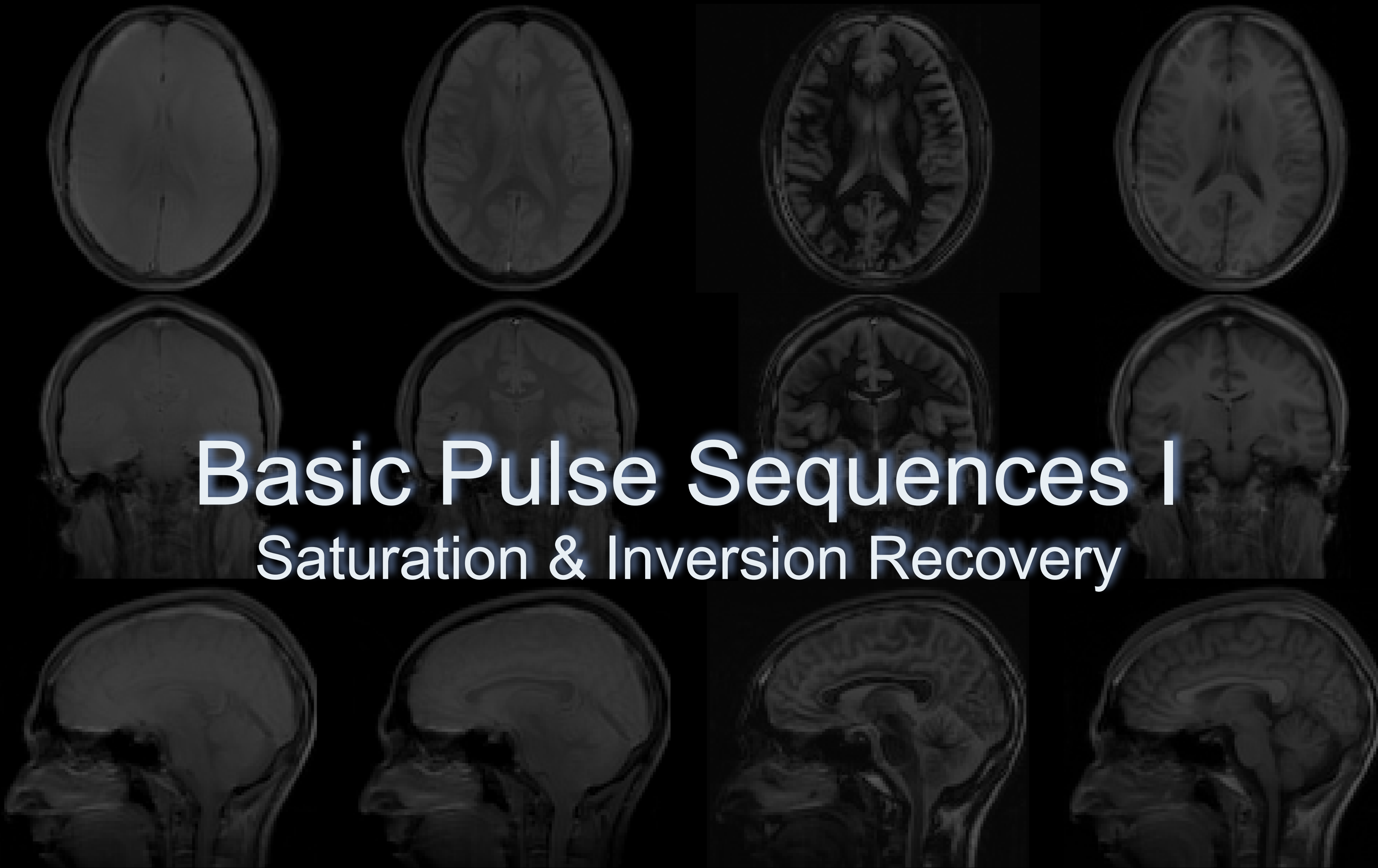

Basic Pulse Sequences I

Saturation & Inversion Recovery

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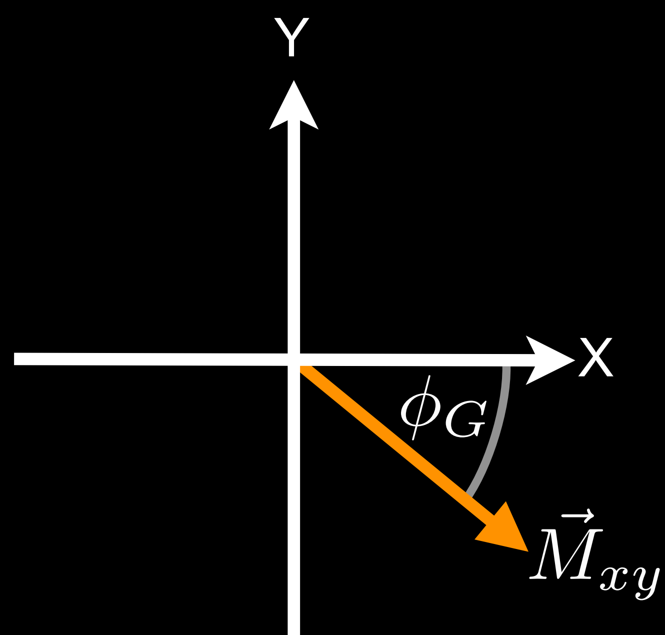
Lecture #5 Learning Objectives

- Explain what the most important equations of motion are for describing spin systems for MRI.
- Understand the assumptions about the B_0, B_1, and Gradient fields.
- Be able to define the magnetic field at any point in space when a gradient is applied.
- Appreciate the gradients change the phase or frequency of the bulk magnetization as a function of spatial position.
- Describe the safety concerns for gradients.

Phase from a Gradient

$$\phi_G(\vec{r}, t) = -\gamma \int_0^t \vec{G}(\tau) \cdot \vec{r}(\tau) d\tau$$

$$R_G = \begin{bmatrix} \cos(\phi_G) & -\sin(\phi_G) & 0 \\ \sin(\phi_G) & \cos(\phi_G) & 0 \\ 0 & & 1 \end{bmatrix}$$



Rotation about the z-axis

Homogeneous Coordinate Gradient Operator

$$\mathbf{G}_{\vec{G}}^{\vec{r}} = \begin{bmatrix} \cos\left(\gamma \int_0^\tau \vec{G}(t)\cdot\vec{r}(t)dt\right) & -\sin\left(\gamma \int_0^\tau \vec{G}(t)\cdot\vec{r}(t)dt\right) & 0 & 0 \\ \sin\left(\gamma \int_0^\tau \vec{G}(t)\cdot\vec{r}(t)dt\right) & \cos\left(\gamma \int_0^\tau \vec{G}(t)\cdot\vec{r}(t)dt\right) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$\vec{M}_H(0_+) = G_{\vec{G}}^{\vec{r}} \vec{M}_H(0_-)$$

Gradient Operator

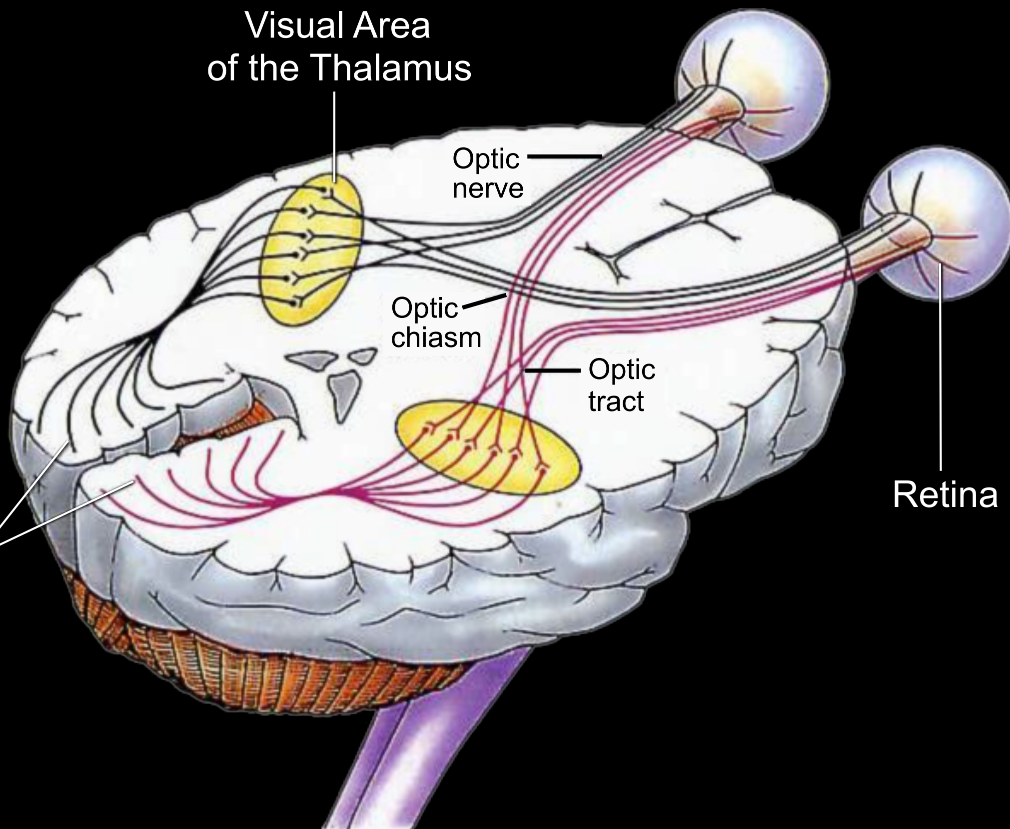
```
% This function returns the 4x4 homogenous coordinate expression for a
% gradient (G) acting on a spin at position (p) for a duration (dt) for a
% particular gyromagnetic ratio (gamma).
%
% SYNTAX: dG=PAM_Grad_op(gamma,G,dt,p)
%
% INPUTS: gamma - gyromagnetic ratio [Hz/T]
%         G     - Gradient vector    [G/cm] (3x1)
%         dt    - time step          [s]
%         p     - spin position      [cm]   (3x1)
%
% OUTPUT: RF - RF pulse operator [4x4]
%
% DBE@UCLA 2015.01.21

function dG=PAM_Grad_op(gamma,G,dt,p)

% Angle of rotation imparted on the spin by the gradient
phi=-2*pi*gamma*(dot(G,p)/10000)*dt % Convert gauss to Tesla

% Homogeneous expression for the GRADIENT MATRIX
dG=[cos(phi) -sin(phi) 0 0;
    sin(phi)  cos(phi) 0 0;
    0         0        1 0;
    0         0        0 1];

return
```

Lecture #6 Learning Objectives

- Appreciate the definition of image contrast.
- Explain what a T1 or T2-weighted image is.
- Describe what a pulse sequence is.
- Understand the saturation recovery pulse sequence and the saturation condition.
- Describe the inversion recover sequence.
- Distinguish between STIR and FLAIR.

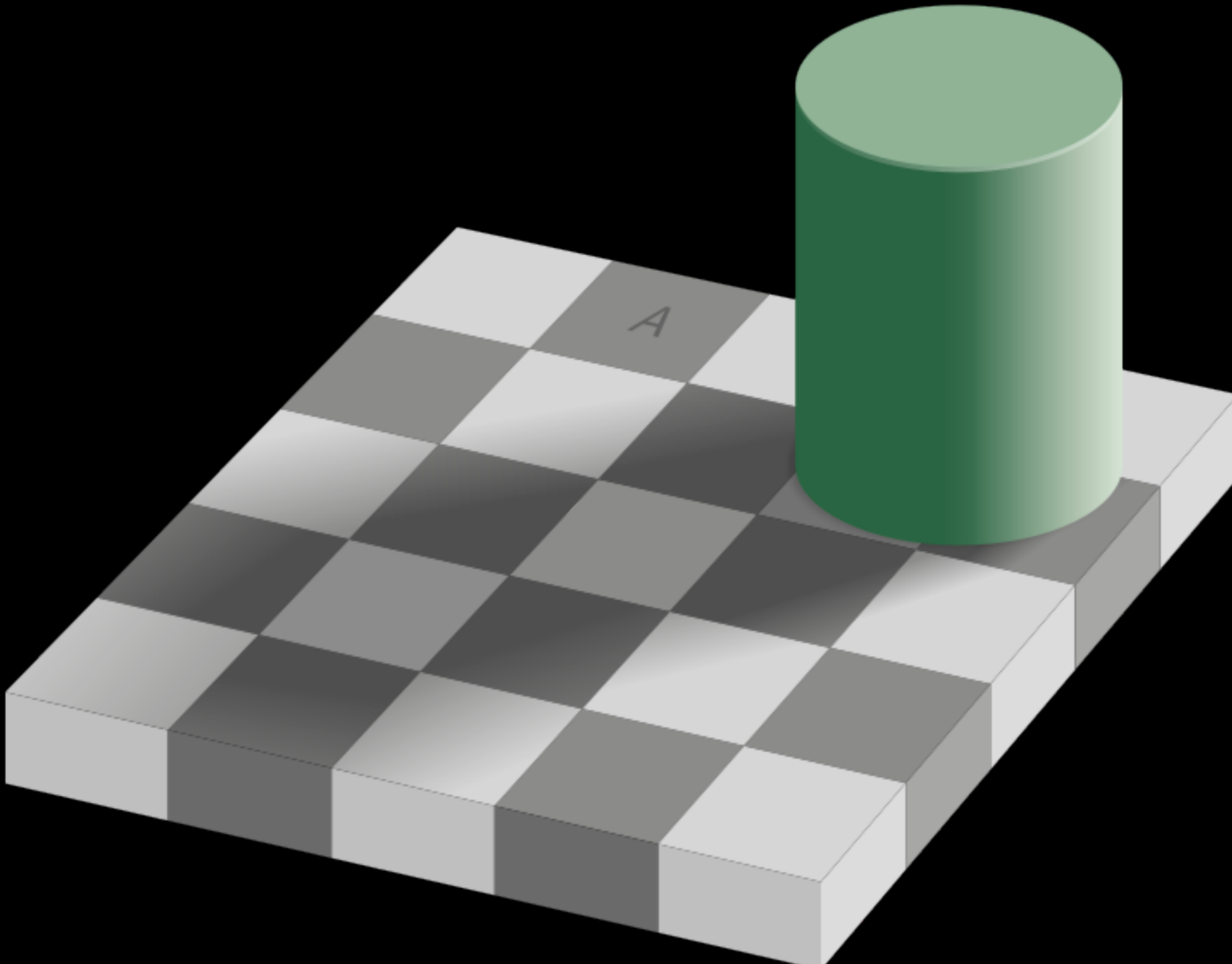
Image Contrast

Why Image Contrast?



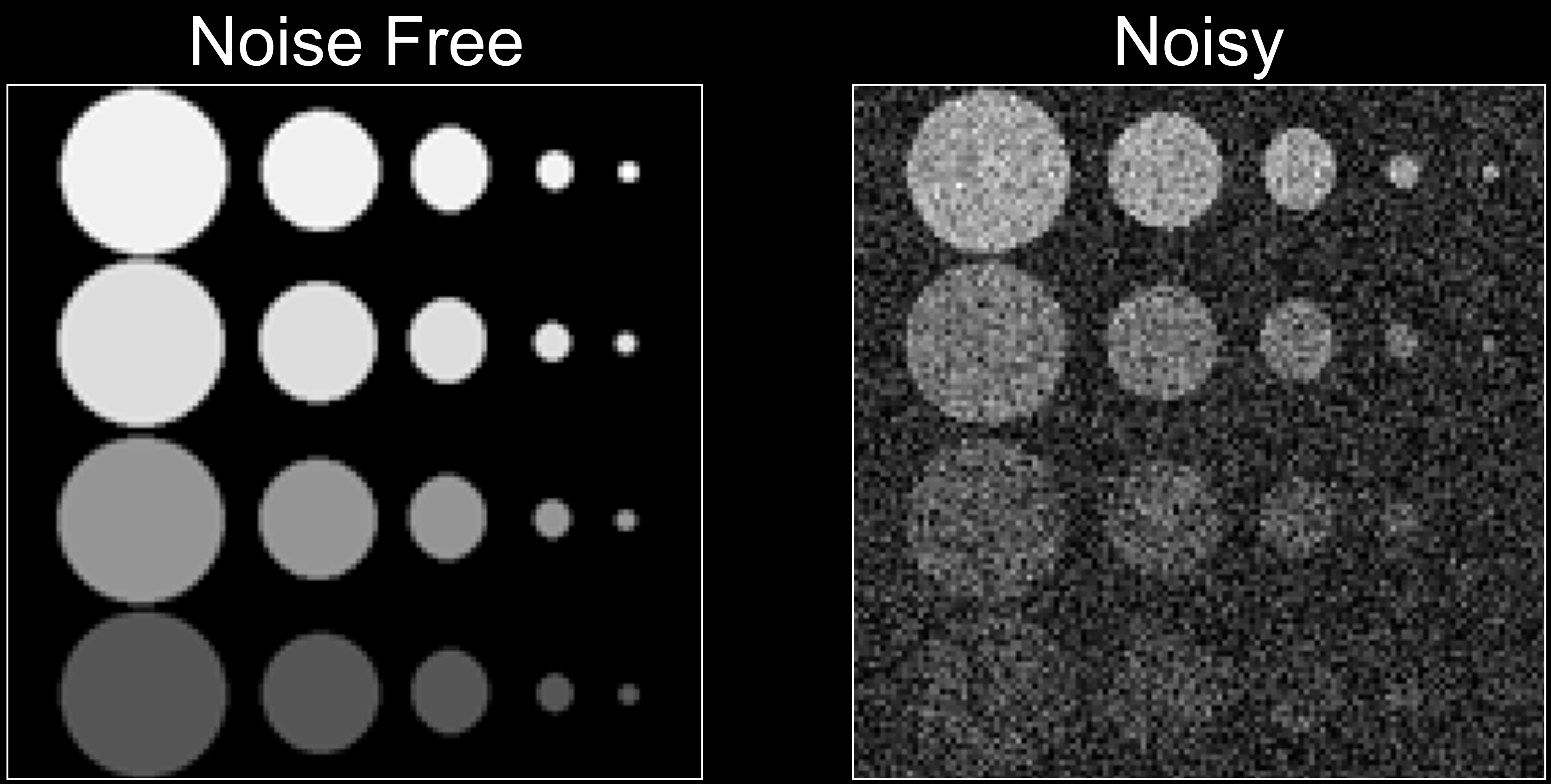
The human visual system is more sensitive to contrast than absolute luminance.

Why Image Contrast?



Which is brighter A or B?

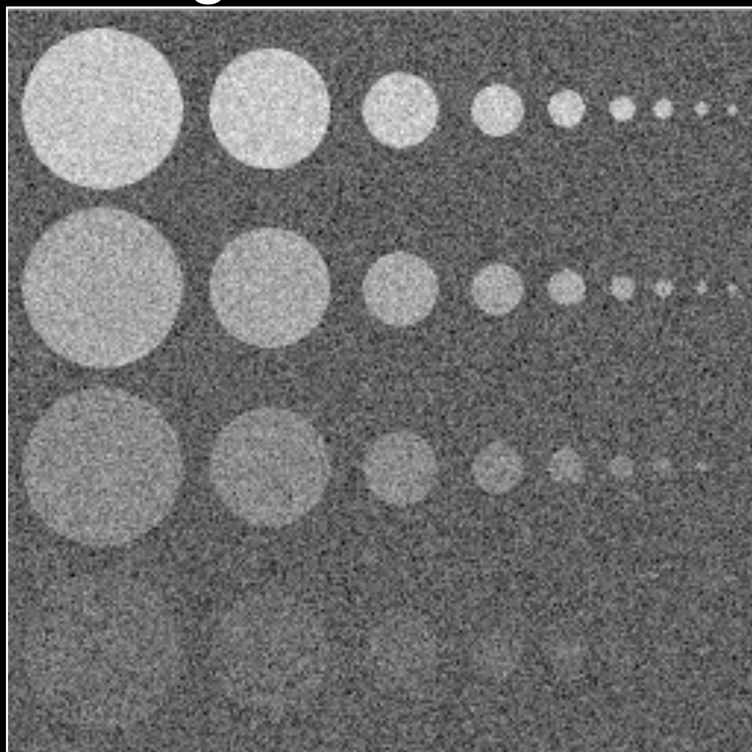
CNR, Object Size, and Noise



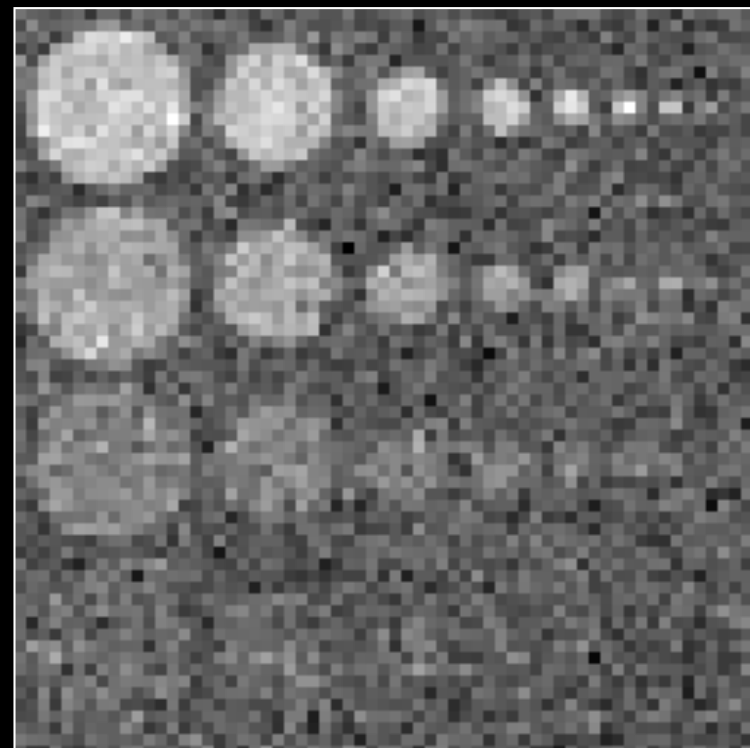
Large high-contrast objects are easier to see in the presence of noise.

CNR, Resolution, and Noise

High Resolution



Low Resolution



Small low-contrast objects are easier to see with higher resolution.

Image signal-to-noise is constant.

Image Contrast

$$\mathcal{C}_{AB} = \frac{|I_A - I_B|}{I_{ref}}$$

$$\mathcal{C}_{AB} = f(\rho, T_1, T_2, T_2^*, D, \ldots)$$

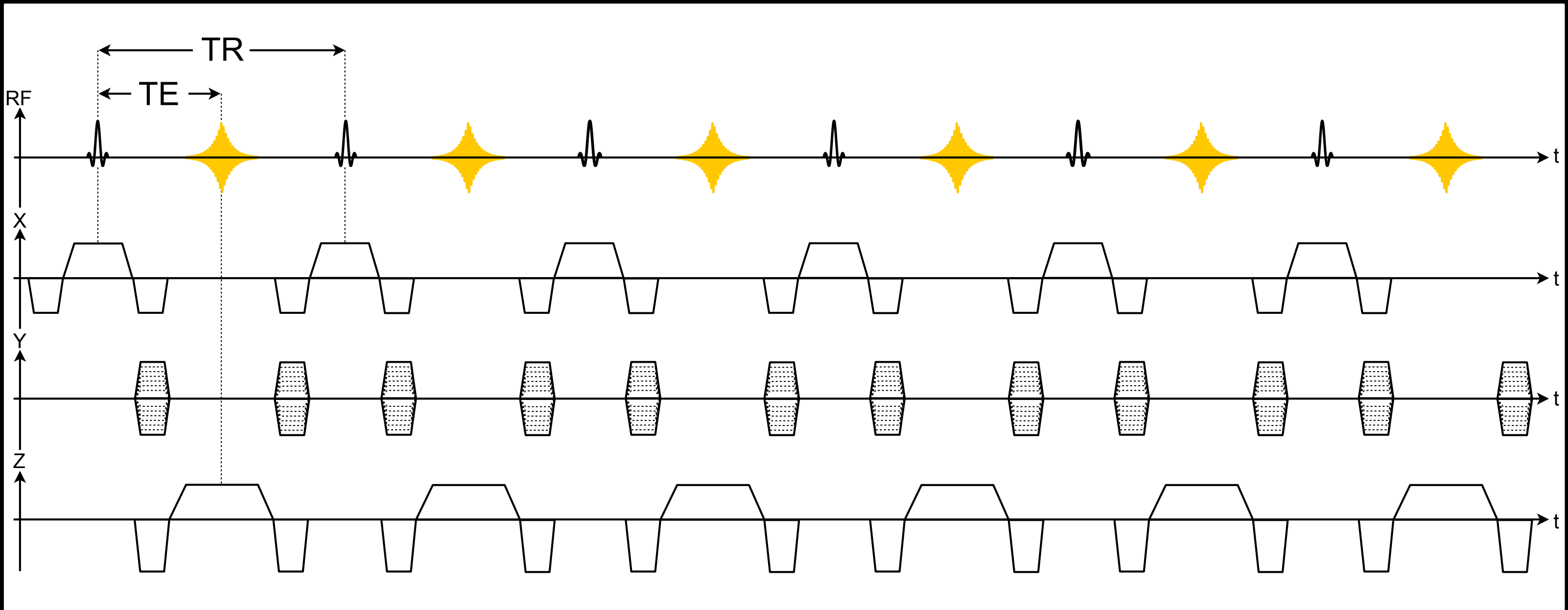
$$\mathcal{C}_{AB} \approx f(T_1) \qquad \mathcal{C}_{AB} \approx f(T_2)$$

A central goal in MRI is to limit image contrast to a single mechanism.

Pulse Sequences

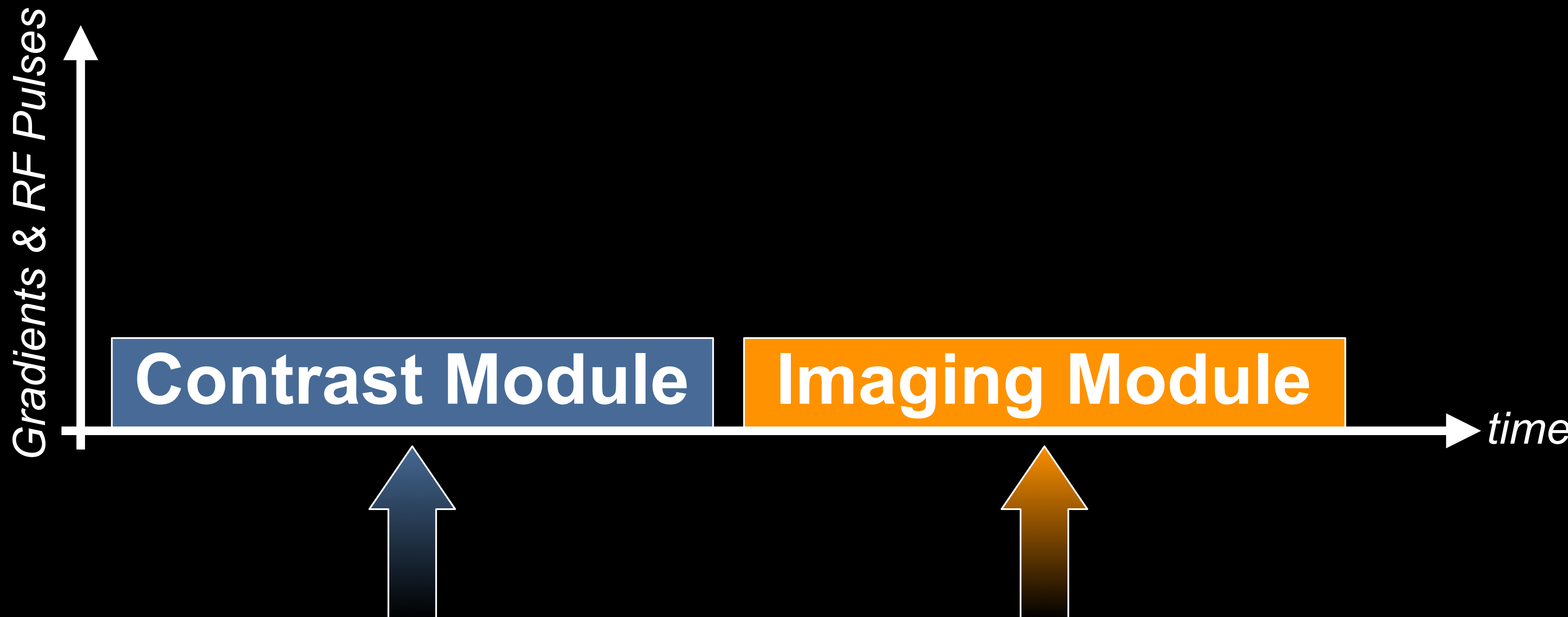
What is a pulse sequence?

Sheet music is a ***timing diagram*** for playing the piano.



A pulse sequence is a ***timing diagram*** for running the scanner.

Pulse Sequences



Inversion Recovery
T2-preparation
Fat Saturation
Tagging

Spoiled Gradient Echo
SPGR, FLASH, T1 FFE
bSSFP
FIESTA, Balanced FFE, True FISP
Spin Echo
Fast or Turbo Spin Echo

How do we keep track of the magnetization's history?

Pulse Sequence Definitions

$\mathrm{M}_z^{(n)}(0_-)$ Longitudinal magnetization ***before*** the n^{th} event.

$\mathrm{M}_z^{(n)}(0_+)$ Longitudinal magnetization ***after*** the n^{th} event.

$\mathrm{M}_{xy}^{(n)}(0_-)$ Transverse magnetization ***before*** the n^{th} event.

$\mathrm{M}_{xy}^{(n)}(0_+)$ Transverse magnetization ***after*** the n^{th} event.

Free? Forced? Relaxation?

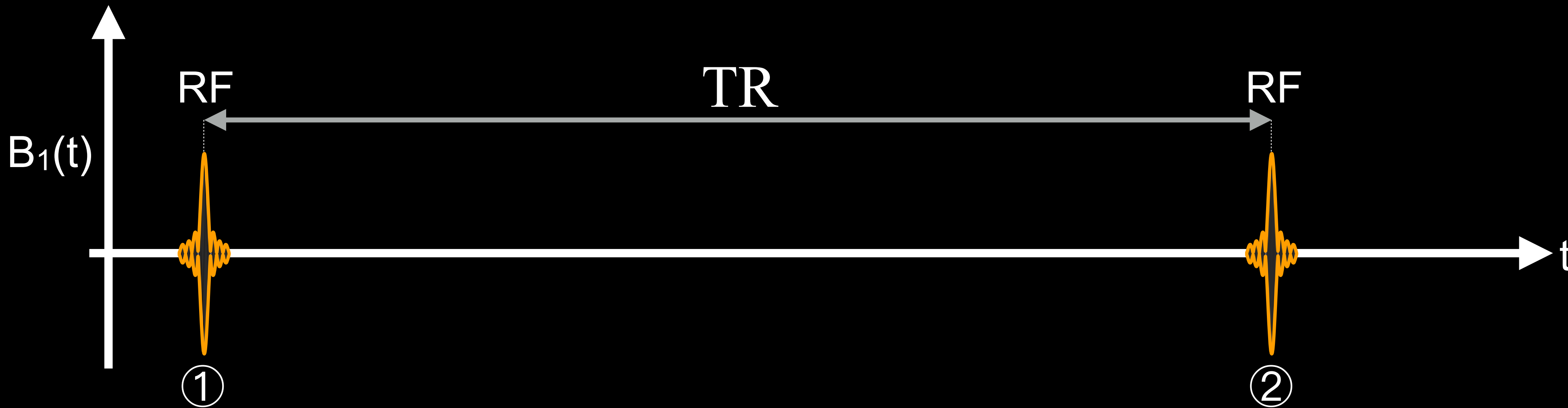
- **We've considered all combinations of:**
  - Free or forced precession
  - With or without relaxation
  - Laboratory or rotating frames
- **Which one's concern M219 the most?**
  - ***Rotating*** **frame**
    - **Free precession with relaxation**

$$M_z(t) = M_z^0 e^{-\frac{t}{T_1}} + M_0\left(1 - e^{-\frac{t}{T_1}}\right) \qquad M_{xy}(t) = M_{xy}^0 e^{-t/T_2}$$

    - **Forced precession without relaxation**

$$\vec{M}^{(n)}(0_+) = \begin{bmatrix} \mathrm{c}^2\theta + \mathrm{s}^2\theta \mathrm{c}\alpha & \mathrm{c}\theta\mathrm{s}\theta - \mathrm{c}\theta\mathrm{s}\theta\mathrm{c}\alpha & -\mathrm{s}\theta\mathrm{s}\alpha \\ \mathrm{c}\theta\mathrm{s}\theta - \mathrm{c}\theta\mathrm{s}\theta\mathrm{c}\alpha & \mathrm{s}^2\theta + \mathrm{c}^2\theta\mathrm{c}\alpha & \mathrm{c}\theta\mathrm{s}\alpha \\ \mathrm{s}\theta\mathrm{s}\alpha & -\mathrm{c}\theta\mathrm{s}\alpha & \mathrm{c}\alpha \end{bmatrix} \vec{M}^{(n)}(0_-)$$

Typical Pulse Sequence…



$$\vec{M}^{(1)}(0_-) = \vec{M}_0 = \begin{bmatrix} 0 \\ 0 \\ M_0 \end{bmatrix}$$

$$\vec{M}^{(1)}(0_+) = RF^{\alpha}_{\theta}\vec{M}^{(1)}(0_-)$$

$$\vec{M}^{(2)}(0_-) = \mathrm{E}(T_1, T_2, TR)\vec{M}^{(1)}(0_+)$$

$$\vec{M}^{(2)}(0_+) = RF^{\alpha}_{\theta}\vec{M}^{(2)}(0_-)$$

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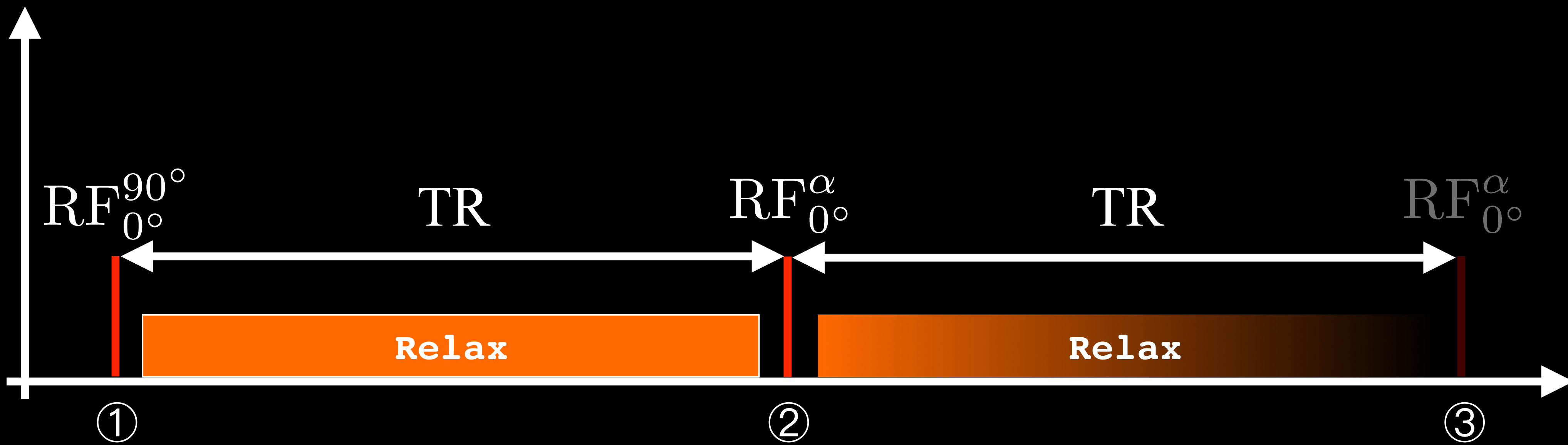
UCLA Radiology

Saturation Recovery

Pulse Sequence Definitions

- TR - Repetition Time
  - Duration of basic pulse sequence repeating block
  - At least one echo acquired per TR
- TE - Echo Time
  - Time from excitation to the maximum of the echo
  - Data is recorded at time TE to form an image

Saturation Recovery



$$(90^{\circ} - \mathrm{TR})_N$$

To The Board...

Saturation Condition

Saturation Condition

- The ***saturation condition*** states:

$$\mathrm{M}_z^{(n)}(0_+) = 0,\ \mathrm{n} \geq 1$$

M_z is ZERO after the event (RF pulse).

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- This is true if the M_{xy} is "gone" before the next 90° RF-pulse is applied:
  - No M_{xy} to convert to M_z
  - How? $TR \gg T_2$

Saturation Condition

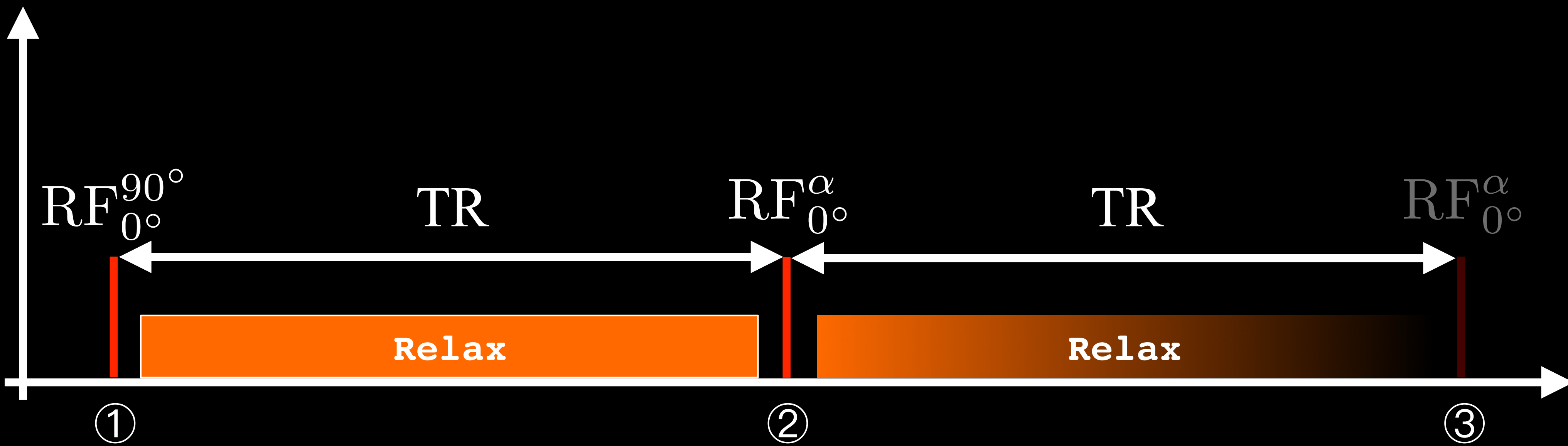
- The ***saturation condition*** states:

$$M_z^{(n)}(0_+) = 0,\ n \geq 1$$

M_z is ZERO after the event (RF pulse).

- This is true if the M_{xy} is “gone” before the next 90° RF-pulse is applied:
  - No M_{xy} to convert to M_z
  - How? $TR >> T_2$
- What if $TR <\sim 3T_2$?
  - M_{xy} can be converted back to M_z
  - Corrupts/complicates image contrast
  - Solution? Spoiler gradients to disperse M_{xy}
- Steady-state solution arises if the saturation conditions are met/enforced

Saturation Recovery



$$(90^\circ - \mathrm{TR})_N$$

To The Board...

SR Contrast

$$A_{fid} \propto \mathrm{M}_z^0 \left(1 - e^{-TR/T_1}\right) \propto \rho \left(1 - e^{-TR/T_1}\right) \quad \text{Eqn. 7.13}$$

- A_{fid} – Signal amplitude immediately after the 90°.
- ρ – proton density.
- If the process of imaging doesn't perturb the magnetization:

$$I\left(\vec{r}\right) \propto \rho\left(\vec{r}\right)\left(1 - e^{-TR/T_1\left(\vec{r}\right)}\right) \quad \text{Eqn. 7.14}$$

SR Contrast

$$I\left(\vec{r}\right) \propto \rho\left(\vec{r}\right)\left(1 - e^{-TR/T_1\left(\vec{r}\right)}\right)$$

The final image is the product of ρ(r) and f(T_1(r)).

$$I\left(\vec{r}\right)_{TR\rightarrow\infty} \propto \rho\left(\vec{r}\right)$$

The image pure pure ρ(r) contrast under this limit.

- Note only *one* parameter adjusts contrast
  - Longer T_1s appear darker with short TRs
- Long T1 will be dark.
- Short T1 will be bright.

SR Contrast

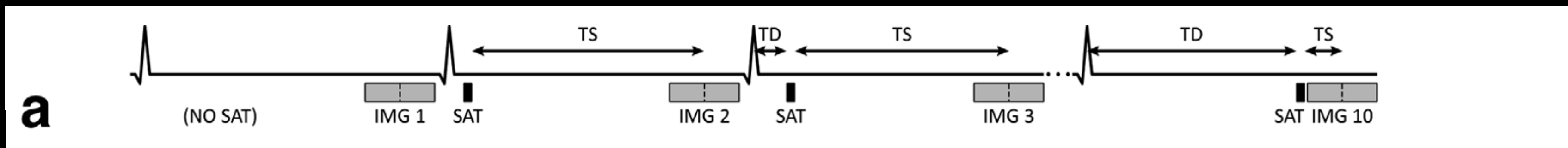
$$I\left(\vec{r}\right)_{TR \rightarrow TR_{opt}} \propto \text{Maximum } T_1 \text{ contrast}$$

$$TR_{opt} = \frac{\ln\left(\frac{T_{1,A}}{T_{1,B}}\right)}{\frac{1}{T_{1,B}} - \frac{1}{T_{1,A}}}$$

Eqn. 7.19

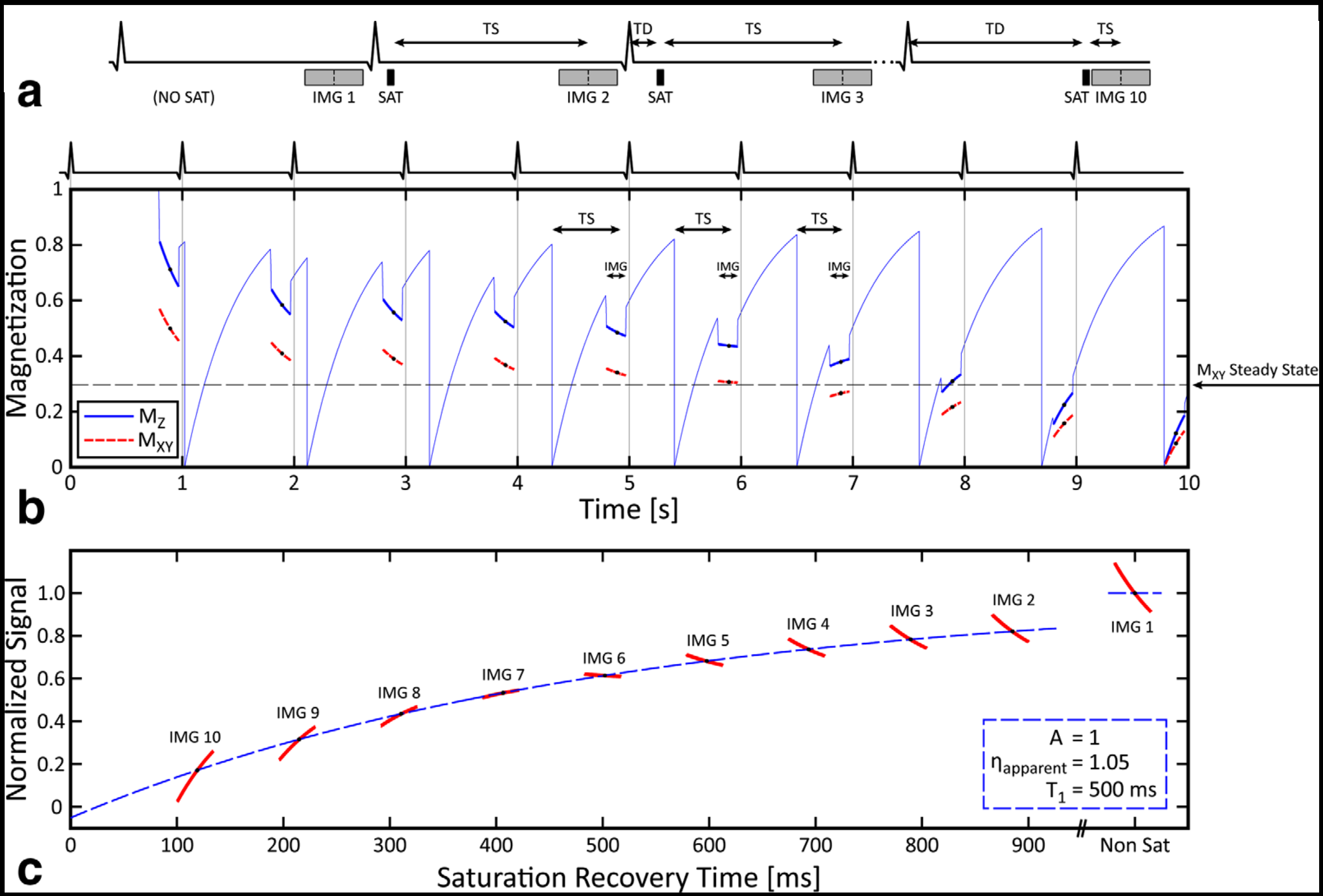
Saturation Recovery - Applications

SAturation recovery single-SHot Acquisition (SASHA)



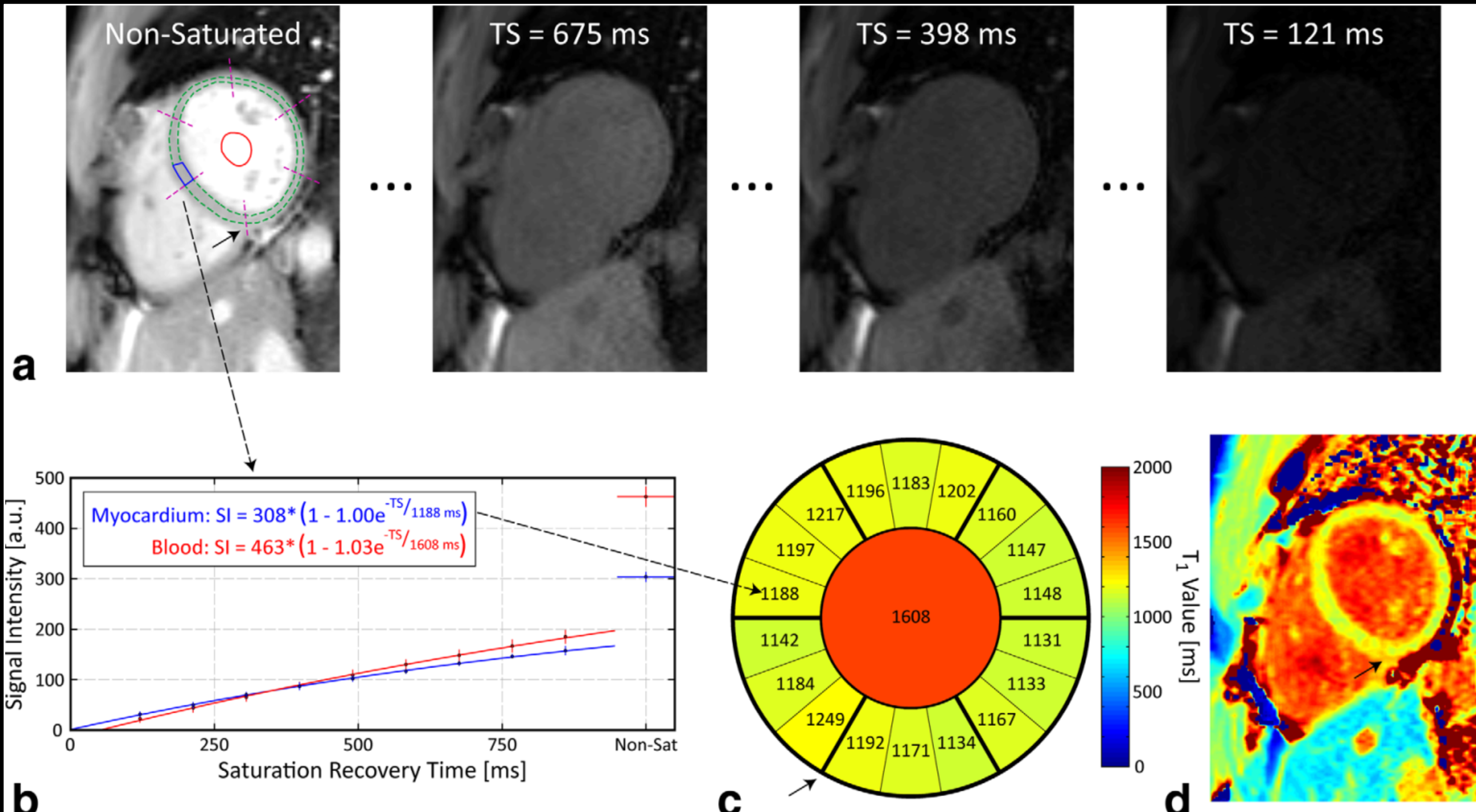
Chow K *et al*. *Mag. Reson. Med.*, v71, i6, p2082-2095, 2014

SAturation recovery single-SHot Acquisition (SASHA)



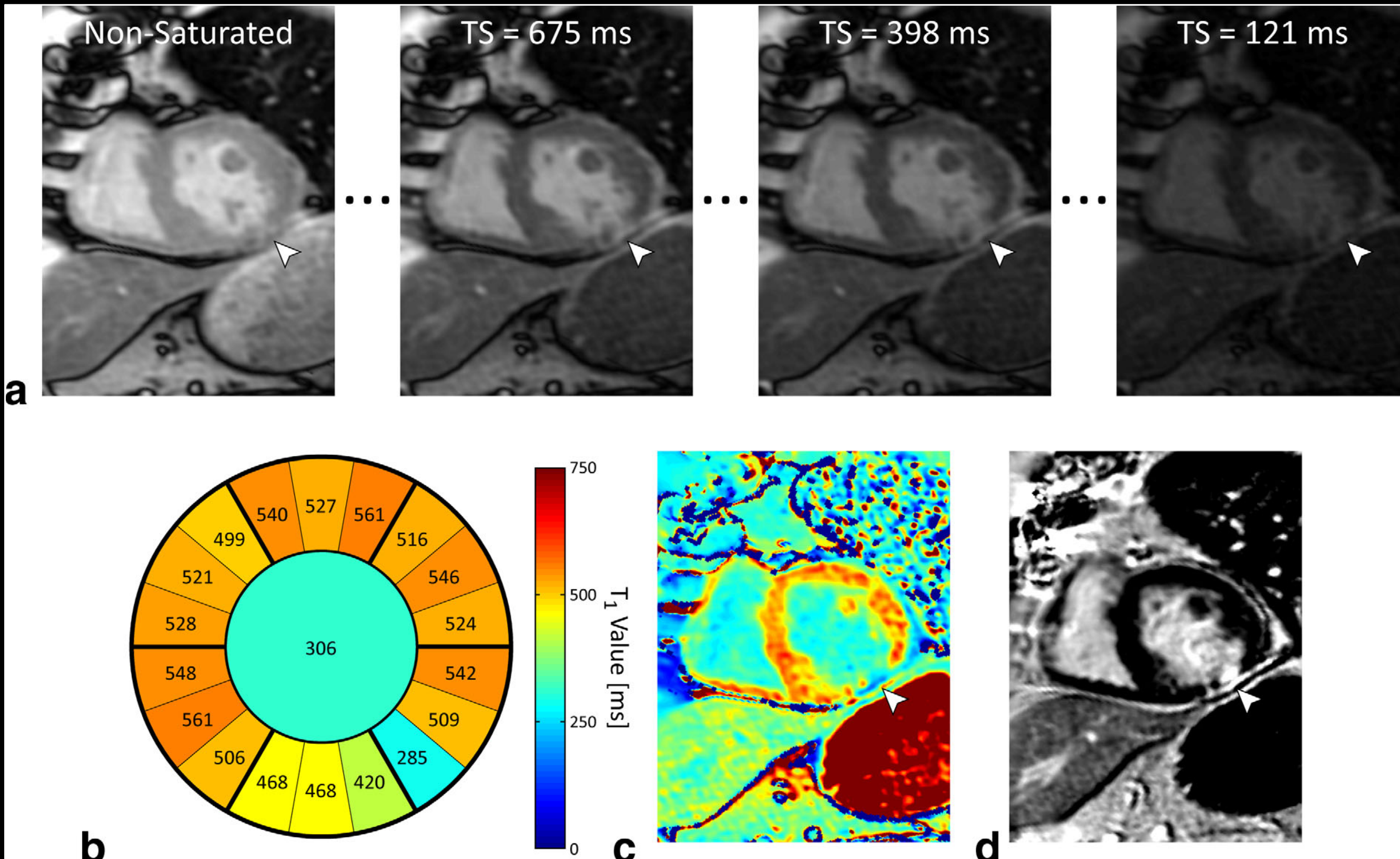
Chow K *et al. Mag. Reson. Med.*, v71, i6, p2082-2095, 2014

SASHA - Normal Subject



Chow K *et al. Mag. Reson. Med.*, v71, i6, p2082-2095, 2014

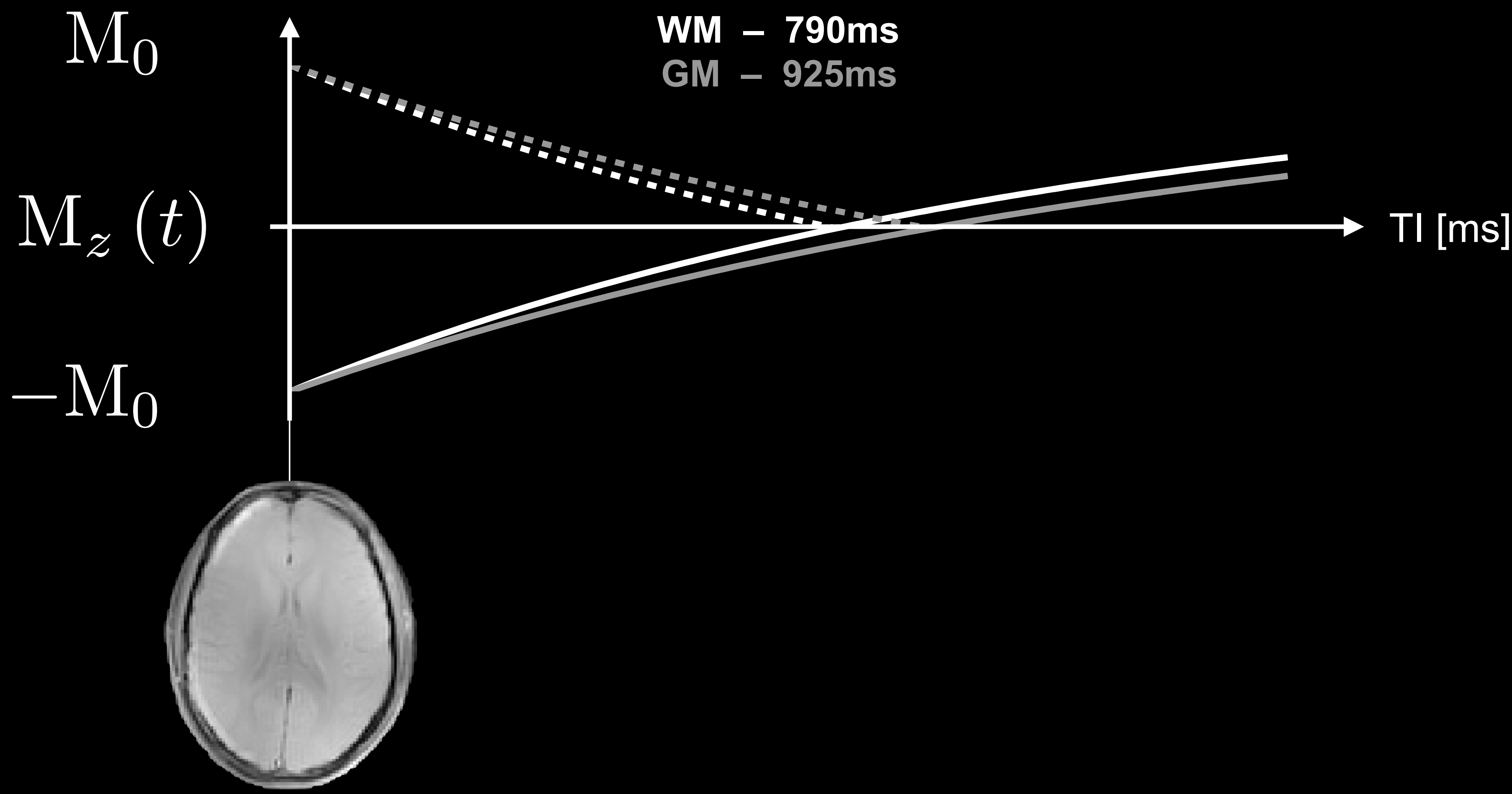
SASHA - Myocardial Infarct



Chow K *et al*. *Mag. Reson. Med.*, v71, i6, p2082-2095, 2014

Inversion Recovery

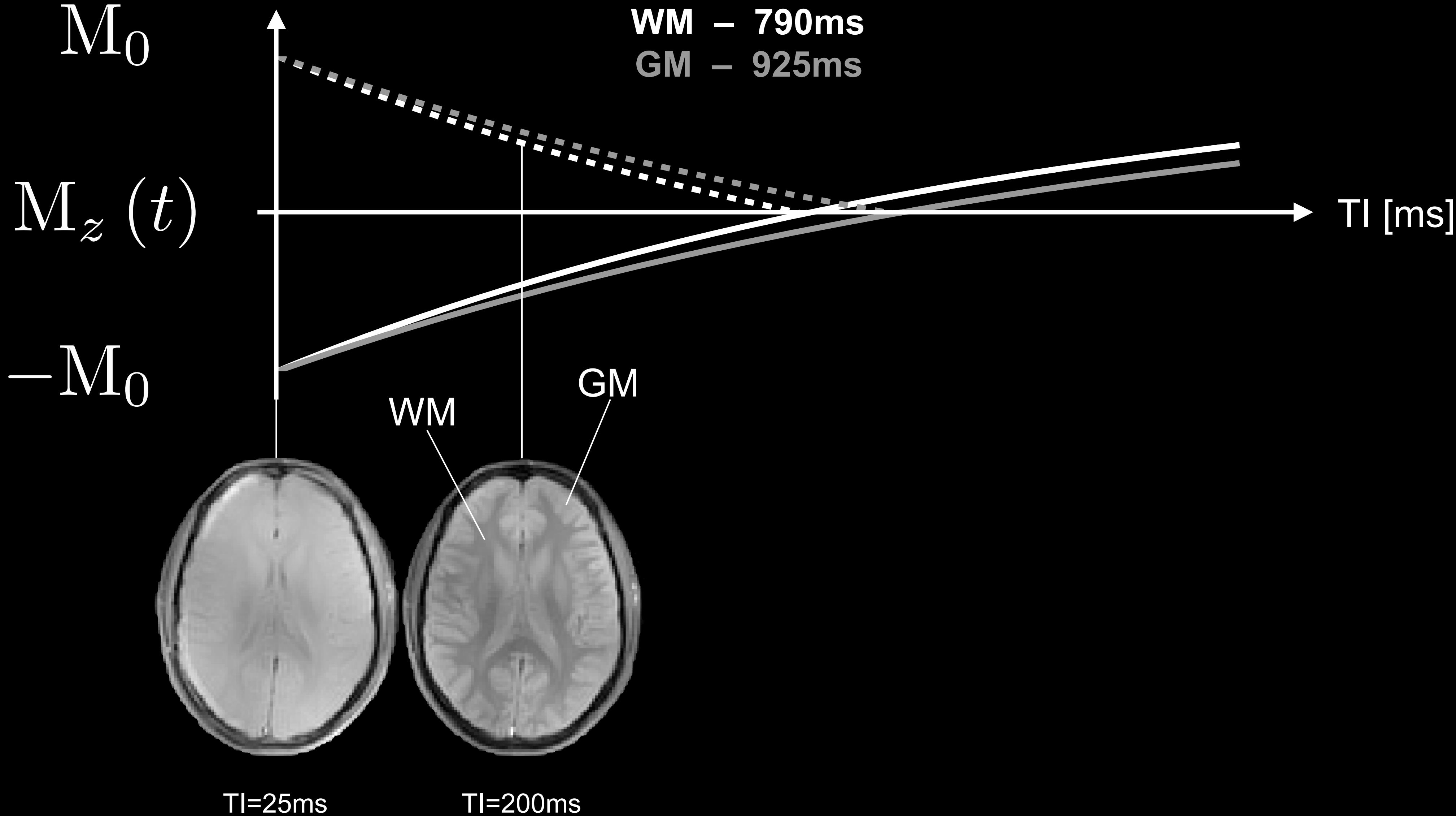
Spin Echo Inversion Recovery



TI=25ms

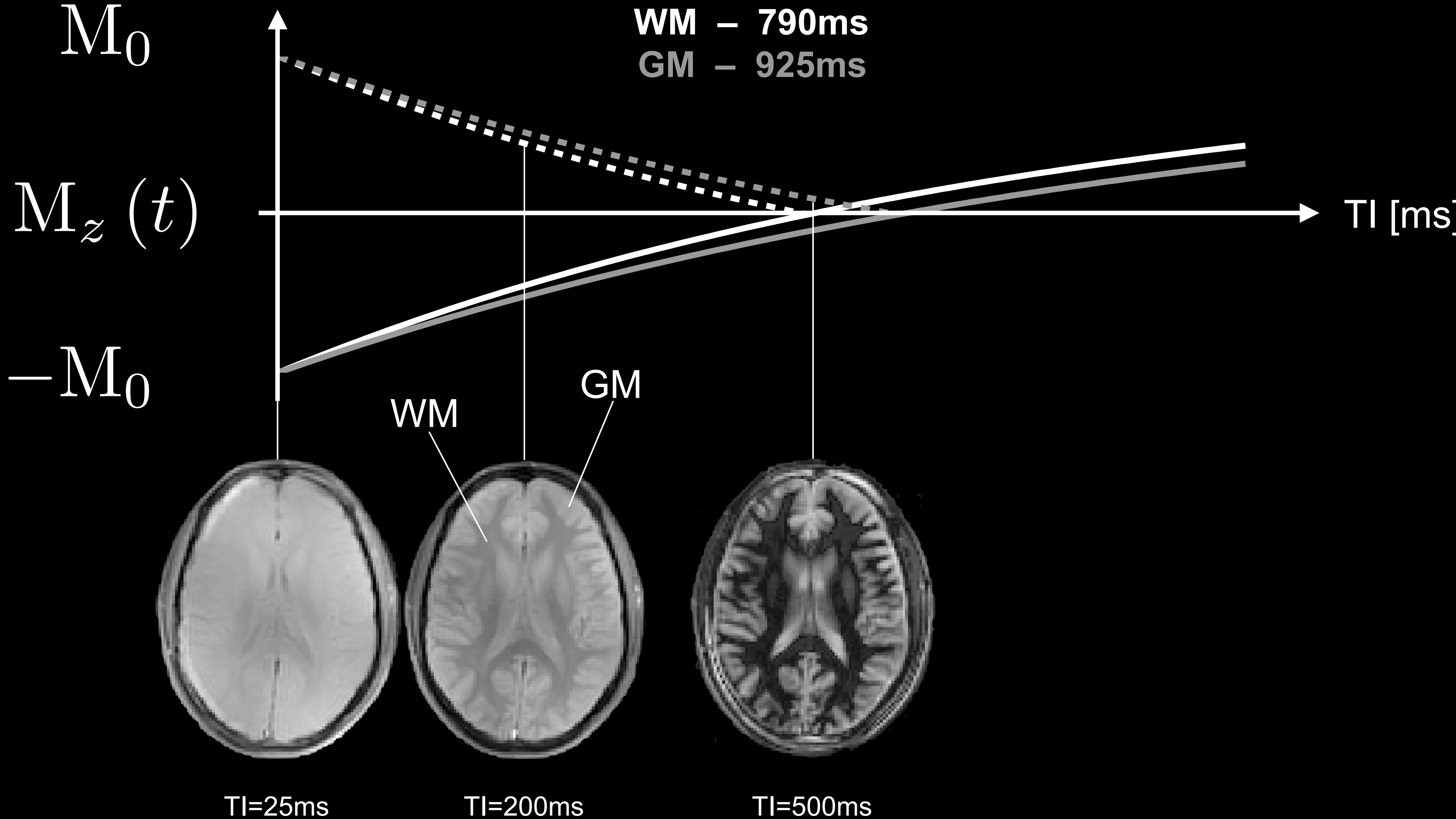
Spin Echo with TE=12ms, TR=2000ms

Spin Echo Inversion Recovery



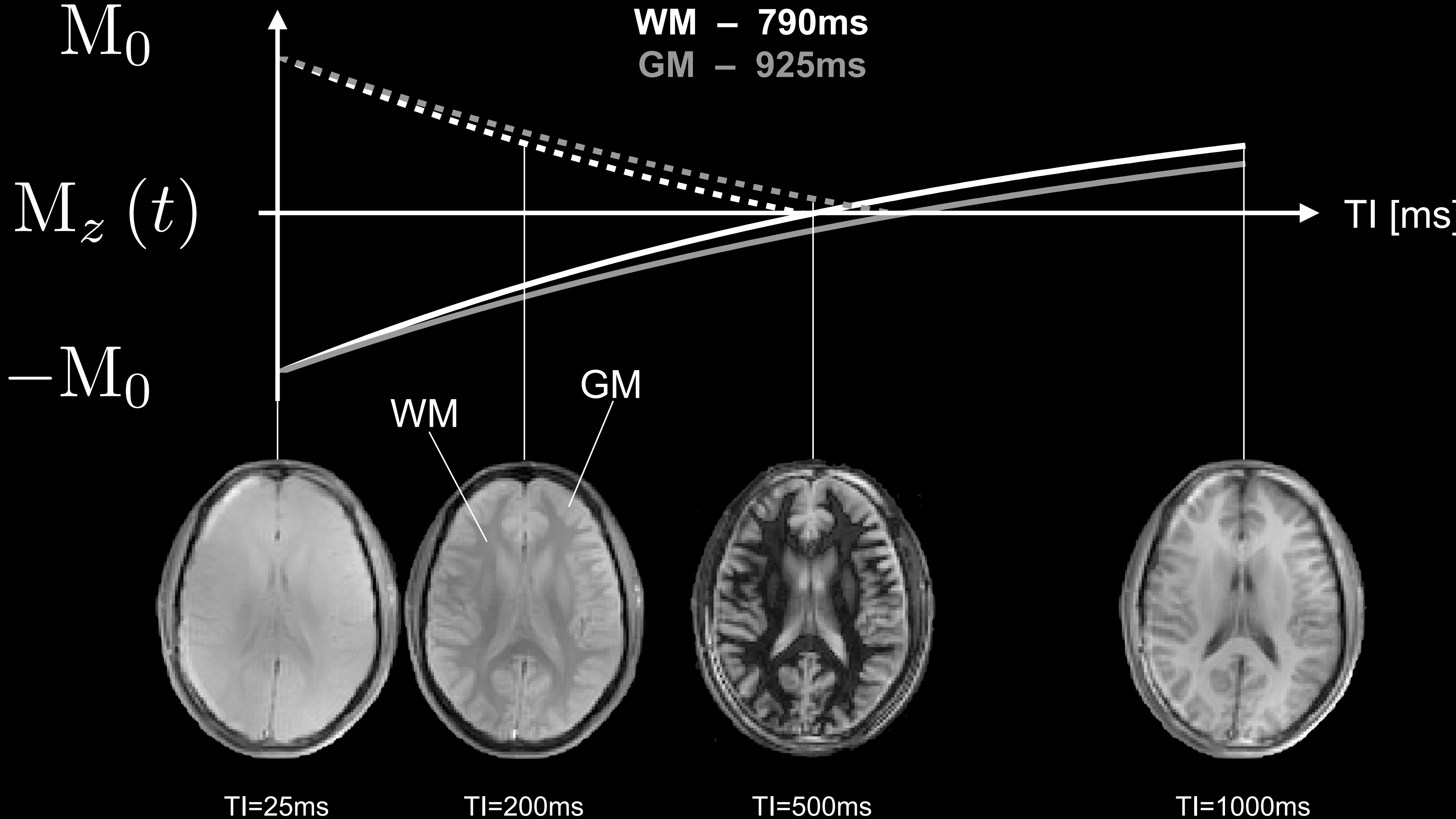
Spin Echo with TE=12ms, TR=2000ms

Spin Echo Inversion Recovery



Spin Echo with TE=12ms, TR=2000ms

Spin Echo Inversion Recovery



Spin Echo with TE=12ms, TR=2000ms

Spin Echo Inversion Recovery

TI=25ms TI=200ms TI=500ms TI=1000ms

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TE=12ms, TR=2000ms

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Inversion Recovery

$$(180° - \mathrm{TI} - 90° - \mathrm{TD})_N$$

To The Board...

IR Contrast

$$A_{fid} \propto \rho \left(1 - 2e^{-TI/T_1} + e^{-TR/T_1}\right)$$

$$I\left(\vec{r}\right) \propto \rho\left(\vec{r}\right)\left(1 - 2e^{-TI/T_1(\vec{r})} + e^{-TR/T_1(\vec{r})}\right)$$ Eqn. 7.21

The final image is the product of ρ(r) and $f(T_1(r))$.

The final image contrast is controlled by TI and TR.

IR Signal Nulling Effect

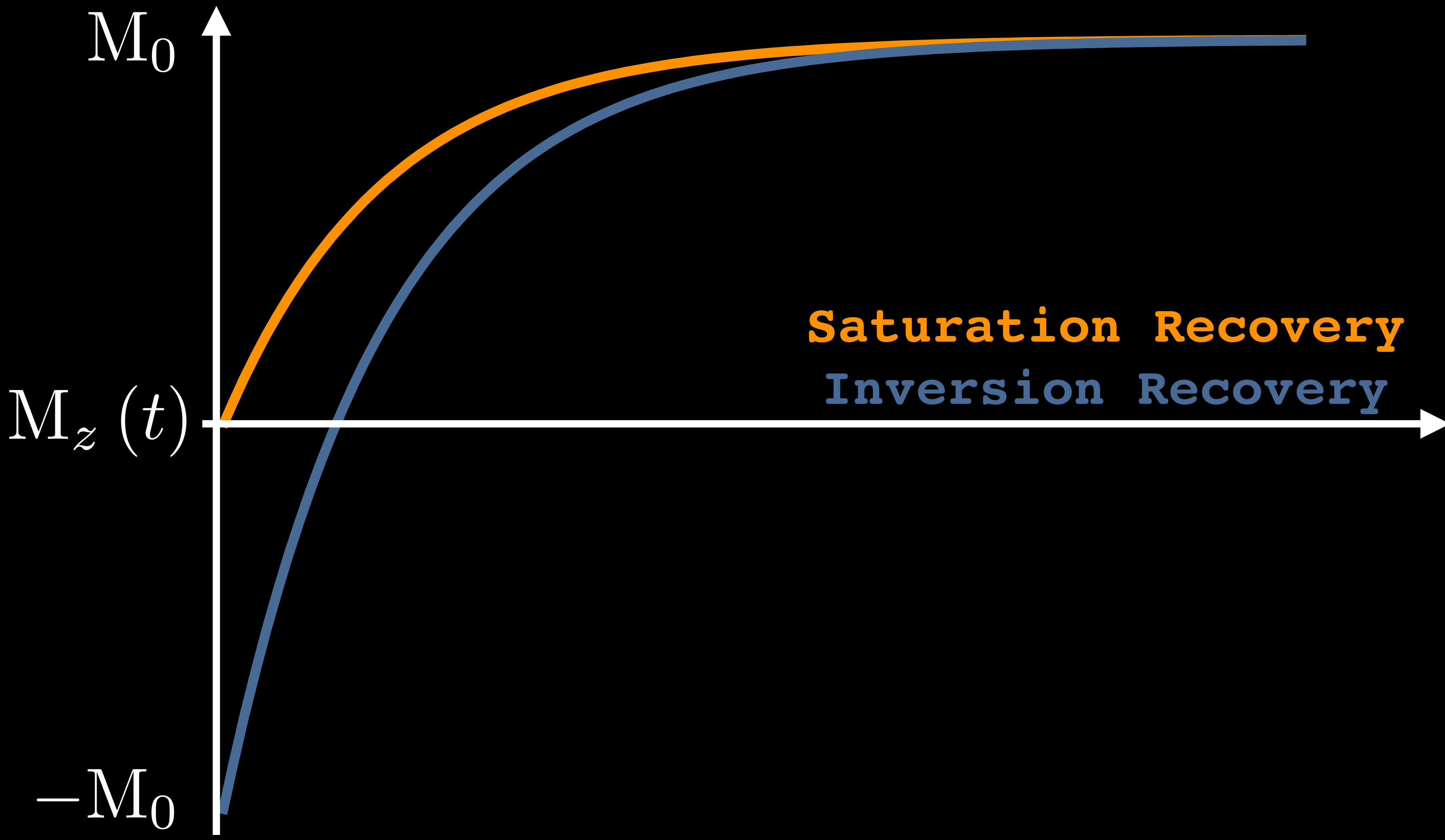
Target T_1

$$TI_{null} = \left[\ln 2 - \ln\left(1 + \exp^{-TR/T_1^0}\right)\right] T_1^0$$

$$TI_{null} = [\ln 2]\, T_1^0, \text{ if TR} \longrightarrow \infty$$

$$I\left(\vec{r}\right) = 0, \text{ if } T_1\left(\vec{r}\right) = T_1^0\left(\vec{r}\right)$$

SR vs. IR



Inversion Pulse - Applications

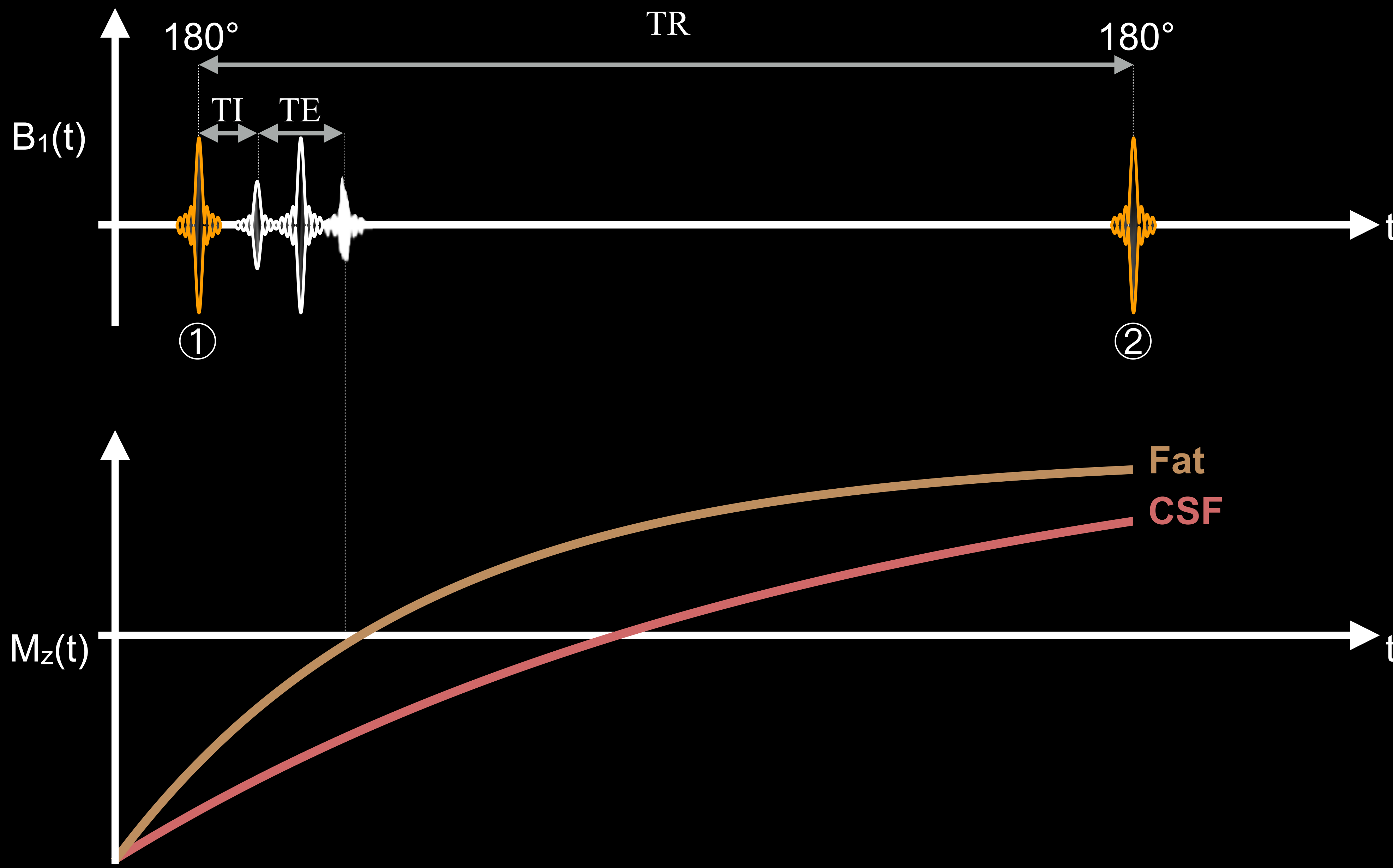
- Greater T_1 contrast than SR
- T_1 species nulling/attenuation
  - FLAIR (Fluid Attenuated Inversion Recovery)
  - STIR (Short Tau Inversion Recovery)
- IR is better than SR for generating contrast when:
  - $\rho(A)=\rho(B)$ and $T_2(A)=T_2(B)$
  - AND
  - $T_1(A)$ and $T_1(B)$ are slightly different
- Quantitative T_1 mapping

$$I(\vec{r}) \propto \rho(\vec{r}) \left(1 - 2e^{-TI/T_1(\vec{r})} + e^{-TR/T_1(\vec{r})}\right) \quad \text{Eqn. 7.21}$$

The final image is the product of $\rho(r)$ and $f(T_1(r))$.

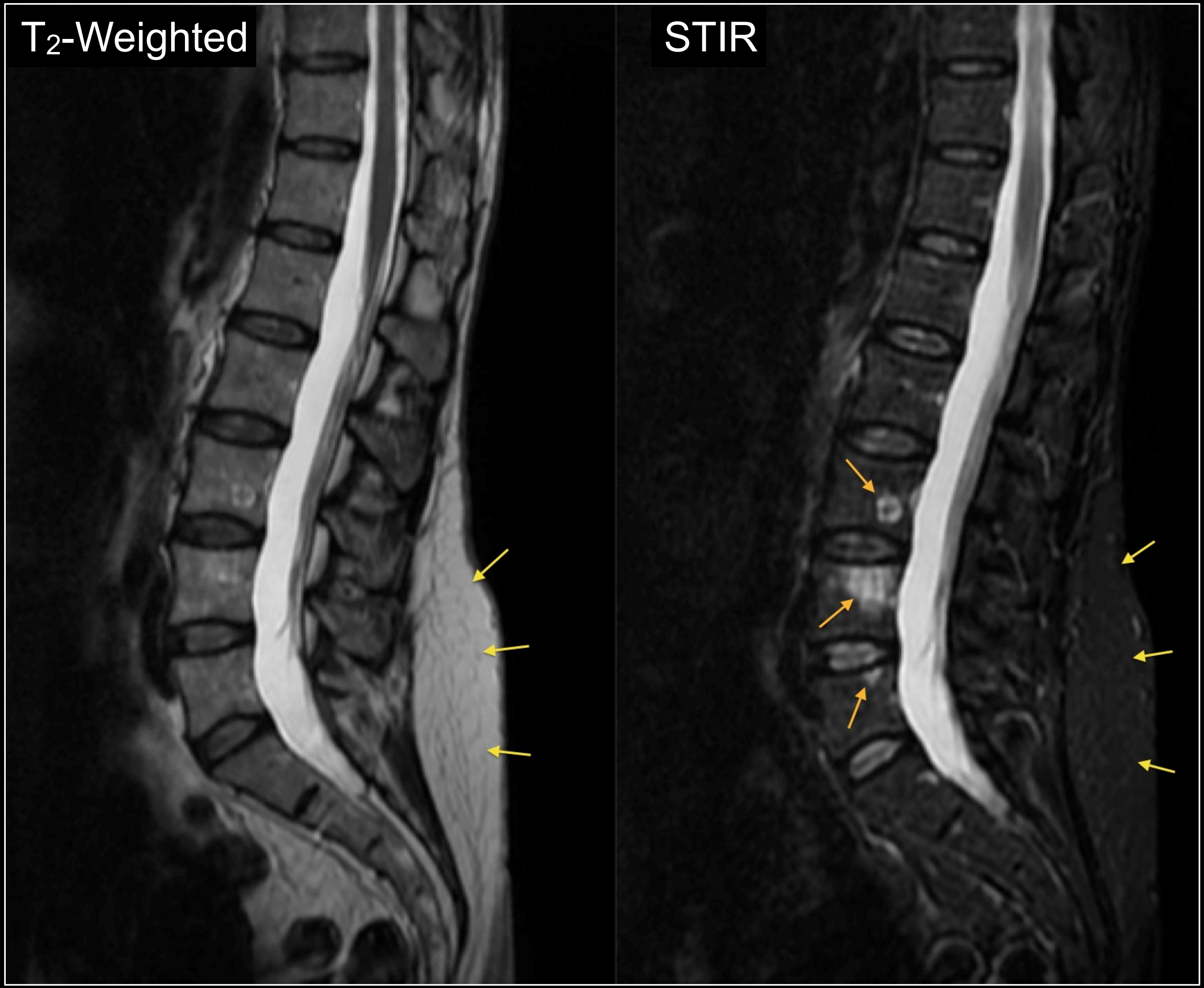
The final image contrast is controlled by TI and TR.

STIR Pulse Sequence



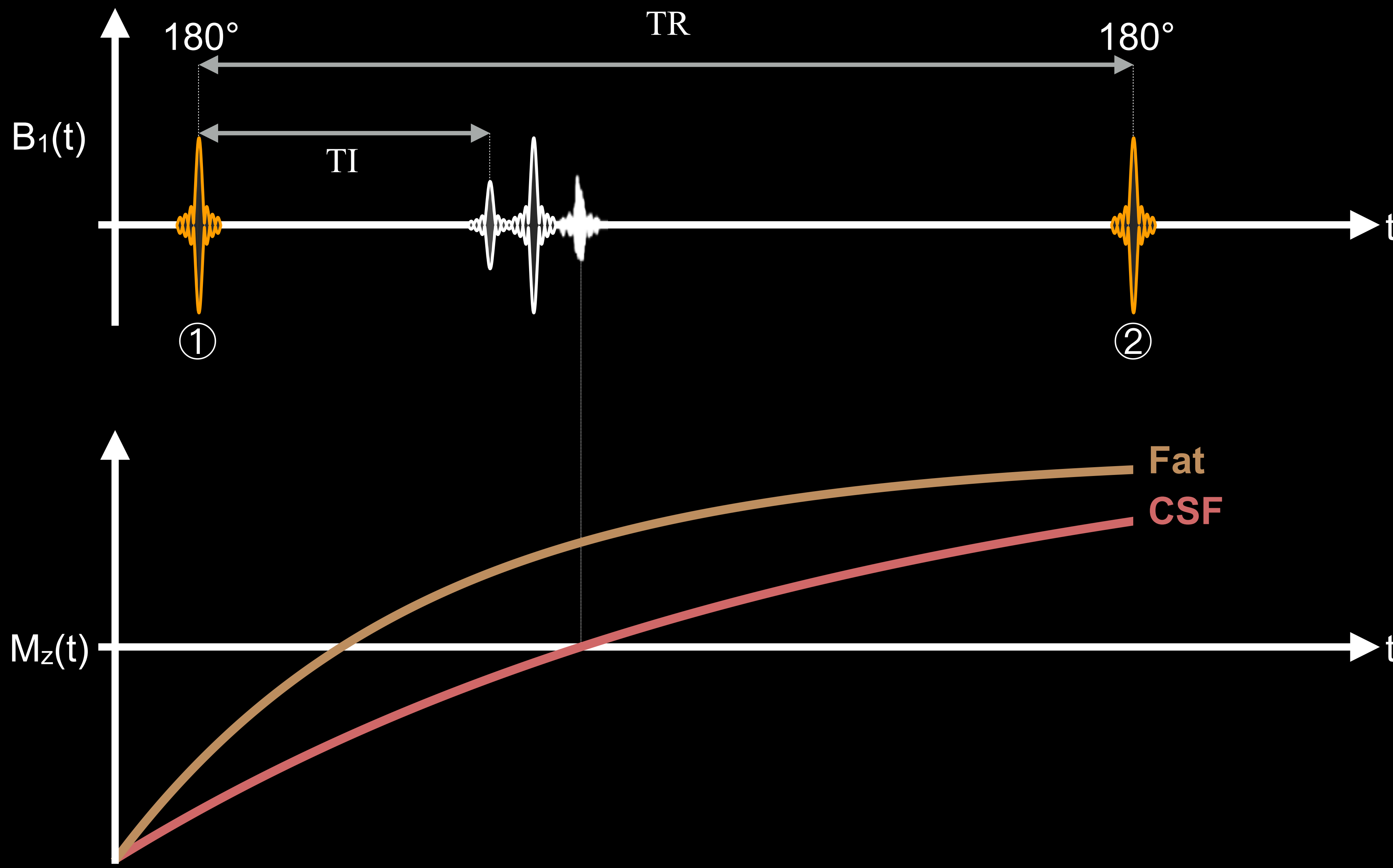
Short Tau Inversion Recovery (STIR) is used to null fat.

STIR Images



http://www.svuhradiology.ie/wp-content/uploads/2015/04/STIRmetscombo.jpg

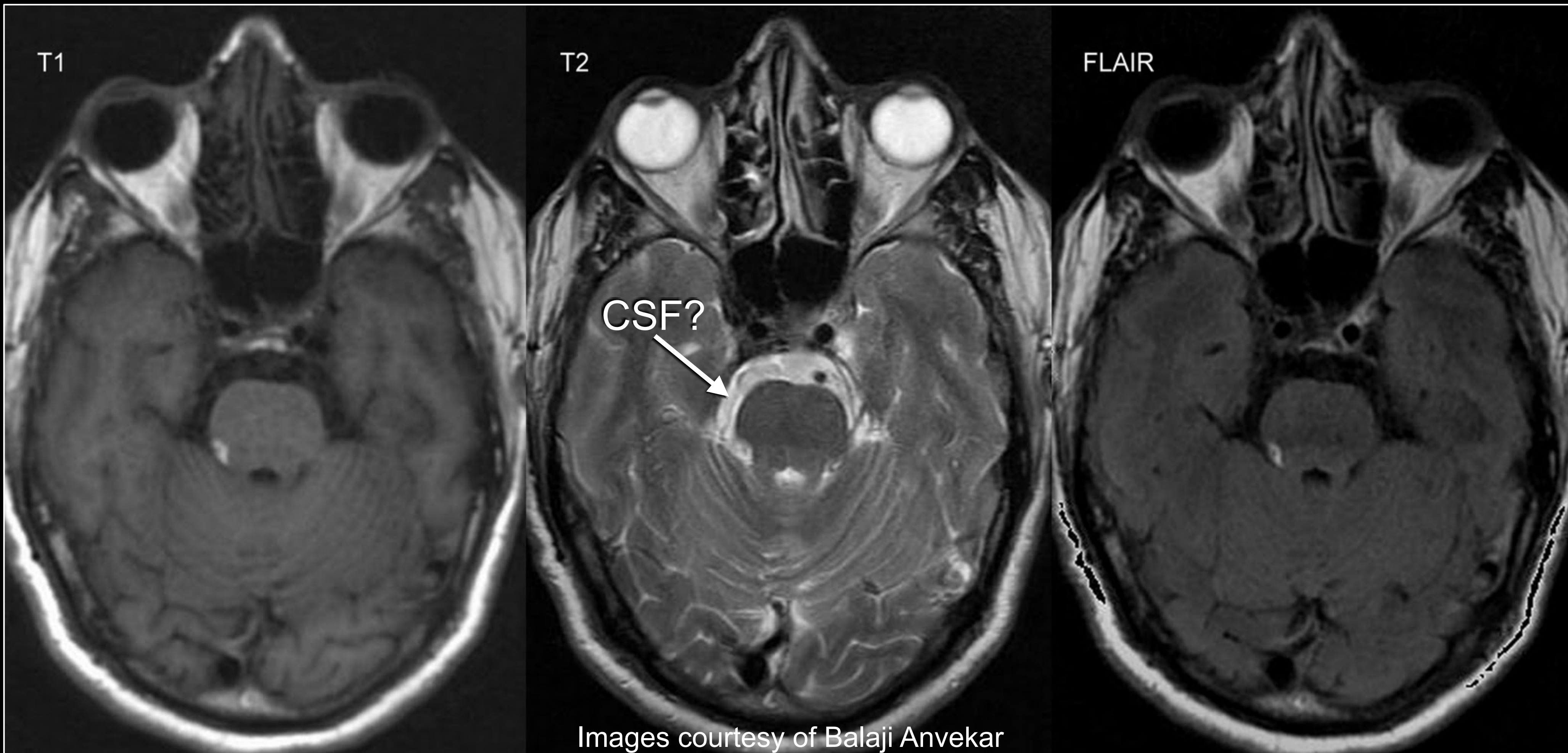
FLAIR Pulse Sequence



FLuid Attenuated Inversion Recovery (STIR) is used to CSF.

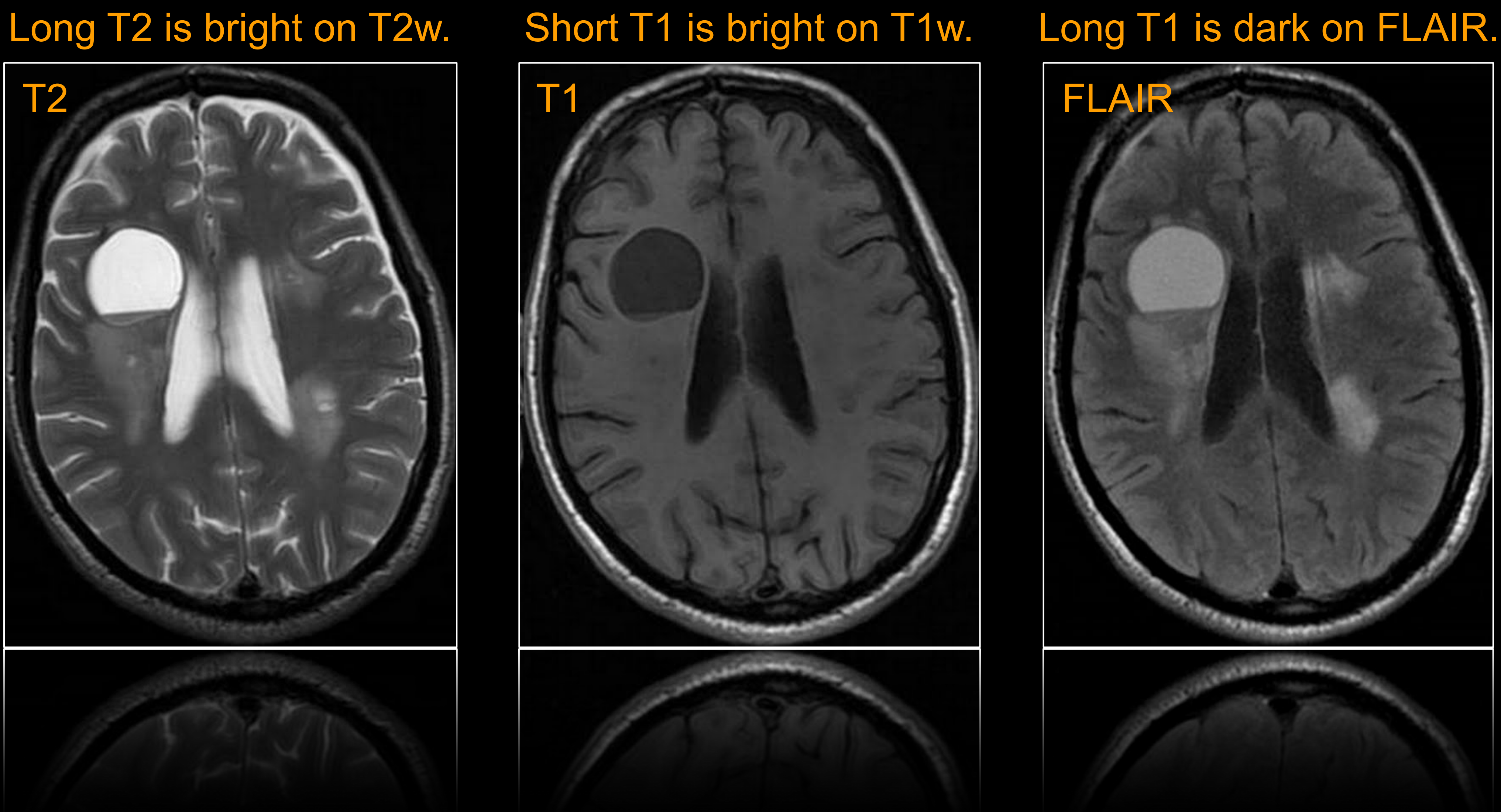
FLAIR Images

FLAIR can distinguish fat from CSF.



http://www.neuroradiologycases.com/2011/11/intracranial-lipoma.html

FLAIR Images



Lesion has long T2 and intermediate T1. Not fat. Not CSF. Cerebral hydatid.

Thanks

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