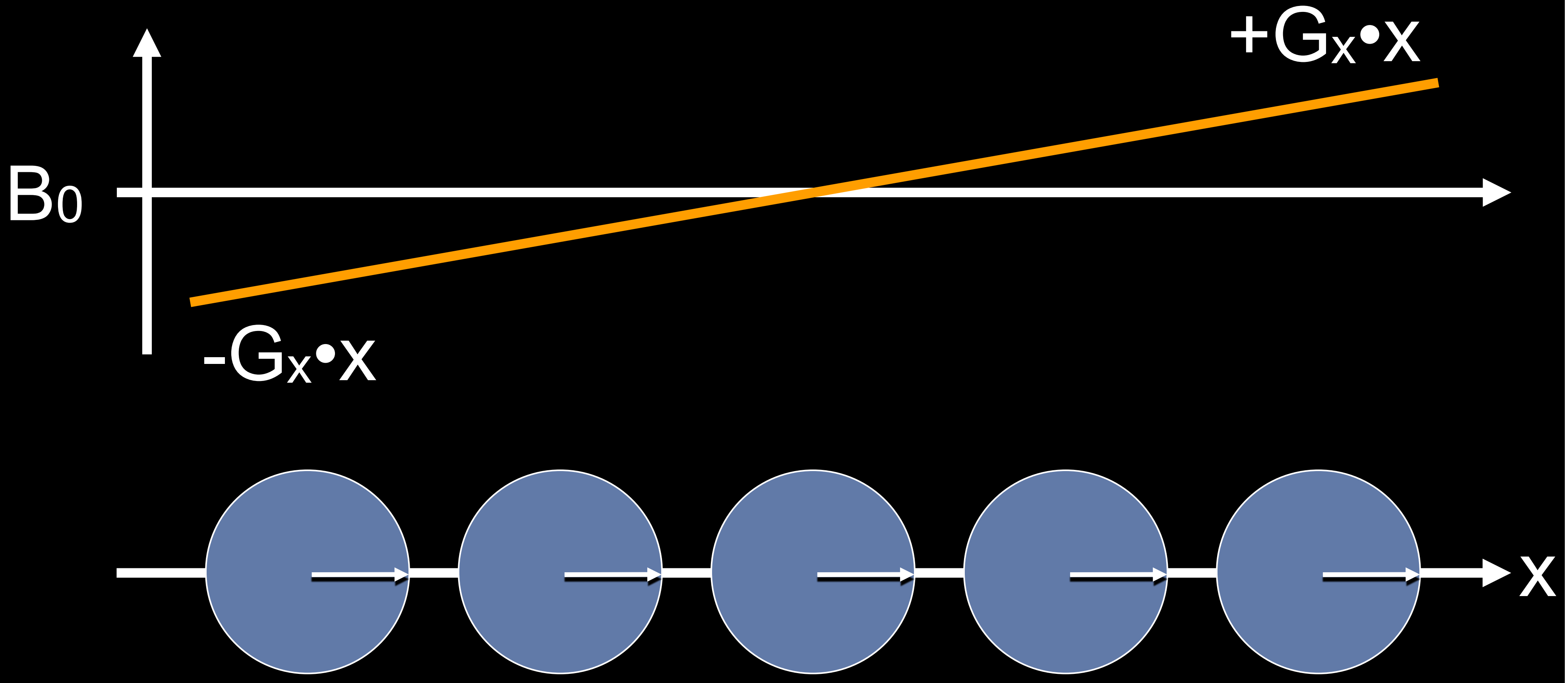
Gradient Echoes & Fat

GRE & Fat/Water Frequency



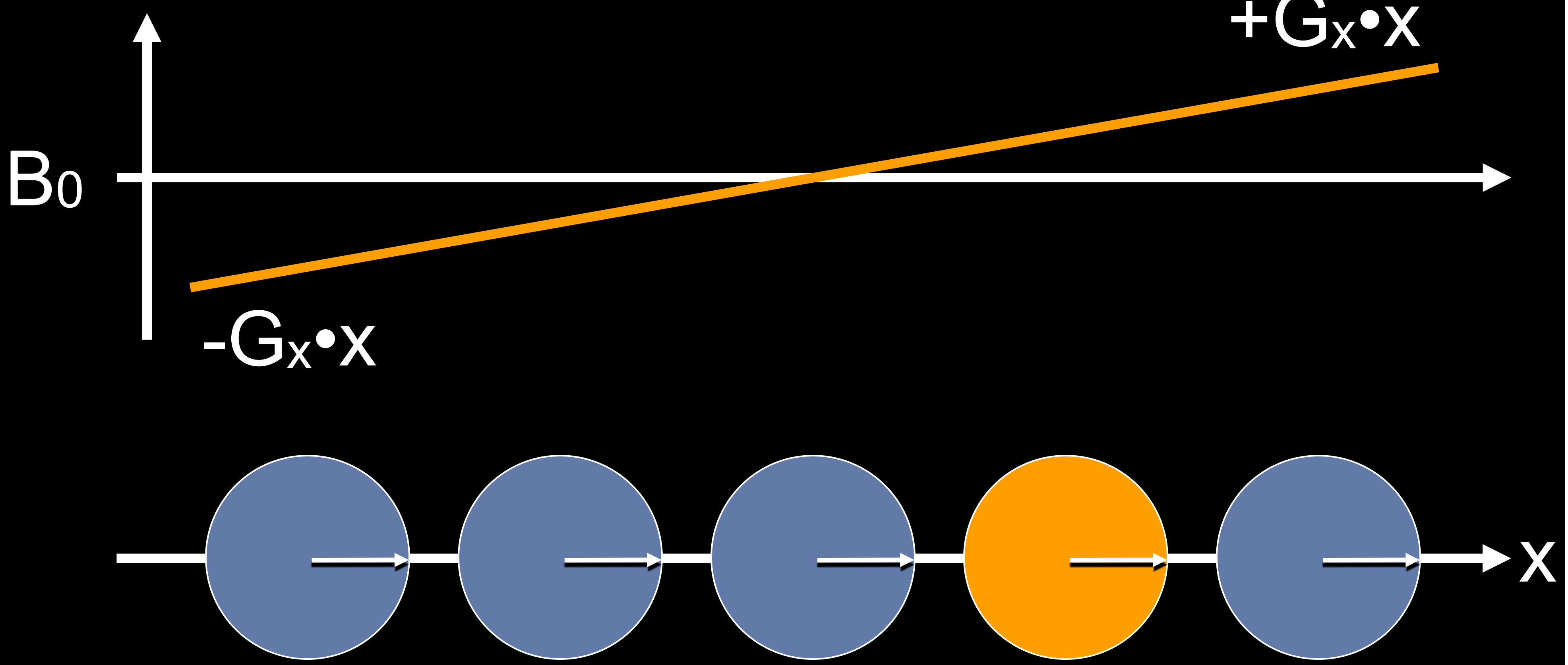
Water Spins in a Uniform Field

GRE & Fat/Water Frequency



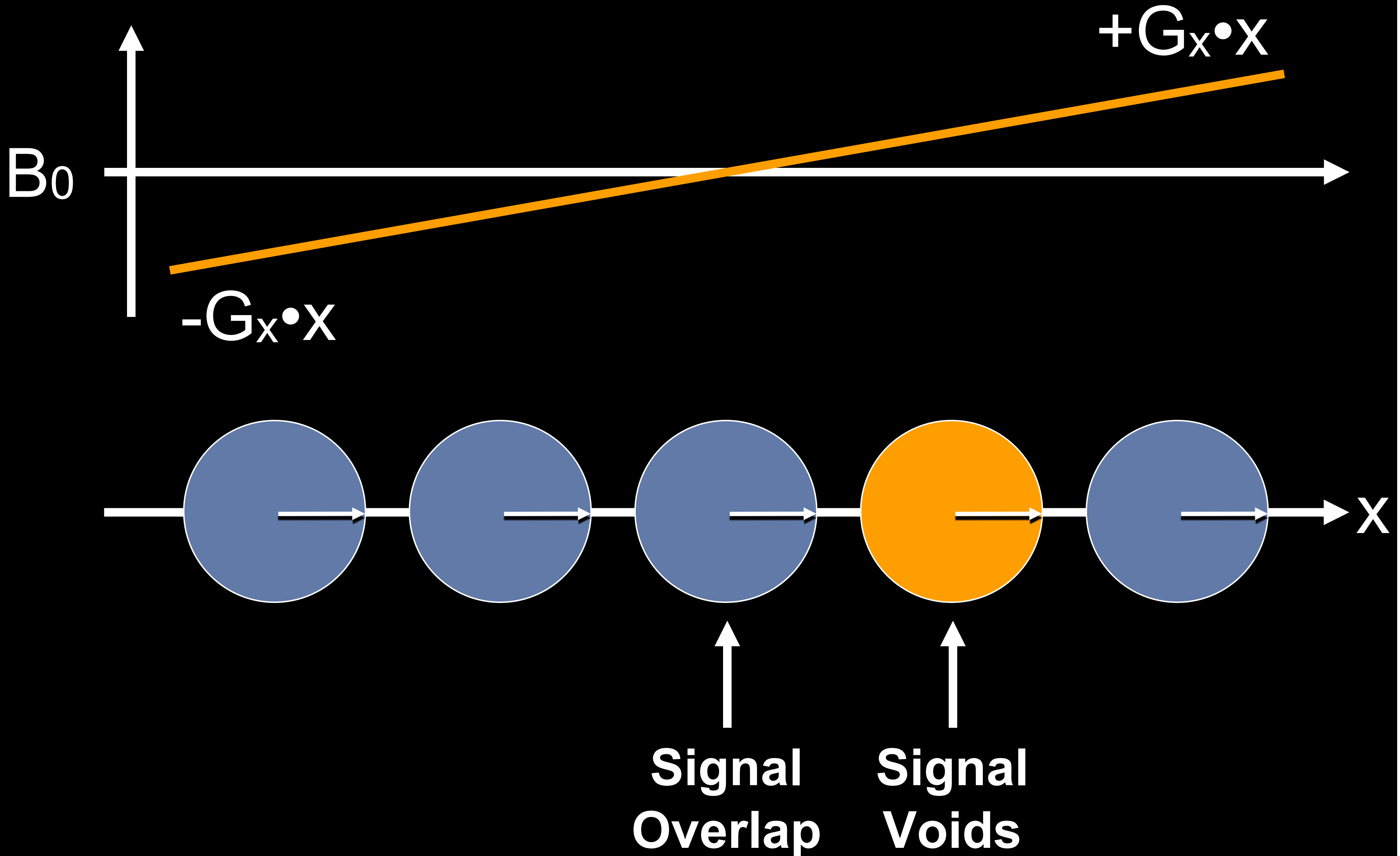
Water Spins in a Gradient Field

GRE & Fat/Water Frequency



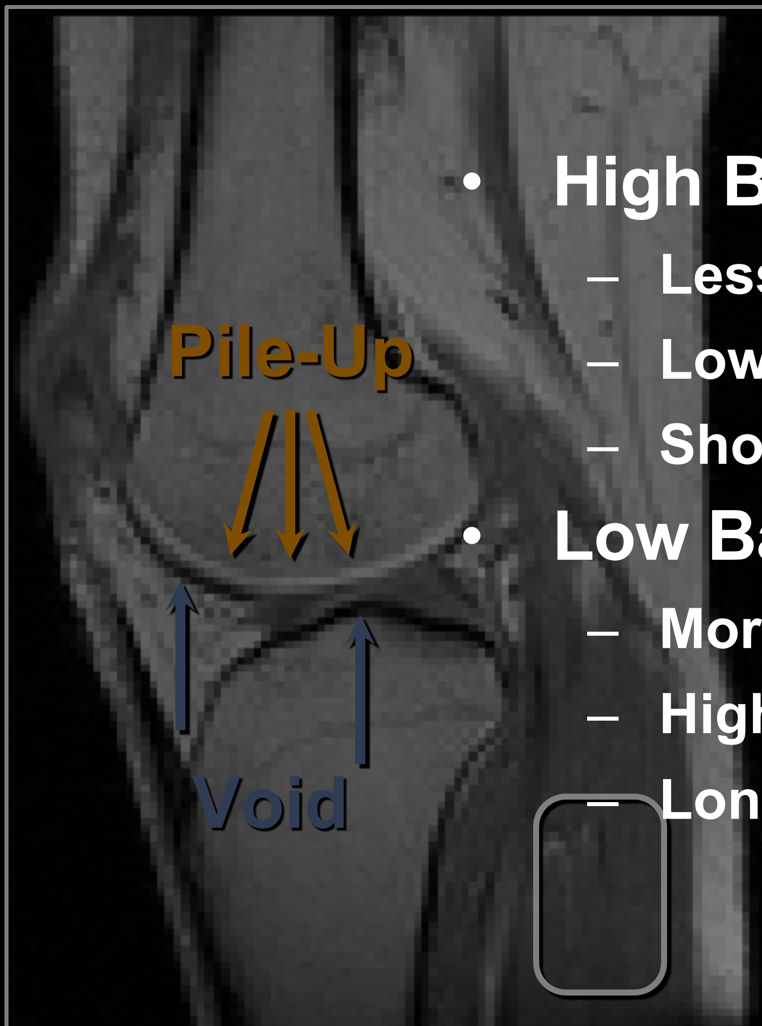
Water & Fat Spins in a Gradient Field

GRE & Fat/Water Frequency

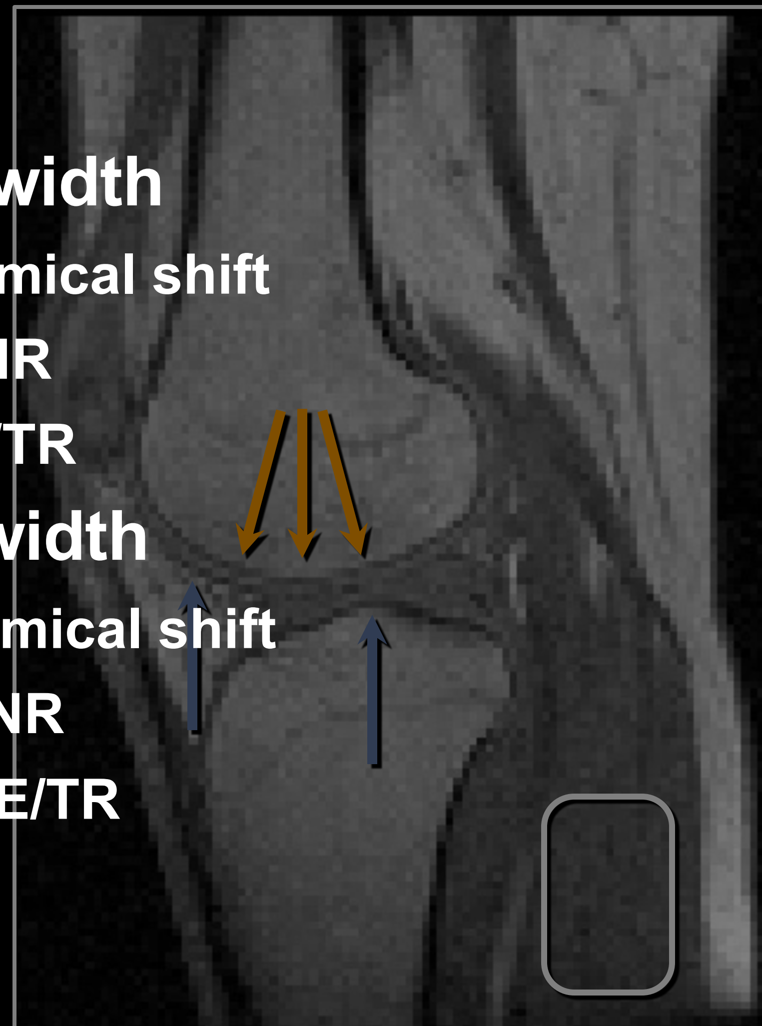


GRE & Fat/Water Frequency

Low Bandwidth



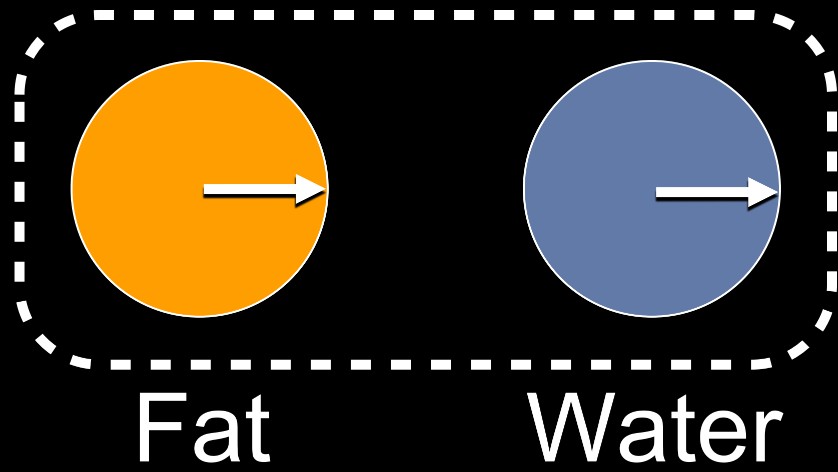
High Bandwidth



- **High Bandwidth**
  - Less chemical shift
  - Lower SNR
  - Short TE/TR
- **Low Bandwidth**
  - More chemical shift
  - Higher SNR
  - Longer TE/TR

GRE and Fat/Water Phase

- **Pixels are frequently a mixture of fat and water**
- **Pixel intensity is the vector sum of fat and water**



In-Phase

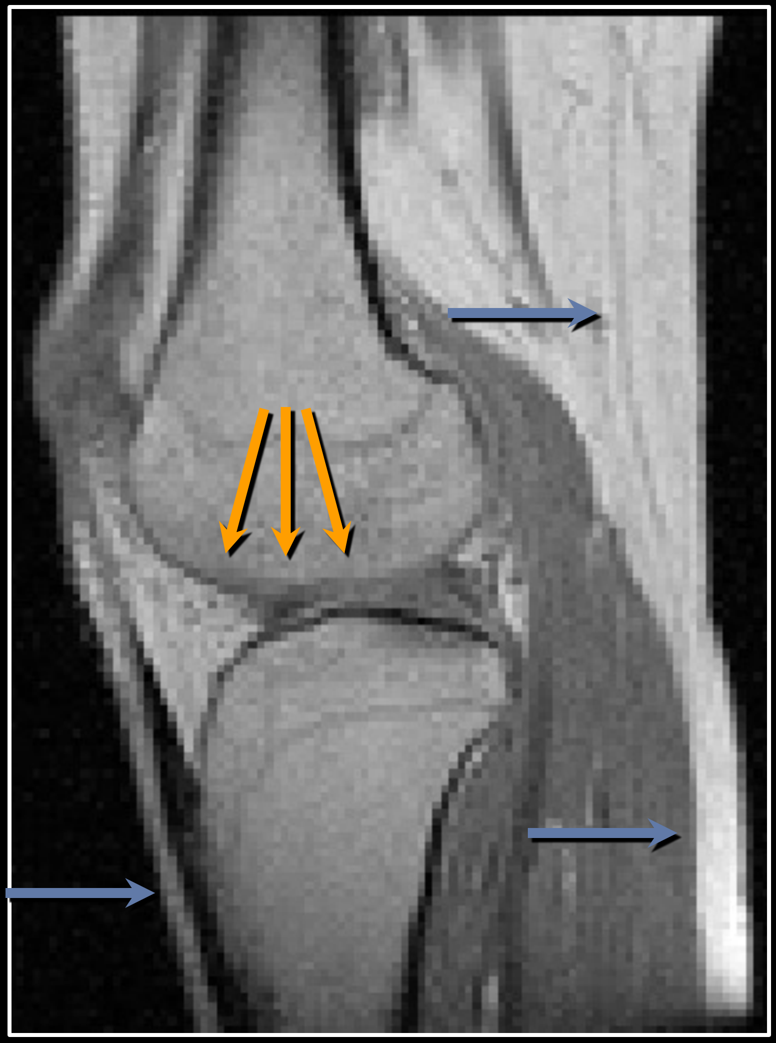
→ + → >0

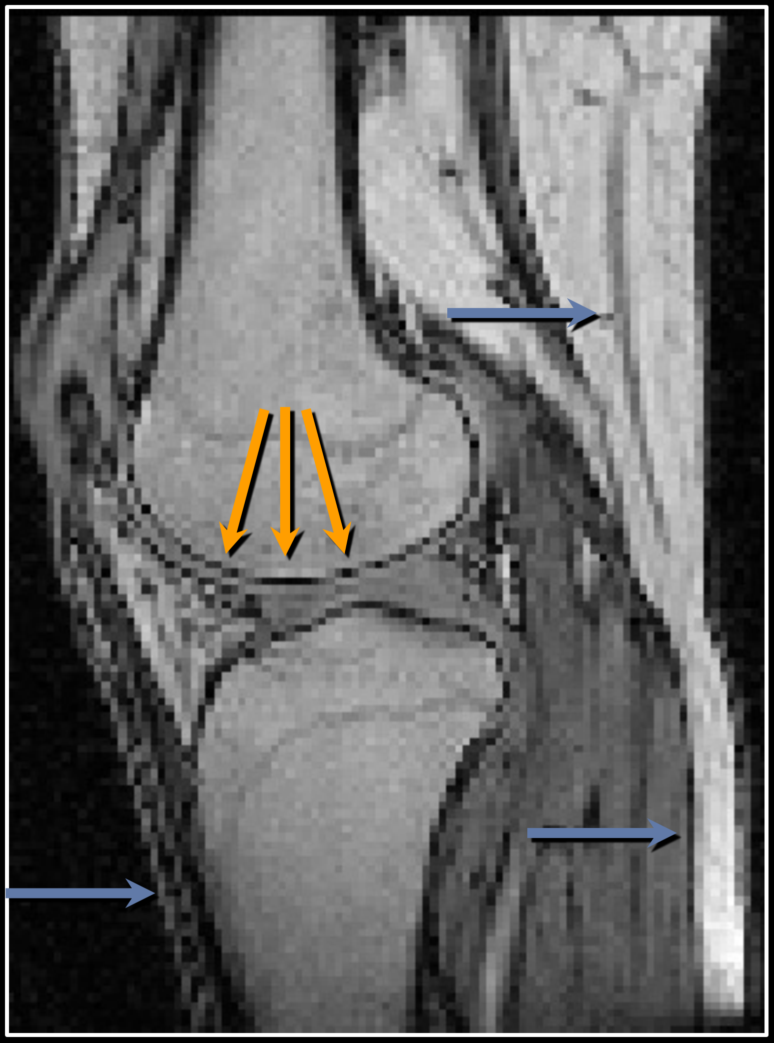
Opposed-Phase

← + → =0

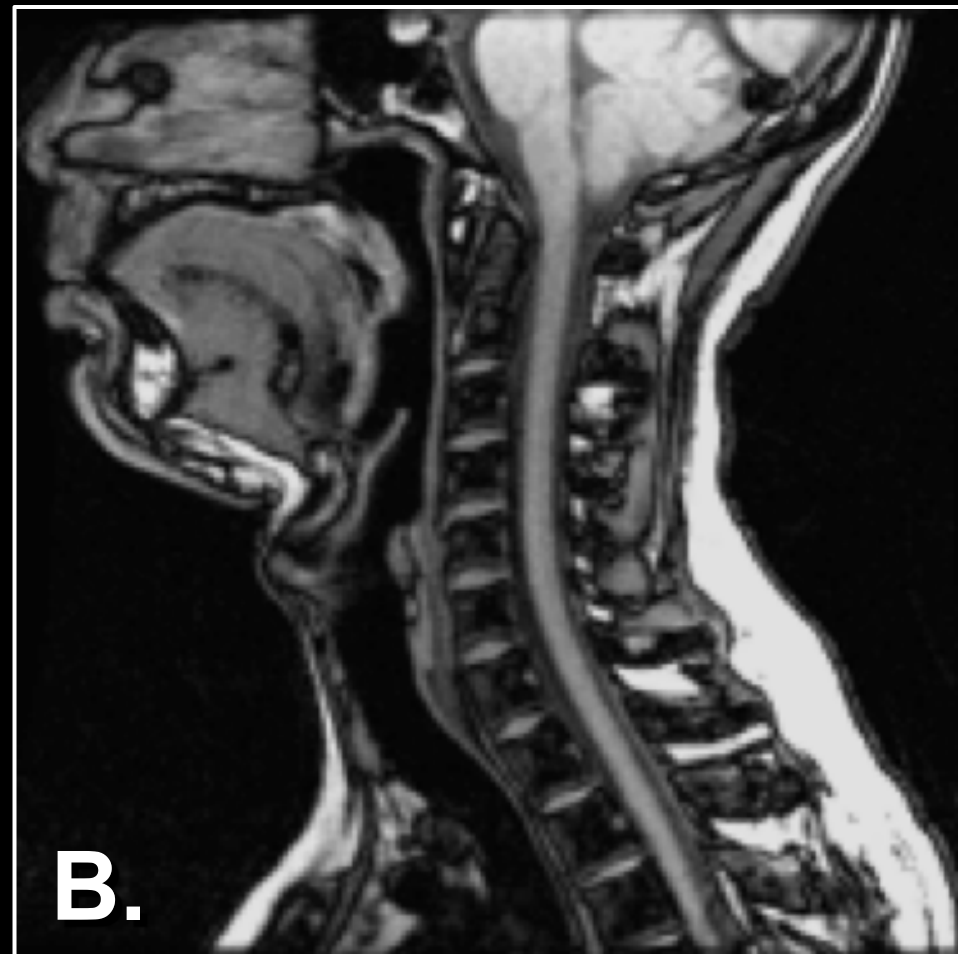
The TE controls the phase between fat and water.

GRE and Fat/Water Phase



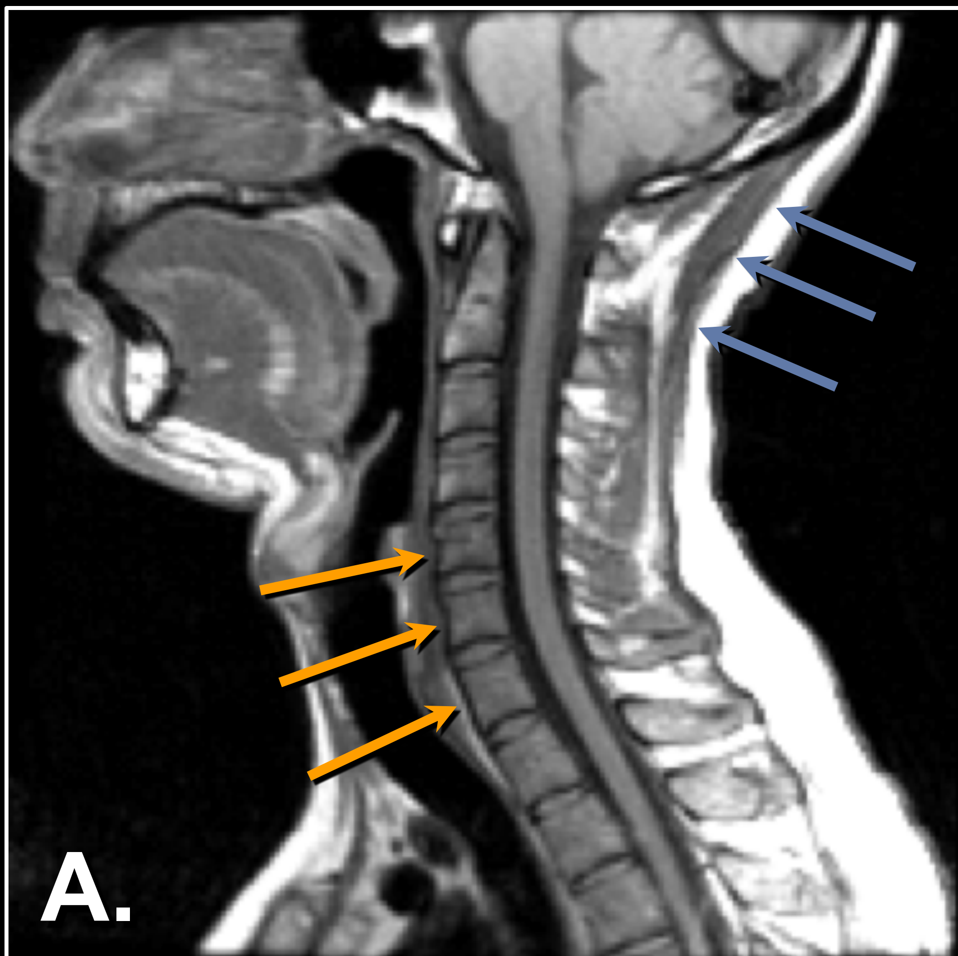


Which image is the in-phase image?

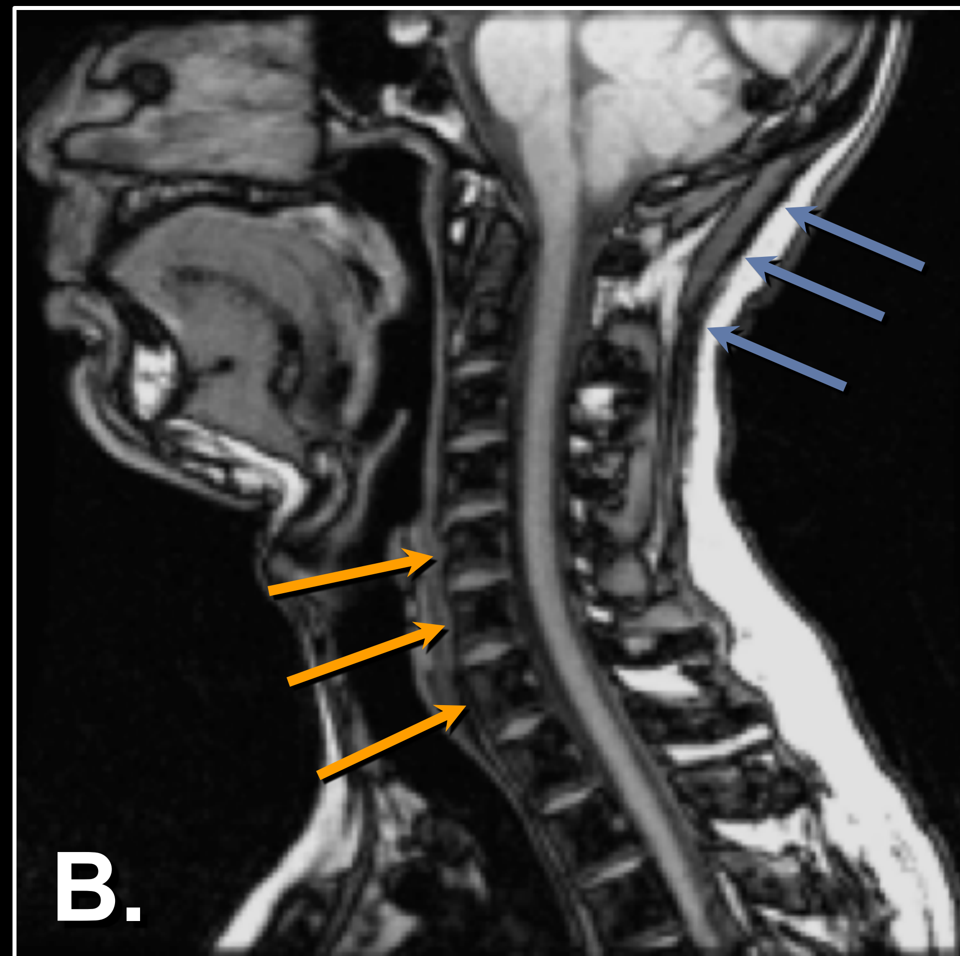


Images Courtesy of Scott Reeder

Which image is the in-phase image?



In-Phase



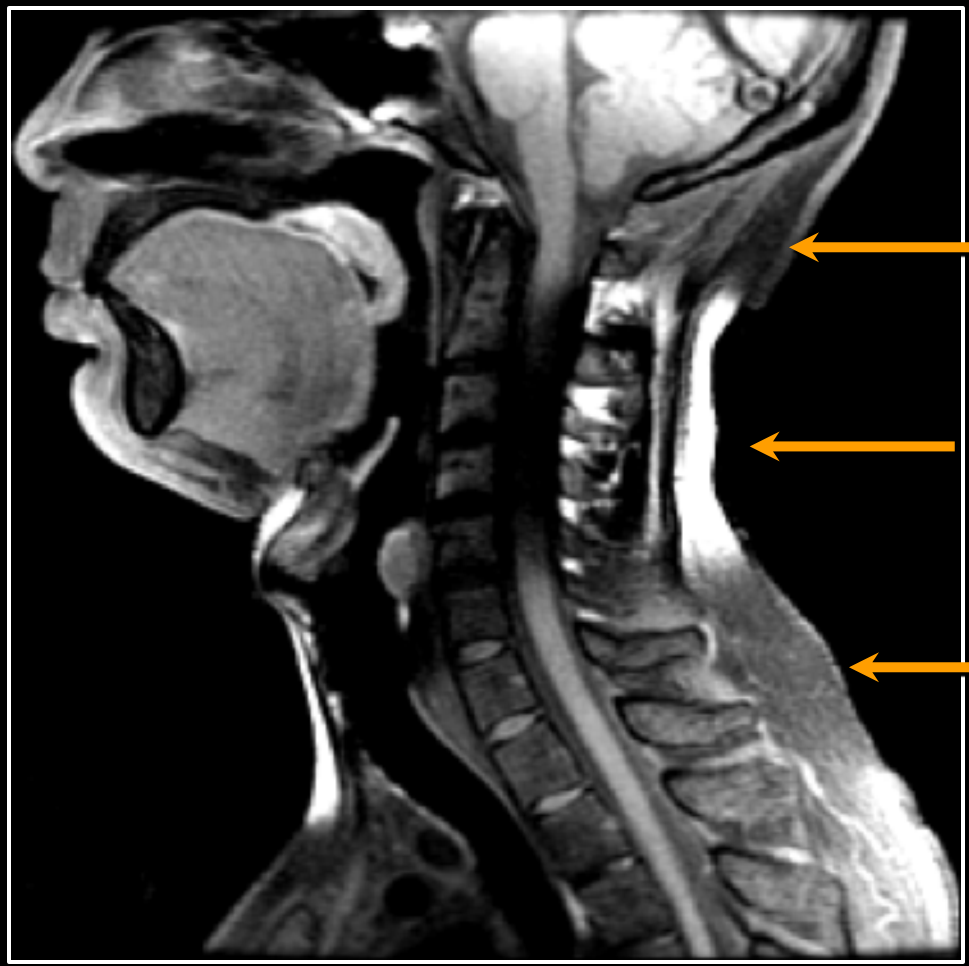
Opposed-Phase

Images Courtesy of Scott Reeder

Gradient Echoes & Fat Suppression

- **Why is fat suppression/separation important?**
  - Fat is bright on most pulse sequences.
  - But so are many other things...
    - CSF & edema
    - Flowing blood
    - Contrast enhanced tissues
- **Fat obscures underlying pathology**
  - Edema, neoplasm, inflammation
- **How can fat be eliminated in GRE images?**
  - Fat saturation pulses
  - Multi-echo acquisitions
    - Dixon/IDEAL

Gradient Echoes & Fat/Water Separation



Fat-Sat Image

Fat-Sat Can Be Spatially Non-Uniform

Images Courtesy of Scott Reeder

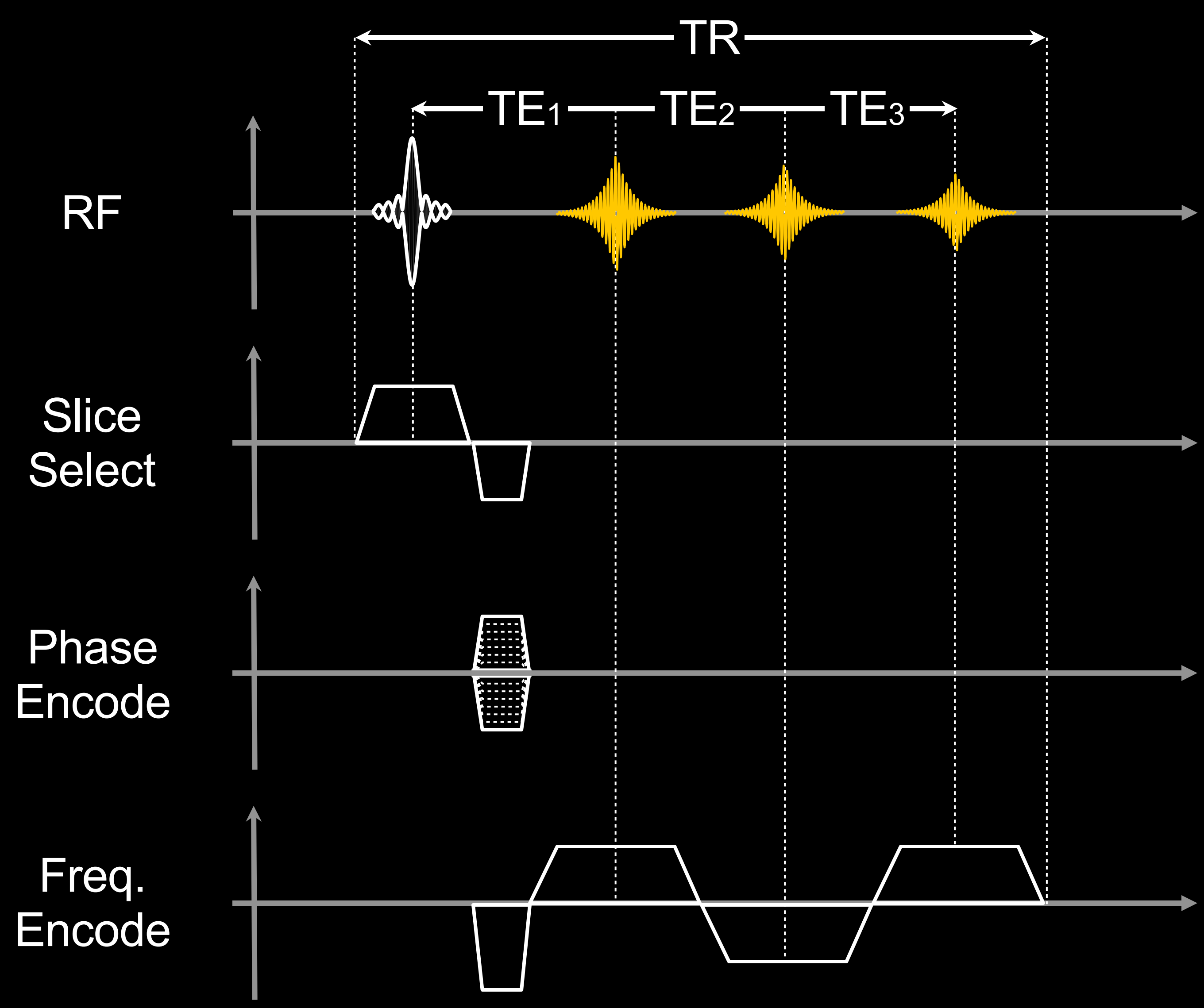
Gradient Echoes & Fat/Water Separation

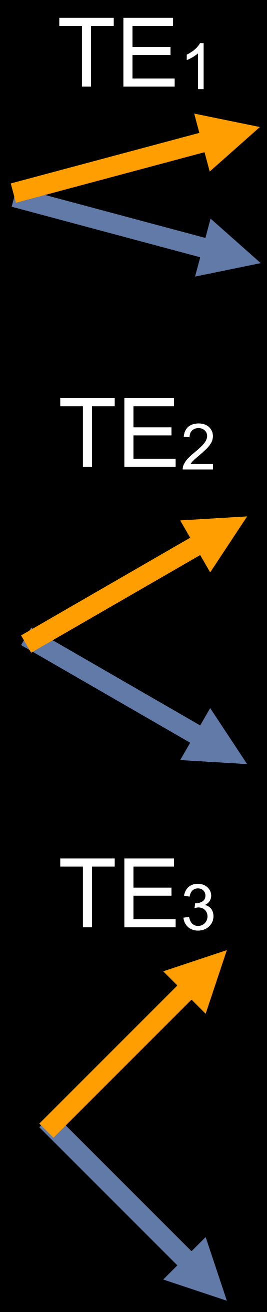
IDEAL Water Image

IDEAL Fat Image

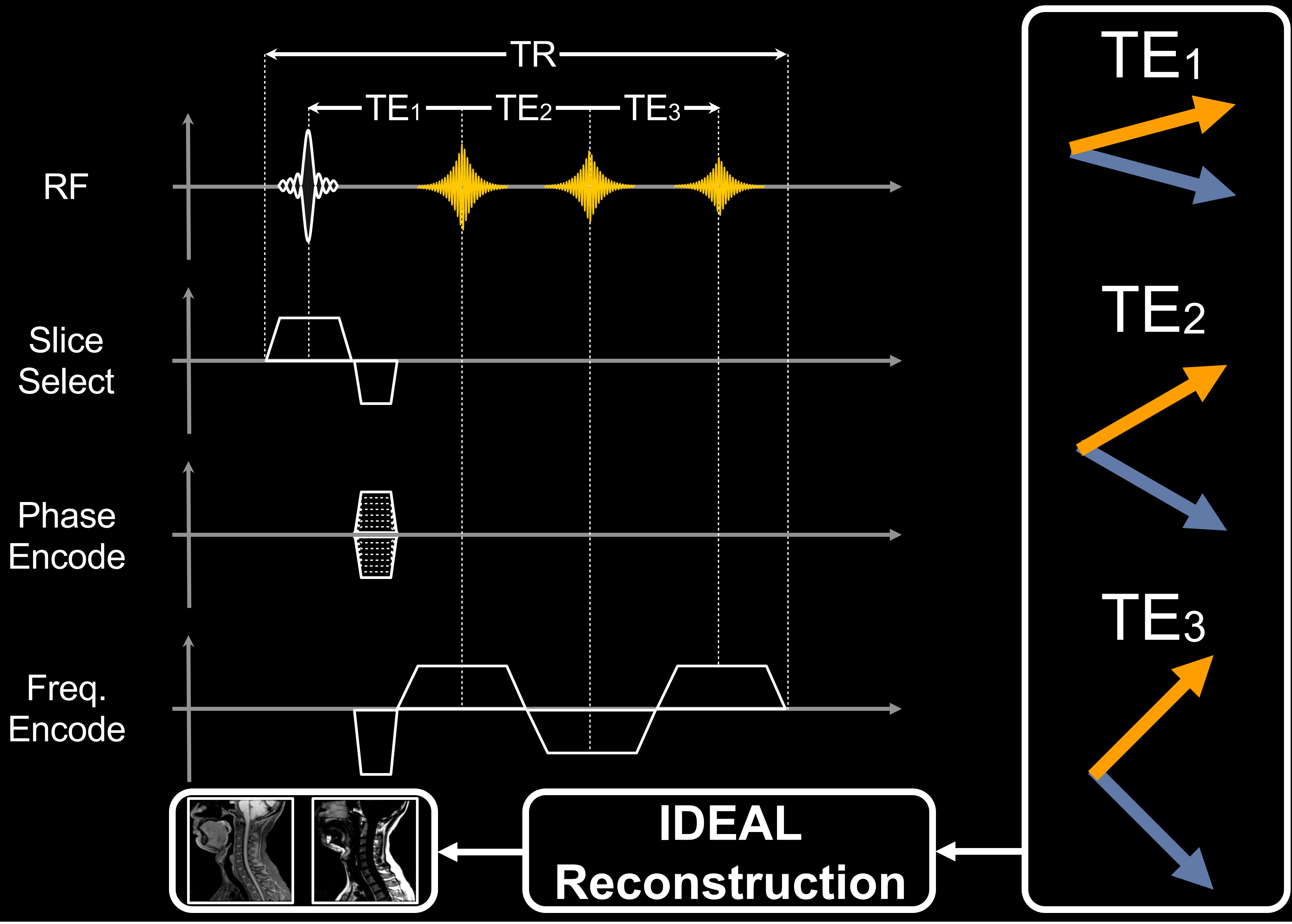
Images Courtesy of Scott Reeder

GRE & Fat/Water Separation - How?



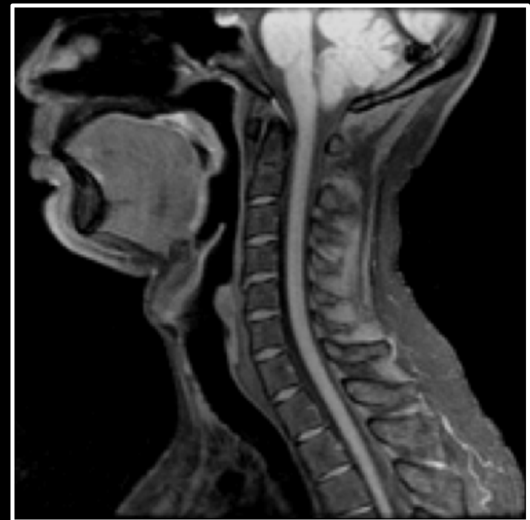


GRE & Fat/Water Separation - How?

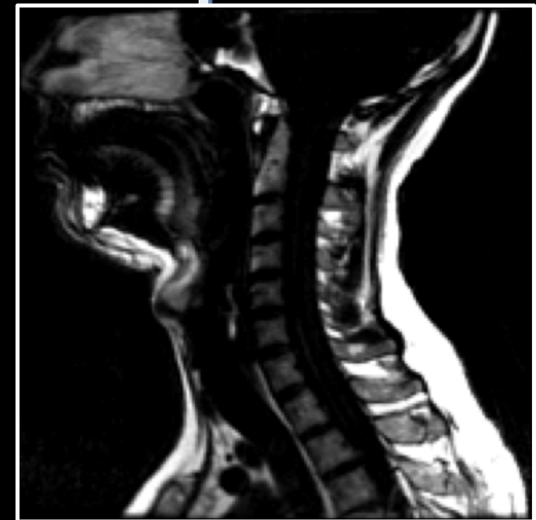


Gradient Echoes & Fat/Water Separation

Imperfect Fat Sat

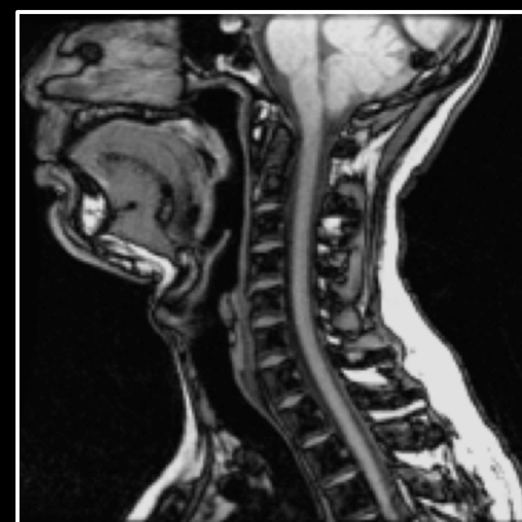


IDEAL water image



IDEAL fat image

in-phase



opposed-phase

Images Courtesy of Dr. Scott Reeder