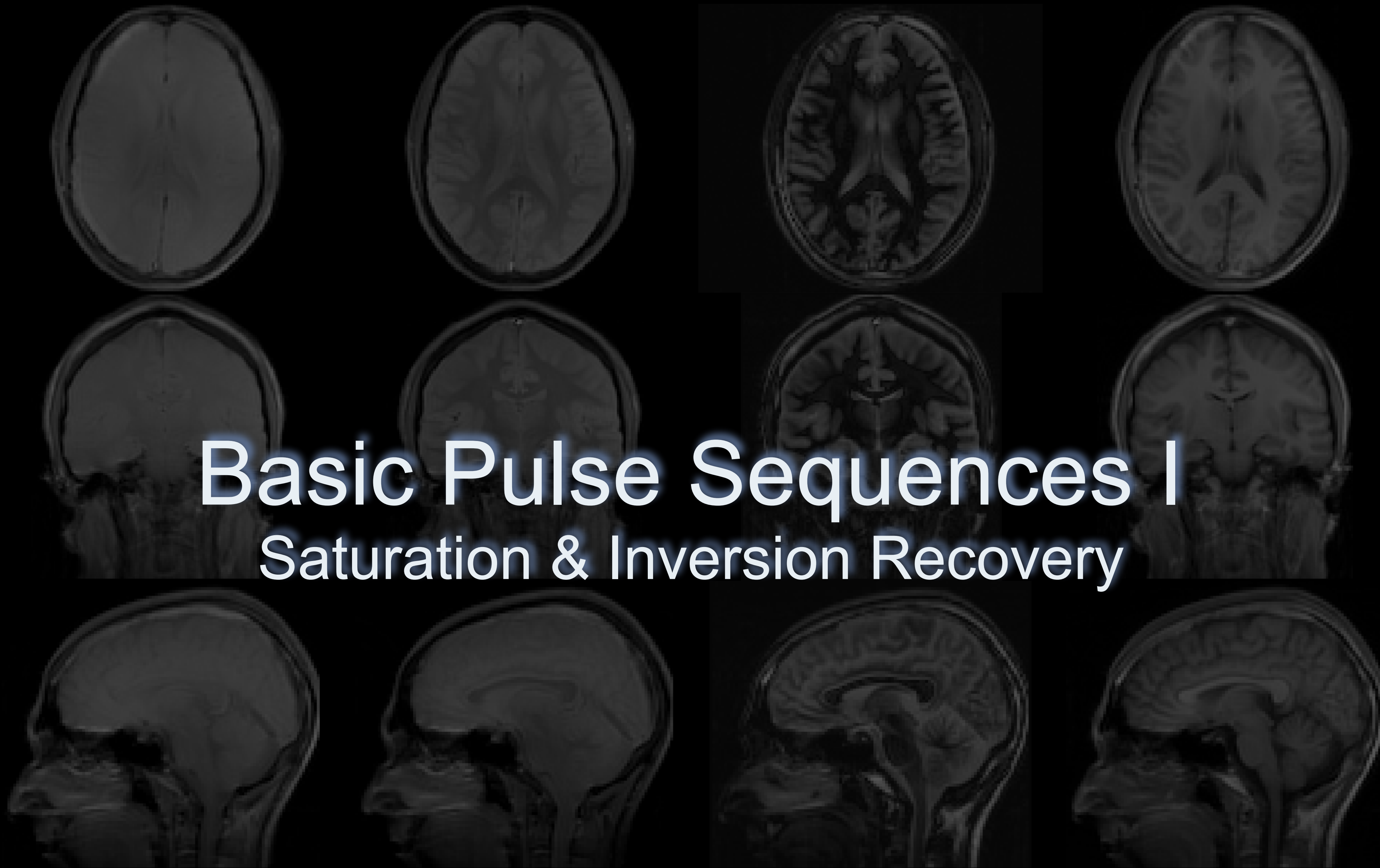
Basic Pulse Sequences I

Saturation & Inversion Recovery



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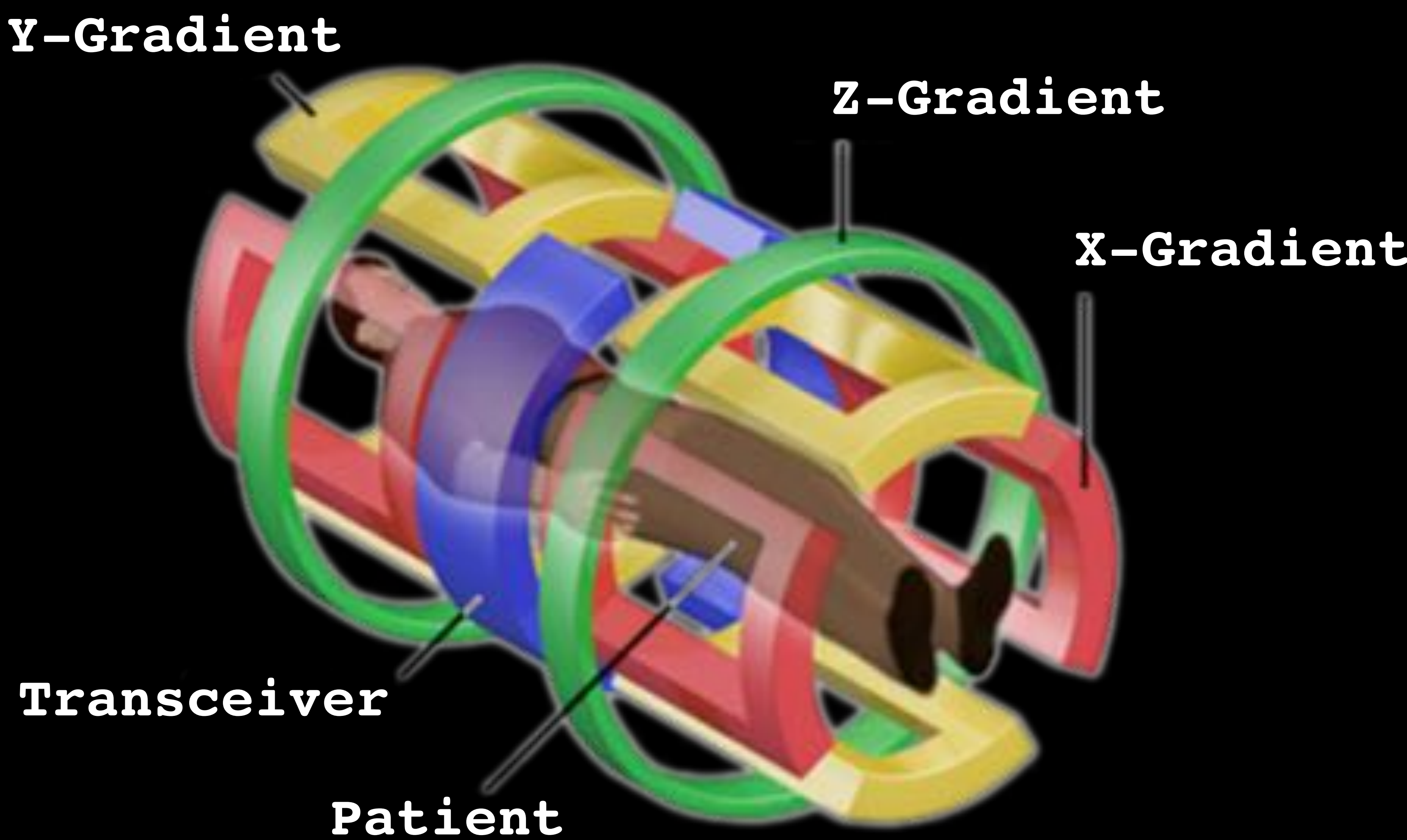
Gradient Hardware



Gradients

Gradients are a special kind of inhomogeneous field whose z-component varies linearly along a specific direction called the gradient direction.

$$\underbrace{B_G}_{\text{B-field from a gradient}},\underbrace{z}_{\text{Points along the z-direction}}\underbrace{(x)}_{\text{Varies with the x-direction}} = \underbrace{G_x}_{\text{x-gradient amplitude}}\underbrace{x}_{\text{x-distance from isocenter}}$$

B-field from a gradient

Points along the z-direction

Varies with the x-direction

x-gradient amplitude

x-distance from isocenter

Free Precession & Gradients

$$\vec{B}_{eff} = \frac{\vec{\omega}_{rot}}{\gamma} + \vec{B}_{rot}$$
$$= \frac{-\gamma B_0 \hat{k}'}{\gamma} + \left(B_0 + \vec{G}\cdot\vec{r}\right)\hat{k}'$$
$$= \left(\vec{G}\cdot\vec{r}\right)\hat{k}'$$

$$\frac{\partial M_{rot}}{\partial t} = \vec{M}_{rot} \times \gamma \vec{B}_{eff}$$
$$= \vec{M}_{rot} \times \gamma \left(\vec{G}\cdot\vec{r}\right)\hat{k}'$$

$$\begin{bmatrix} \frac{dM_{x'}}{dt} \\ \frac{dM_{y'}}{dt} \\ \frac{dM_{z'}}{dt} \end{bmatrix} = \begin{vmatrix} \hat{i}' & \hat{j}' & \hat{k}' \\ M_{x'} & M_{y'} & M_{z'} \\ 0 & 0 & \gamma \vec{G}\cdot\vec{r} \end{vmatrix}$$

$$M_{x'} = M_{x'}^0 \cos\left(-\gamma \vec{G}\cdot\vec{r}\right) - M_{y'}^0 \sin\left(-\gamma \vec{G}\cdot\vec{r}\right)$$

$$M_{y'} = M_{x'}^0 \sin\left(-\gamma \vec{G}\cdot\vec{r}\right) + M_{y'}^0 \cos\left(-\gamma \vec{G}\cdot\vec{r}\right)$$

$$M_{z'} = M_{z'}^0$$

Gradients - Frequency & Phase

$$M_{x'} = M^0_{x'} \cos\left(-\gamma \vec{G} \cdot \vec{r}\right) - M^0_{y'} \sin\left(-\gamma \vec{G} \cdot \vec{r}\right)$$

$$M_{y'} = M^0_{x'} \sin\left(-\gamma \vec{G} \cdot \vec{r}\right) + M^0_{y'} \cos\left(-\gamma \vec{G} \cdot \vec{r}\right)$$

$$M_{z'} = M^0_{z'}$$

$$\omega_{\vec{G}}\left(\vec{r}\right) = -\gamma\left(\vec{G} \cdot r\right)\hat{k}'$$

The frequency of *free precession* in the *rotating frame* is a function of space ($\vec{r}$) in the presence of an applied gradient ($\vec{G}$).

$$\phi_{\vec{G}} = \int_0^{t_{grad}} \vec{\omega}_{\vec{G}}(\vec{r}, t)dt$$

$$= -\int_0^{t_{grad}} \gamma \vec{G}(t) \cdot \vec{r}(t)dt$$

$$\phi_{\vec{G}}(x, t) = -\gamma G_x \cdot x \cdot t_{grad}$$

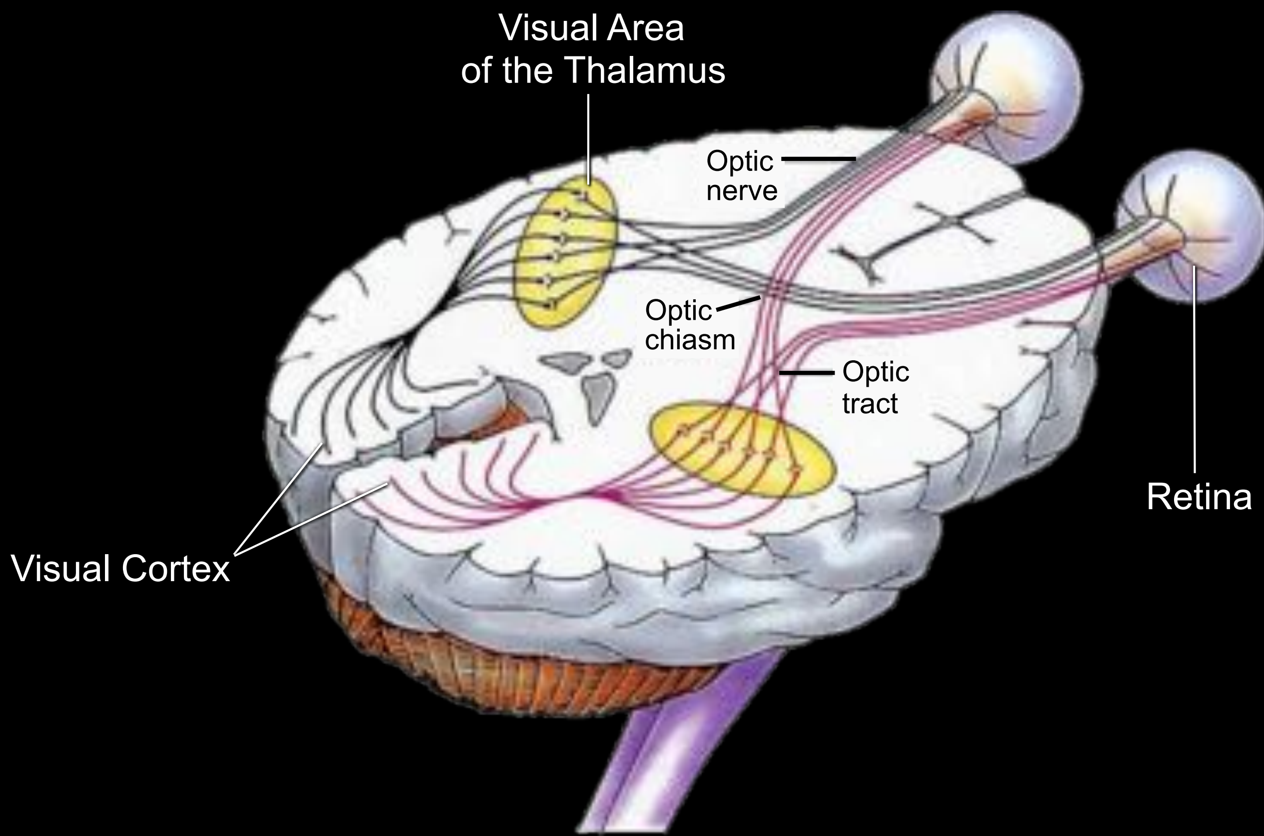
The phase of the spin in the *rotating frame* is a function of position (*x*) and gradient duration (t_{grad}) in the presence of an applied gradient (G_x).

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.

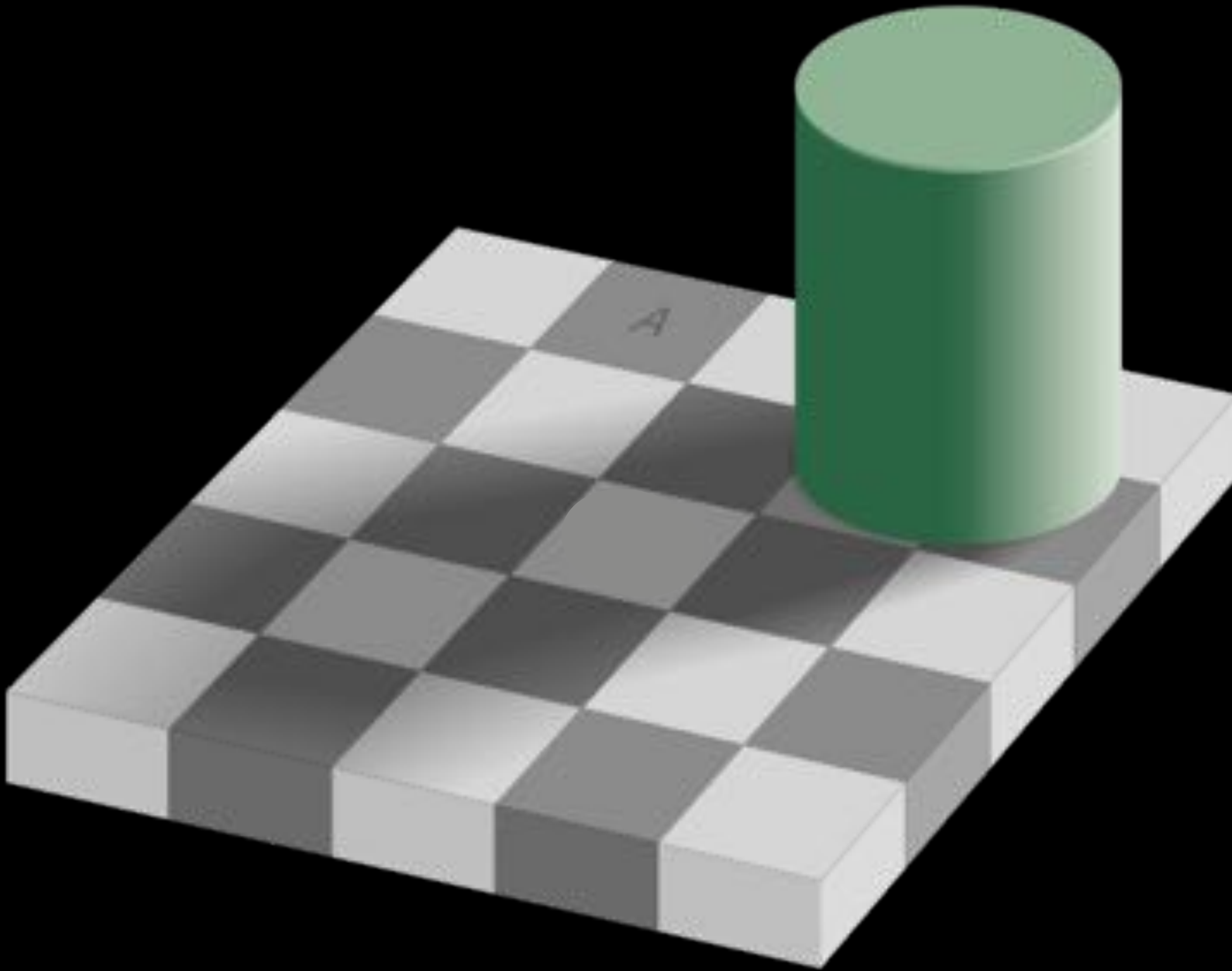
Image Contrast

Why Image Contrast?



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

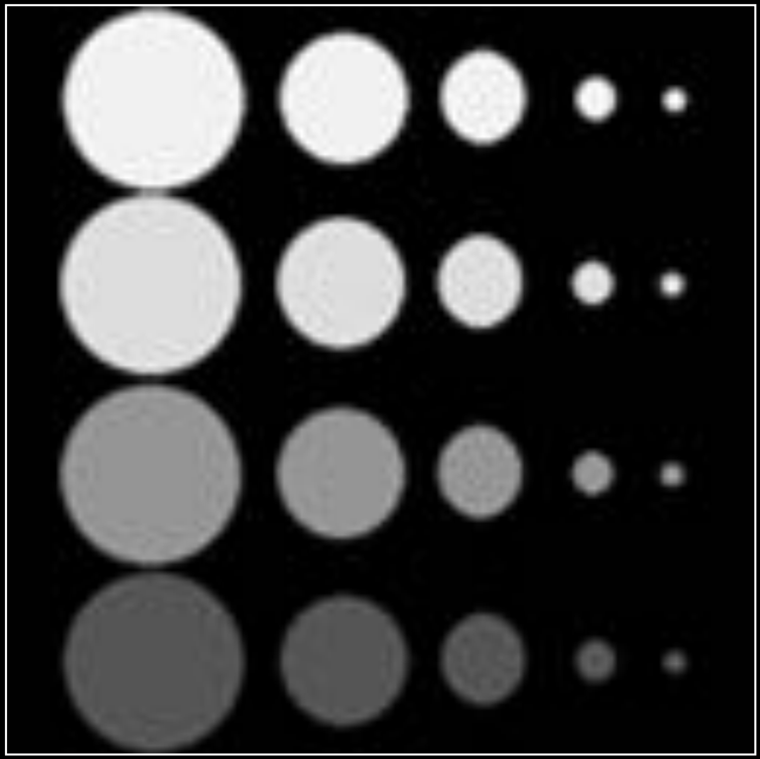
Why Image Contrast?



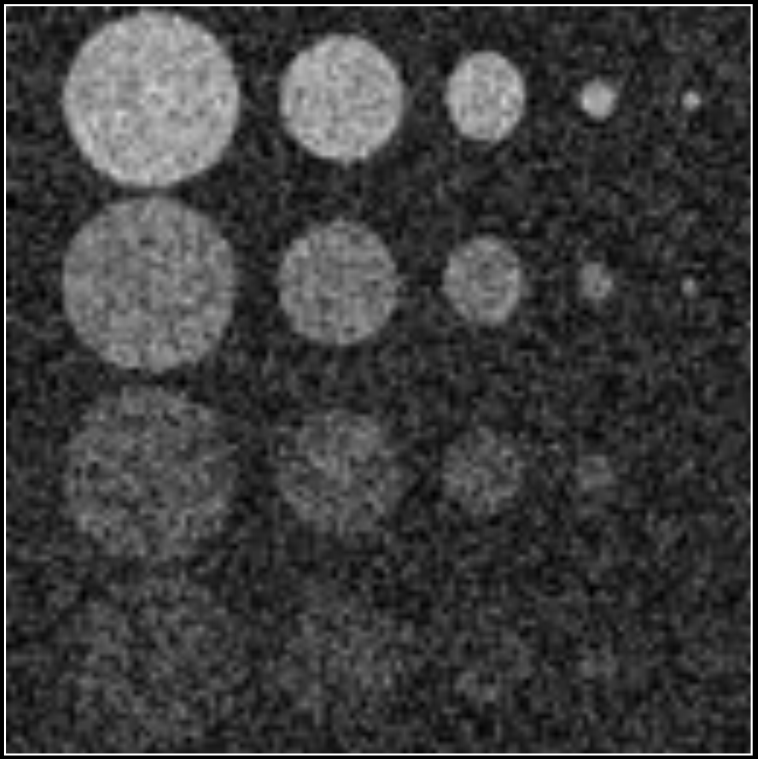
Which is brighter A or B?

CNR, Object Size, and Noise

Noise Free



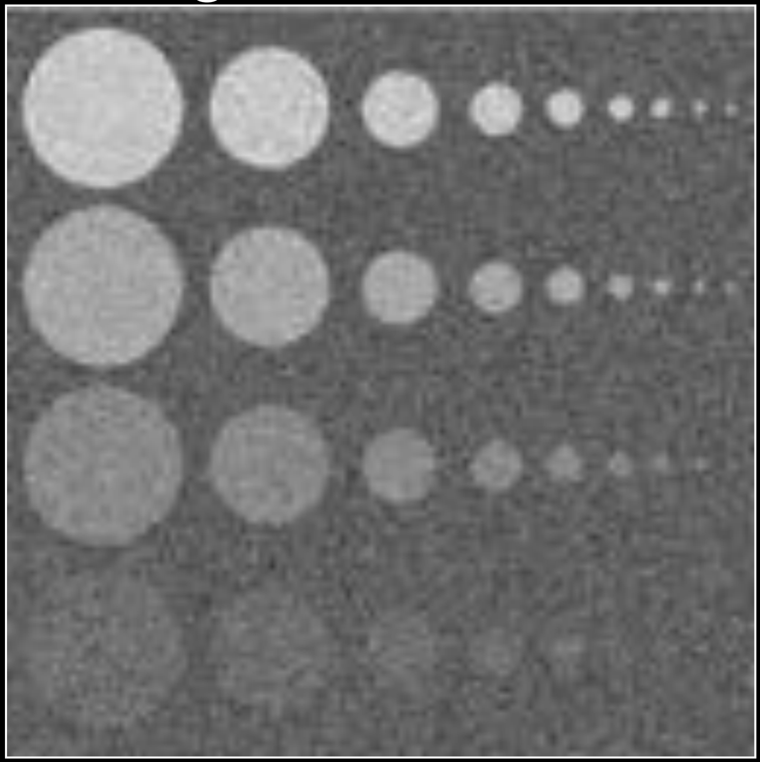
Noisy



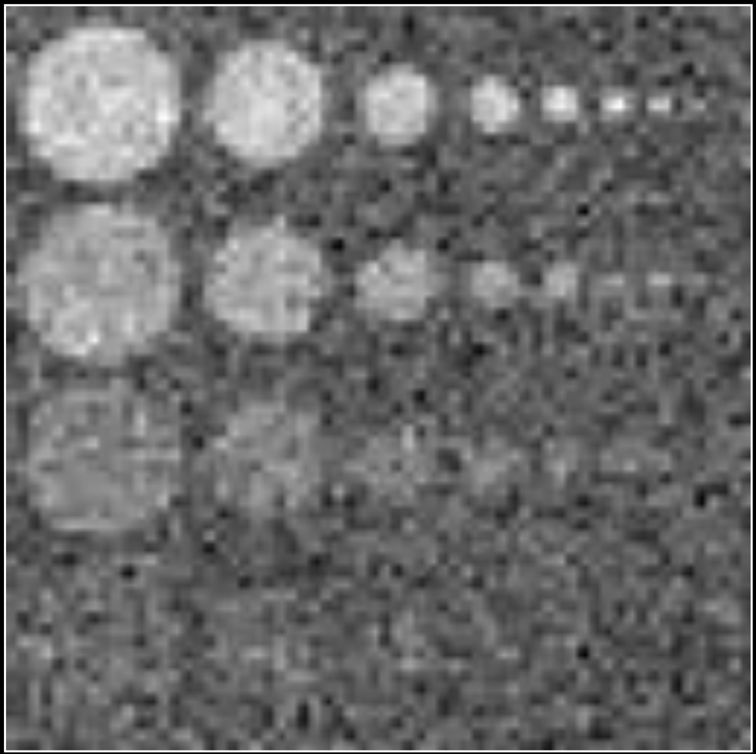
Large high-contrast objects are easier to see in the presence of noise.

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

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

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

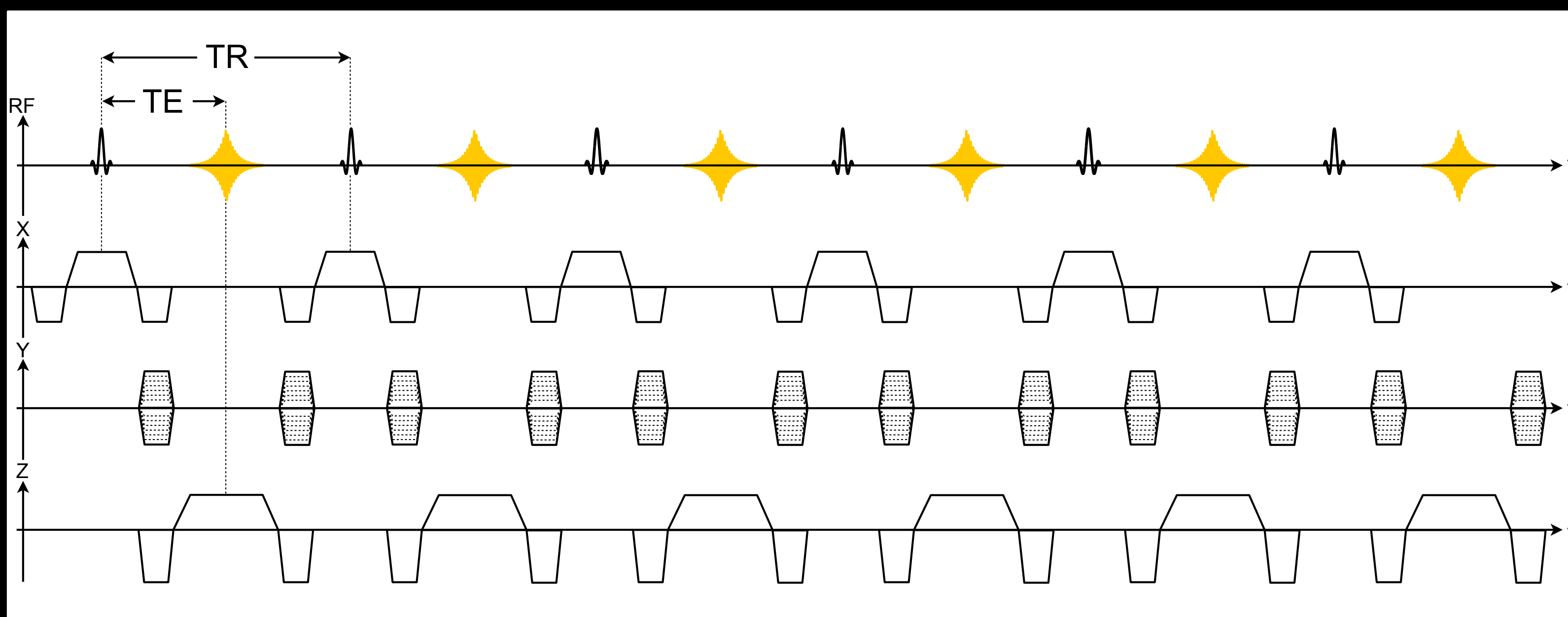
$$\mathcal{C}_{AB} \approx f(T_1) \qquad \mathcal{C}_{AB} \approx f(T_2)$$

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

Pulse Sequences

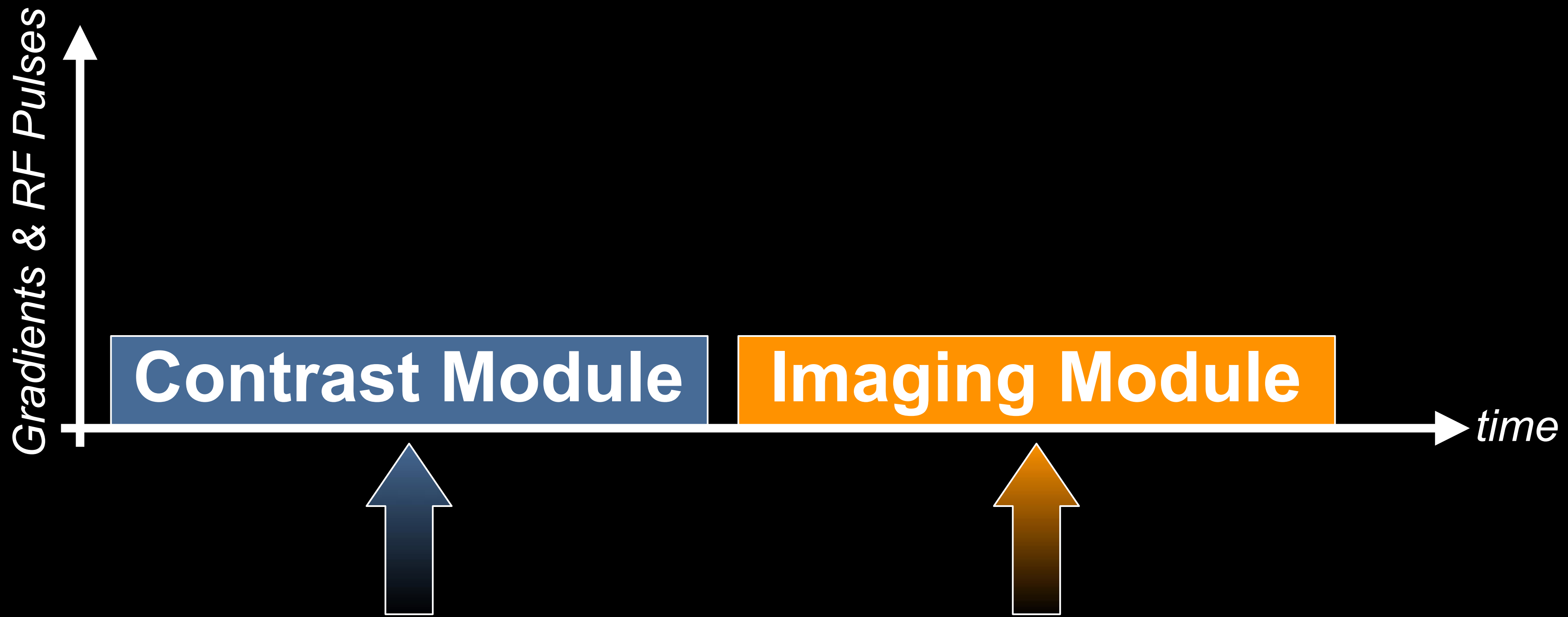
What is a pulse sequence?

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?

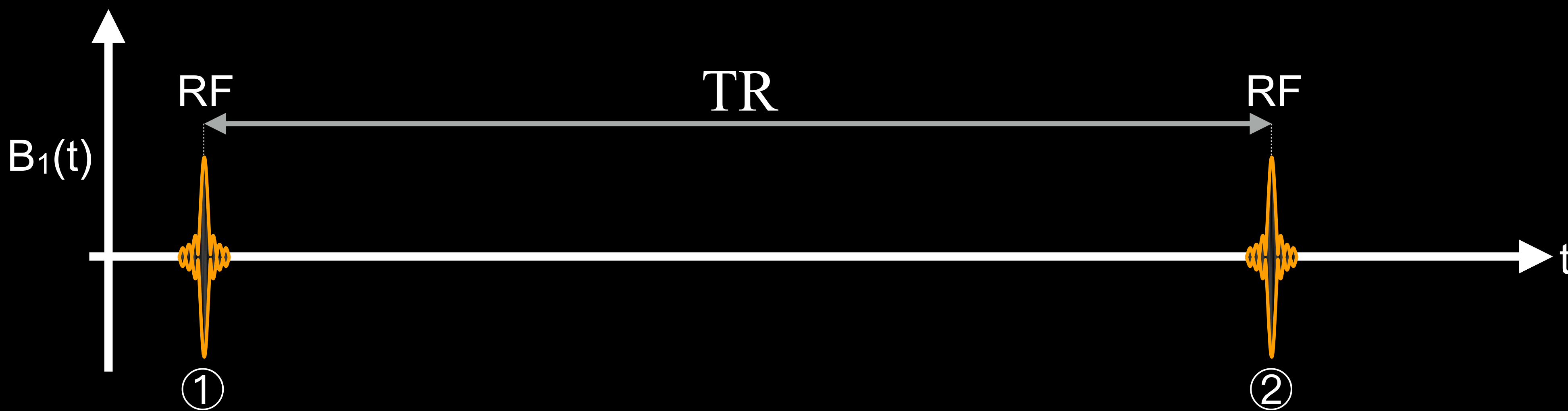
- **We've considered all combinations of:**
  - Free or forced precession
  - With or without relaxation
  - Laboratory or rotating frames
- **Which one's concern M219 the most?**
  - ***Rotating* frame**
    - **Free precession with relaxation**

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

    - **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…



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

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

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

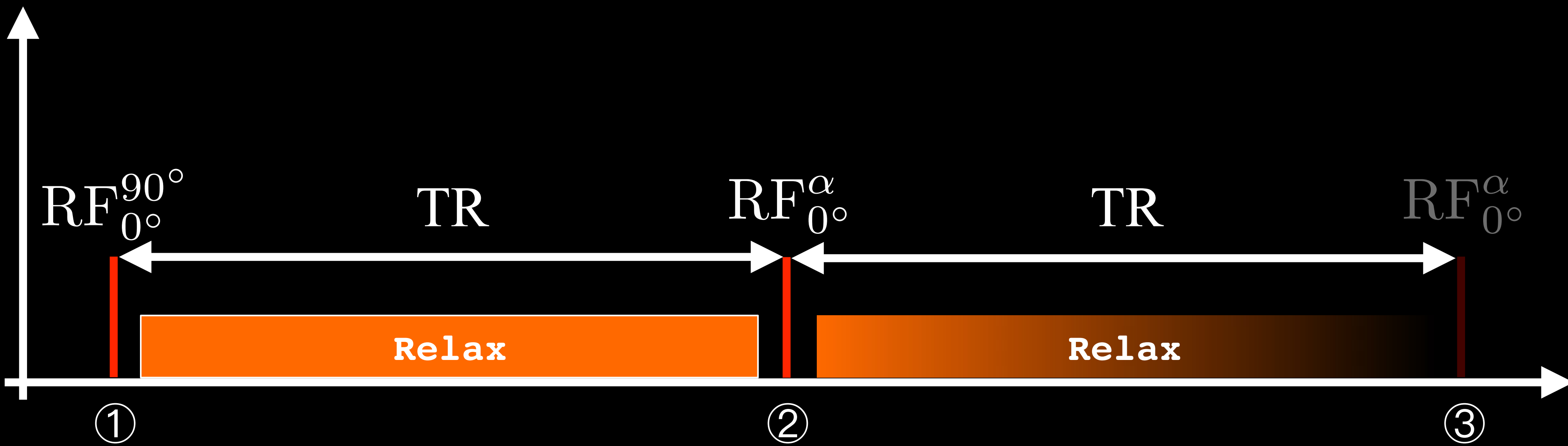
$$\vec{M}^{(2)}(0_+) = RF_\theta^\alpha \vec{M}^{(2)}(0_-)$$

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



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

To The Board...

Saturation Condition

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

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

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? $TR >> T_2$

Saturation Condition

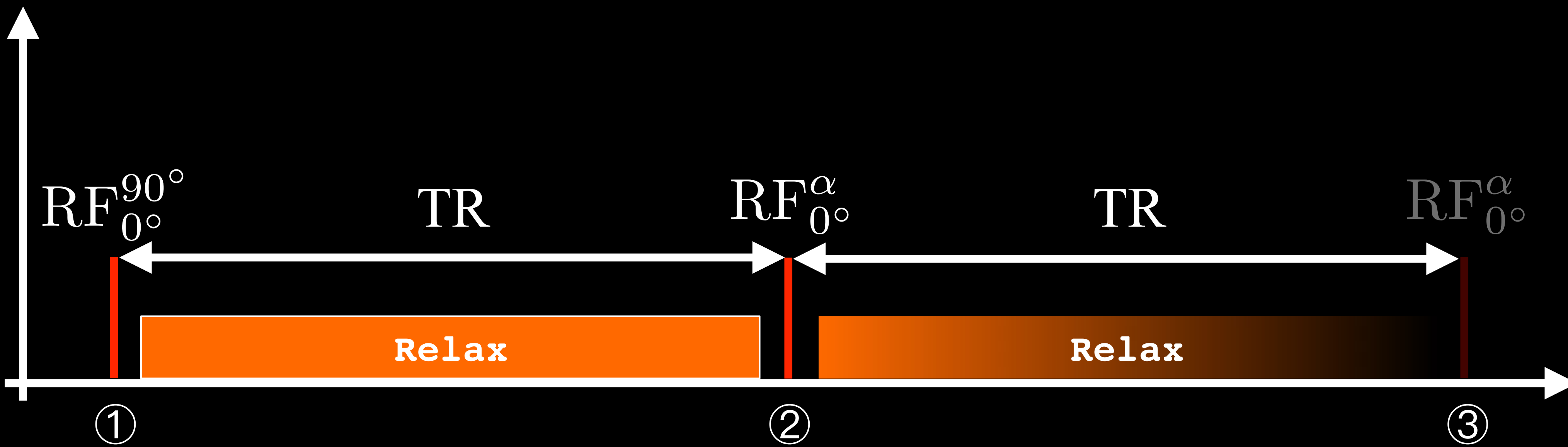
- The ***saturation condition*** states:

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

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<~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



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

To The Board...

SR Contrast

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

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

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

SR Contrast

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

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

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

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

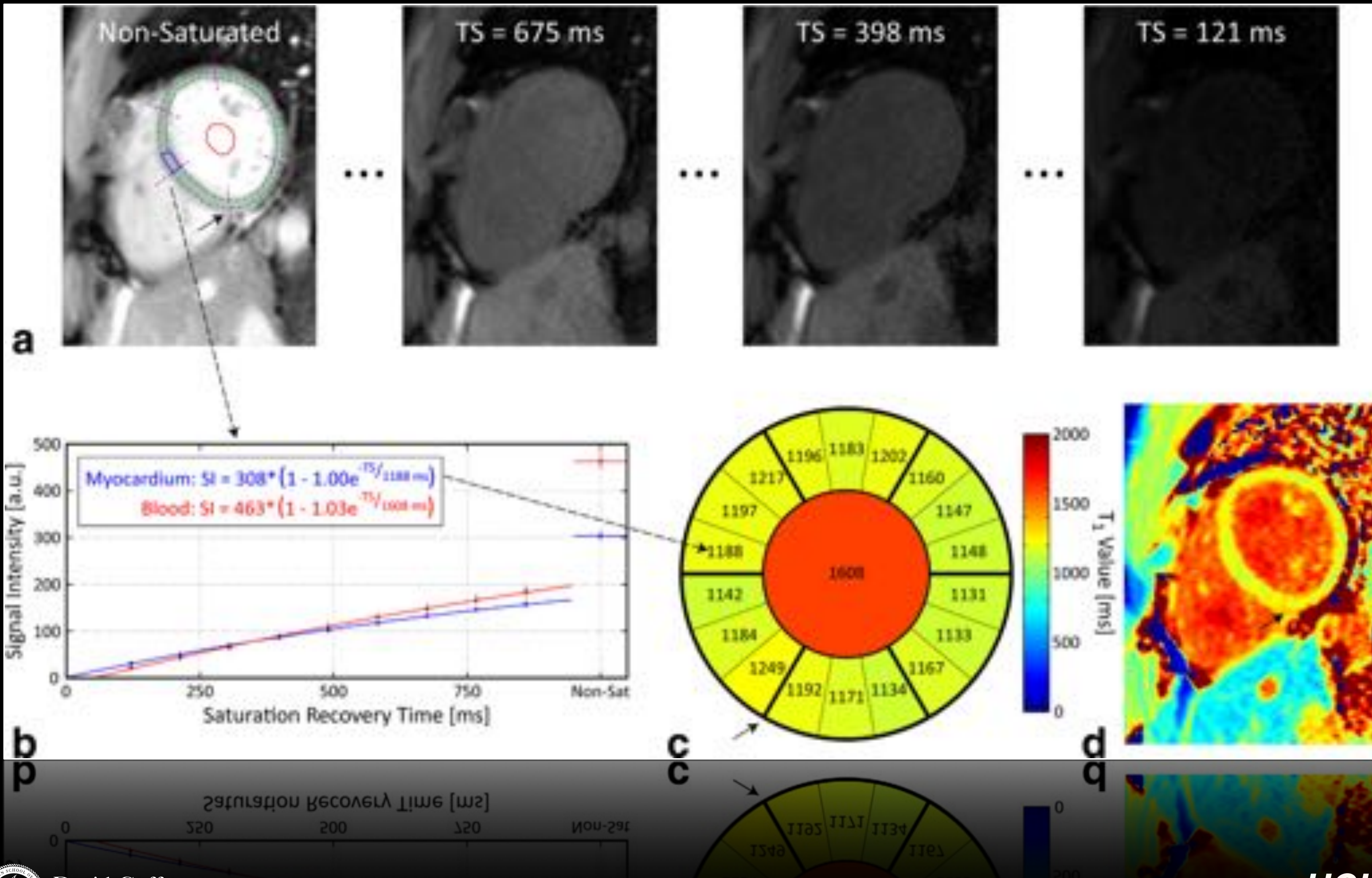
$$I\left(\vec{r}\right)_{TR\rightarrow TR_{opt}} \propto \text{Maximum } T_1 \text{ contrast}$$

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

Eqn. 7.19

Saturation Recovery - Applications

SASHA - Normal Subject



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

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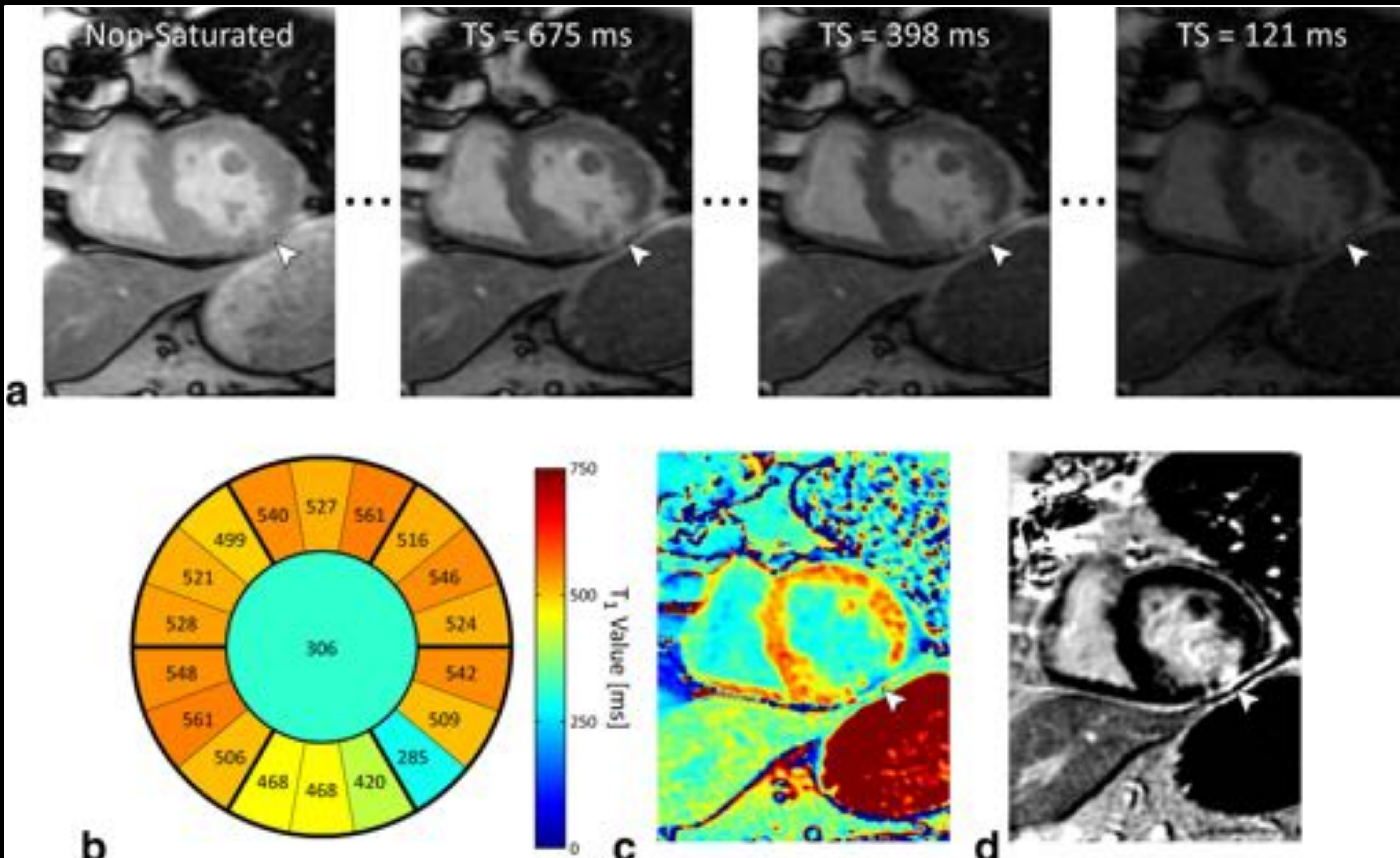
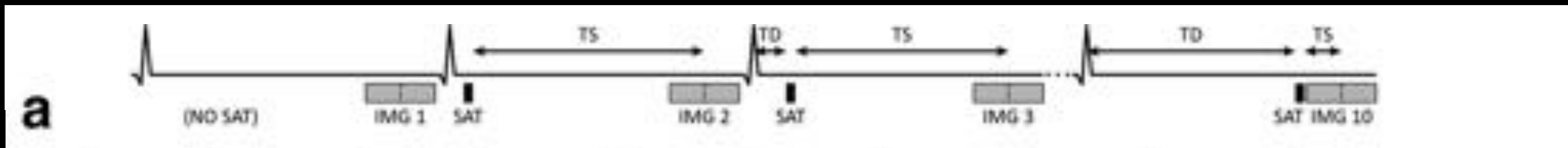
SASHA - Myocardial Infarct



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

SAturation recovery single-SHot Acquisition (SASHA)



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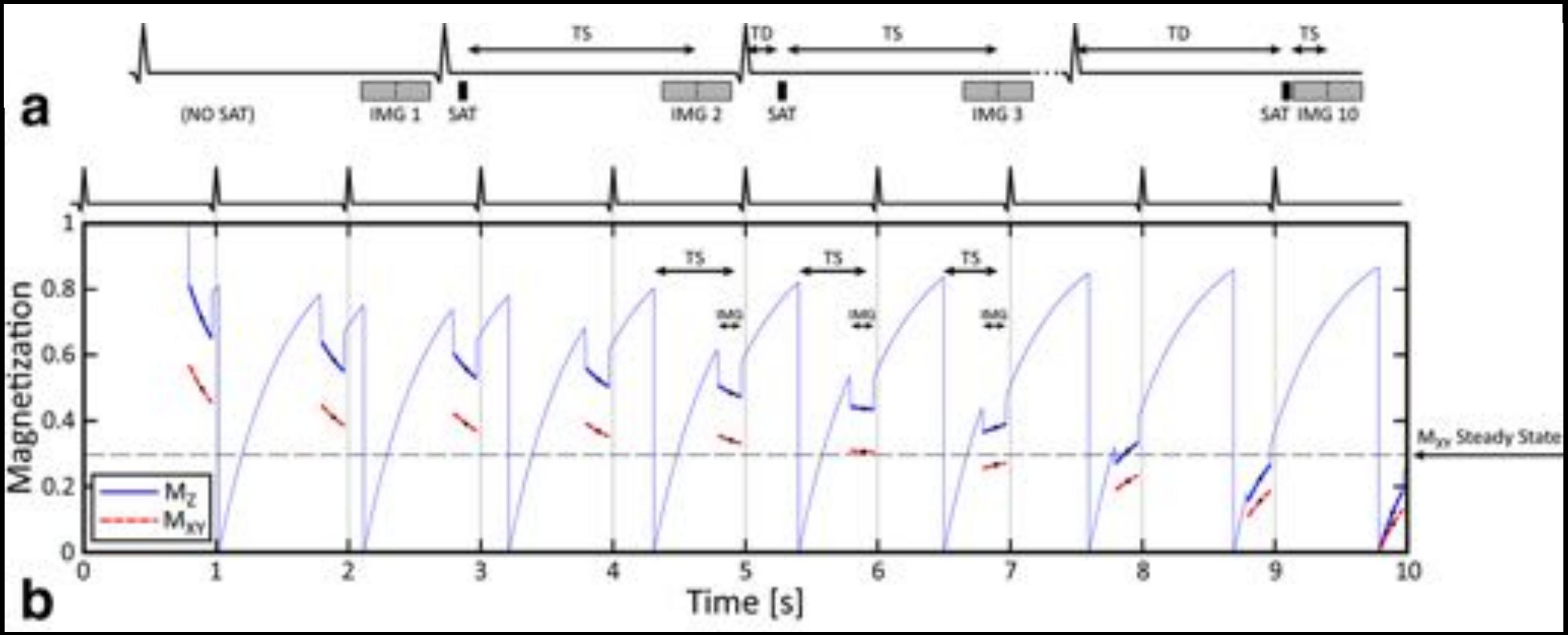

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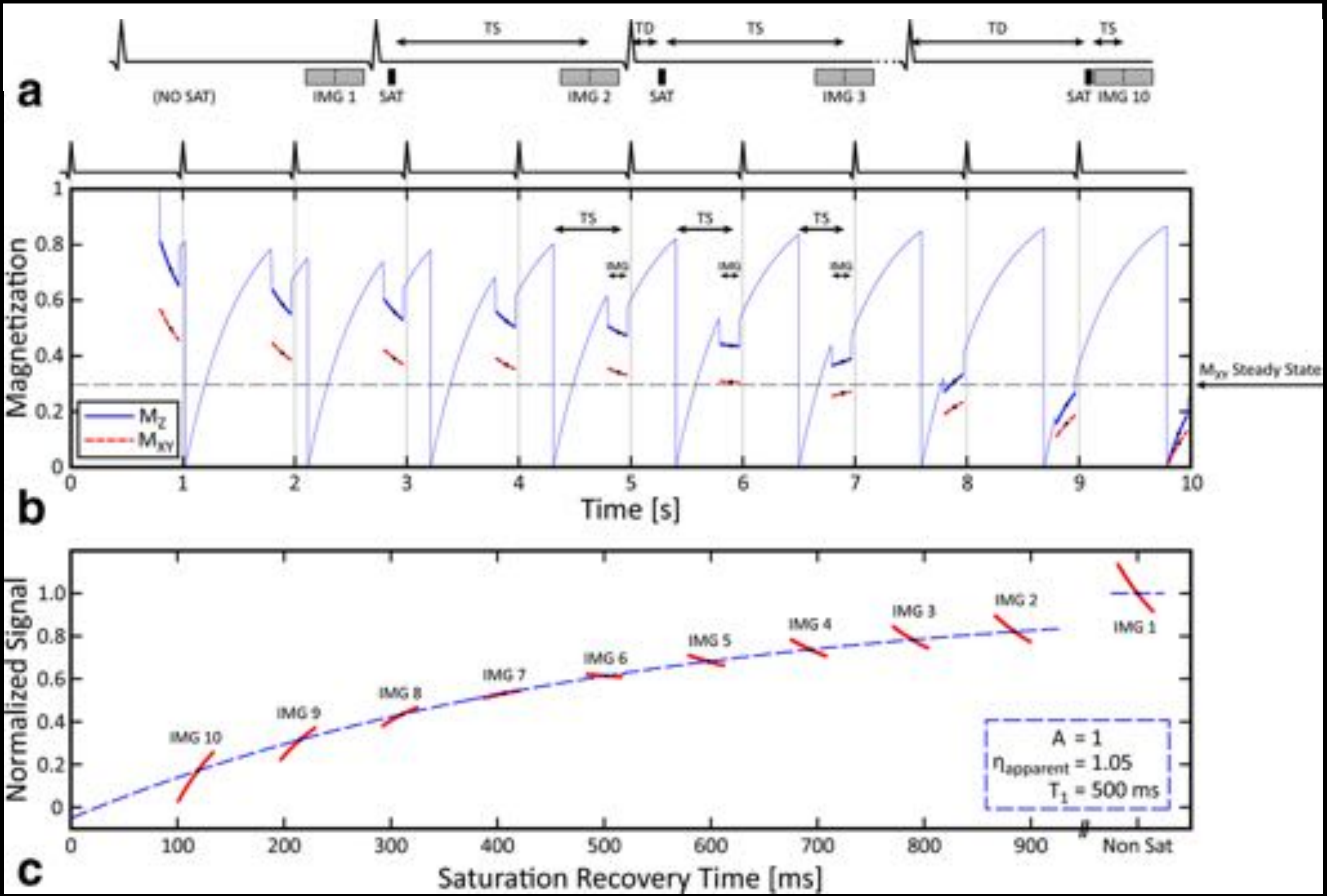
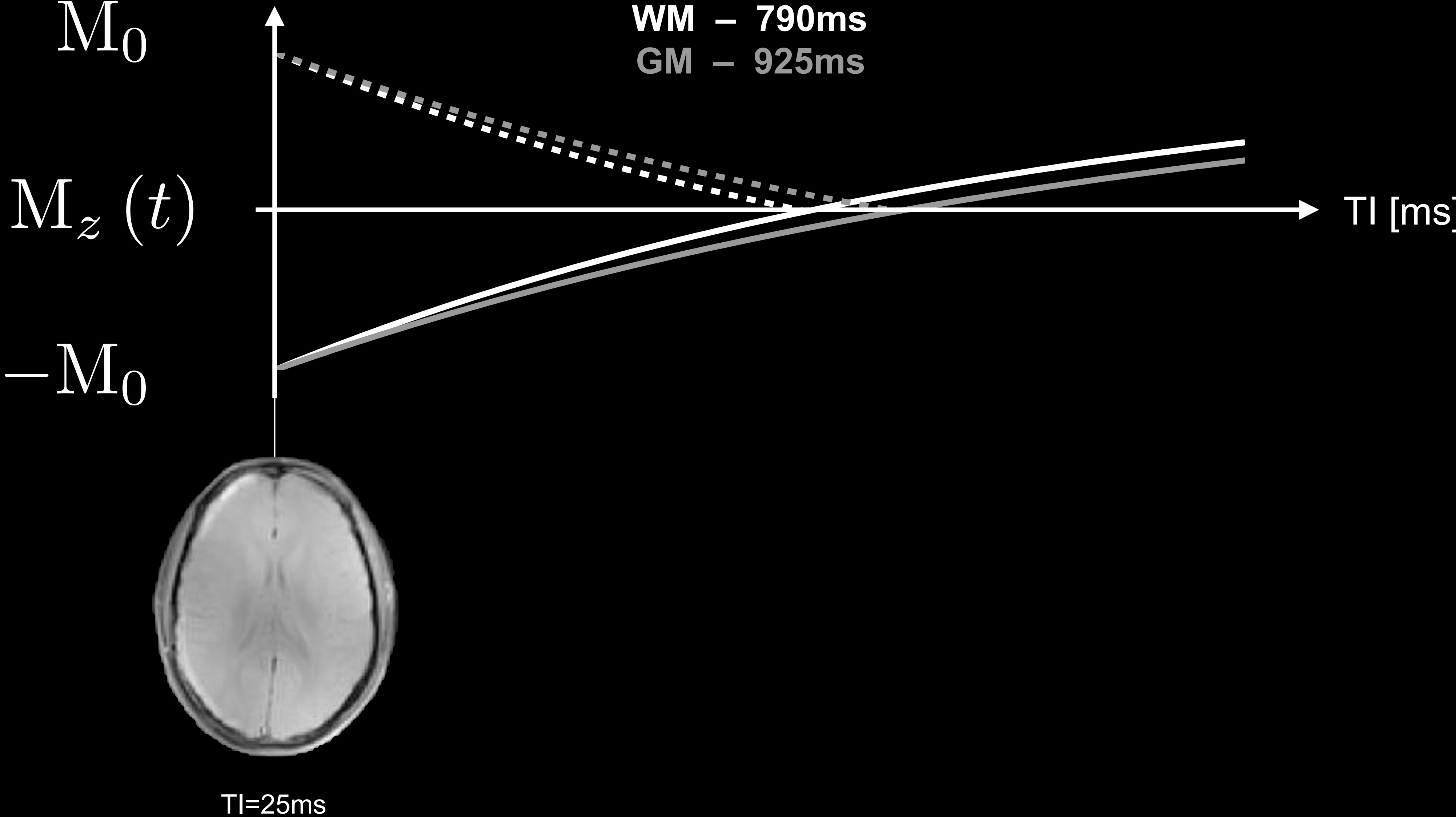


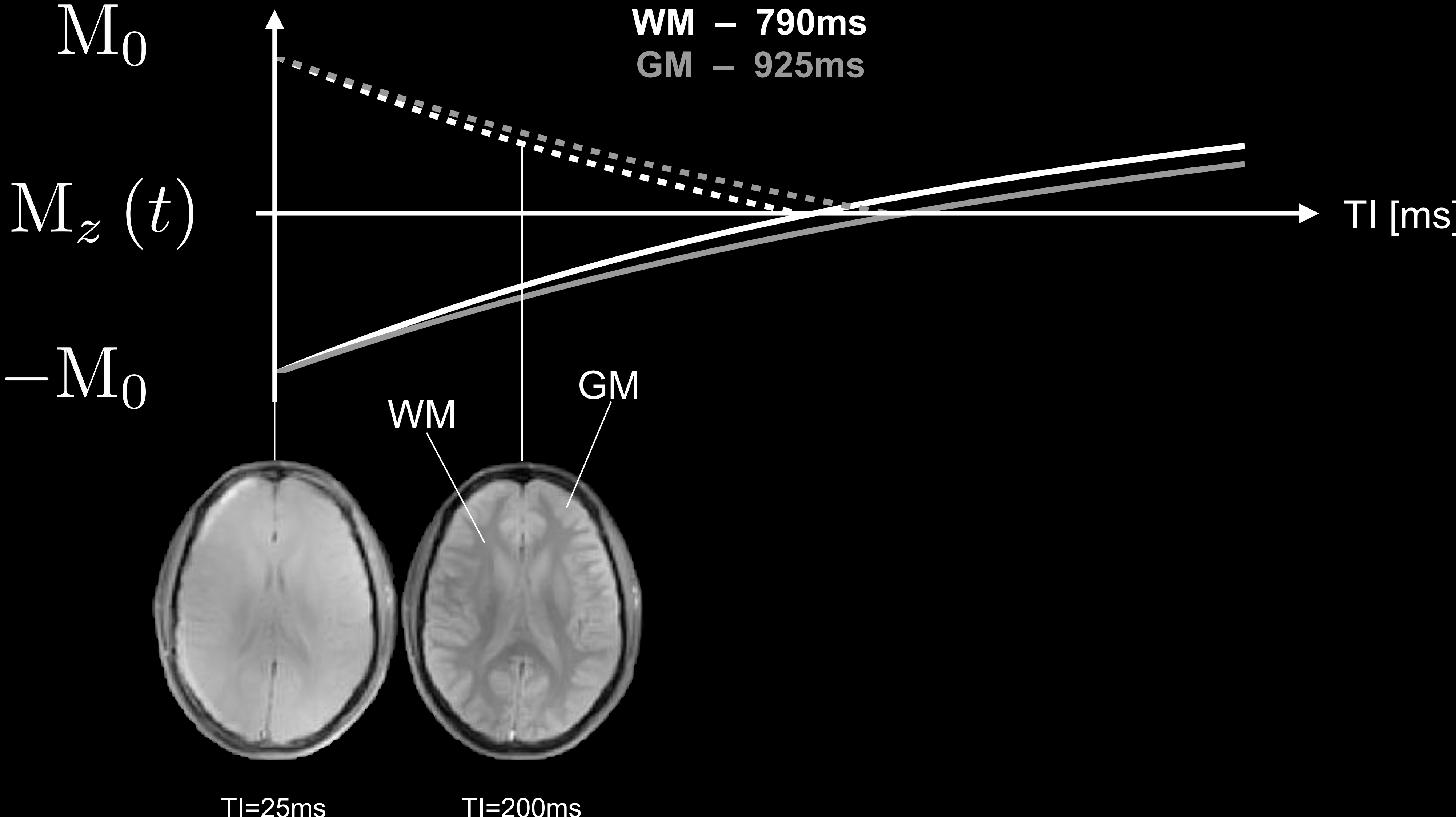
Inversion Recovery

Spin Echo Inversion Recovery



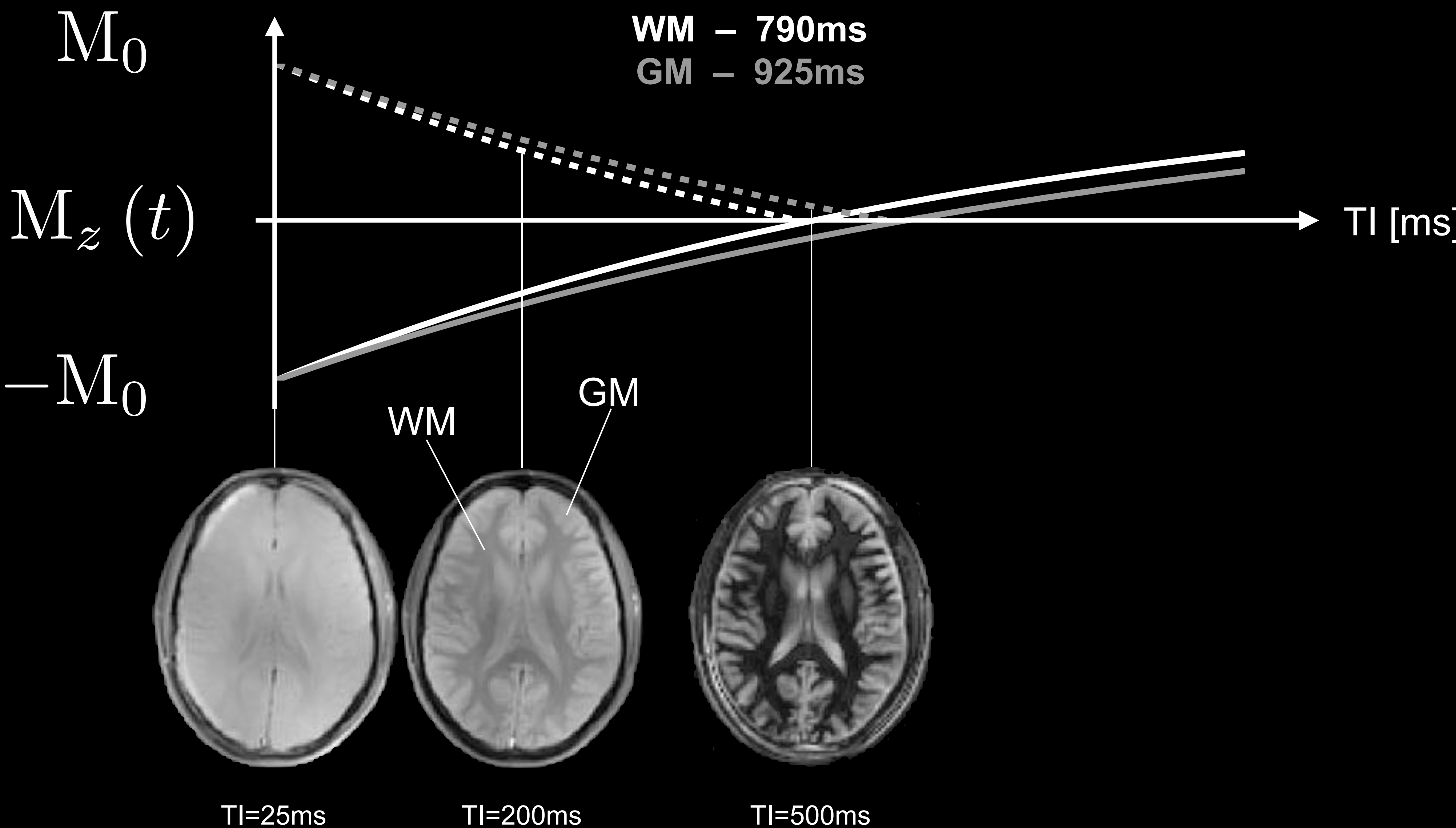
Spin Echo with TE=12ms, TR=2000ms

Spin Echo Inversion Recovery



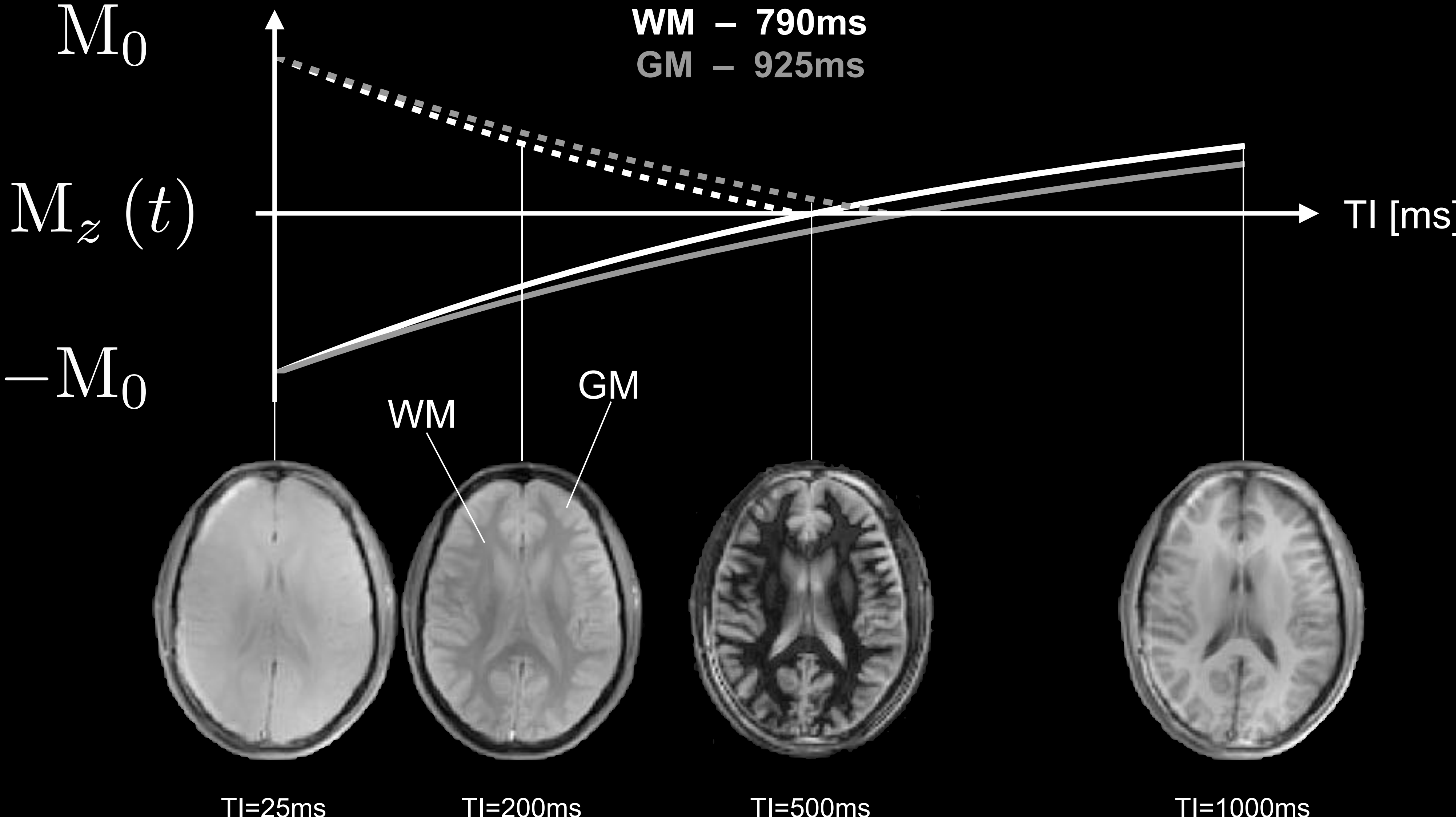
Spin Echo with TE=12ms, TR=2000ms

Spin Echo Inversion Recovery



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

Spin Echo Inversion Recovery



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

Spin Echo Inversion Recovery

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

TE=12ms, TR=2000ms

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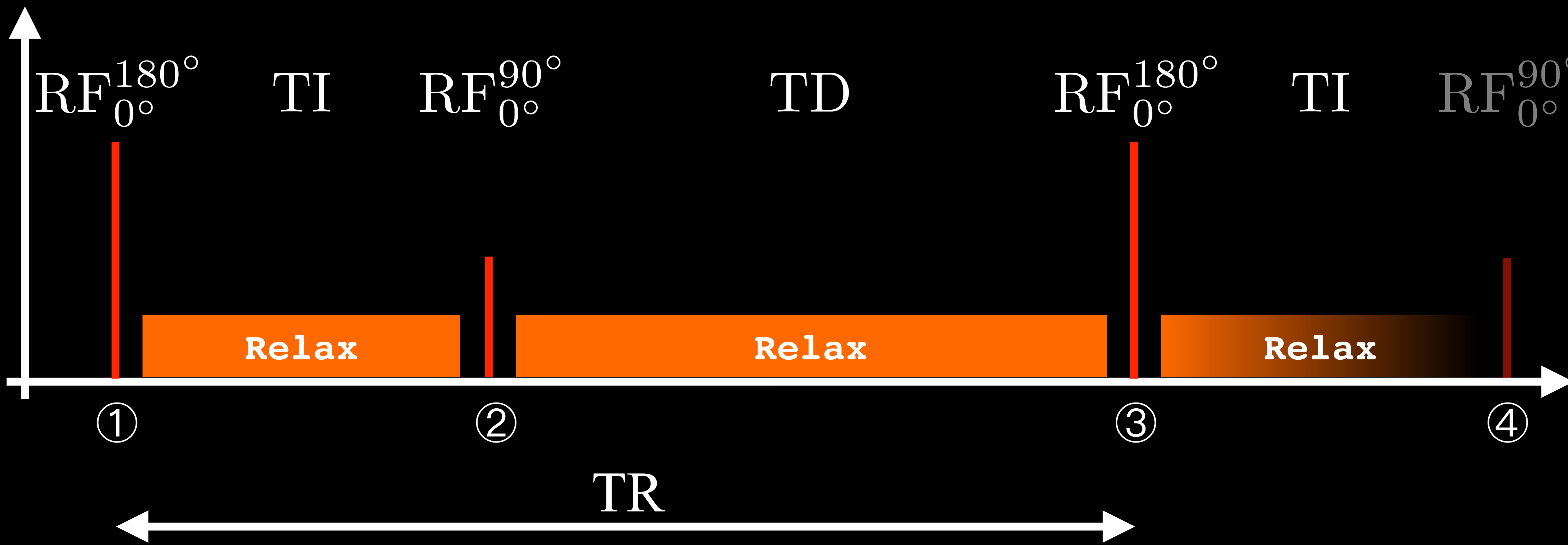
Inversion Recovery



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

To The Board...

IR Contrast

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

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

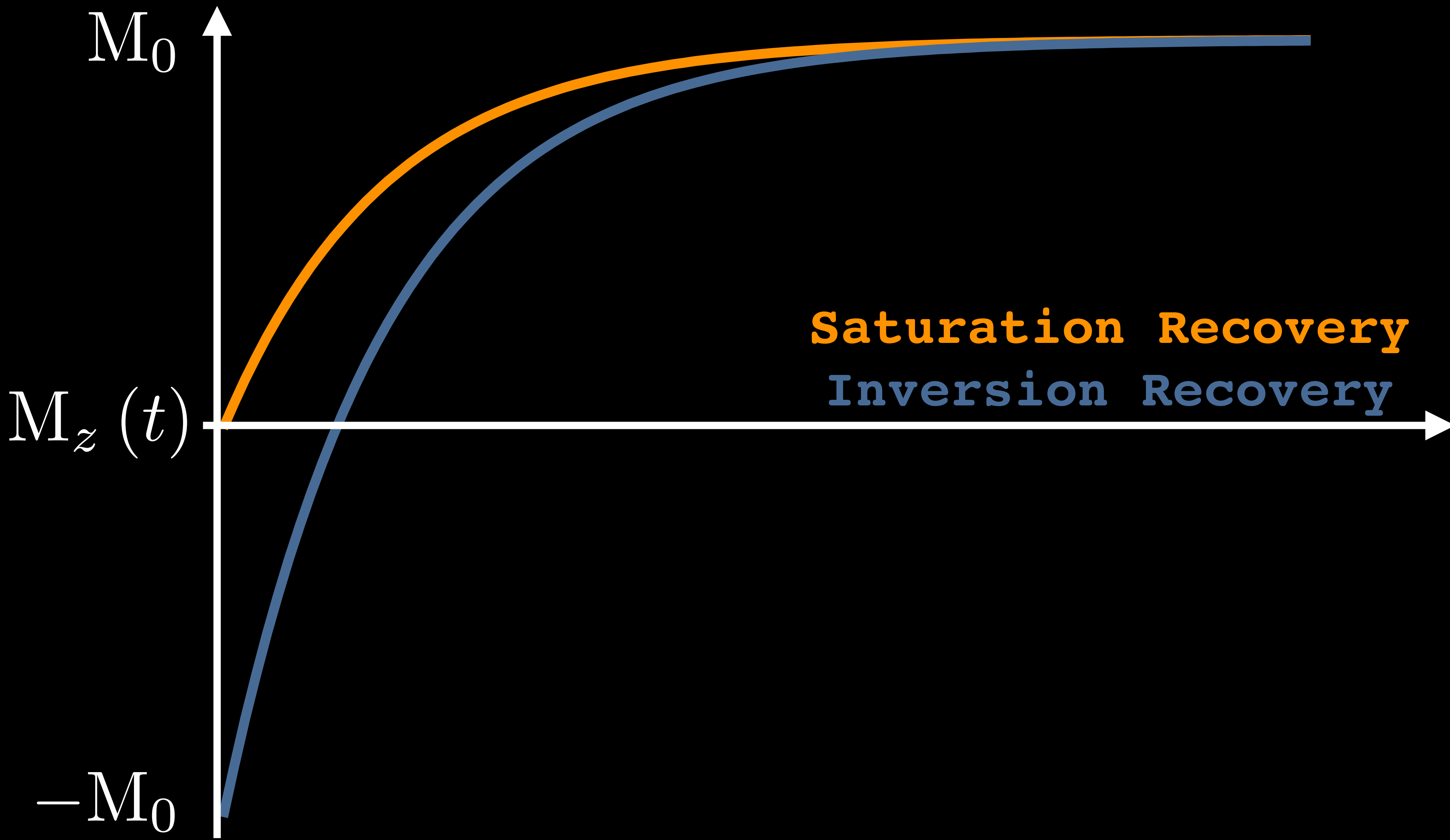
Target T_1

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

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

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

SR vs. IR



Inversion Pulse - Applications

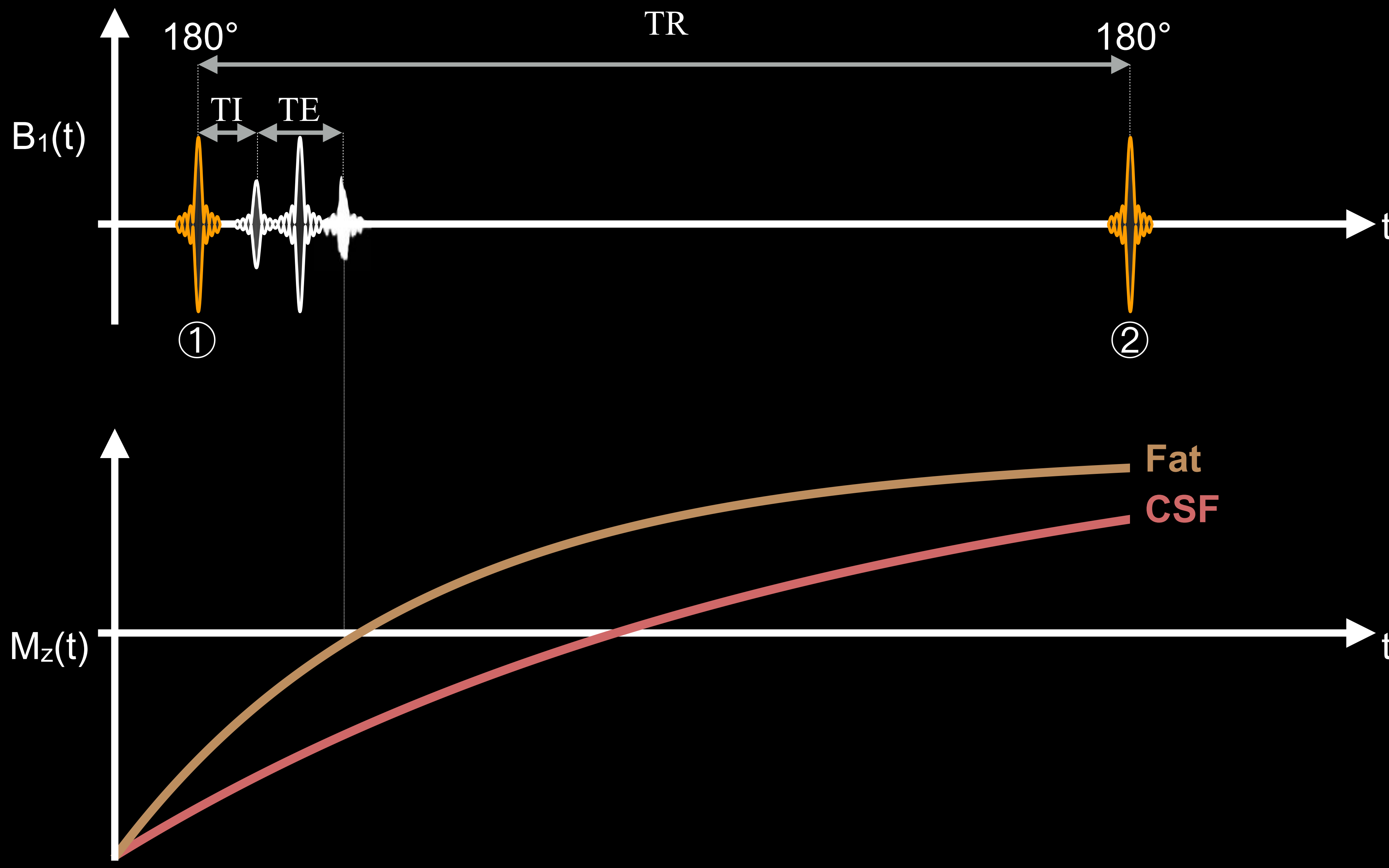
- Greater T_1 contrast than SR
- T_1 species nulling/attenuation
  - FLAIR (Fluid Attenuated Inversion Recovery)
  - STIR (Short Tau Inversion Recovery)
- IR is better than SR for generating contrast when:
  - ρ(A)=ρ(B) and T_2(A)=T_2(B)
  - AND
  - T_1(A) and T_1(B) are slightly different
- Quantitative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

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

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

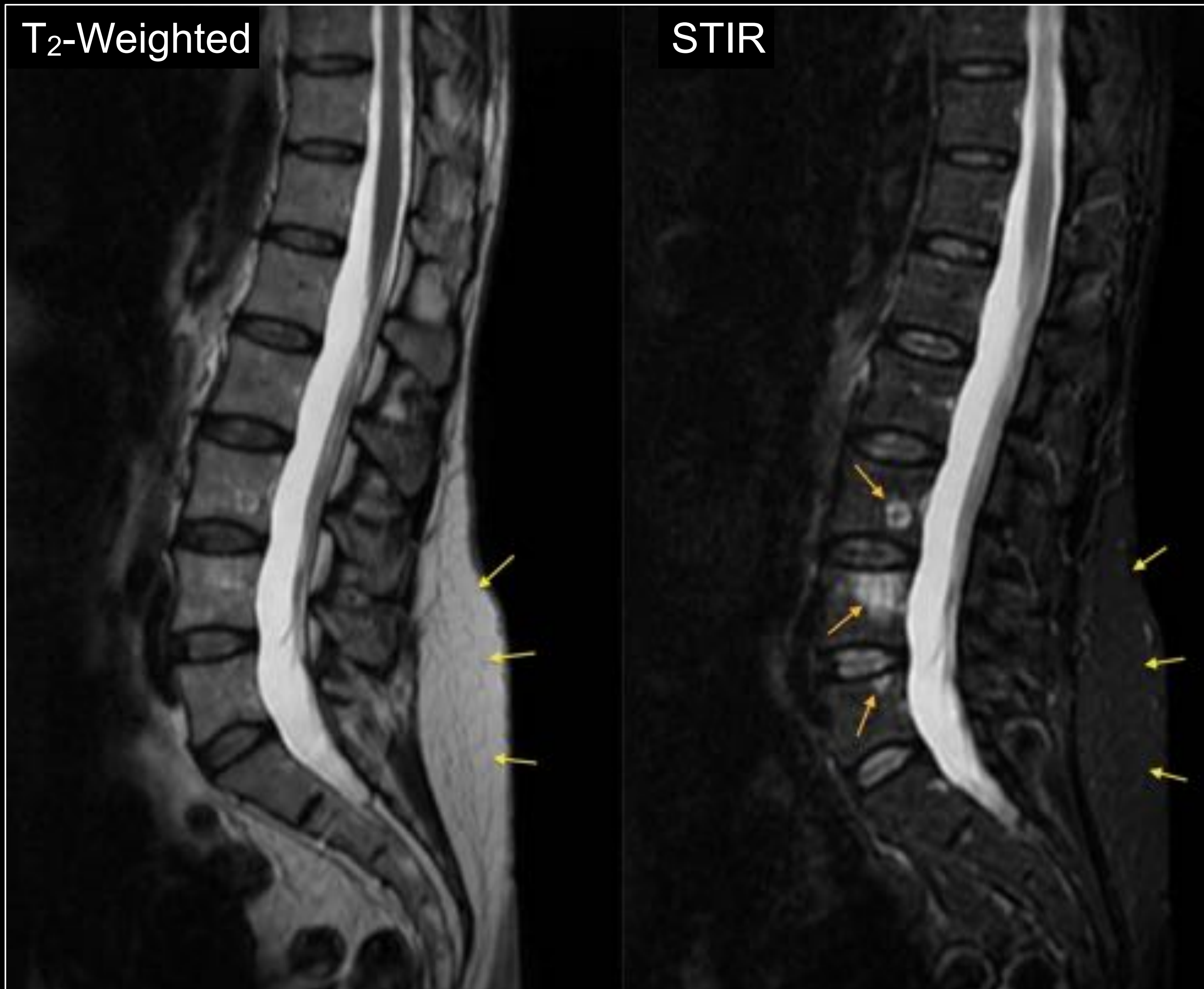
The final image contrast is controlled by TI and TR.

STIR Pulse Sequence



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

STIR Images



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

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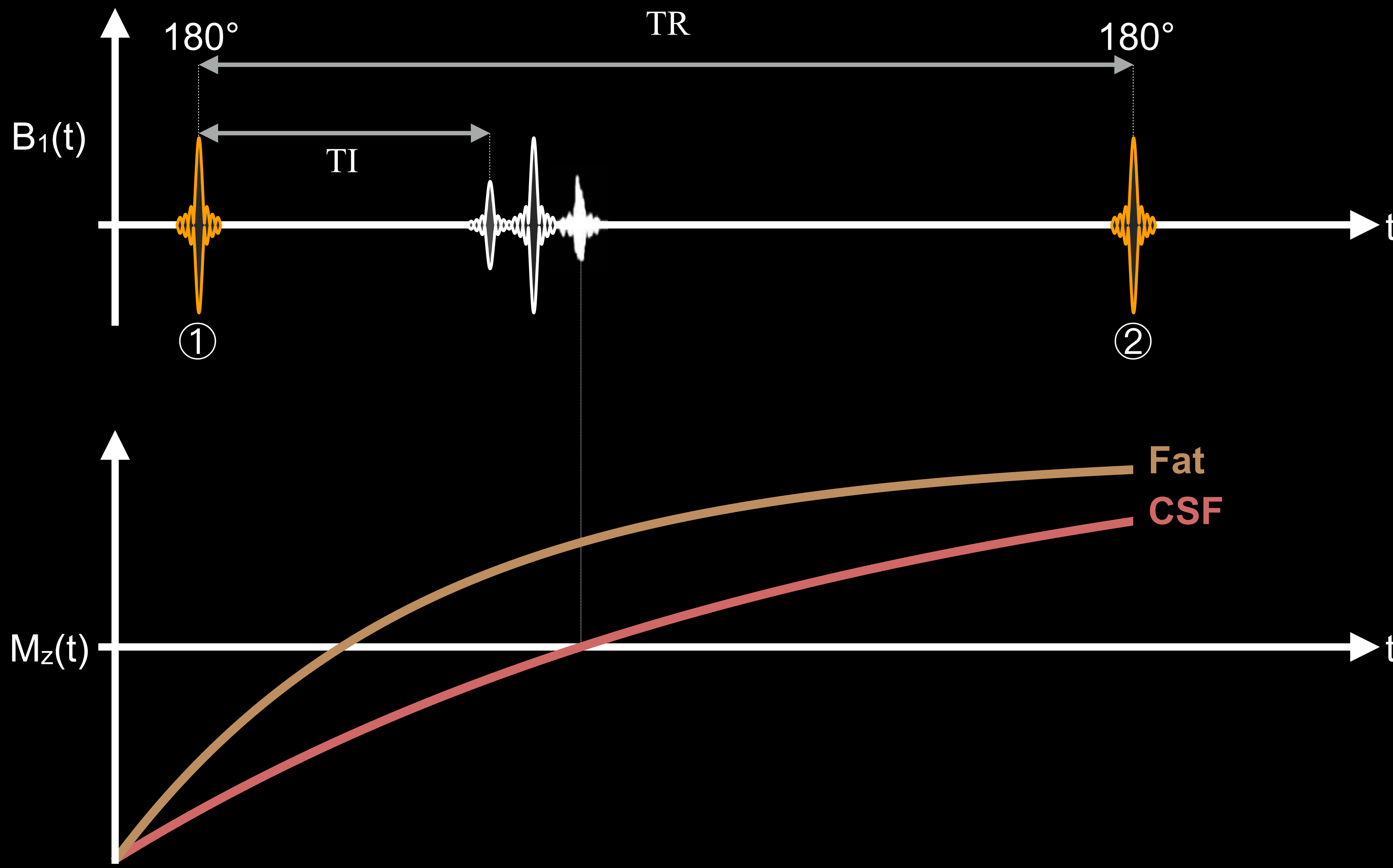
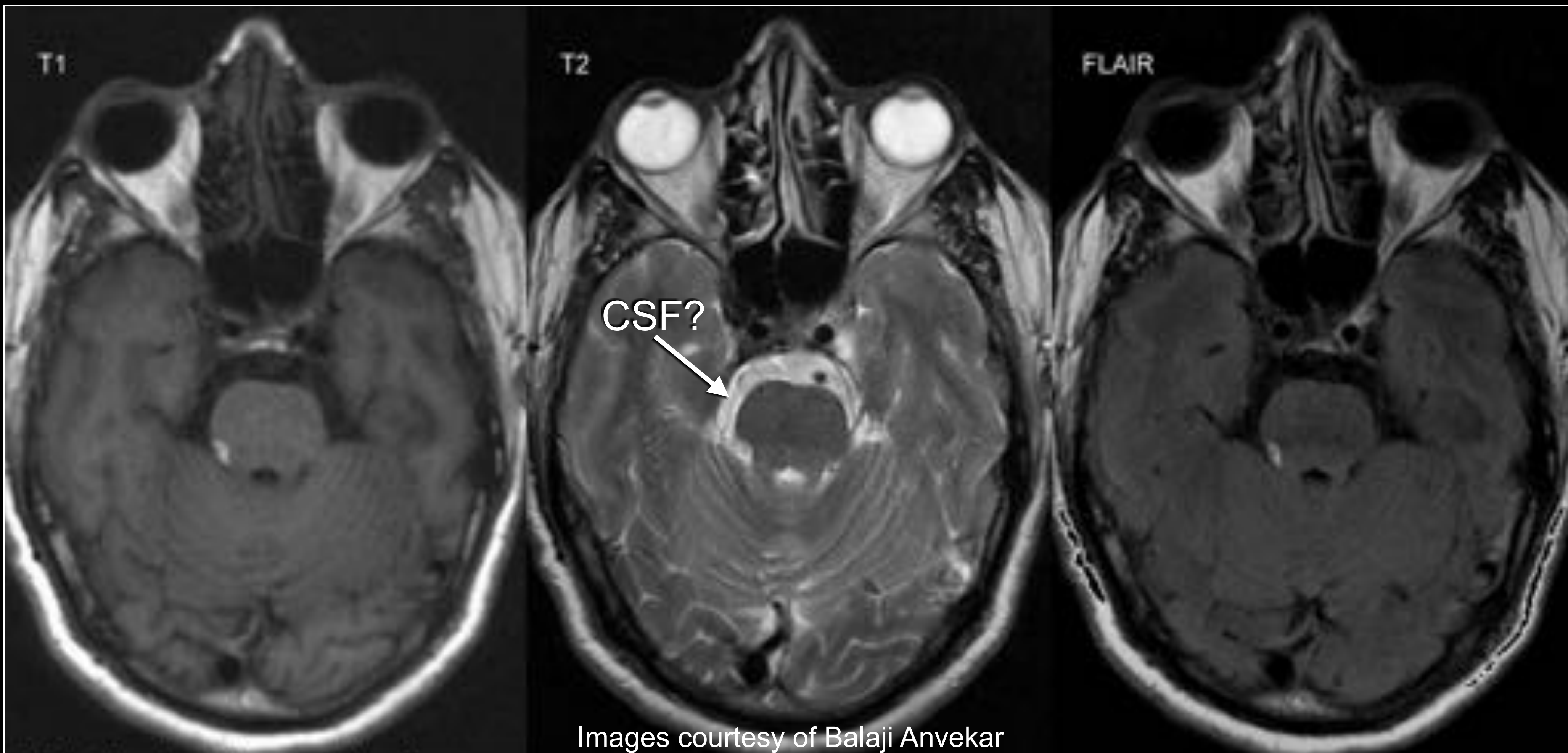
FLAIR Pulse Sequence



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

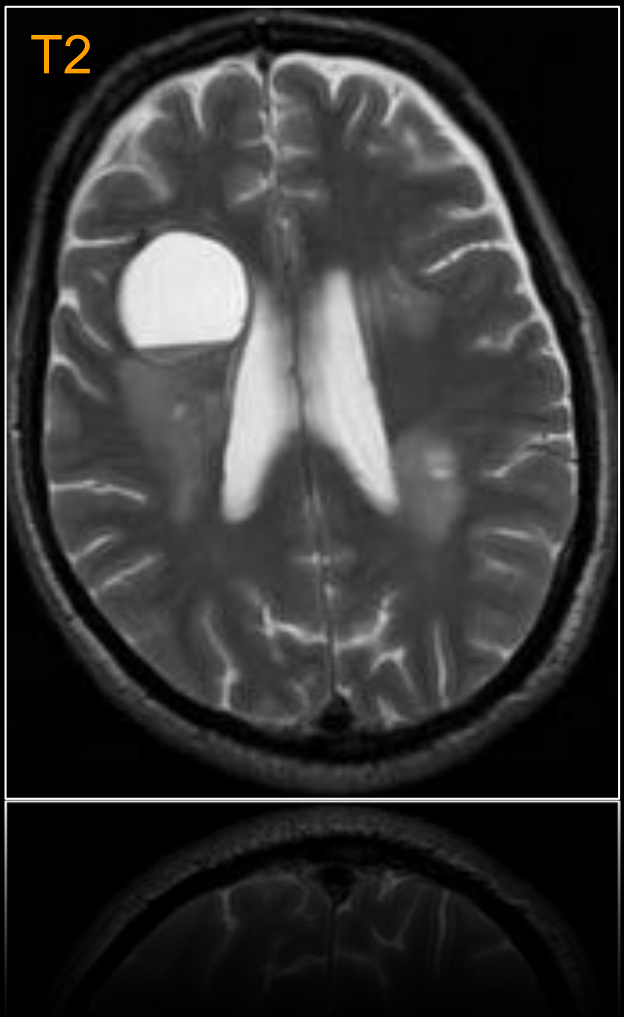
FLAIR Images

FLAIR can distinguish fat from CSF.

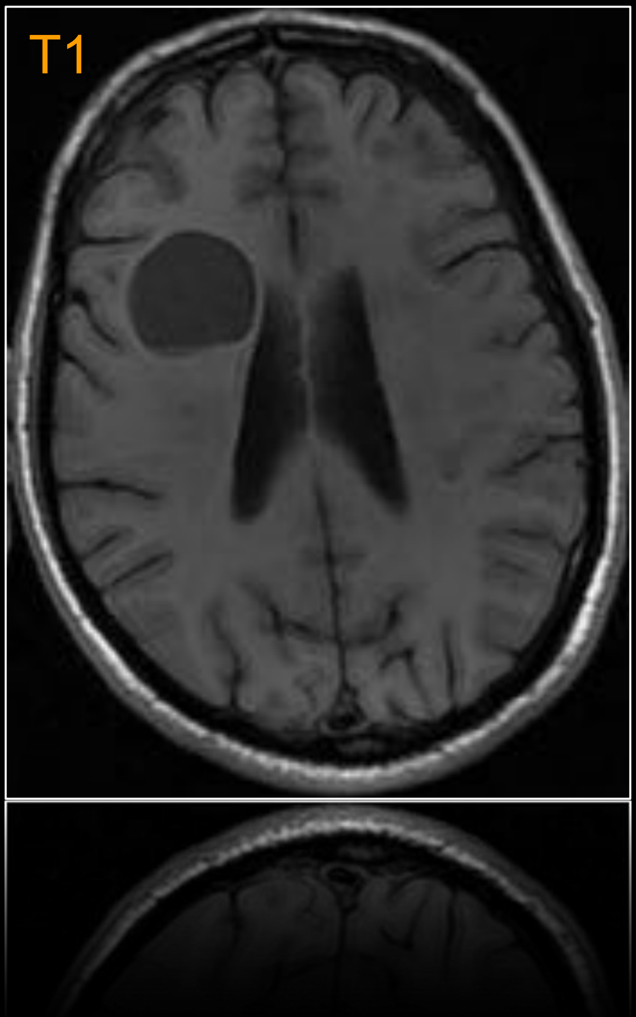


FLAIR Images

Long T2 is bright on T2w.



Short T1 is bright on T1w.



Long T1 is dark on FLAIR.

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

Thanks

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