Rad229 – MRI Signals and Sequences

Daniel Ennis & Brian Hargreaves
dbe@stanford.edu –or– bah@stanford.edu

Lecture-15B — Magnetization Preparation II - Diffusion

Diffusion Weighted Imaging

Daniel Ennis
dbe@stanford.edu

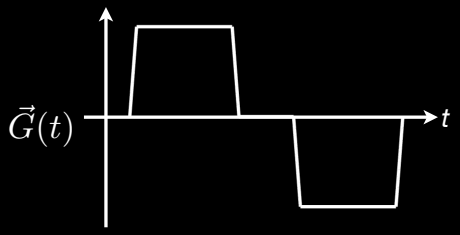
Learning Objectives

- Recall a simple expression for how the MRI signal depends on diffusion.
- Understand how gradients control diffusion sensitivity.
- Appreciate how the spin echo DWI sequence is built.
- Describe the steps required to measure diffusion with MRI.
- Distinguish high and low ADC from DWI-based images.
- Explain the concept of T_2 shine through from the signal eqn.

Diffusion and Gradients

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

- $\phi(t)$: Phase from a Gradient
- $\vec{G}(\tau)$: Applied Gradient
- $\vec{r}(\tau)$: Spin History (Random Walk!)

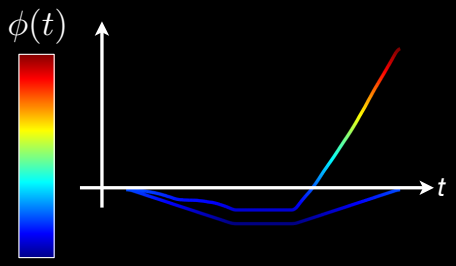


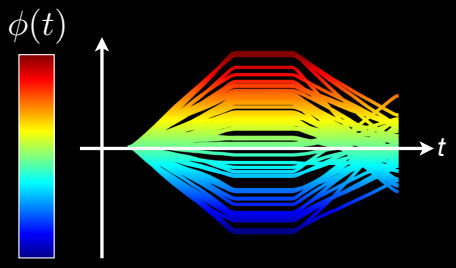
What is the b-value?

Diffusion Weighted Signal

$$S = S_0 e^{-\langle \phi^2 \rangle} = S_0 e^{-bD}$$

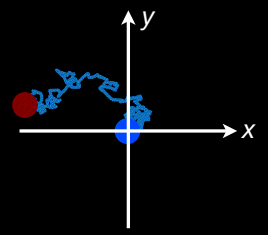
- S: Diffusion Weighted Signal
- S_0: Signal without Diffusion Effects
- $\langle \phi^2 \rangle$: Variance of the Phase Distribution
- b: b-value
- D: Diffusion Coefficient





Movies courtesy of Kévin Moulin

Stationary vs. Diffusing Spin

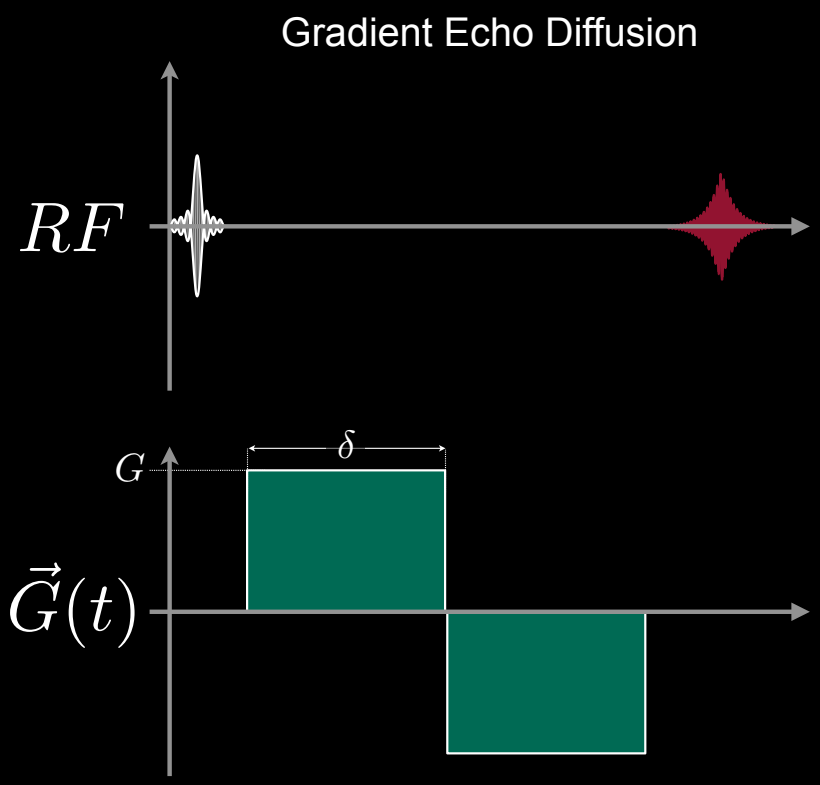


An ensemble of diffusing spins will accumulate different amounts of phase.

The larger the phase dispersion, The higher the diffusion coefficient.

Longer and stronger diffusion gradients contribute more sensitivity to diffusion.

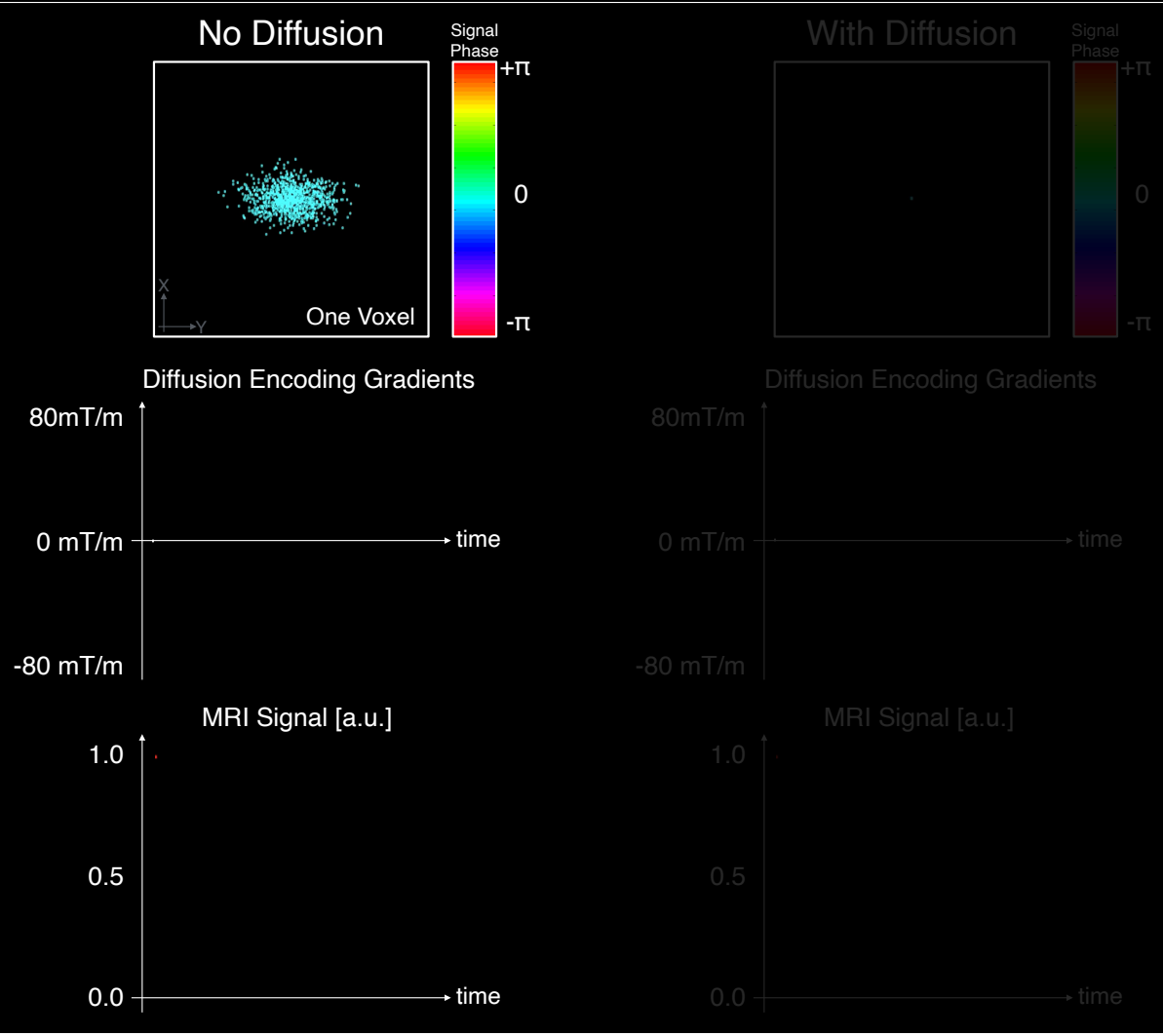
Diffusion – Gradients



$$b = \frac{2}{3}\gamma^2 G^2 \delta^3$$

Diffusion sensitizing gradients can be added to gradient and spin echo sequences.

Diffusion – Gradients



Diffusion encoding gradients label the spins with MR-phase that depends on position.

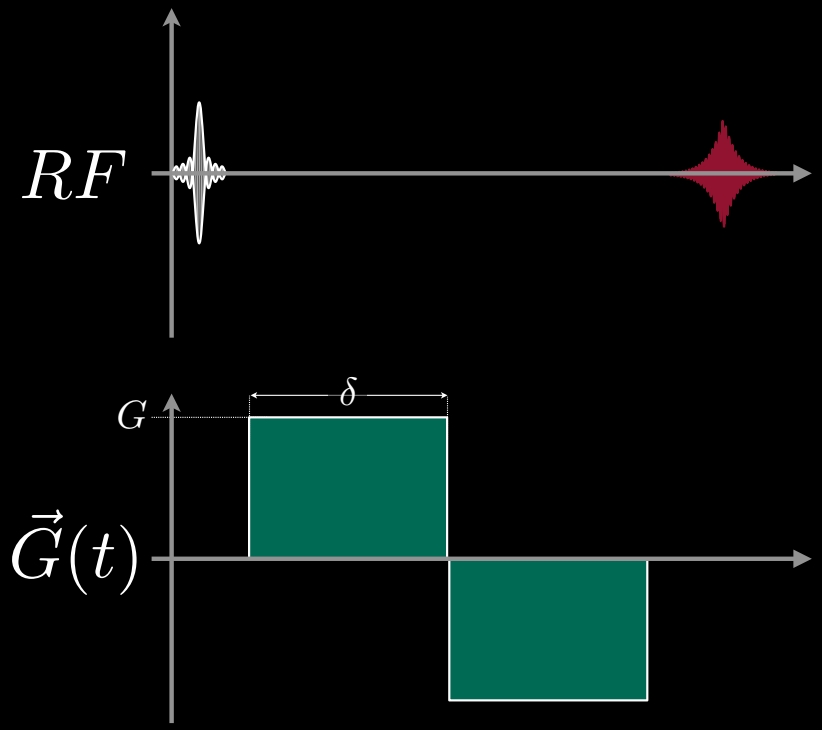
MR-phase for stationary spins phase can be "rewound".

MR-phase for diffusing spins phase can NOT be "rewound".

This leads to signal loss (attenuation) that depends on the diffusion coefficient.

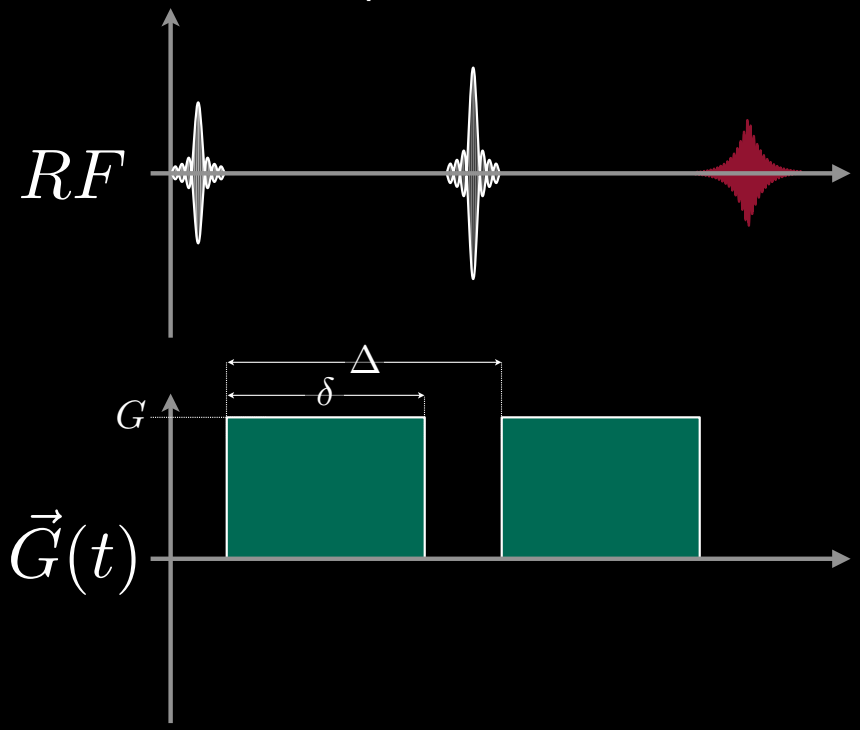
Diffusion – Gradients

Gradient Echo Diffusion



$$b = \frac{2}{3}\gamma^2 G^2 \delta^3$$

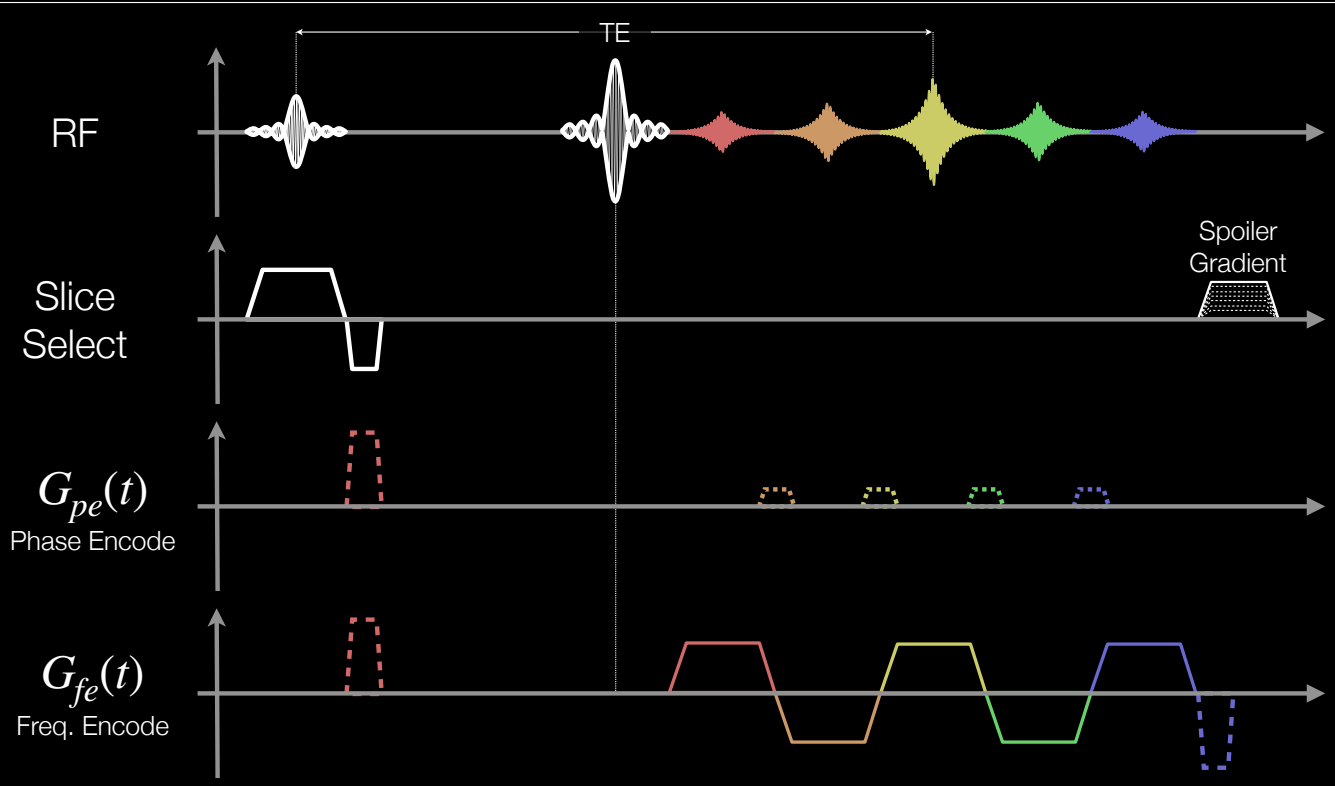
Spin Echo Diffusion

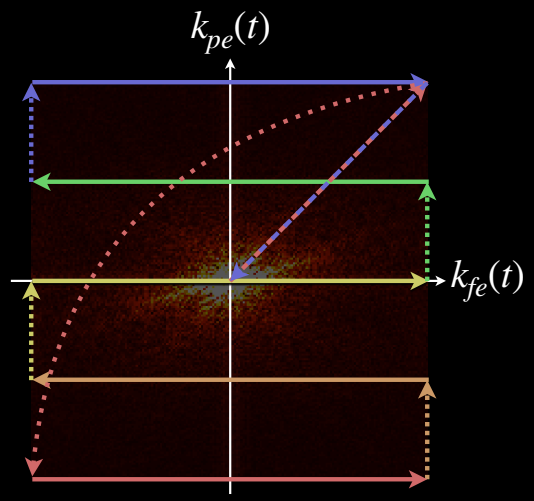


$$b = \gamma^2 G^2 \delta^2 \left(\Delta - \delta/3\right)$$

Diffusion sensitizing gradients can be added to gradient and spin echo sequences.

Spin Echo EPI

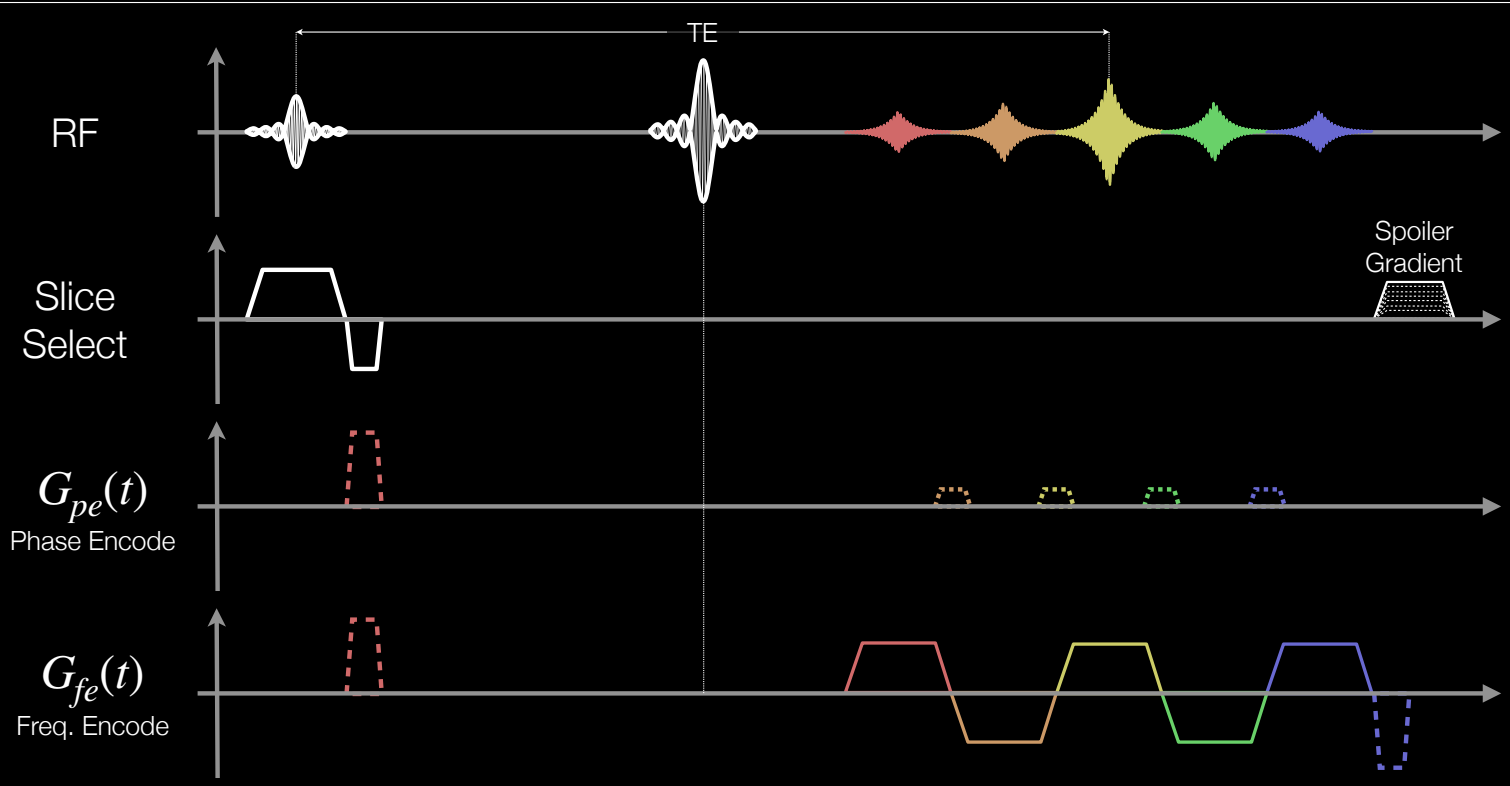


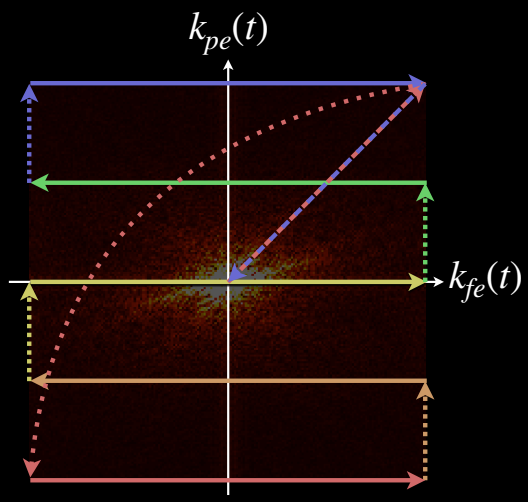


$$S_0 = \rho\left(1 - e^{-\frac{TR}{T1}}\right) e^{-\frac{TE}{T2}}$$

Spin echo sequences refocus sources of off-resonance and are a common base sequence for DWI.

Spin Echo EPI – Longer TE

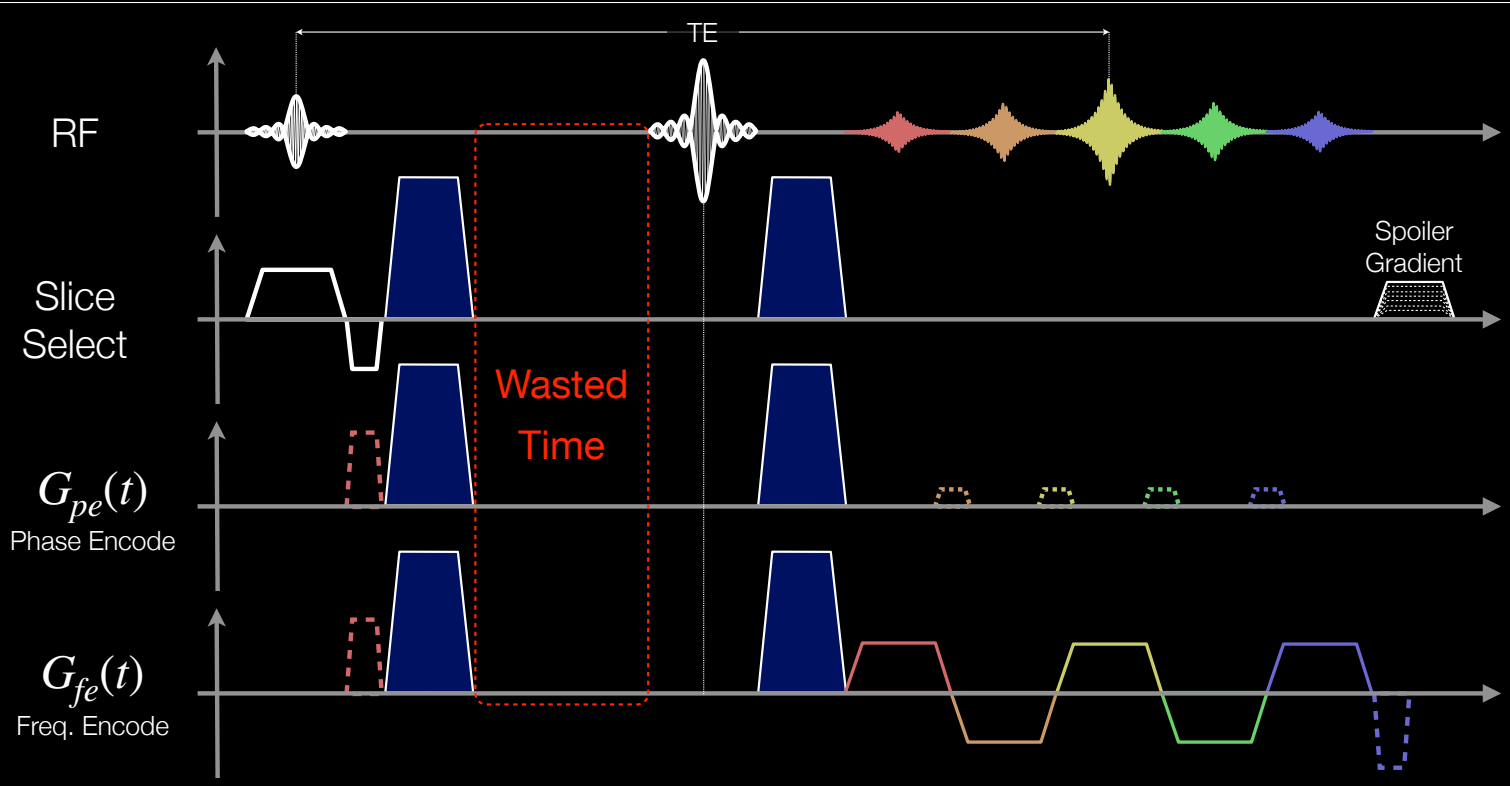


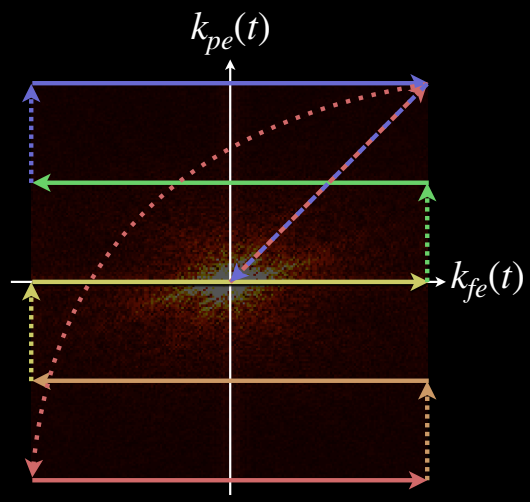


$$S_0 = \rho\left(1 - e^{-\frac{TR}{T1}}\right)e^{-\frac{TE}{T2}}$$

Delaying the refocusing pulse lengthens the TE, but provides time to add diffusion encoding gradient.

Diffusion Weighted Spin Echo EPI

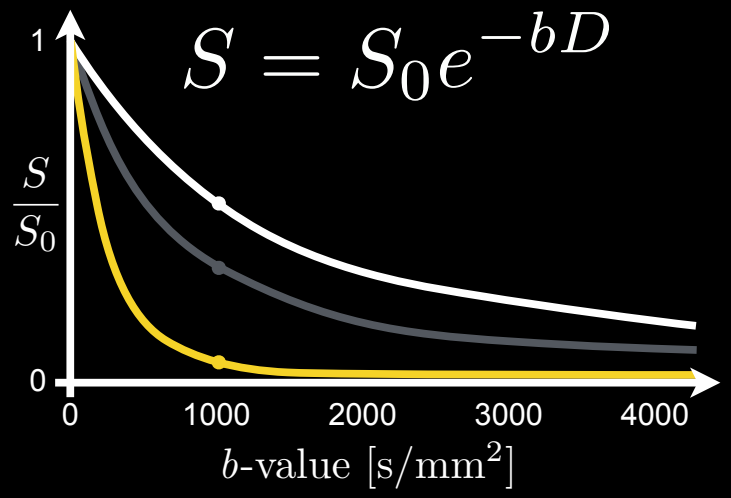




$$S = \rho\left(1 - e^{-\frac{TR}{T_1}}\right) e^{-\frac{TE}{T_2}} e^{-bD}$$

The addition of diffusion encoding gradient sensitizes the signal equation to diffusion.

Diffusion – b-value [s/mm²]



Tissue	Diffusion Coefficient [10^{-6} mm²/s]
White matter	670-800
Cortical grey matter	800-1000
Deep grey matter	700-850
CSF	3000-3400

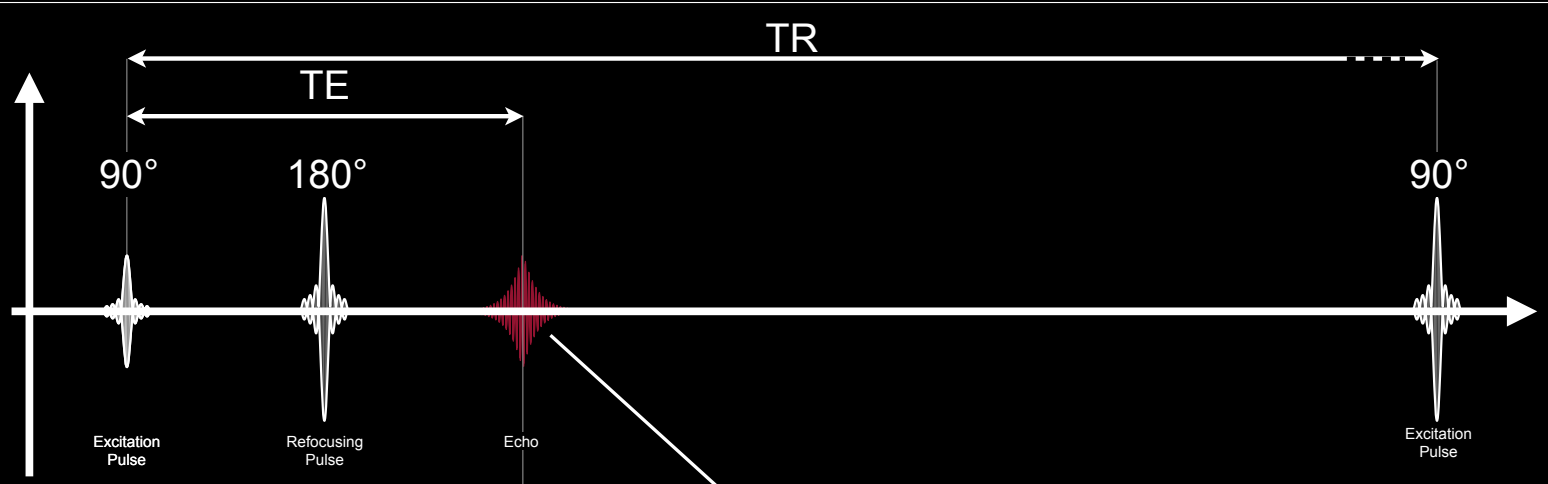
Experiment:
1) Set b=0, Measure S_0
2) Set b≠0, Measure S
3) Calculate D

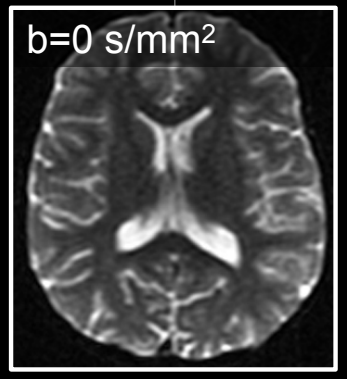
High D --> High signal loss
Low D --> Low signal loss

High b-value --> High diffusion sensitivity, but low SNR
Low b-value --> Low diffusion sensitivity, but high SNR

https://radiopaedia.org/articles/apparent-diffusion-coefficient-1?

Diffusion Measurements





$$S = S_0$$

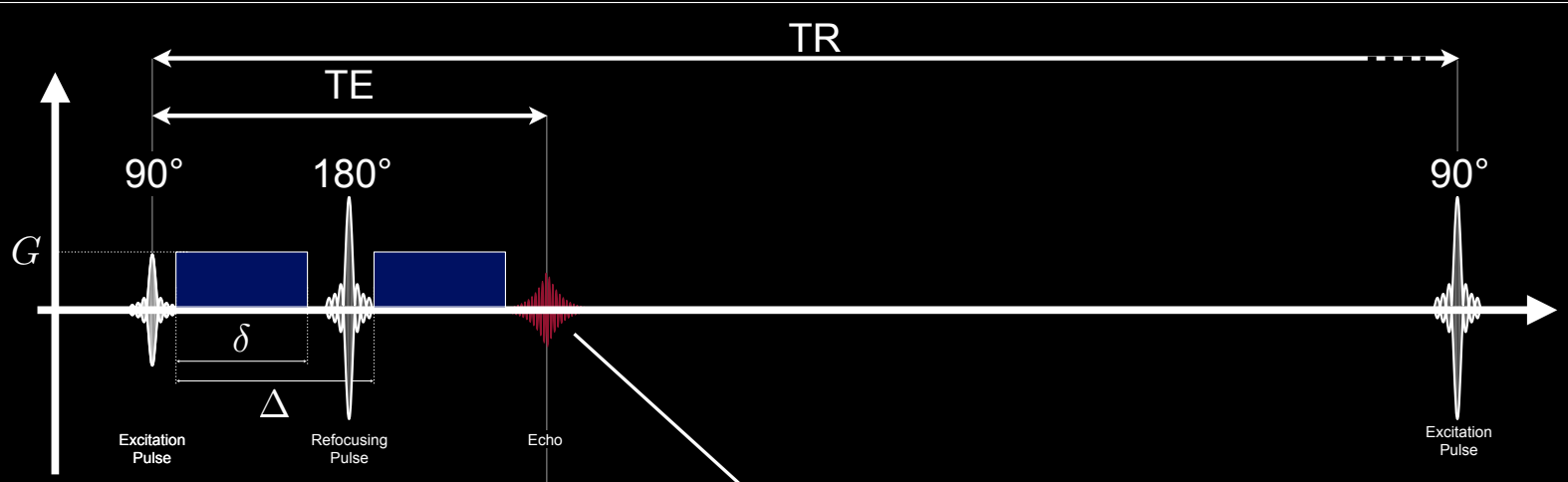
(Non-Diffusion Weighted Imaging)

$$S_0 = \rho \left(1 - e^{-\frac{TR}{T1}}\right) e^{-\frac{TE}{T2}}$$

Minimize the TE for best SNR.
"Maximize" TR for best SNR.

Image: http://mriquestions.com/making-a-dw-image.html

Diffusion Measurements



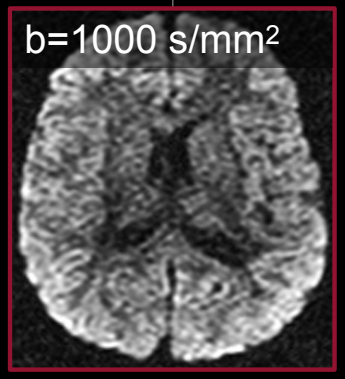
$$S = S_0 e^{-bD}$$

(Diffusion Weighted Imaging)

$$b = \gamma^2 G^2 \delta^2 \left(\Delta - \frac{\delta}{3}\right)$$

(Controls Diffusion Weighting)

This is what we control on the scanner.

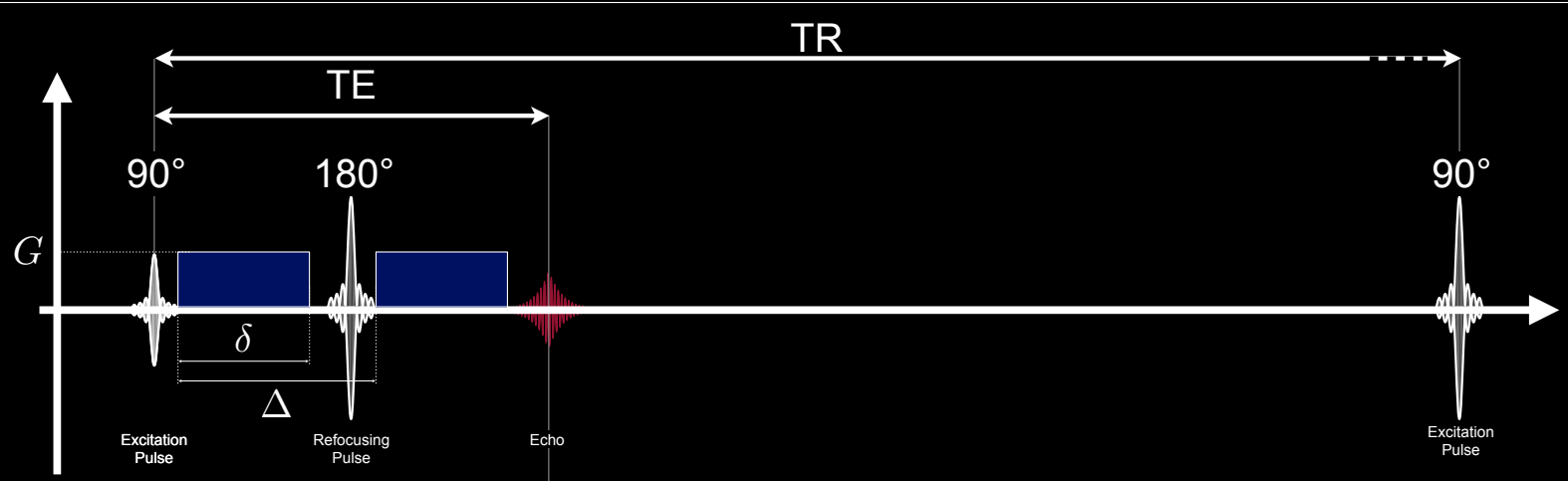


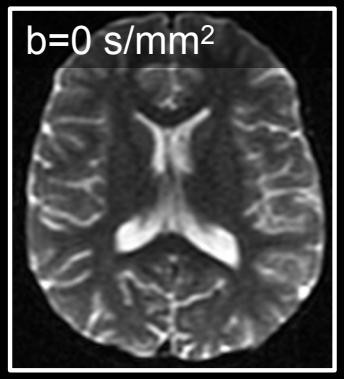
$$S = \rho \left(1 - e^{-\frac{TR}{T_1}}\right) e^{-\frac{TE}{T_2}} e^{-bD}$$

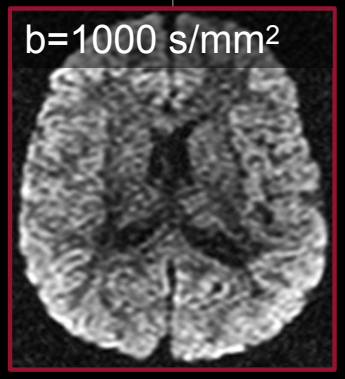
Match the TE and TR to S_0.
Adjust b-value for best contrast.

Image: http://mriquestions.com/making-a-dw-image.html

Diffusion Measurements

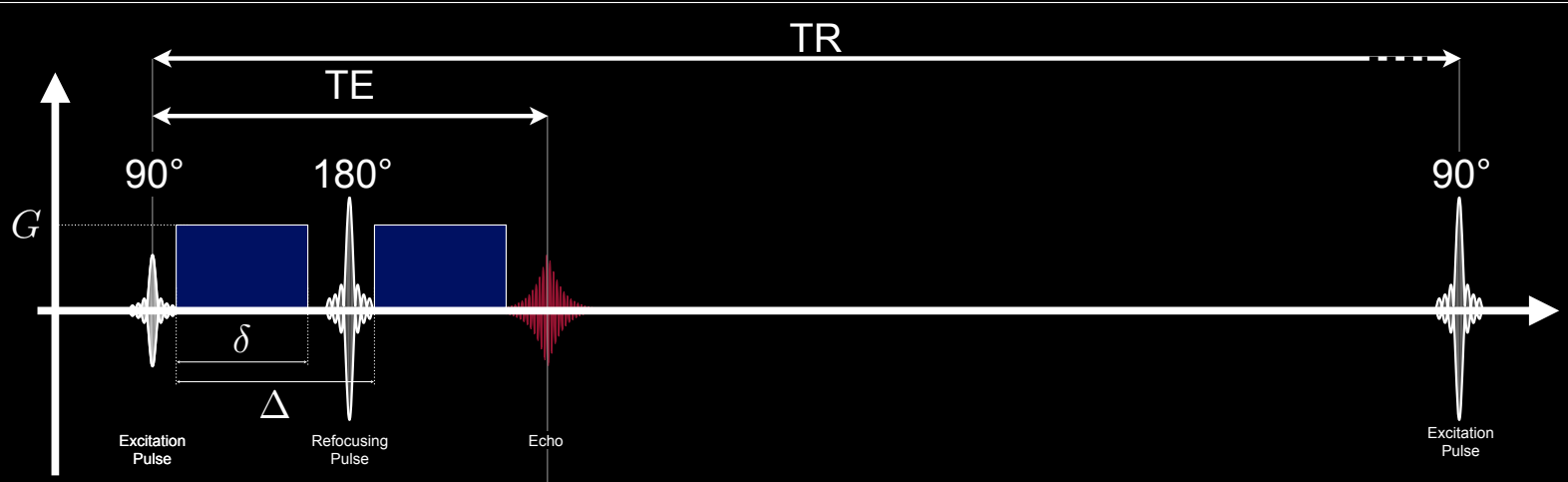


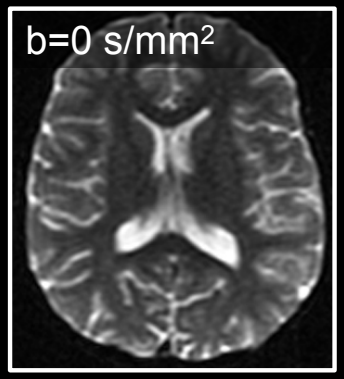


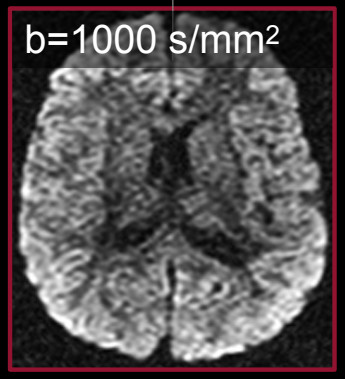


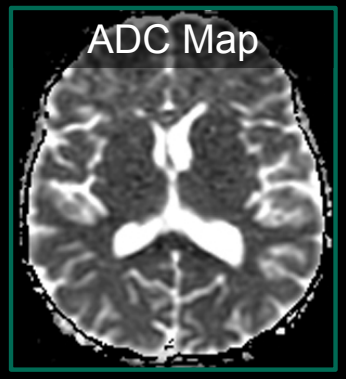
$$S_0 \qquad S = S_0 e^{-\frac{b}{D}}$$

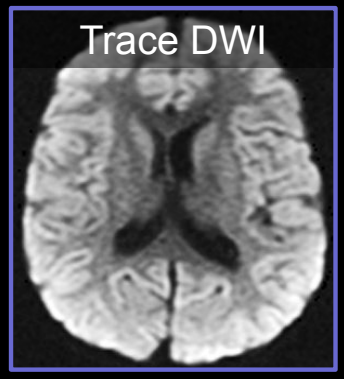
Diffusion Measurements











$$S_0 \qquad S = S_0 e^{-\frac{b}{D}}$$

DWI Example – Chronic Infarct

Does the lesion have a higher or lower diffusion coefficient?

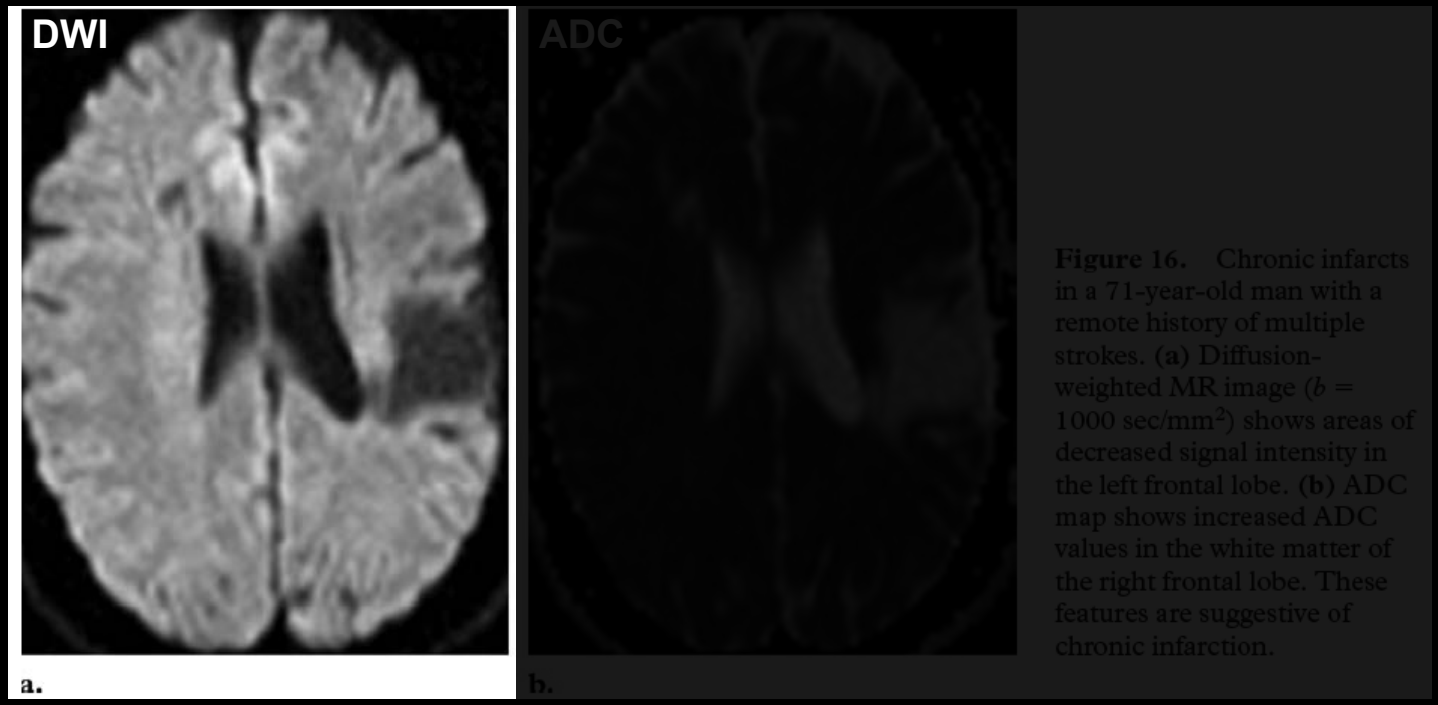
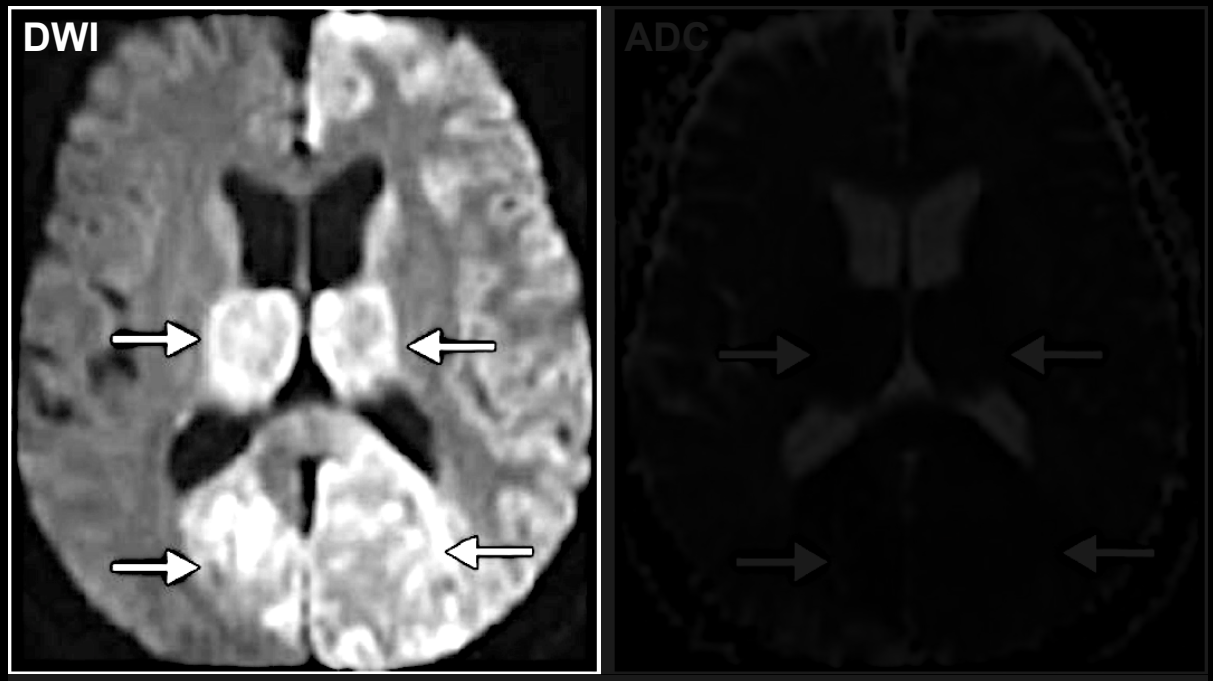


Figure 16. Chronic infarcts in a 71-year-old man with a remote history of multiple strokes. **(a)** Diffusion-weighted MR image (b = 1000 sec/mm^2) shows areas of decreased signal intensity in the left frontal lobe. **(b)** ADC map shows increased ADC values in the white matter of the right frontal lobe. These features are suggestive of chronic infarction.

Srinivasan A, et al. State-of-the-art imaging of acute stroke. Radiographics 2006;26 Suppl 1:S75-95.

DWI Example - Acute Stroke

Does the lesion have a higher or lower diffusion coefficient?



a. b.

Figure 15. Acute stroke of the posterior circulation in a 77-year-old man. **(a)** Diffusion-weighted MR image (b = 1000 sec/mm^2) shows bilateral areas of increased signal intensity (arrows) in the thalami and occipital lobes. **(b)** ADC map shows decreased ADC values in the same areas (arrows). These findings are indicative of acute ischemia.

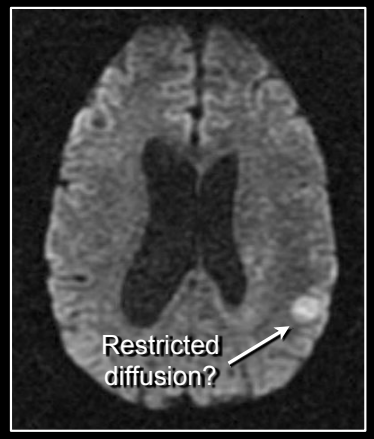
Srinivasan A, et al. State-of-the-art imaging of acute stroke. Radiographics 2006;26 Suppl 1:S75-95.

DWI – T_2 Shine Through

- **High** signal intensity on DWI:
  - Low (restricted) diffusion (spins didn't move too far)
  - OR Long T2 (signal didn't decay too much)
- **Low** signal intensity on DWI:
  - High diffusion coefficient
  - OR short T2 (signal decayed a lot)

$$S = \left(1 - e^{-\frac{TR}{T_1}}\right) e^{-\frac{TE}{T_2}} e^{-bD}$$

Trace DWI



ADC Map

T2w Spin Echo

http://mri-q.com/t2-shine-through.html

What else can we measure with diffusion?

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