Overview of MRI Pulse Sequences and Image Acquisition

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Outline

Image Acquisition Review

Pulse Sequence Diagram

Sequence Classifications

- By RF Pulse Usage
- By Readout

Sequences with Novel Contrast

Basics of Image Acquisition

Preparatory Stuff → Excite Tissue

Data Readout ← Spatial Encoding

Reconstruction

Preparatory: tack-ons (e.g., fat sat)

Excite: slice/slab selection

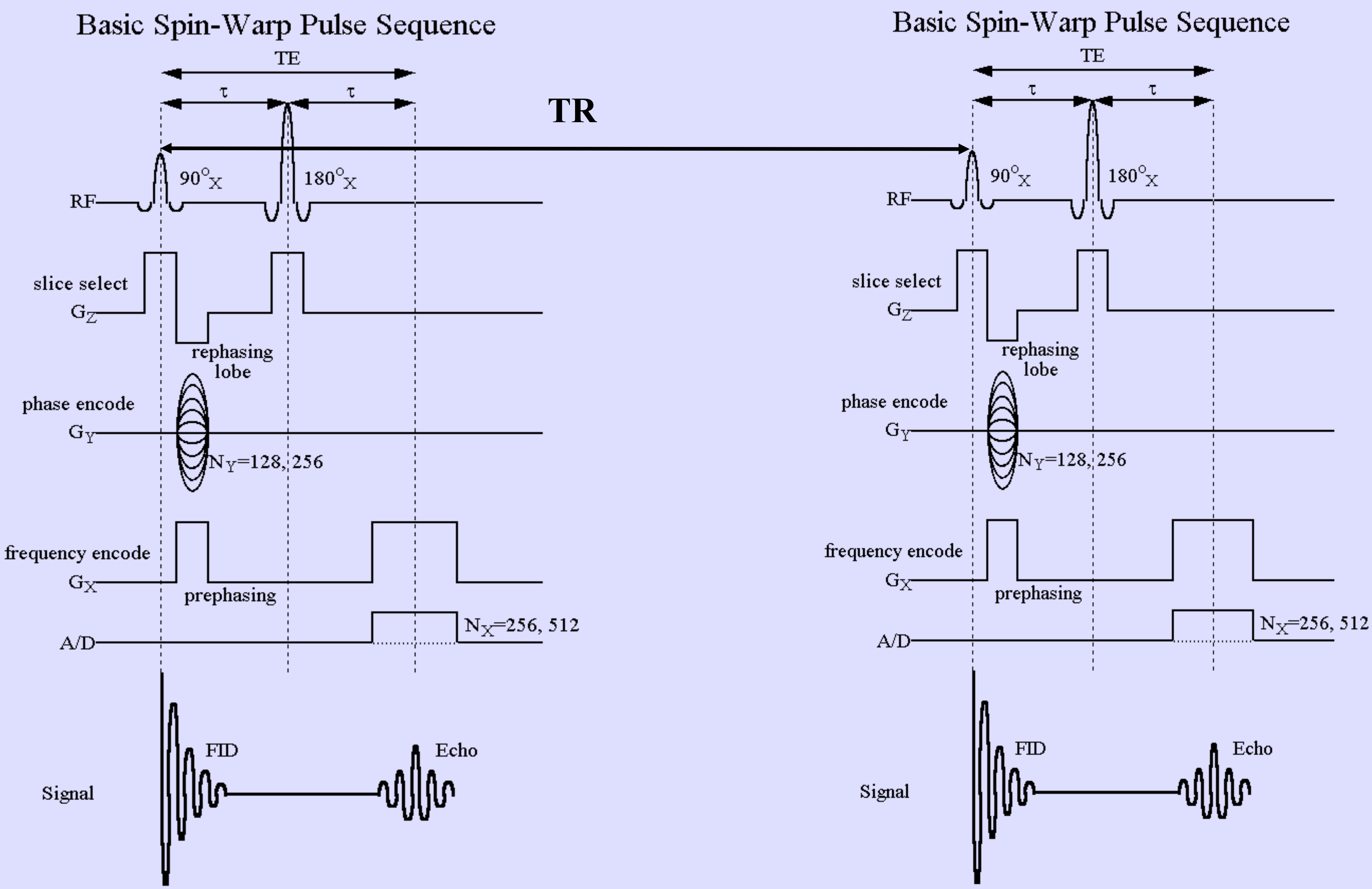
Spatial Encoding: gradients modulate phases spatially.

Readout: k-space trajectory will affect image characteristics.

Reconstruction: Inverse Fourier transform (& filtering), and other stuff.

Image contrast: from all steps in the process.

Pulse Sequence Diagram (Spin-Warp)



Basic Pulse Sequence Taxonomy

By use of RF pulses/echo:

- SE
- GRE
- IR
- Stimulated echo*

By readout:

- 2D vs. 3D
- Single-echo vs. “fast”
- EPI
- “Partial” k-space (e.g., partial fourier, pMRI, compressed sensing, keyhole)
- Non-cartesian readout (e.g., radial, spiral)

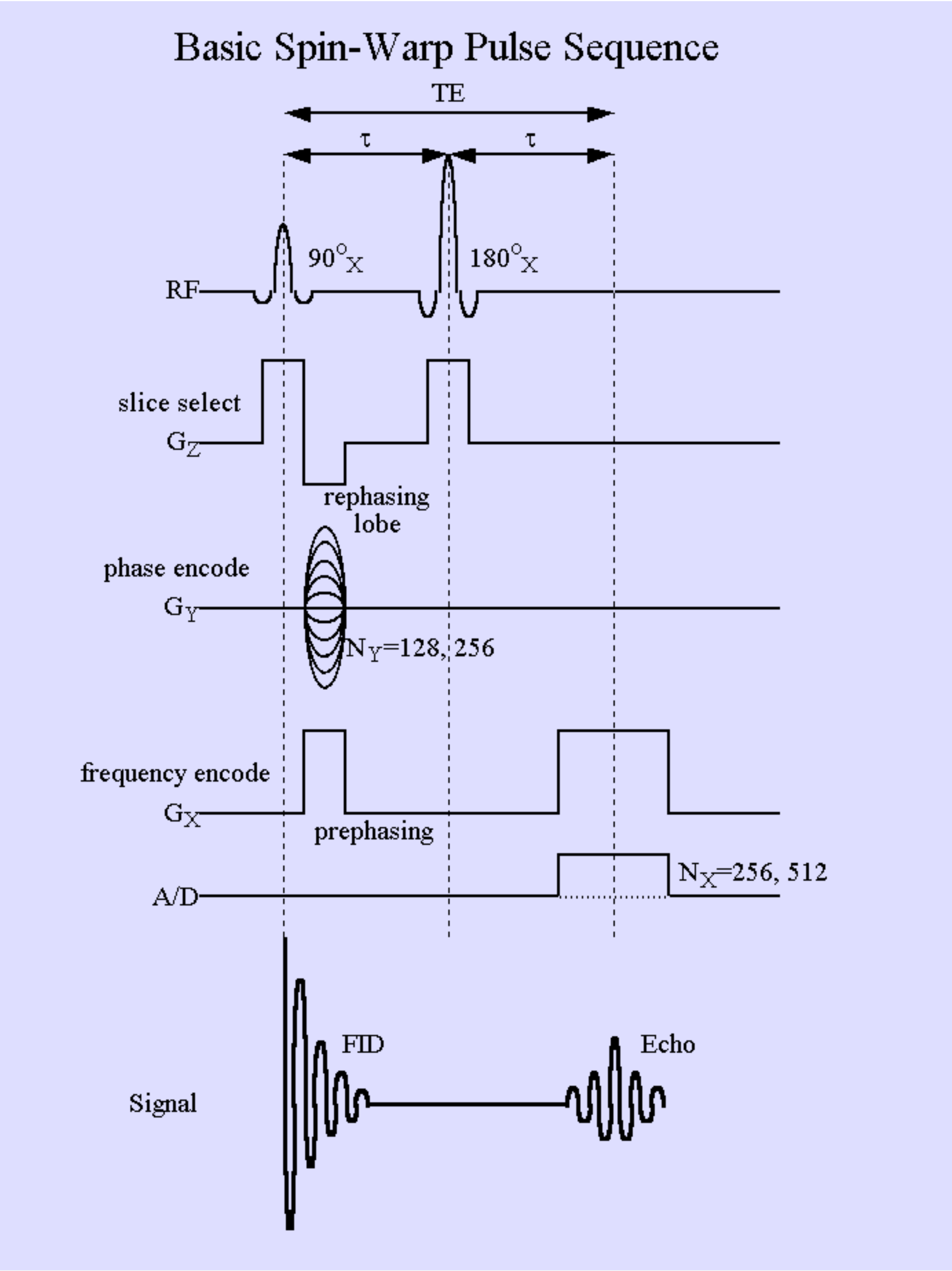
Sequence Classifications According to RF Pulses/Echo

Spin Echo

Spin Echo: use RF to create the echo

Pro – Insensitive to inhomogeneity of the magnet and inhomogeneity caused by magnetic susceptibility of patient tissue (T_2^*)

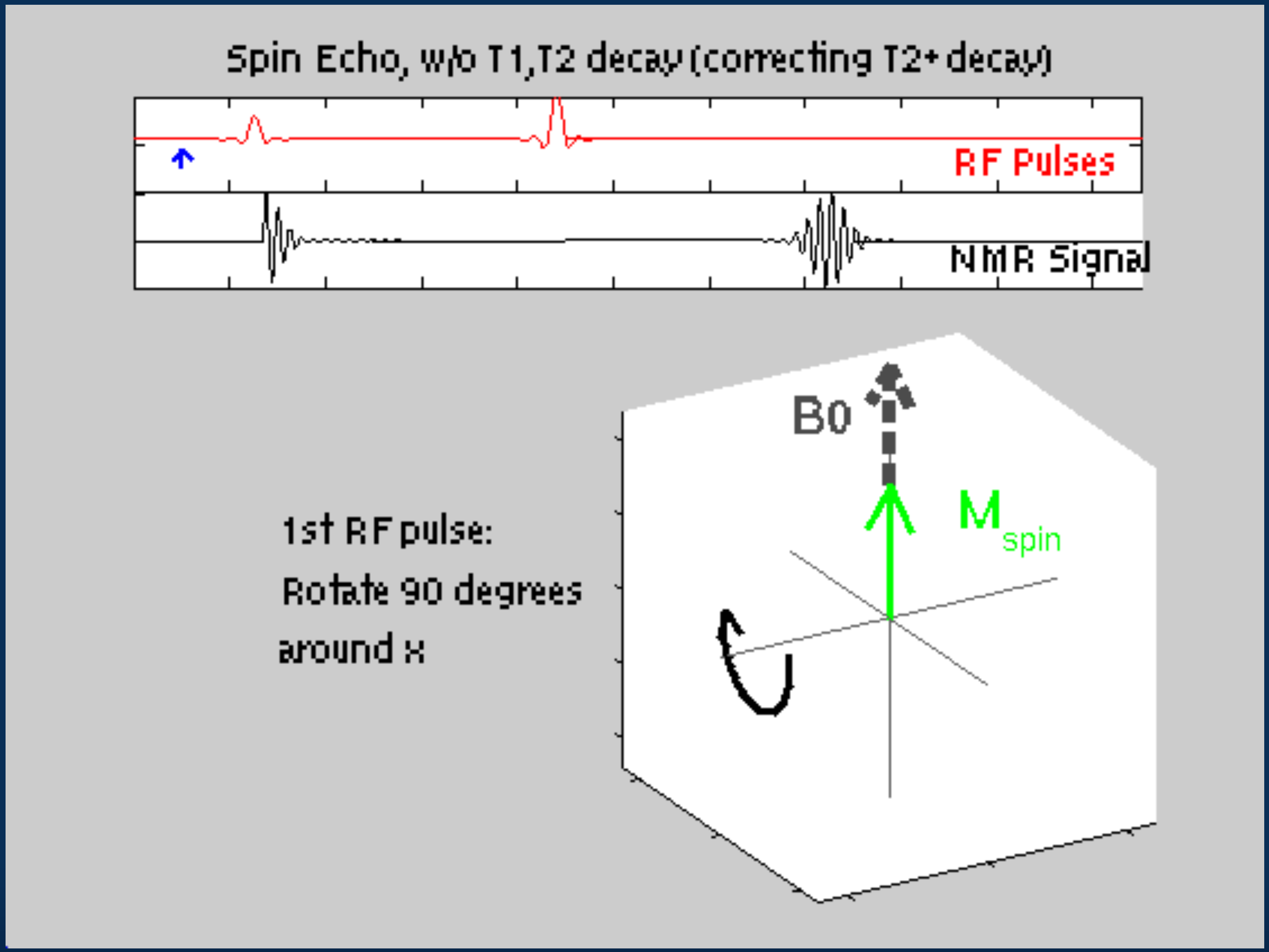
Con – Takes longer to play out, more RF per unit time (SAR).



Spin Echo Corrects T2*

Basic Carr-Purcell-Meiboom-Gill sequence ($90^o{}_x$, $180^o{}_y$)

Variation in local magnetic field leads to differences in phases of spin.



Spin in red leads in phase (always progresses CW).

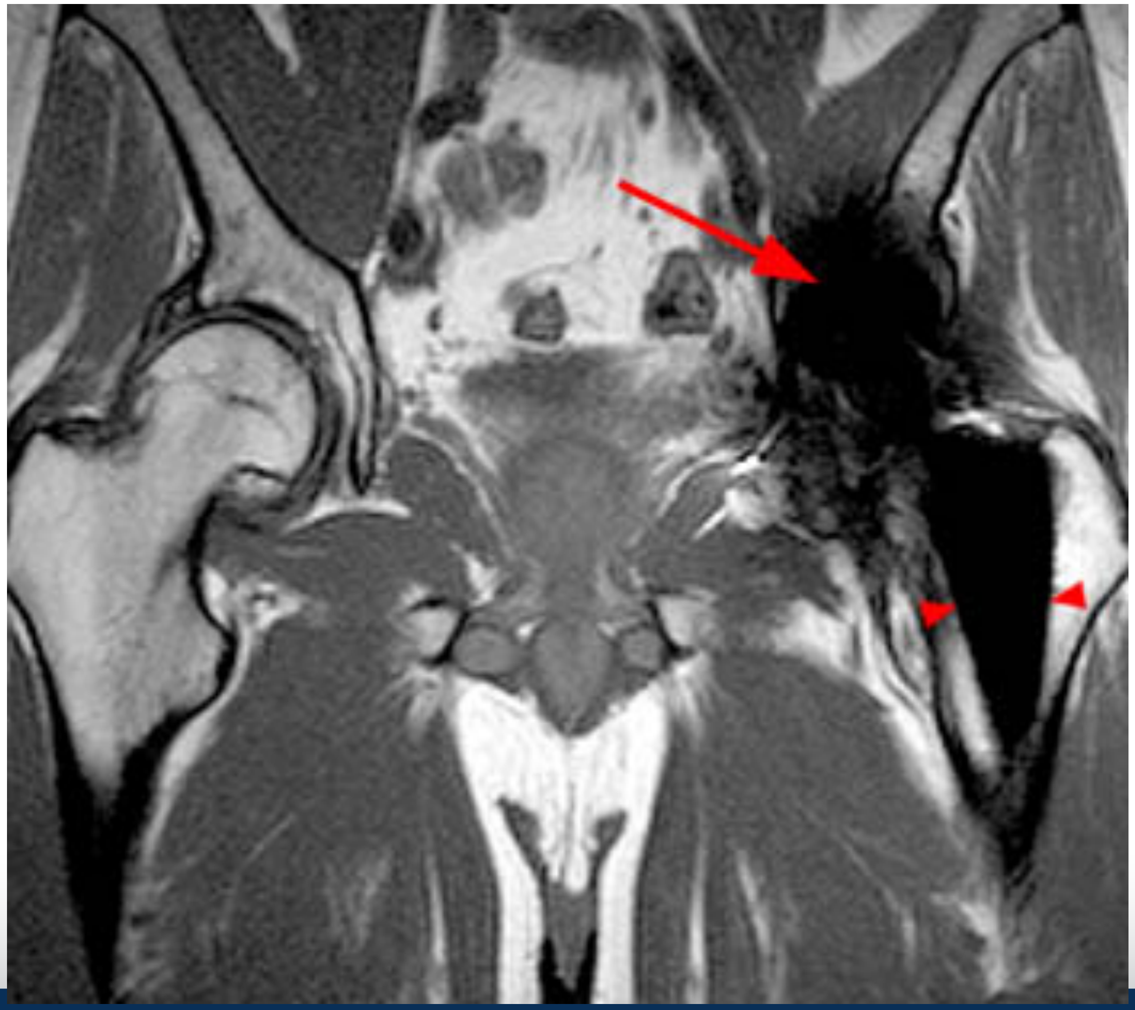
Spin in blue lags in phase (always progresses CCW)

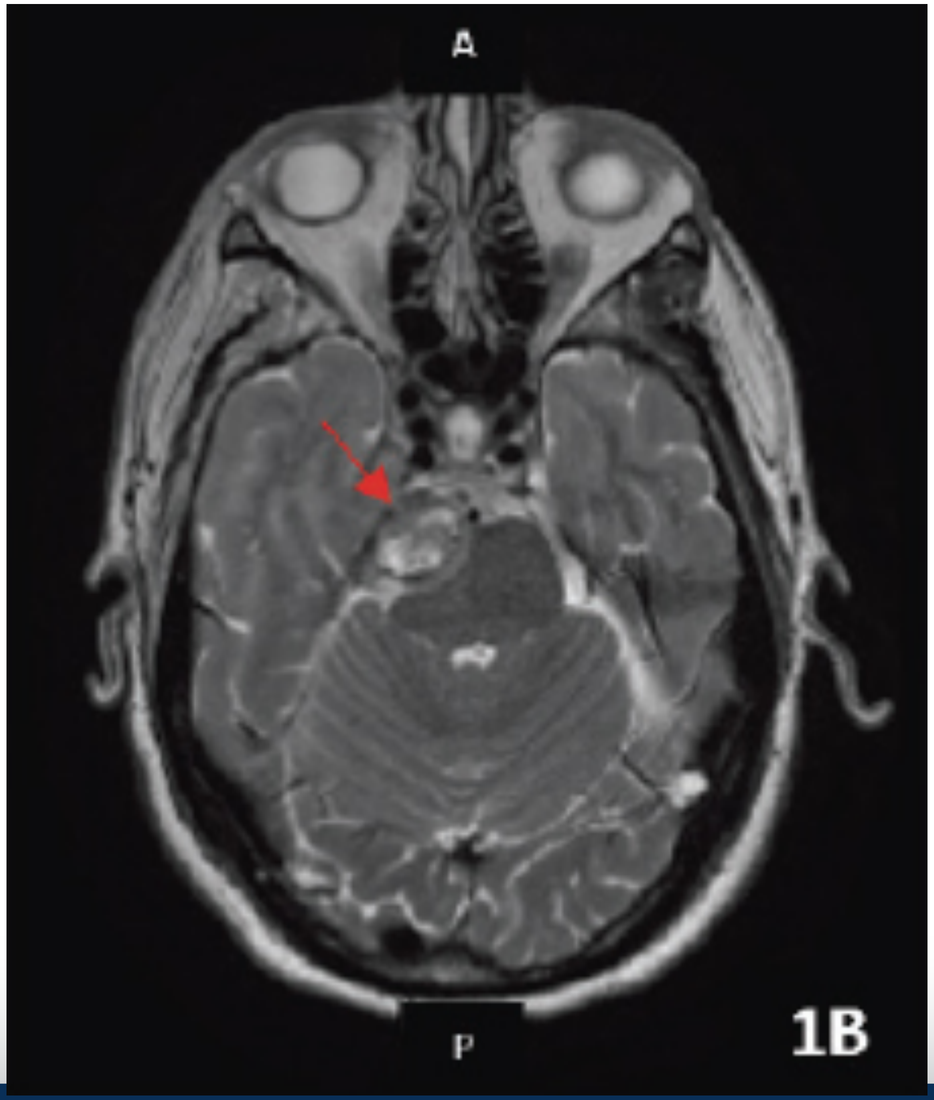
Spin Echo Examples

- T2W imaging generally acquired using SE techniques.
- Useful when implants/metal may cause distortion (e.g., braces, hip).
- Other contrasts available (e.g., IR).

Bourlon, et al. Oncology, 2014

Awh, MRI Web Clinic (radsource.us), February 2011



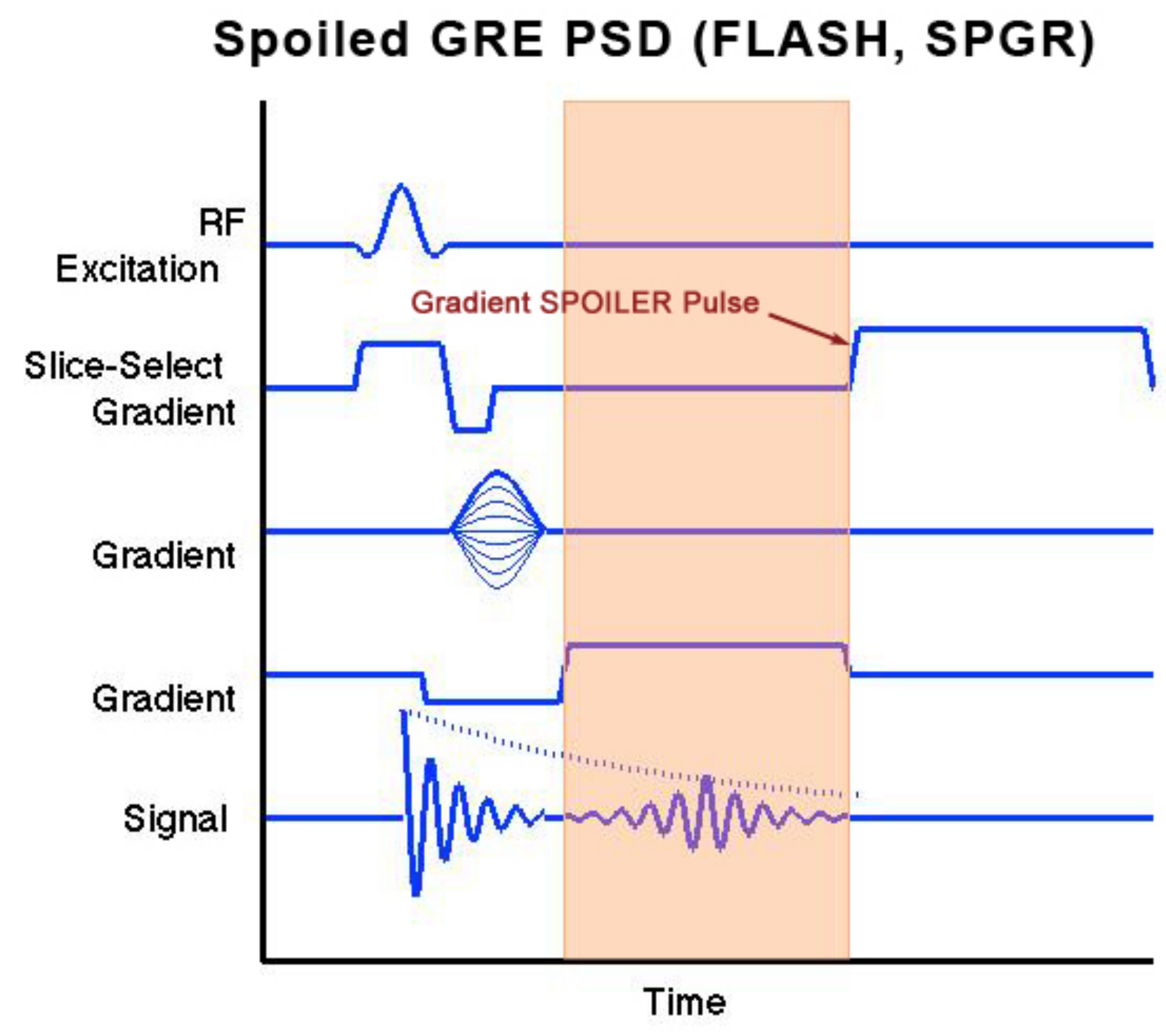


Gradient Echo

Gradient (or "Field") Echo: use gradient/B-field to create the echo

Pro – Very fast, less RF per unit time (small flip angle).

Con – Sensitive to susceptibility (pro or con?)



Pictures from Allison, et al. (MRI: Pulse Sequences RSNA web module)

Gradient Echo

Transverse magnetization often still exists at end of TR period.

Different types of gradient echo sequences, based on what you do at the end:

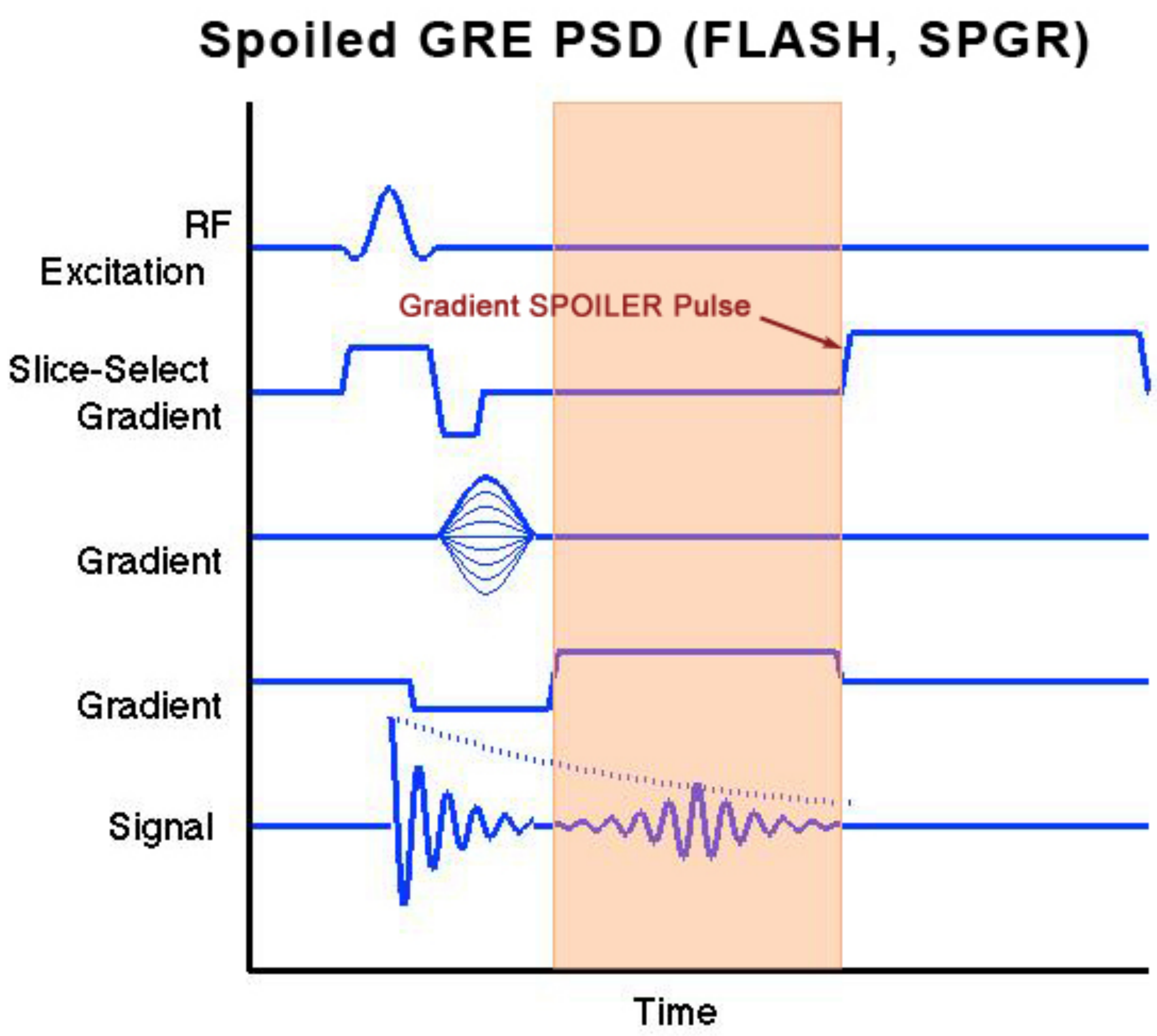
1) Do nothing.
2) Spoil the transverse magnetization (e.g., SPGR).
3) Rewind the transverse magnetization (e.g., SSFP).

Spoiled Gradient Echo Example

Spoiled Gradient Echo – one excitation, read out one line of k-space, then crush the signal and start again.

Sometimes in use.

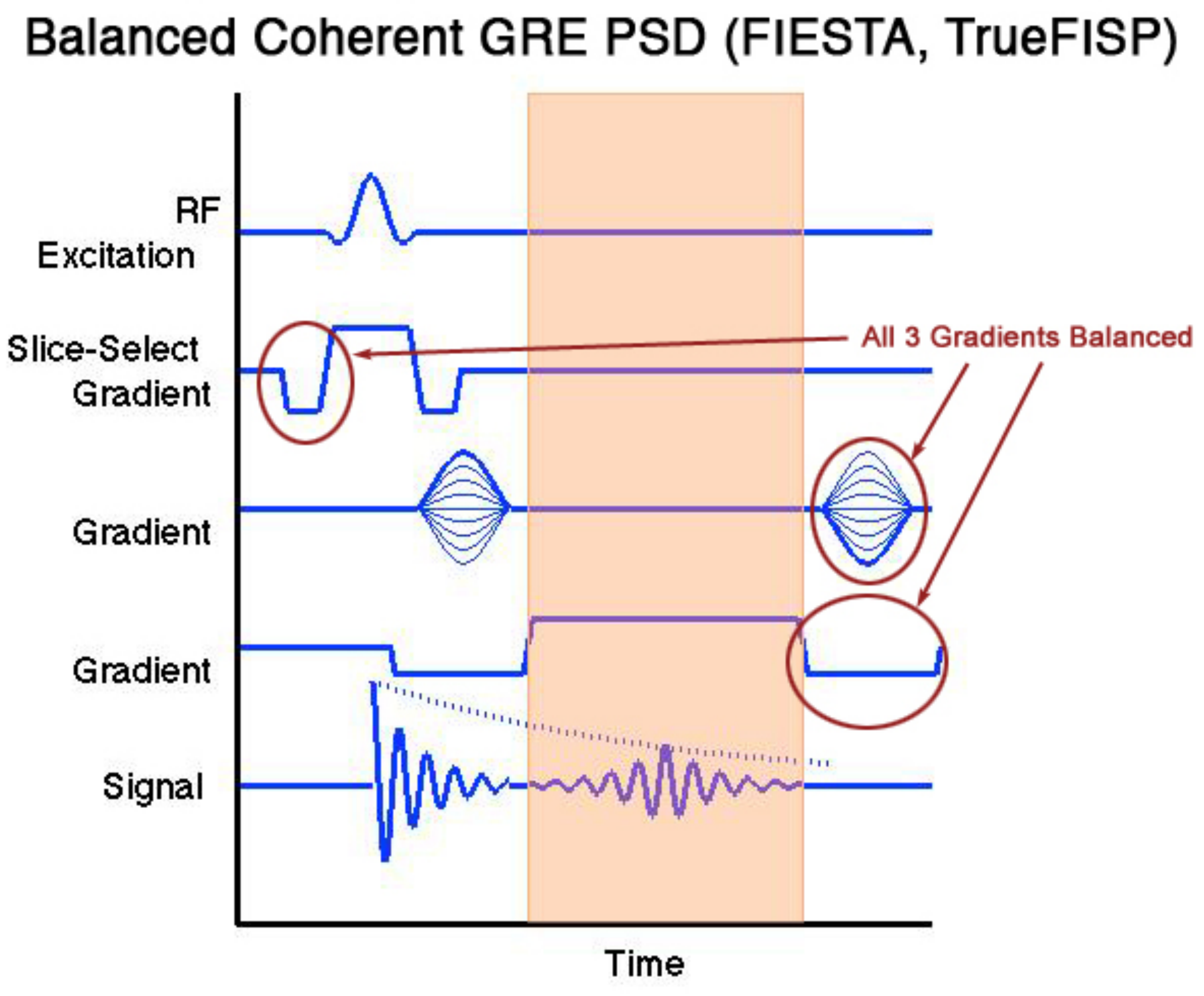
Spoiled gradient echo (SPGR)
T1 Fast Field Echo (T1-FFE)
Fast Low Angle SHot (FLASH)



Pictures from Allison, et al. (MRI: Pulse Sequences RSNA web module)

Coherent Gradient Echo Example

Balanced Coherent Gradient Echo – One excitation, one line readout, rewind by reversing phase-encoding.



Fast Imaging Employing Steady State Acquisition (FIESTA)

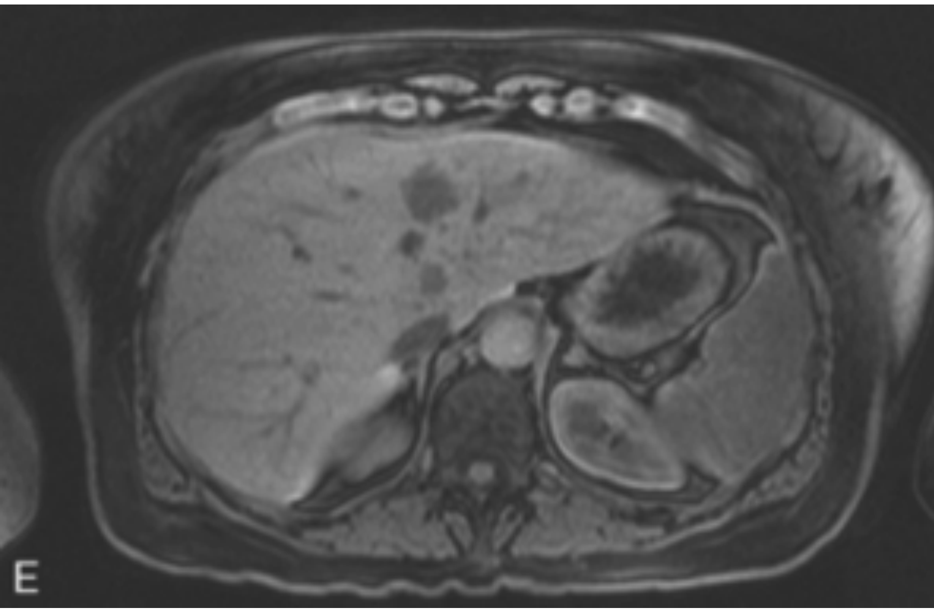
TrueFISP

Balanced Fast-Field Echo (b-FFE)

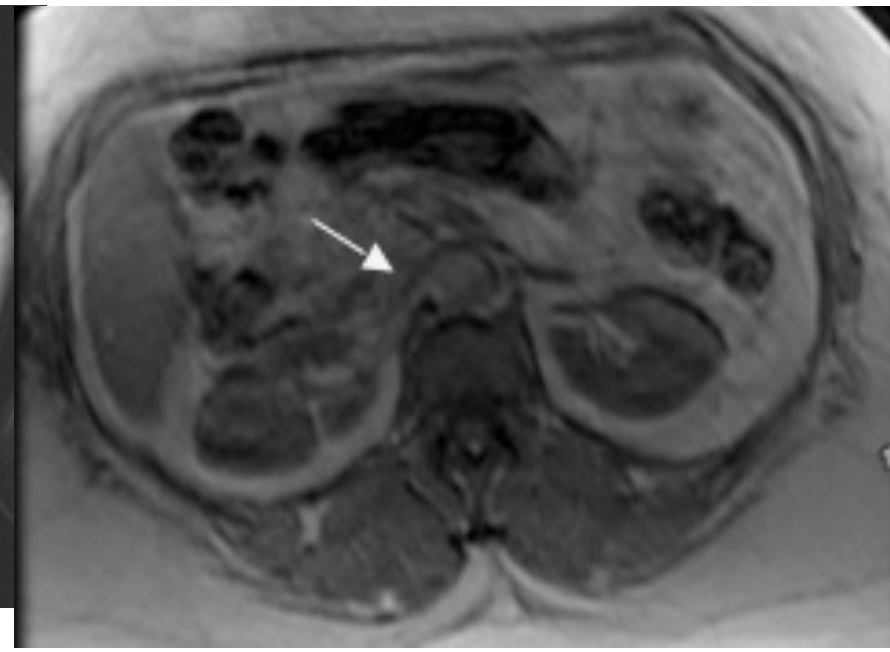
Pictures from Allison, et al. (MRI: Pulse Sequences RSNA web module)

Gradient Echo Examples

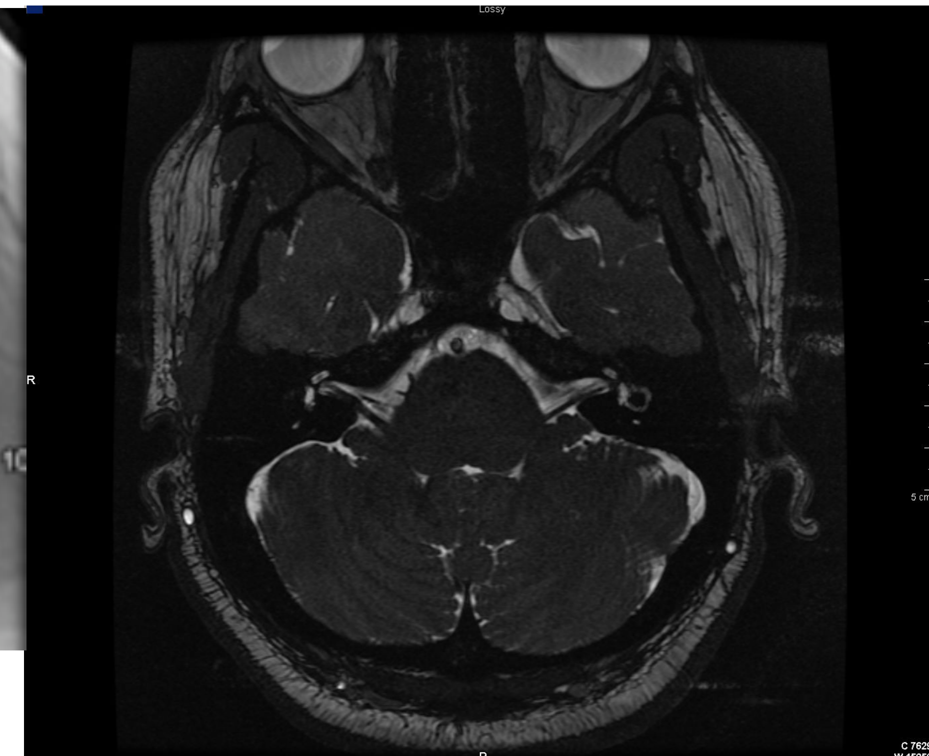
- Many different types of contrast.
- Fast versions of GRE are clinical standard for T1W.

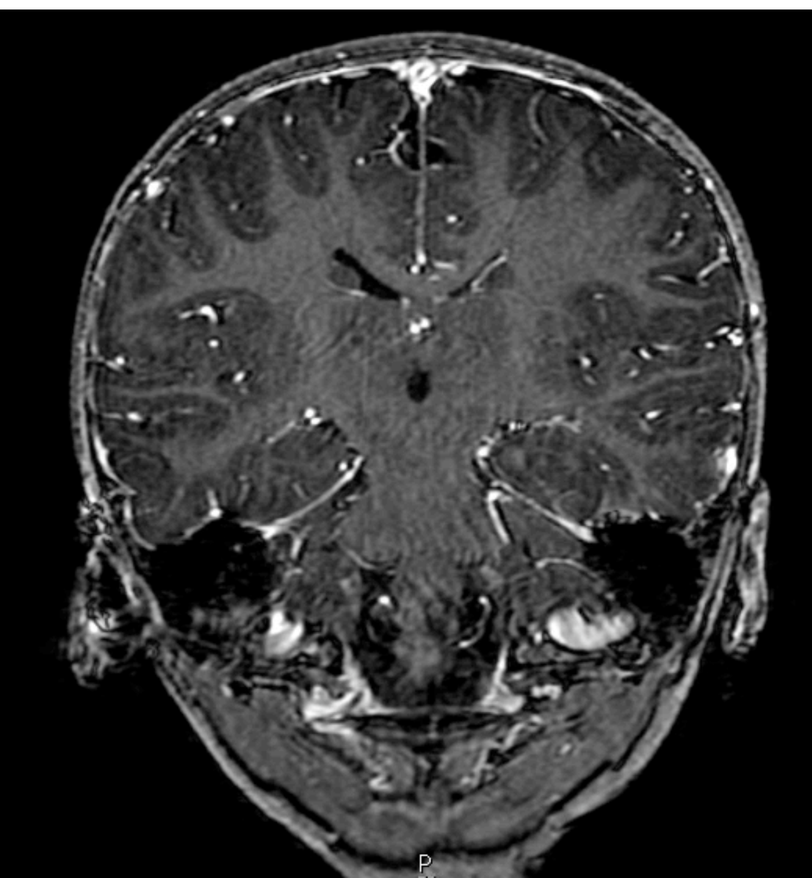


https://clinicalgate.com/liver-metastases-3/



Pictures from Allison, et al. (MRI: Pulse Sequences RSNA web module)





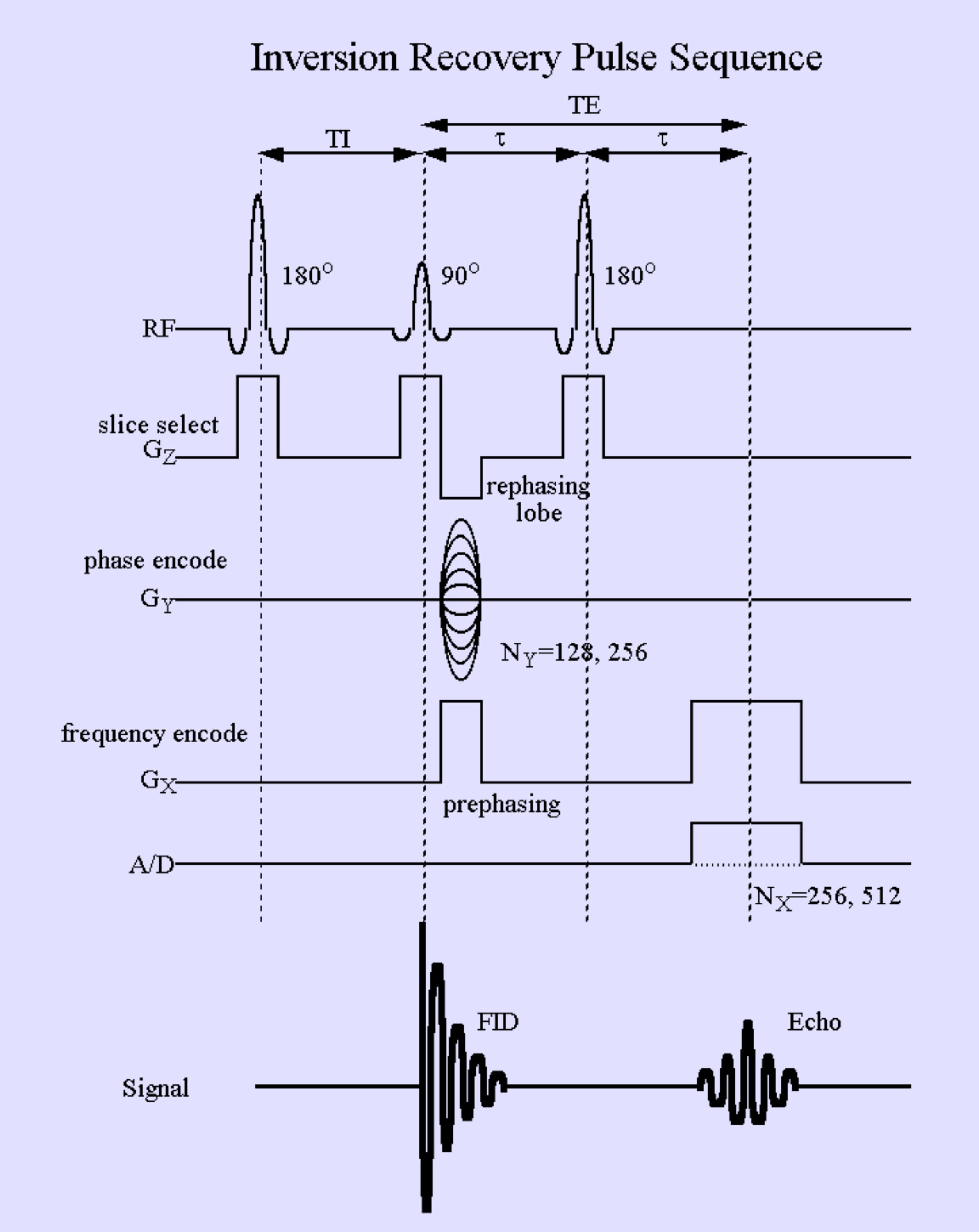
Inversion Recovery

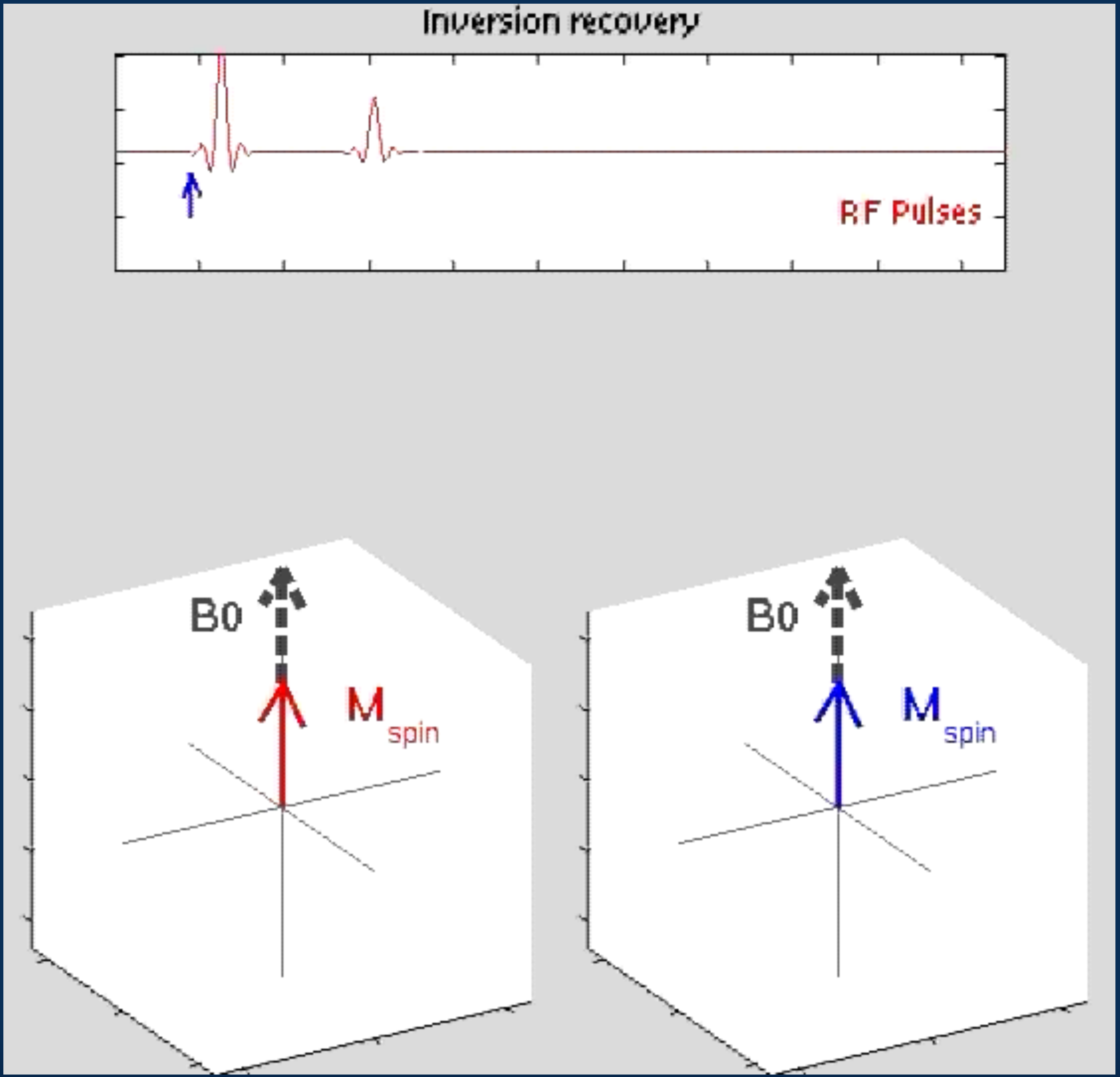
Add a 180° pulse at the beginning of a sequence.

Fire off pulse, then wait for a given amount of time (TI)…

Different tissues relax at different rates (R1 = 1/T1).

How to recognize IR pulse sequence in diagram? Initial 180° RF pulse, then a waiting period.




Inversion recovery
RF Pulses
B0
M spin
B0
M spin

Inversion Recovery Uses

T2 FLAIR – use IR + T2W SE to null CSF.

Wattjes, et al. AJNR, 2007

STIR – use IR to null fat. Lower SNR, but better near susceptibility artifacts.

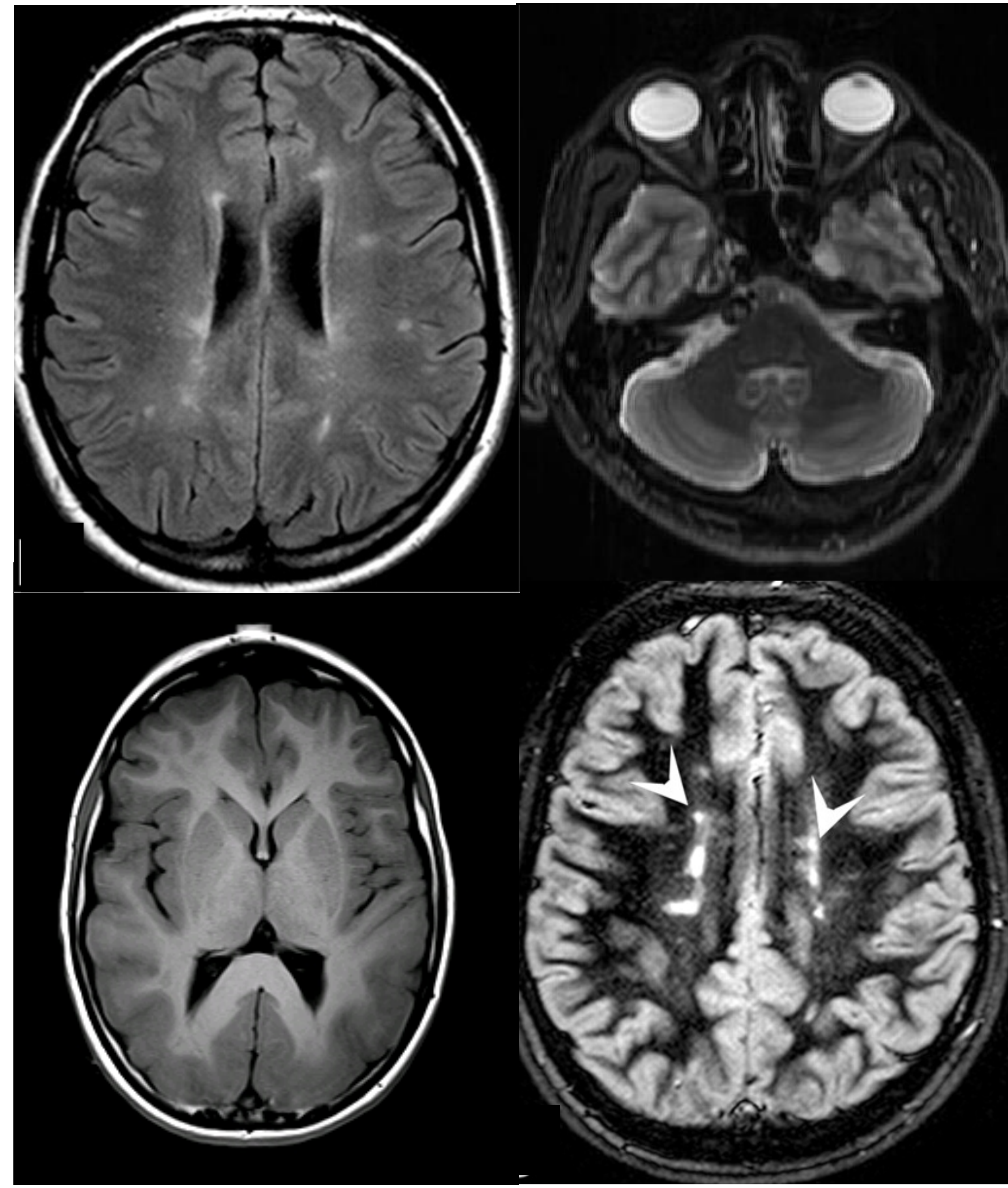
http://www.neuroradiologycases.com/2011/08/blog-post_9213.html

T1 FLAIR – use IR to generate T1 contrast with an SE.

http://mri-q.com/t1-flair.html

Dual IR – for black-blood sequence, or MS (CSF, White Matter suppresion).

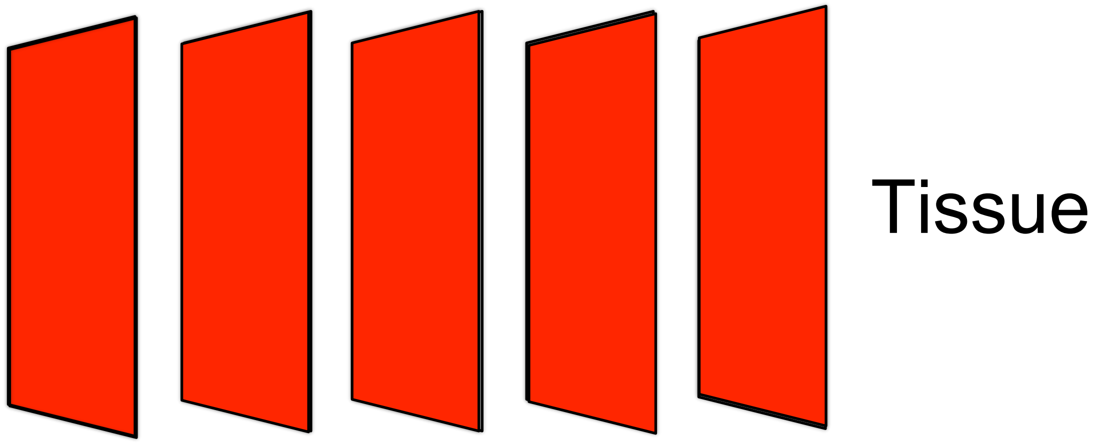
Wattjes, et al.AJNR, 2007

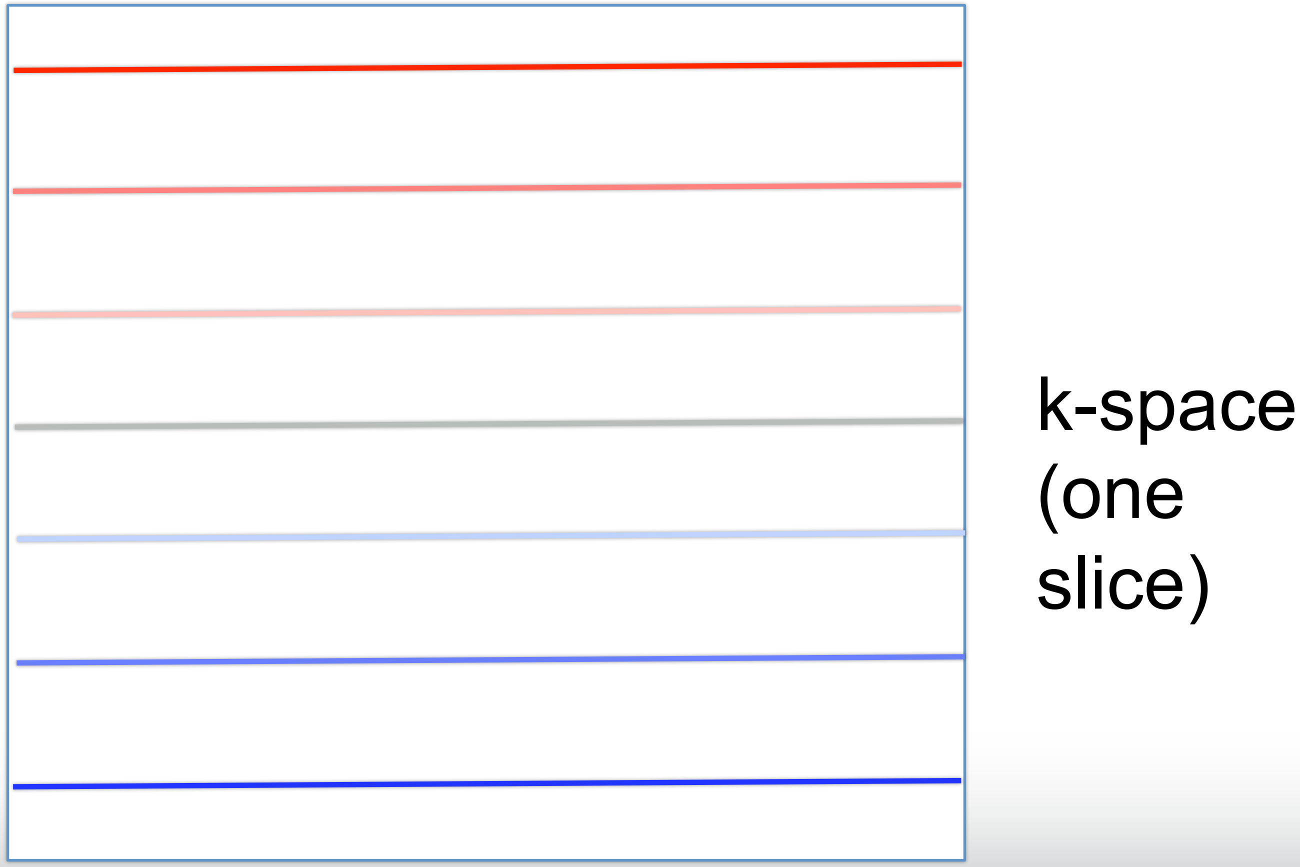


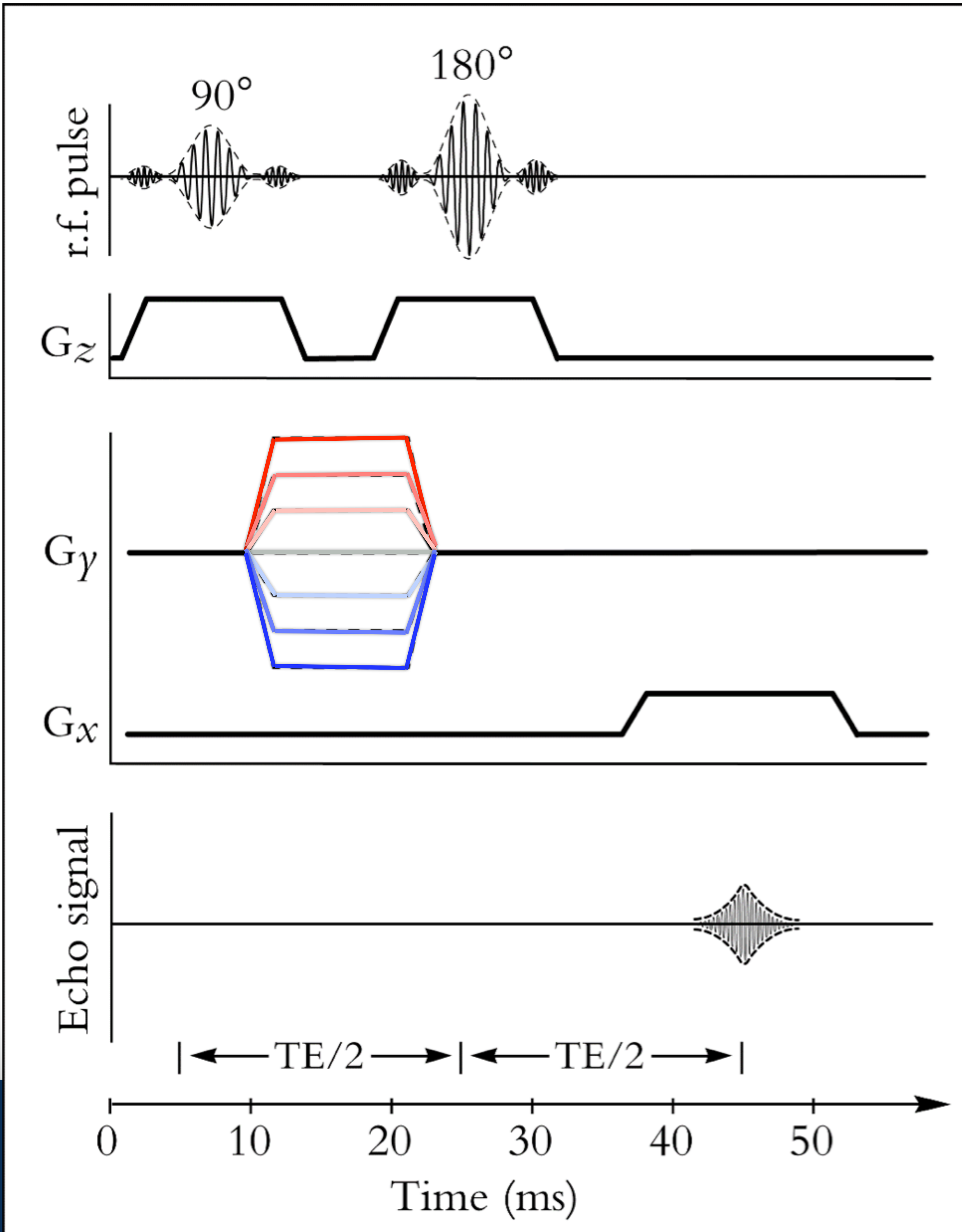
Sequence Classifications According to Readout

2D vs. 3D

2D: excitation of thin slices (sequential), readout of data into multiple, 2D k-spaces.

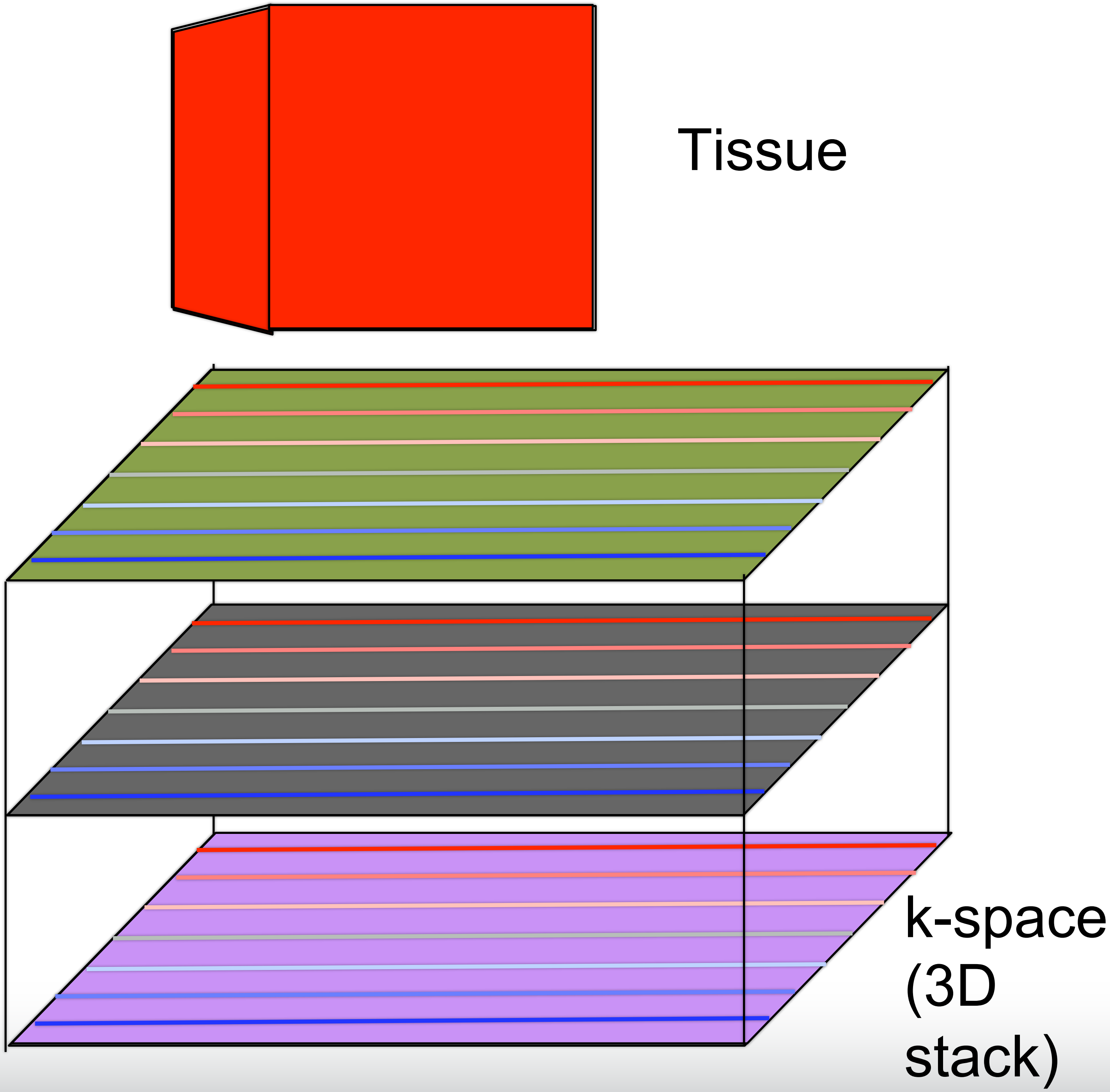


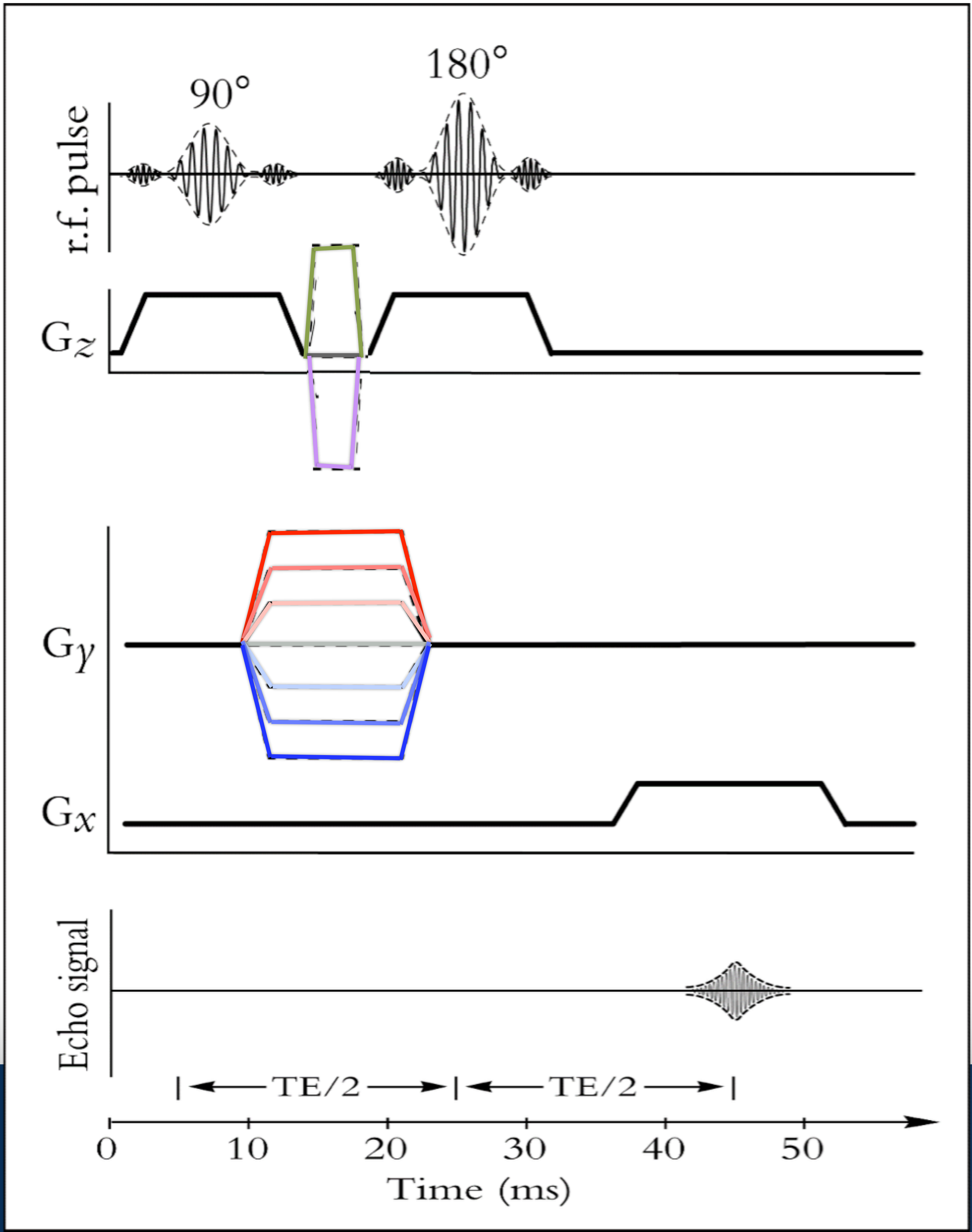




2D vs. 3D

3D: excitation of thick slab, readout of data into one 3D k-space.



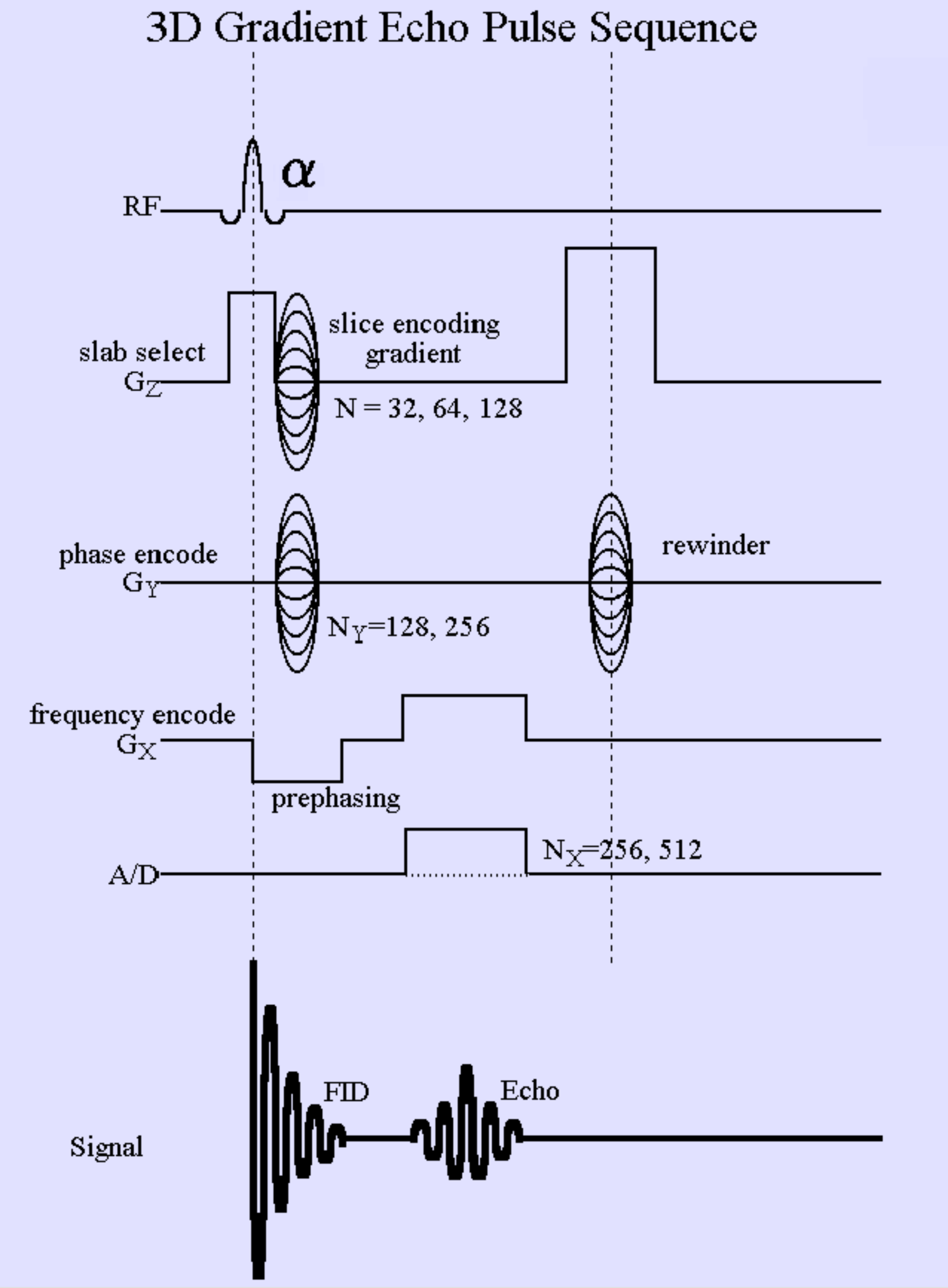


2D vs. 3D

2D: excitation of thin slices (sequential), readout of data into multiple, 2D k-spaces.

3D: excitation of thick slab, readout of data into one 3D k-space.

Pros: isotropic voxels (3D), higher SNR per volume (3D), faster (2D).



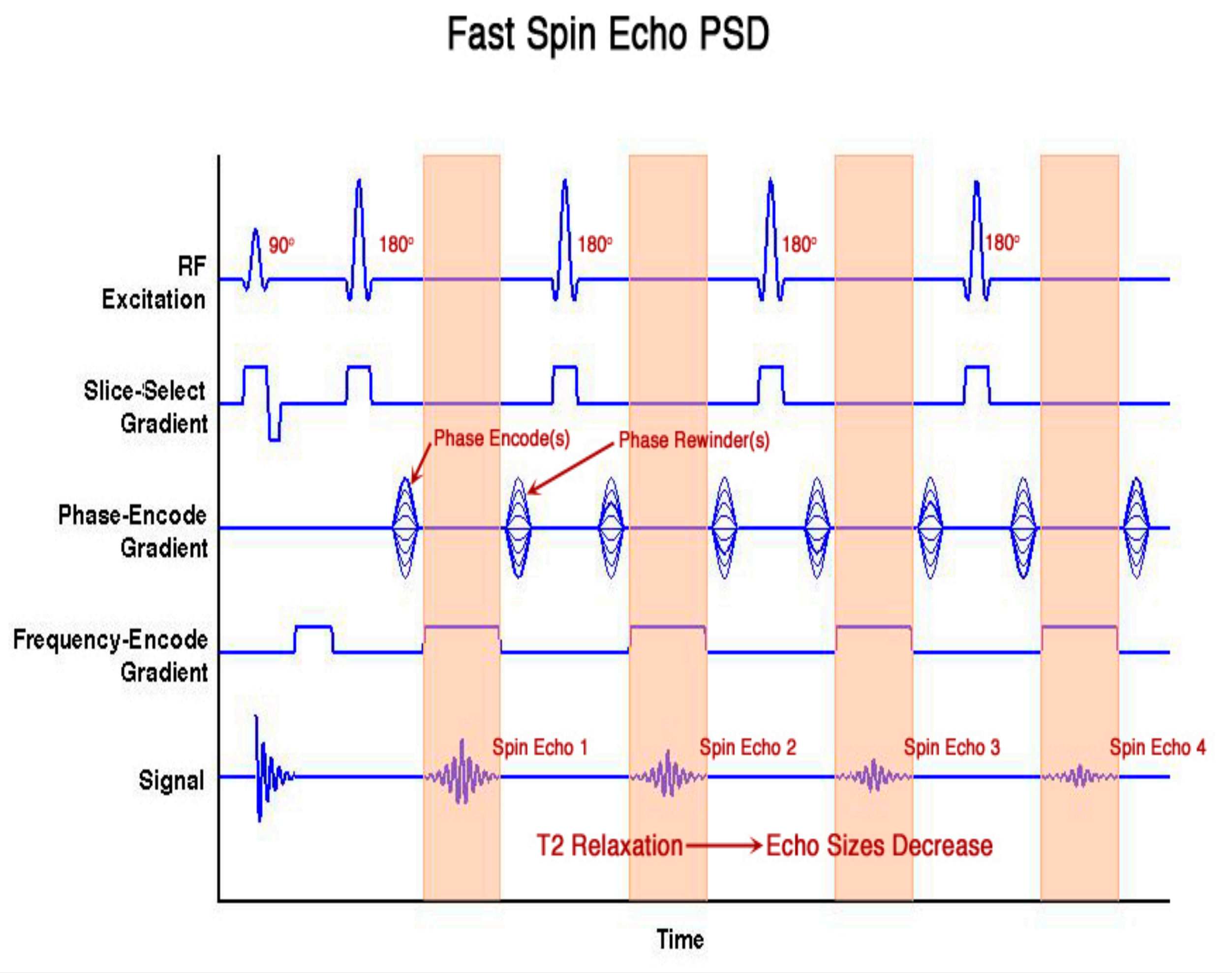
"Fast" Techniques – Echo Train Readout

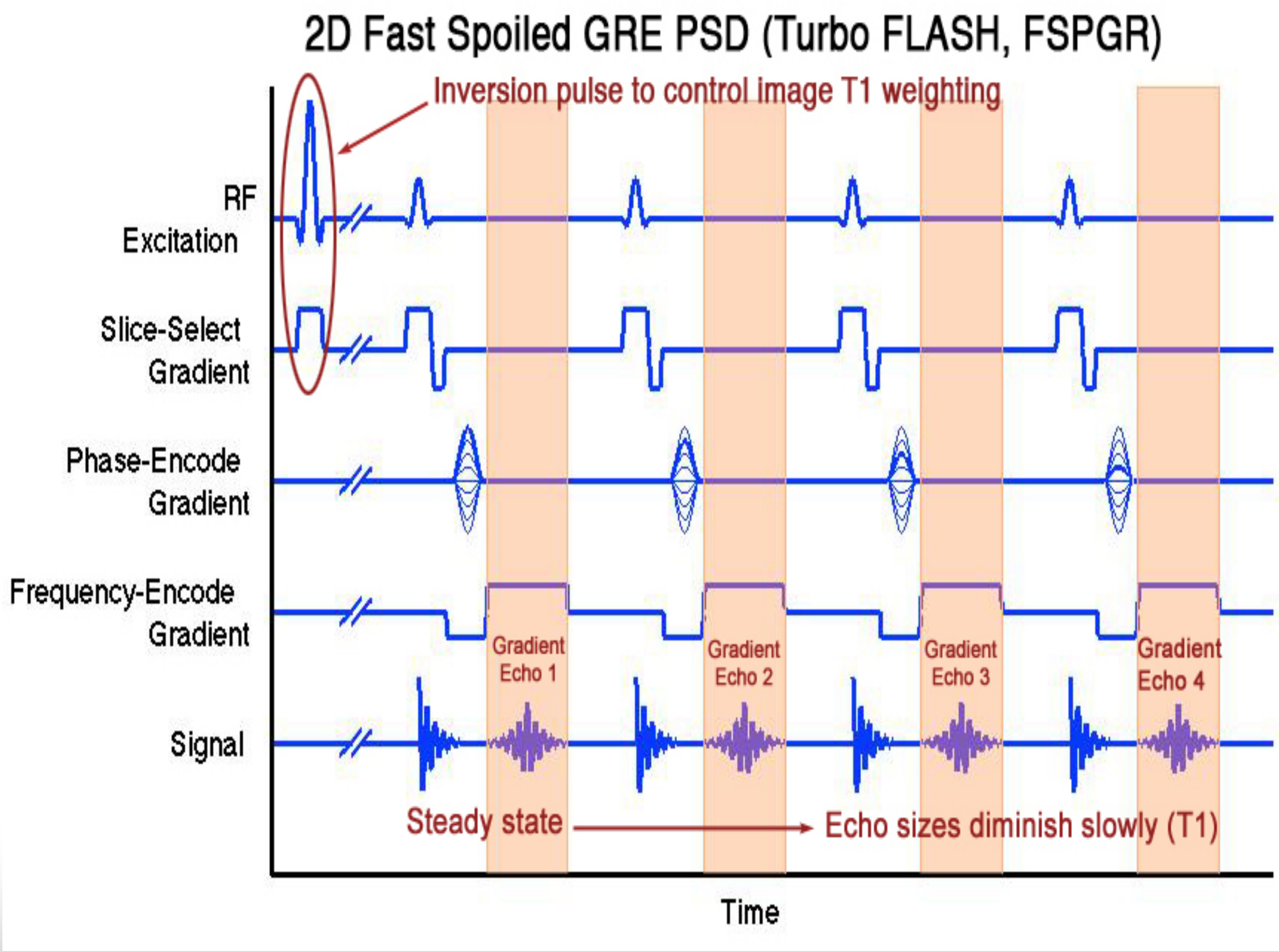
Readout multiple echoes with each excitation or preparation – "echo train".

Pictures from Allison, et al. (MRI: Pulse Sequences RSNA web module)

Might even be one-shot (e.g., SSFSE)

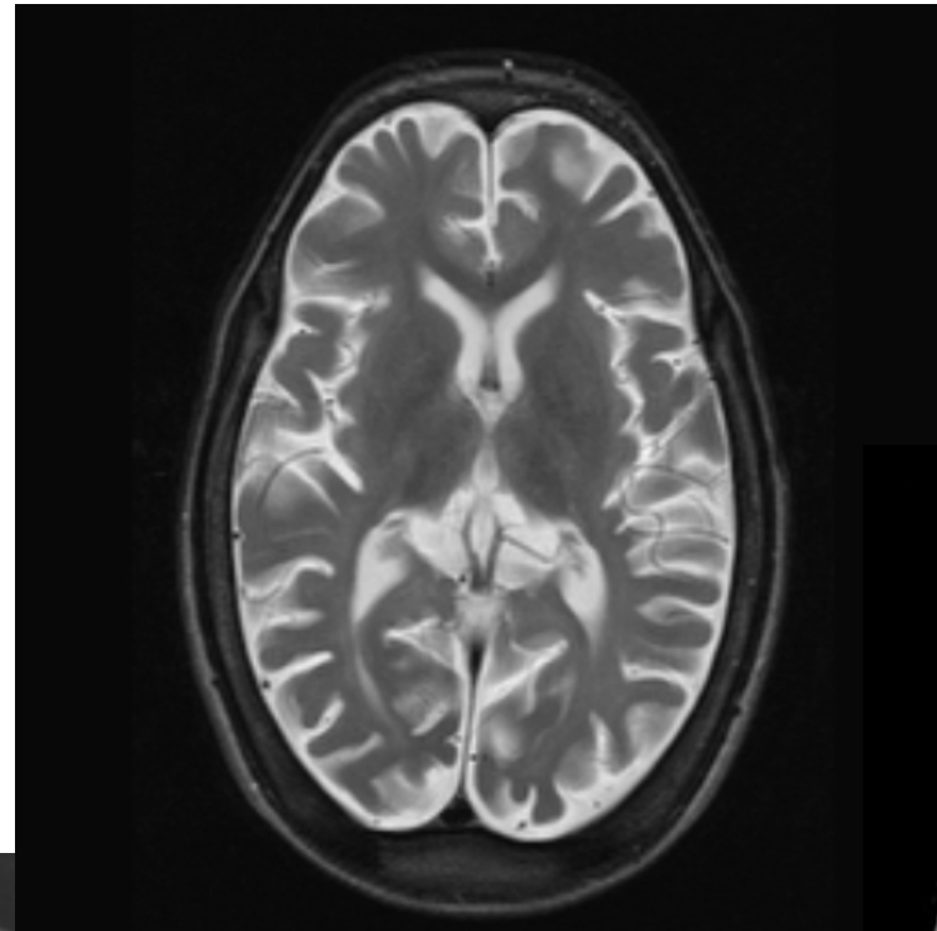
Examples:



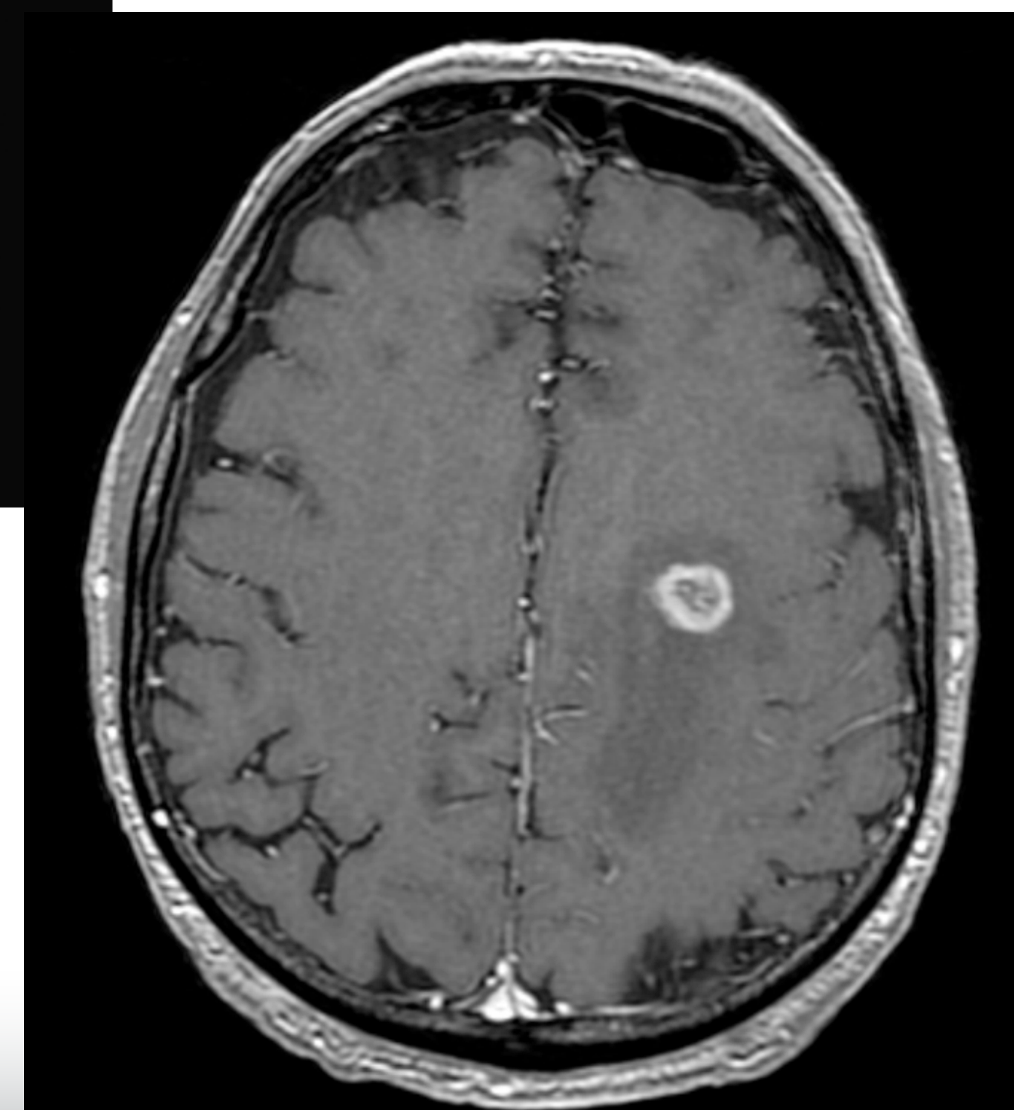


"Fast" Techniques – Examples

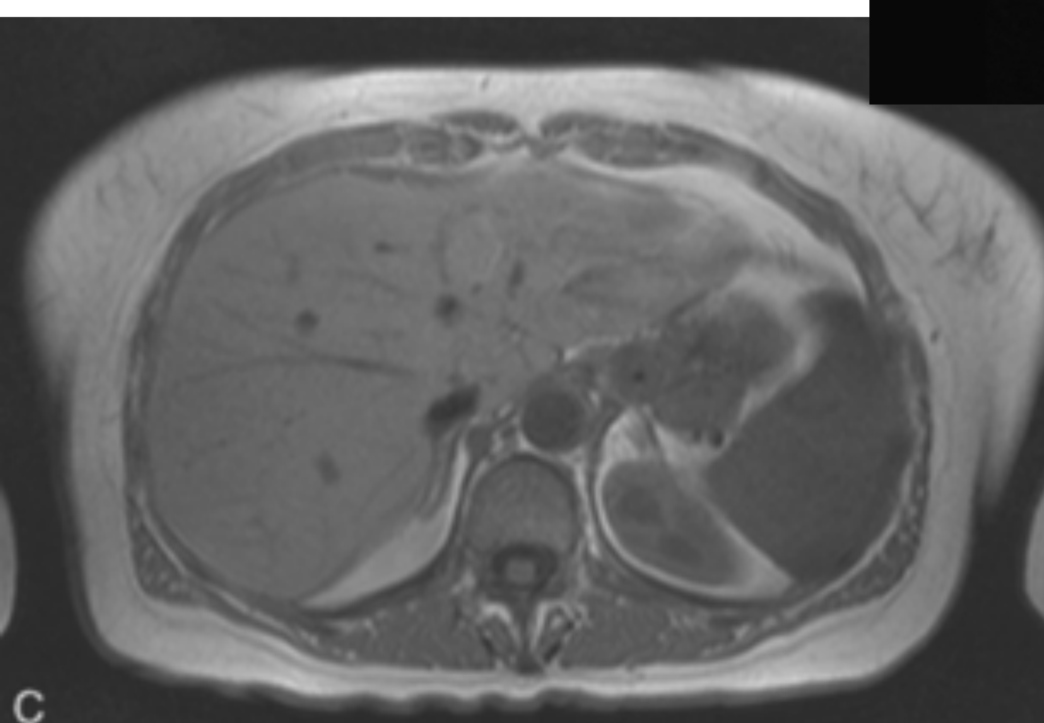
Fast Spin Echo



FSPGR/MPRAGE/TFE



HASTE (SSFSE with Partial Fourier)



https://clinicalgate.com/liver-metastases-3/

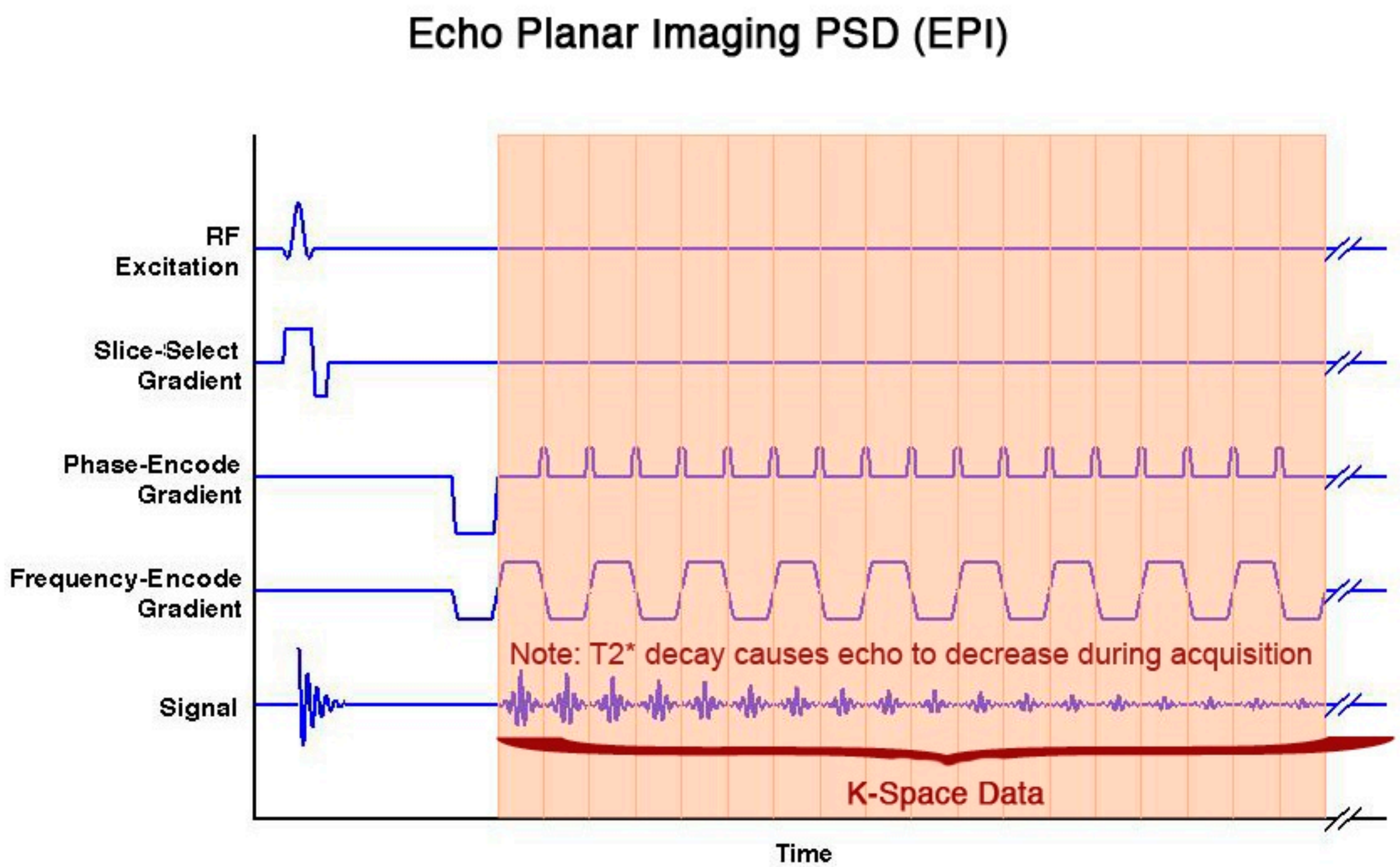
Echo-Planar Imaging

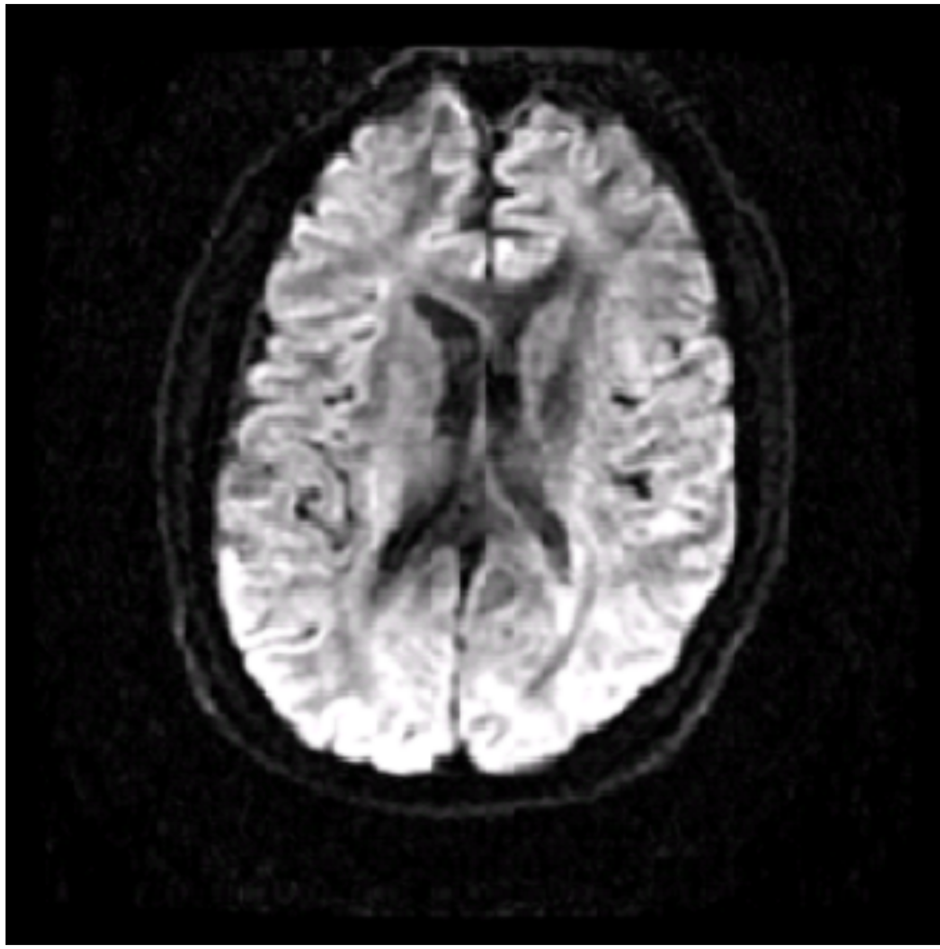
First described by Mansfield in 1977.

One or more excitations → one image, rapidly acquired.

SE or GRE possible

Common uses: DWI, fMRI





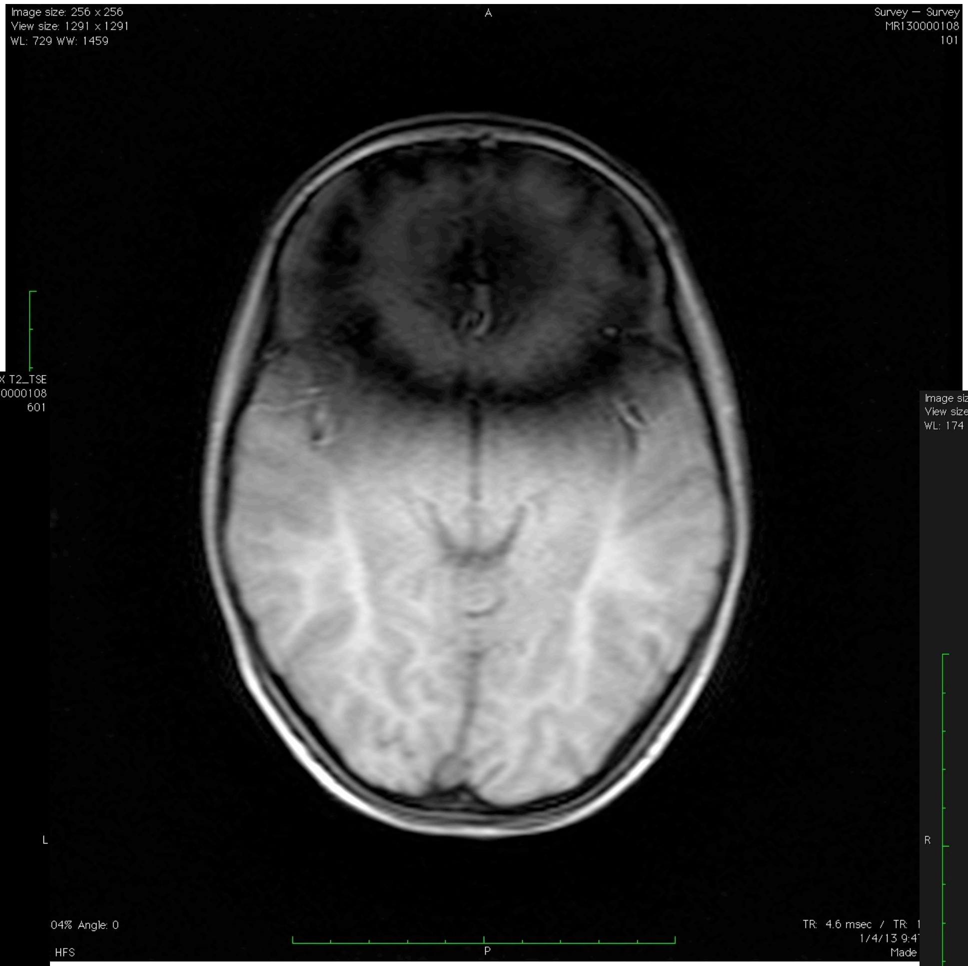
Pictures from Allison, et al. (MRI: Pulse Sequences RSNA web module)

Echo-Planar Imaging

Extremely fast.

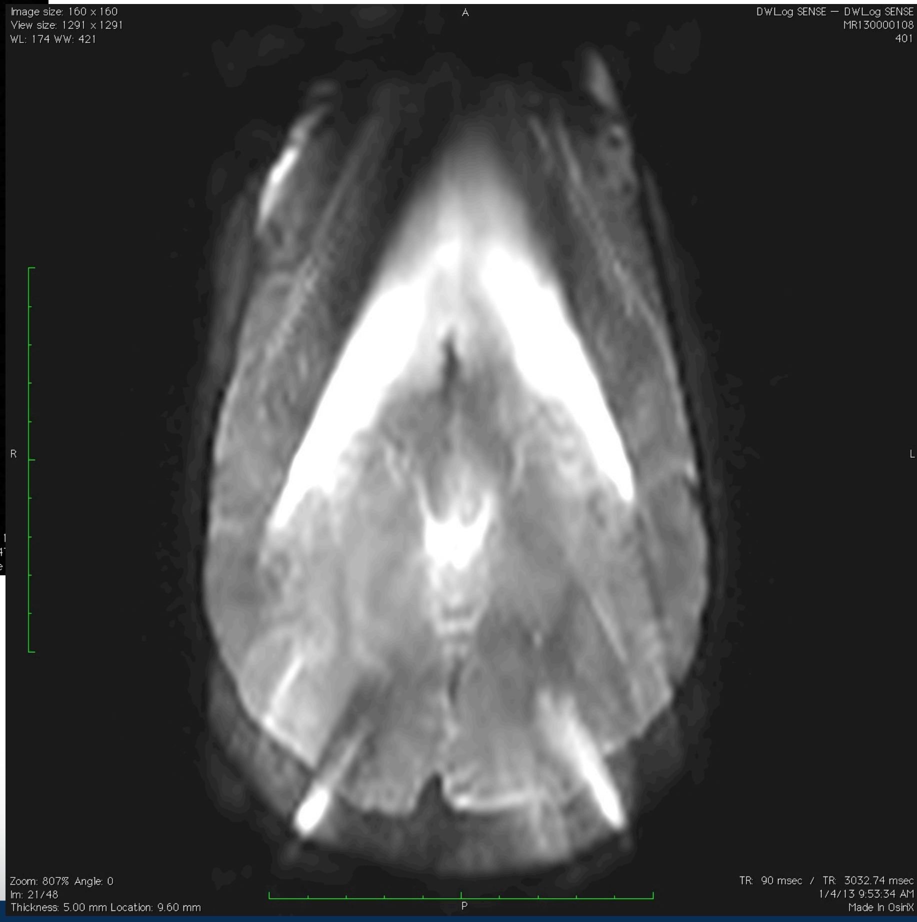
Very susceptible to off-resonance effects.

FSE



GRE

EPI



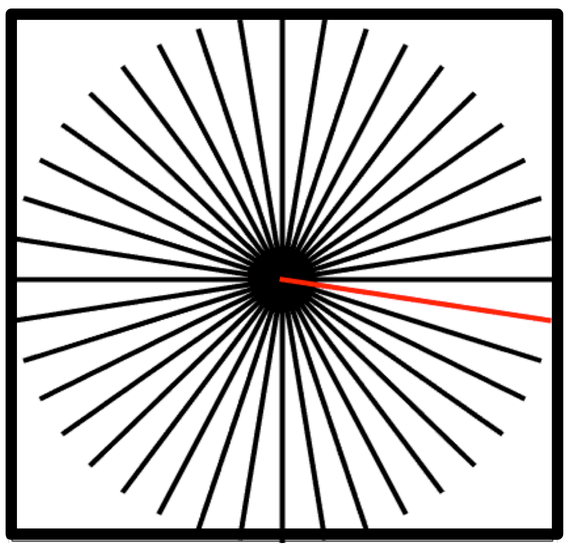
Non-Cartesian Readout

Cover at least ½ of k-space “by hook or by crook”.

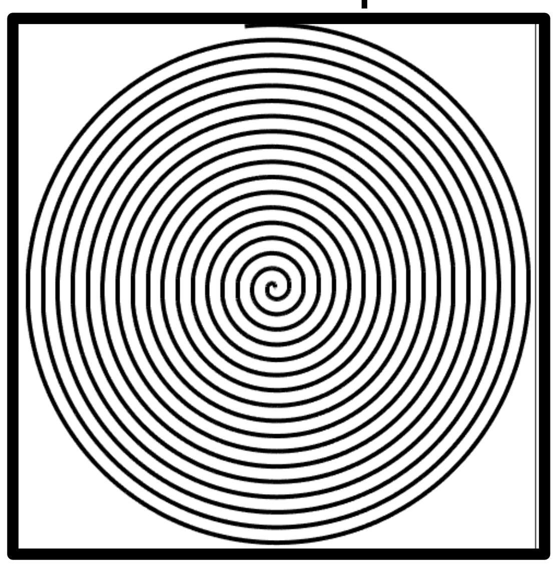
Different advantages/disadvantages.

E.g., Radial (motion resistant, short TE), Spiral (fast readout)

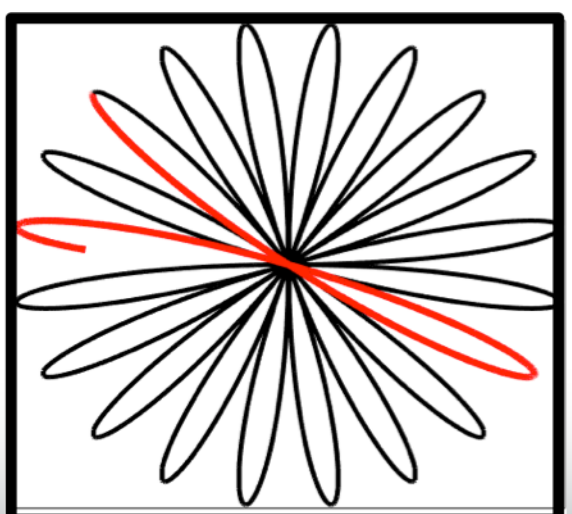
Radial



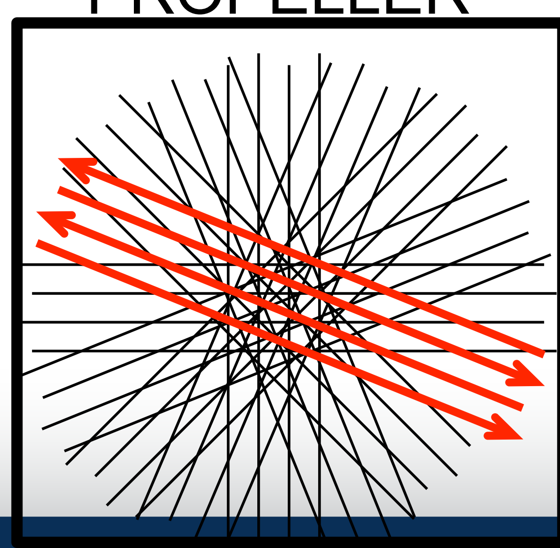
1-shot Spiral



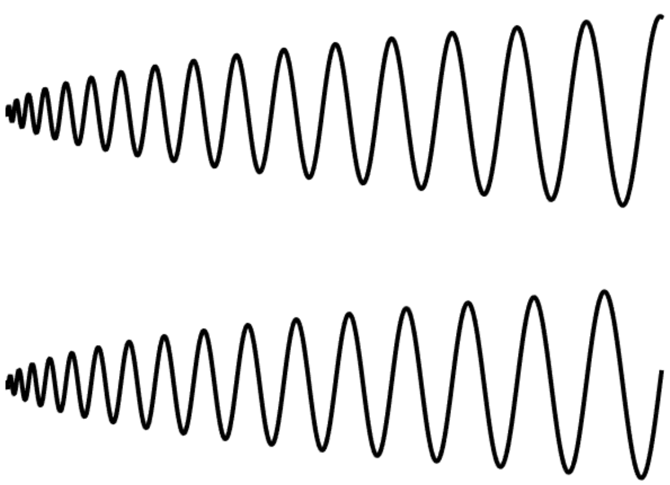
Rosetta



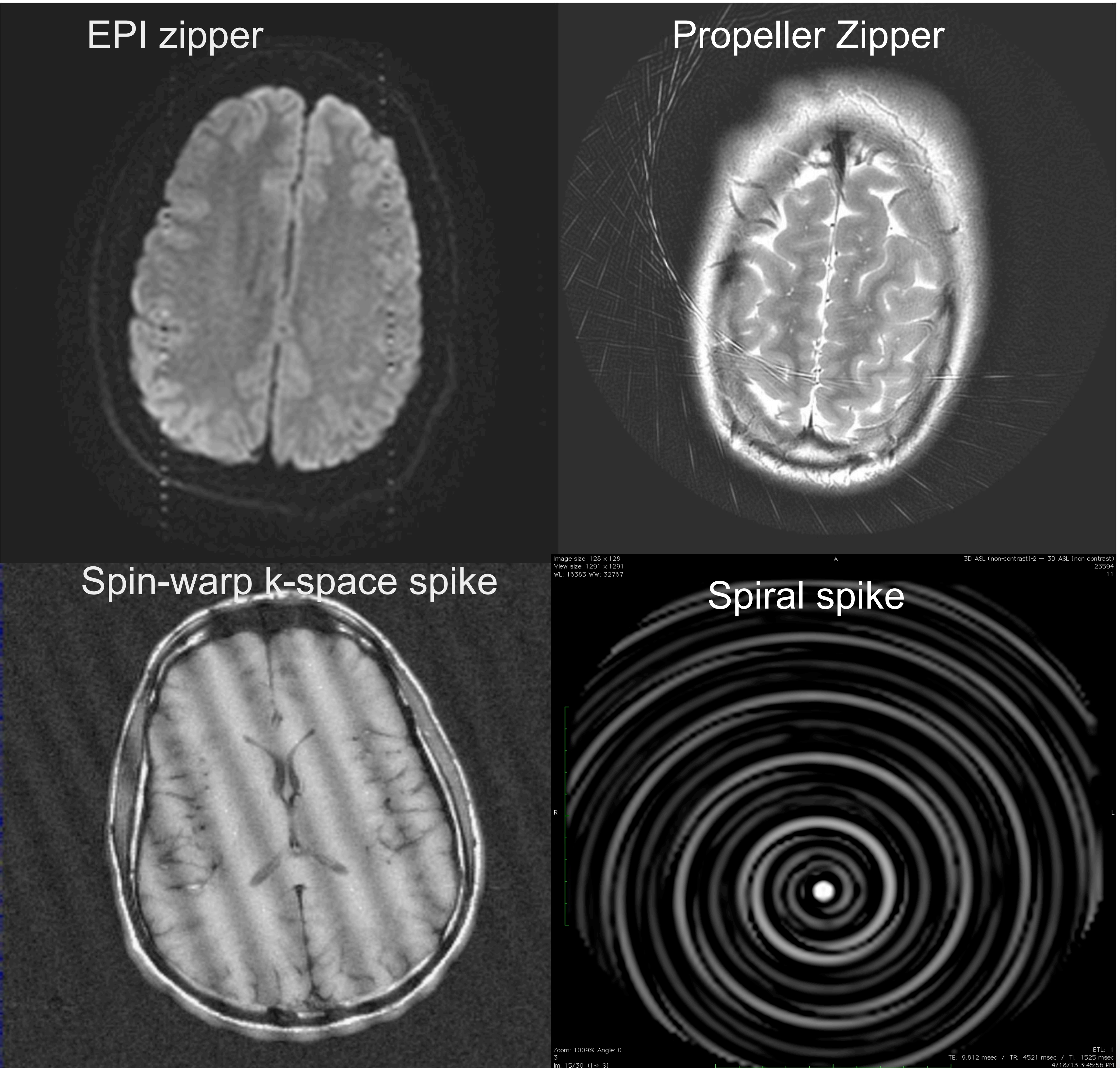
PROPELLER



Spiral gradients



Non-Cartesian Readout Artifacts



- phase-/frequency-encoding doesn’t occur in rows/columns of k-space
- Direction of readout = frequency encoding
- Artifacts occuring along particular directions change in appearance.

Pictures from Yanasak, et al. (MRI: Artifacts RSNA web module)

Fast Imaging via Partial k-space Sampling

Scan time for 2D imaging:

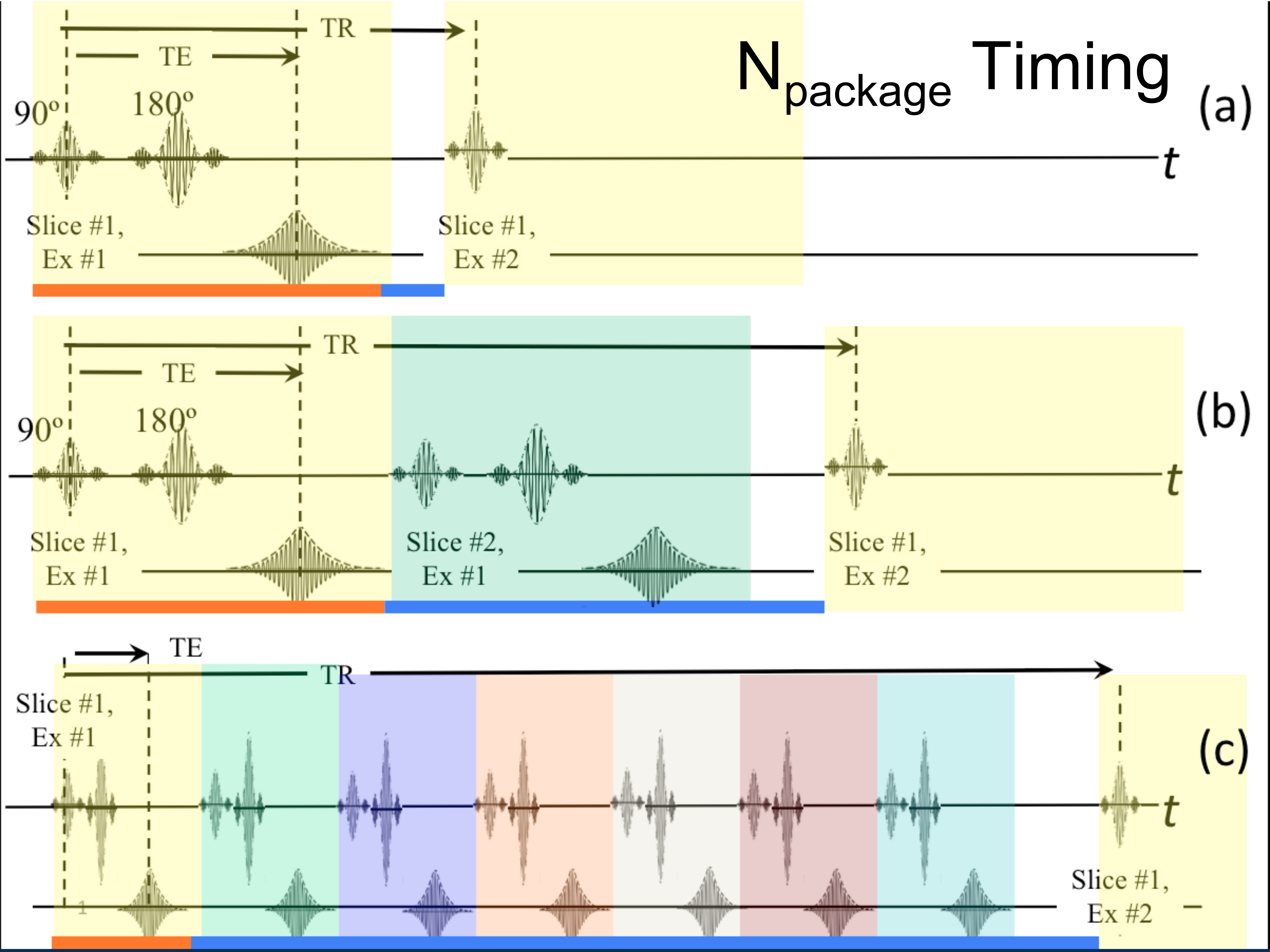
$$T_{Scan} = N_{\phi} \times TR \times N_{package} \times NEX$$

N_{ϕ} = number of phase encodings
TR = repetition time
$N_{package}$ = # of packages (image slices, TE, TR)
NEX (or, No. Acq.) = number of excitations (1, 2, n).

Speed: ultimately must ***reduce the amount of data sampled in k-space.***

Multiple techniques to do this.

Many techniques can be combined, and with other sequences.



N package Timing
(a)
TR
TE
90°
180°
t
Slice #1, Ex #1
Slice #1, Ex #2
(b)
TR
TE
90°
180°
t
Slice #1, Ex #1
Slice #2, Ex #1
Slice #1, Ex #2
(c)
TE
TR
t
Slice #1, Ex #1
Slice #1, Ex #2

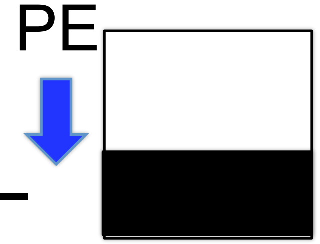
Partial Fourier

Only approximately 50% of k-space needed to construct an image.

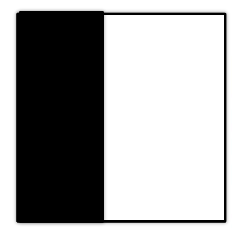
k-space

Two forms:

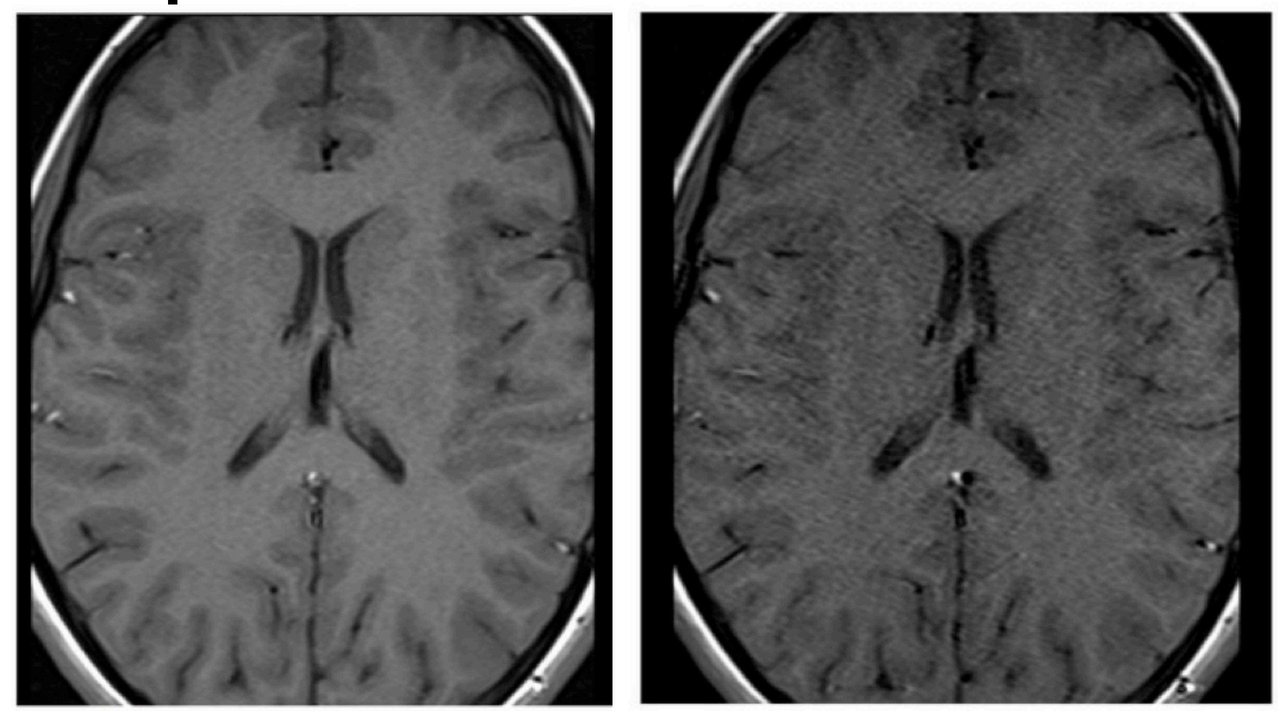
PE



Less Phase-encoding – save time.



Asymmetric echo/partial readout – reduce TE.



Full Fourier	Partial Fourier
FOV 150	FOV 150
matrix 256x256	matrix 256x256
High SNR	Low SNR

https://mrimaster.com/technique%20SNR.html

Usually around 60% is scanned - central region is fully scanned to avoid detrimental errors in contrast information.

View Sharing

Methods for improving temporal resolution (i.e., "faster scanning") in 4D scanning:

Scan portions of k-space at each time point

→ like partial fourier, but more dramatic.

Shift the portion location over time.

Use data from groups of frames to fill in missing portions.

Useful for watching image contrast evolve.

→ Scan center of k-space more often.

Types of View Sharing

http://mri-q.com/tricks-or-twist.html

Keyhole imaging:

Scan all of k-space once.

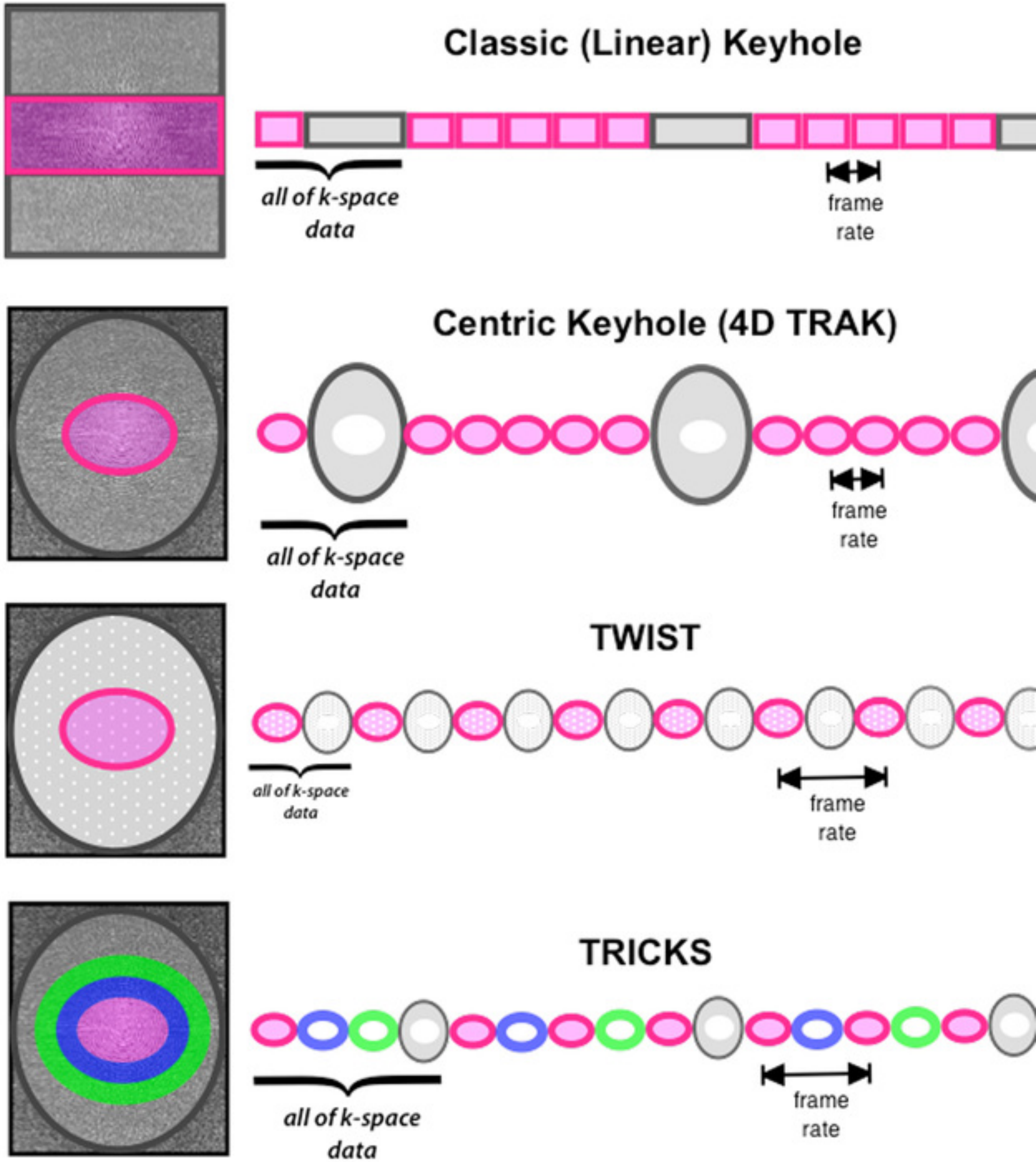
Rescan the middle few rows → contrast.

TRICKS (GE):

Scan regions in k-space, with more scanning in the center.

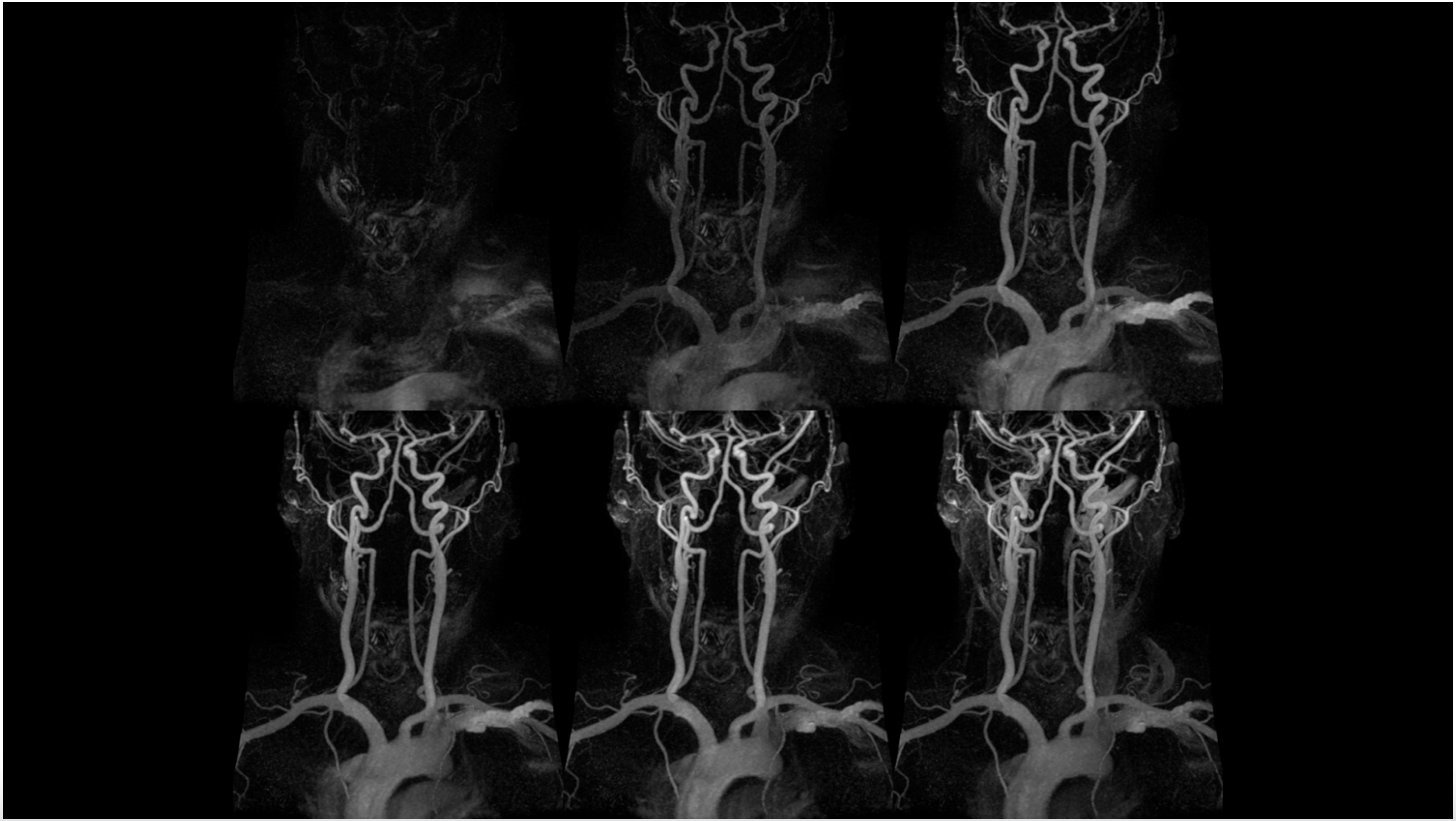
TWIST (Siemens)

4D TRAK (Philips)



Types of View Sharing

TRICKS example

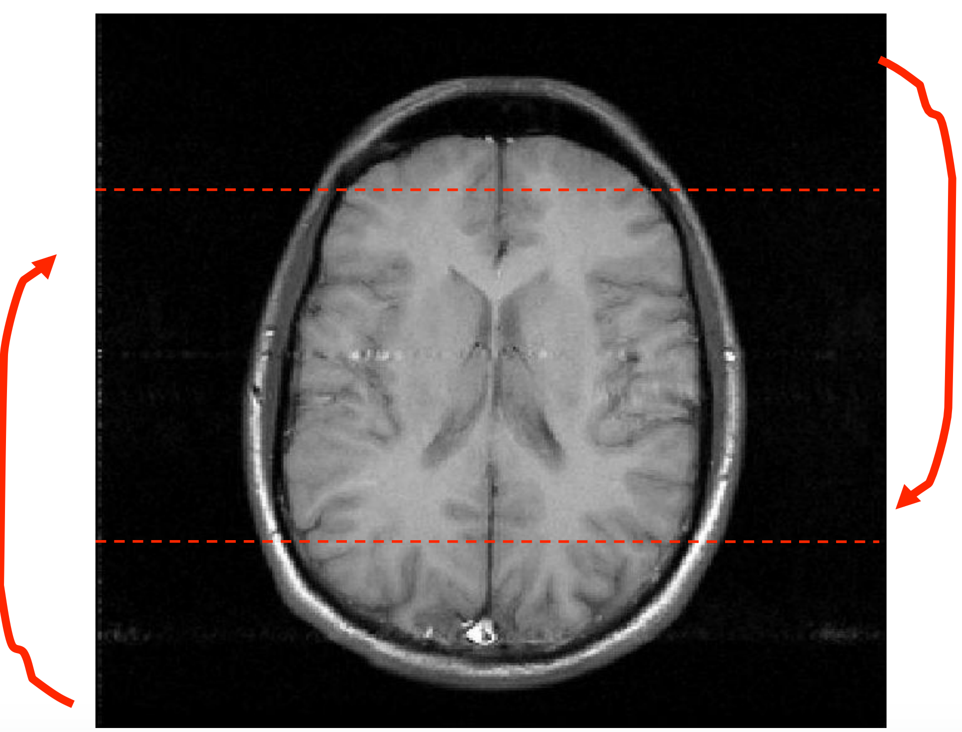


pMRI

Portion of spatial encoding information is replaced by data from multiple receiver coil elements

→ less phase encoding.

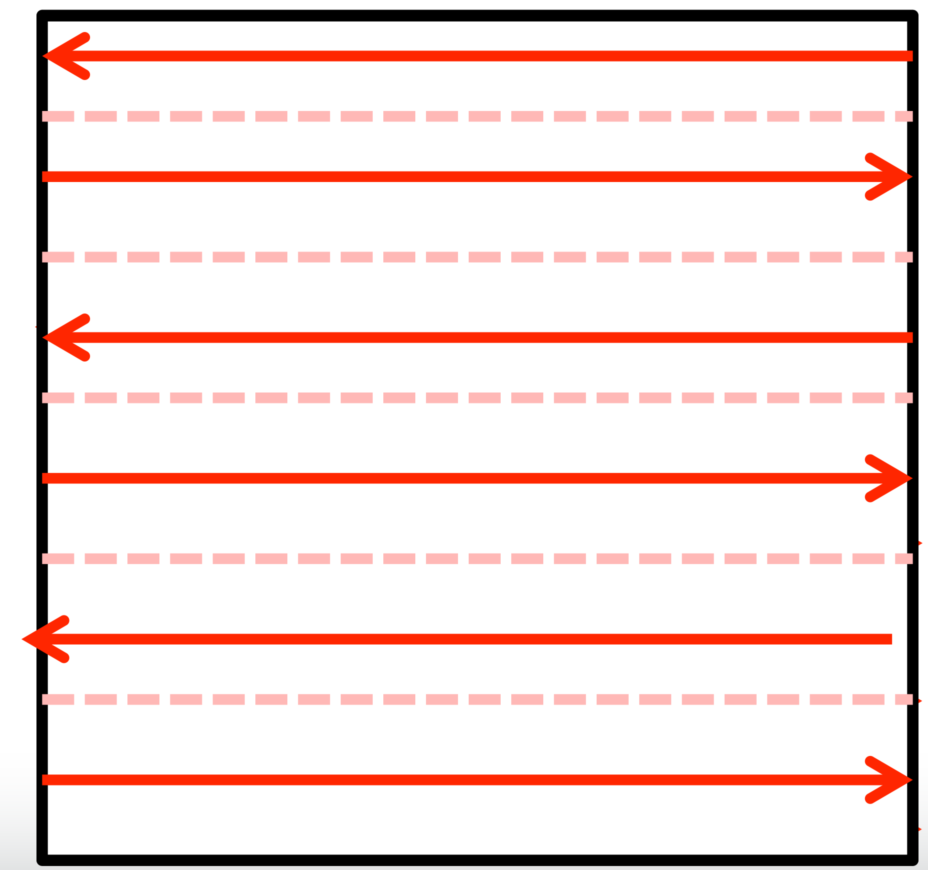
Undersampling for each element, but oversampling for whole system.

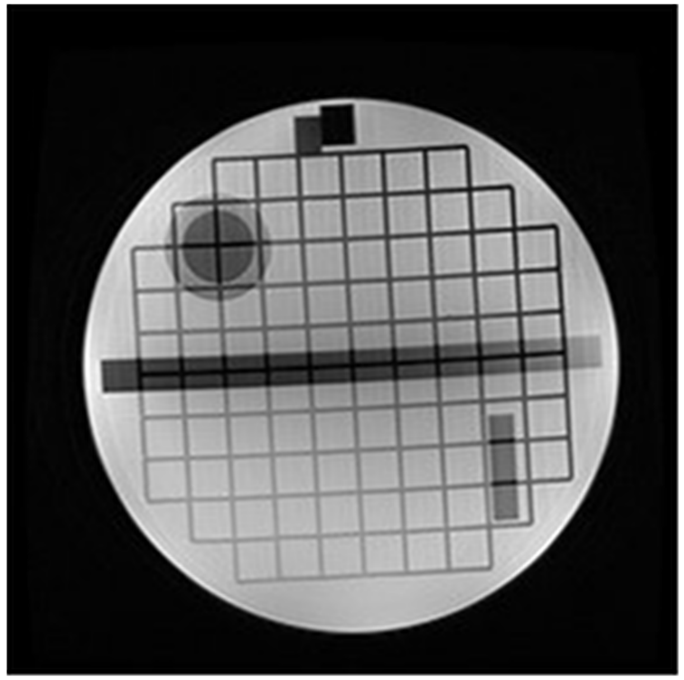


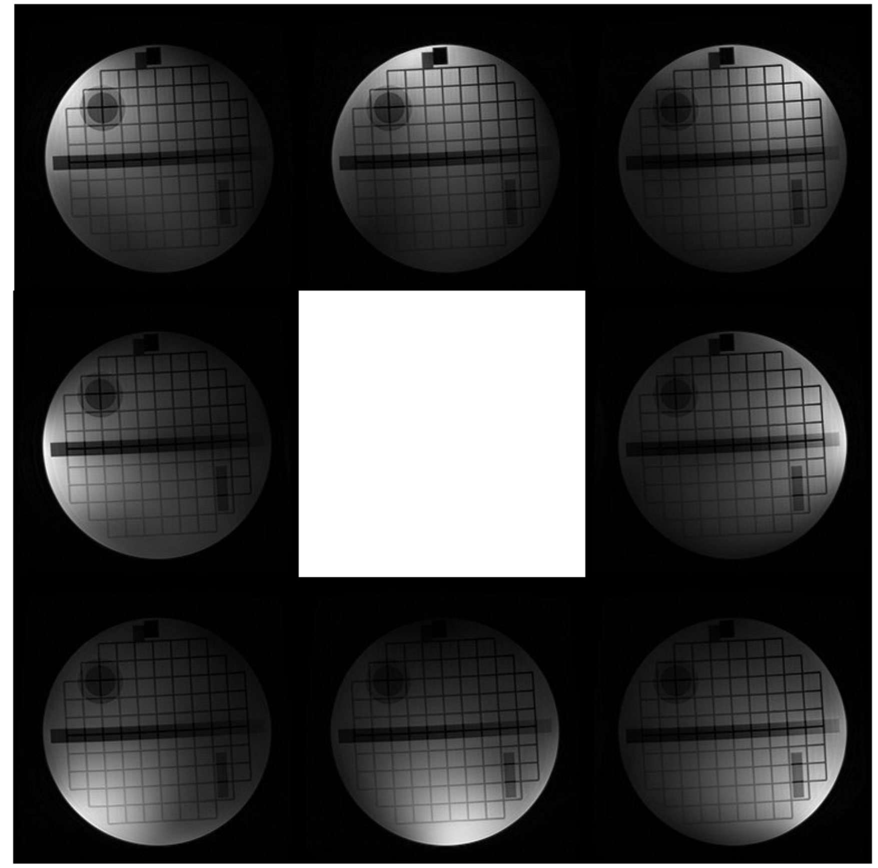
Smaller FOV

aliasing

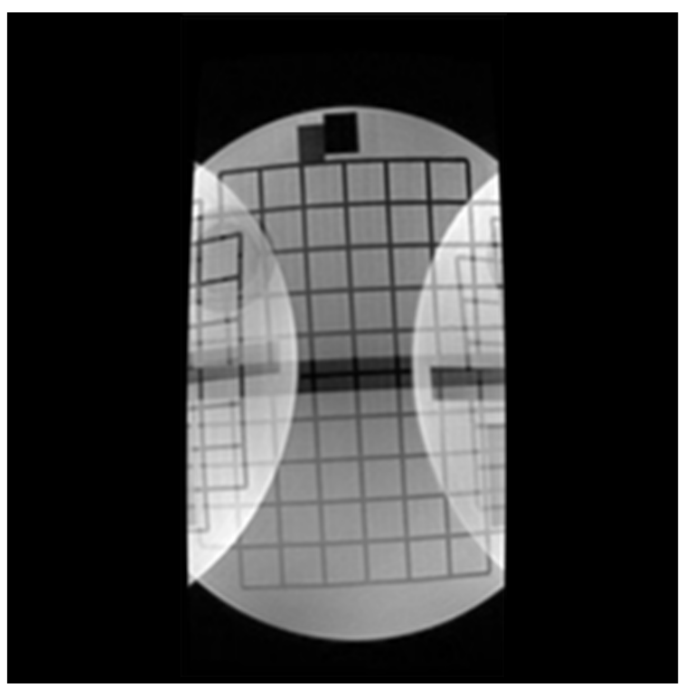
k-space

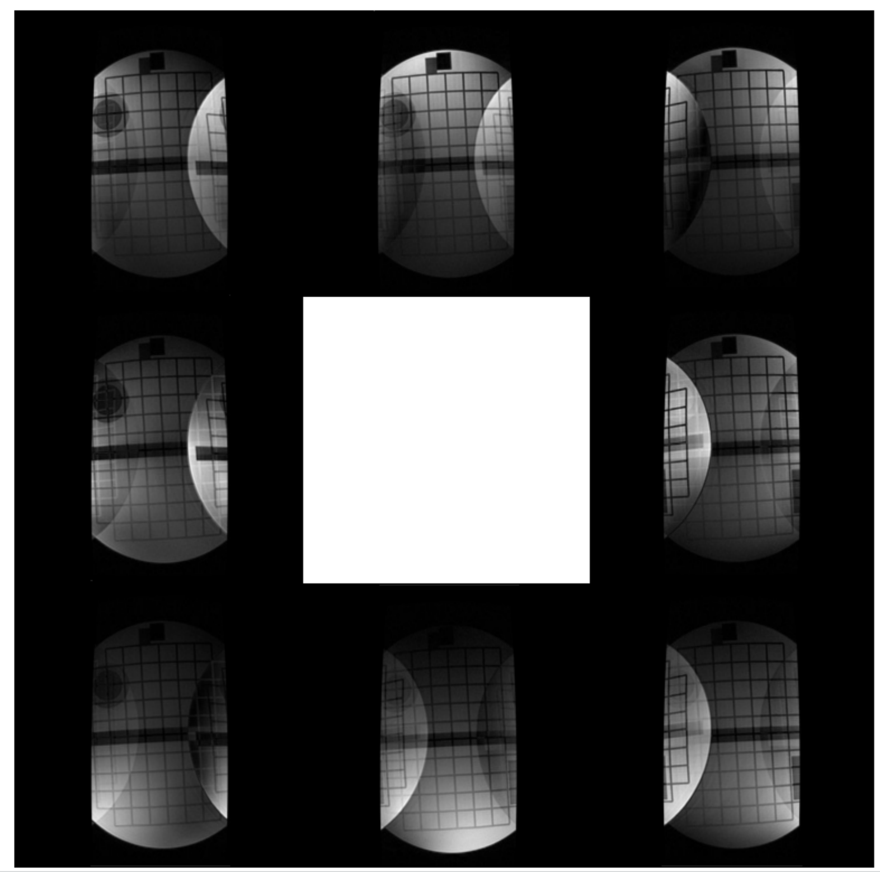






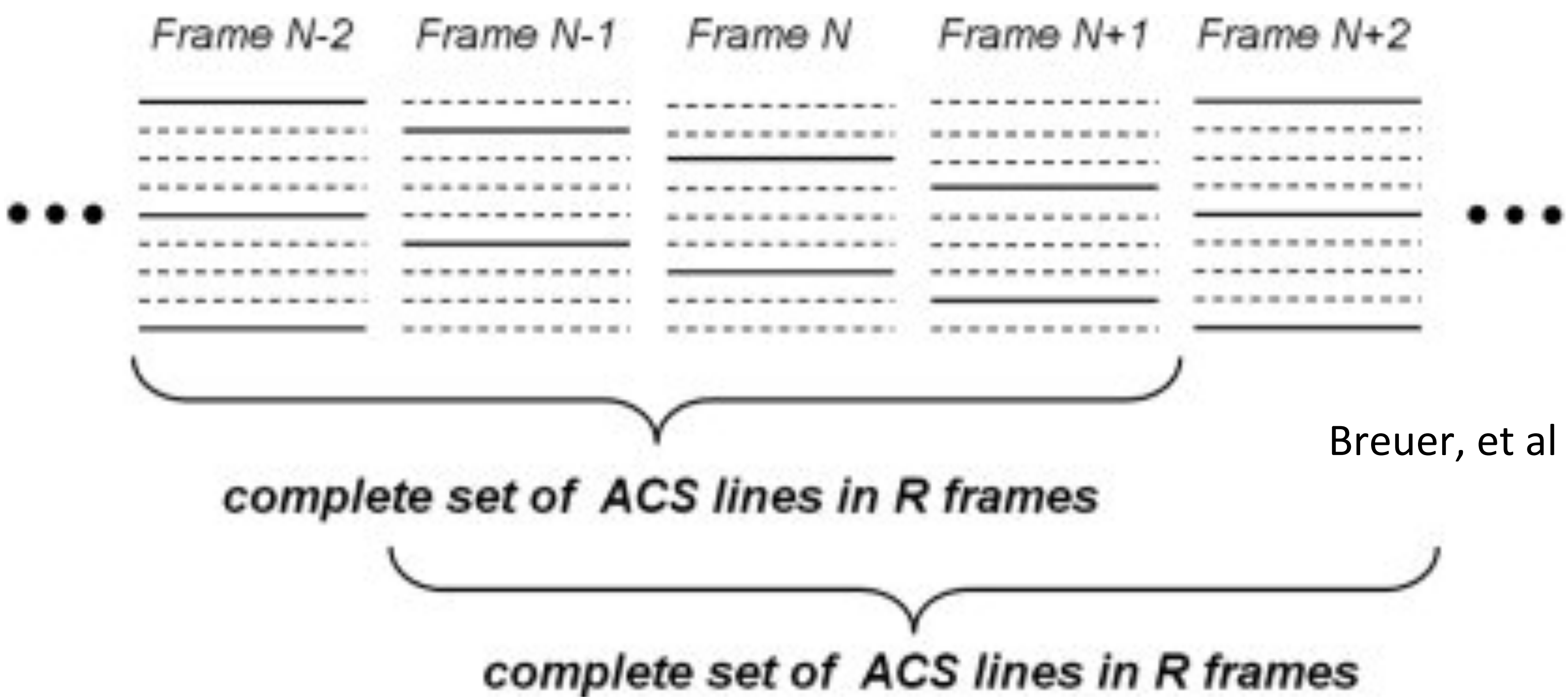
Yanasak, et al. Adv. Med. Phys., 2014





pMRI

Undersampling can be spread out in the phase-encode direction(s), the slice-select direction, the temporal direction, or various combinations.



Breuer, et al MRM 2005

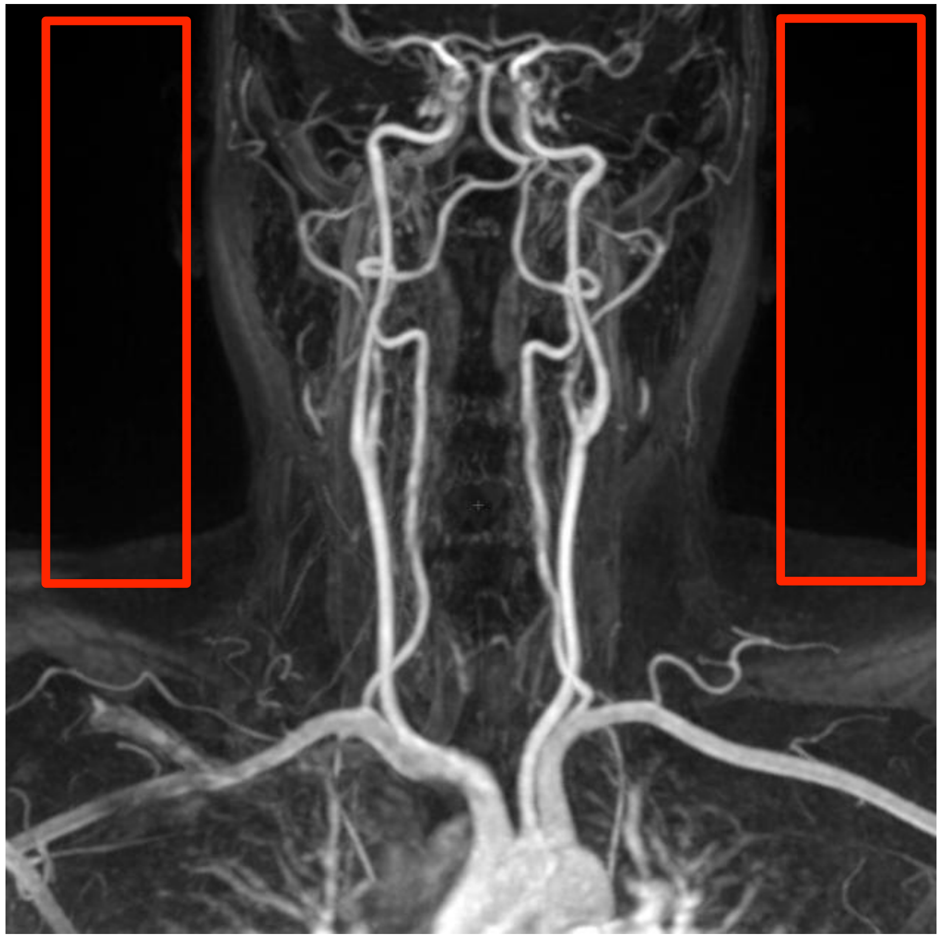
Example: TSENSE (undersample regularly in time).

Compressed Sensing

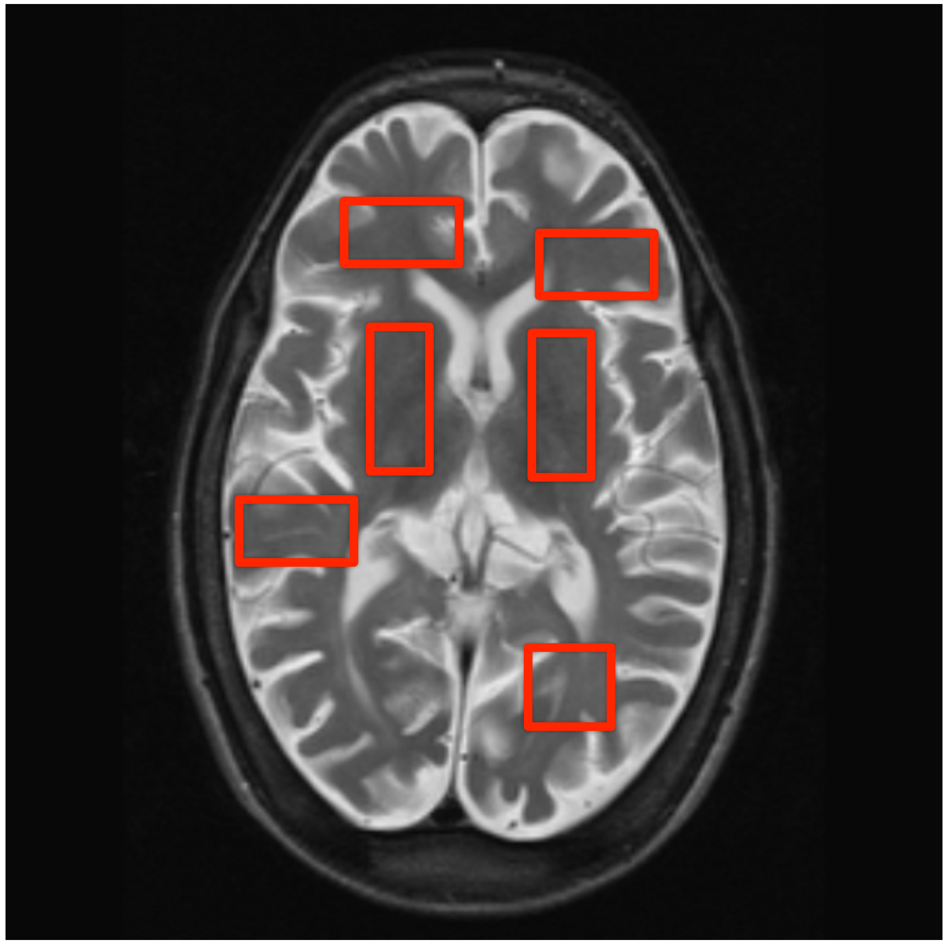
Non-uniform sampling of k, t data.

Dramatically undersampling data → lossy.

Many images are sparse in spatial information:



MR Angiography



T2W Brain Imaging (smooth)

Sparse in the pixel domain.

Sparce in spatial-gradient domain.

https://radiopaedia.org/cases/normal-neck-mra

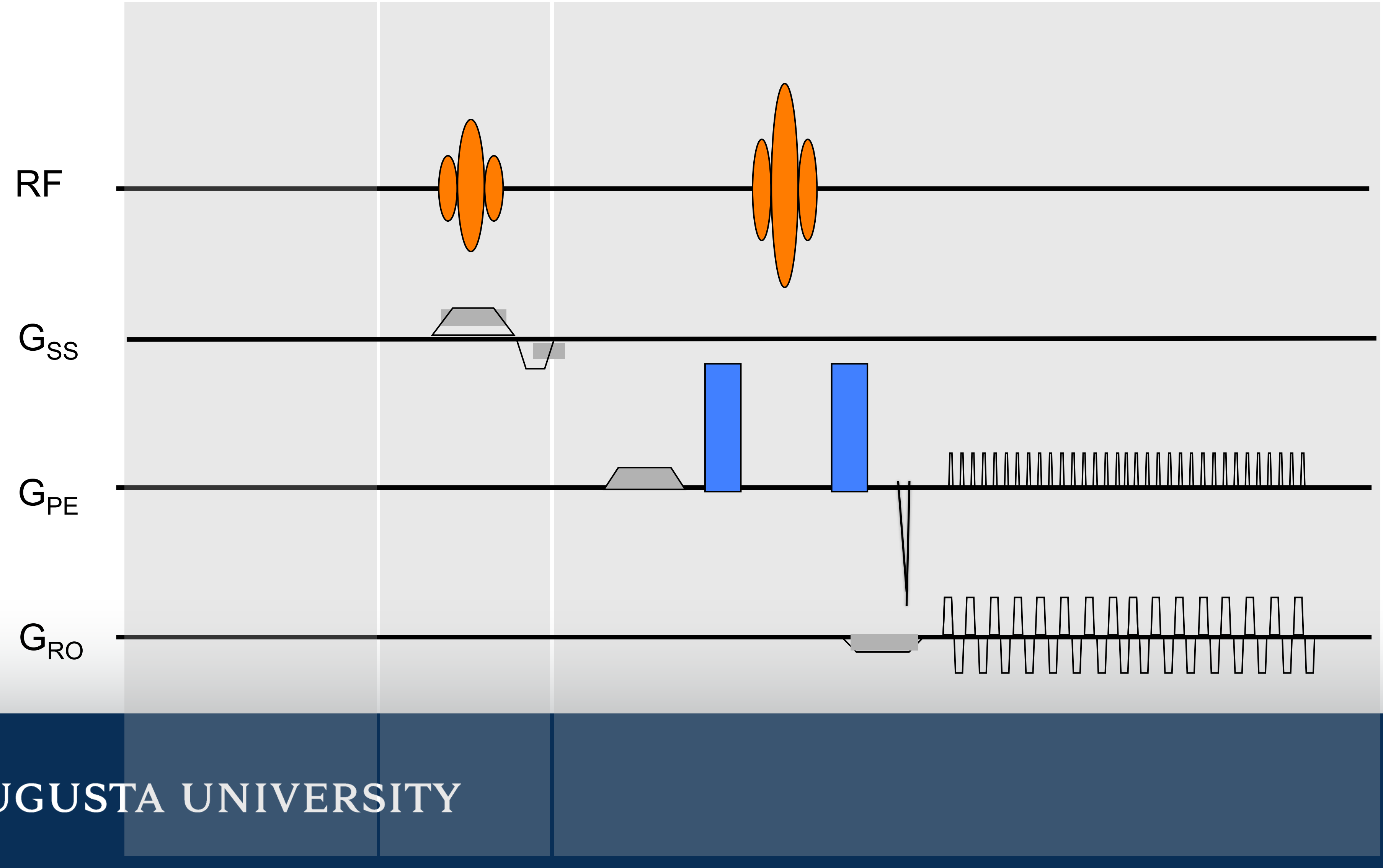
Other Special Sequences to Generate Novel Contrasts

Diffusion Imaging

Add two strong gradient pulses (or bipolar) to a T2-type of sequence (usually SE-EPI).

If spins within a voxel move between pulses, they incur a phase shift.

Randomization of phases in a voxel → no signal.



Diffusion Imaging

Weighting adjusted via “b” (magnitude & timing of gradients) & direction of gradients:

$$S_{DWI} = S_o \exp(-b\mathrm{D})$$

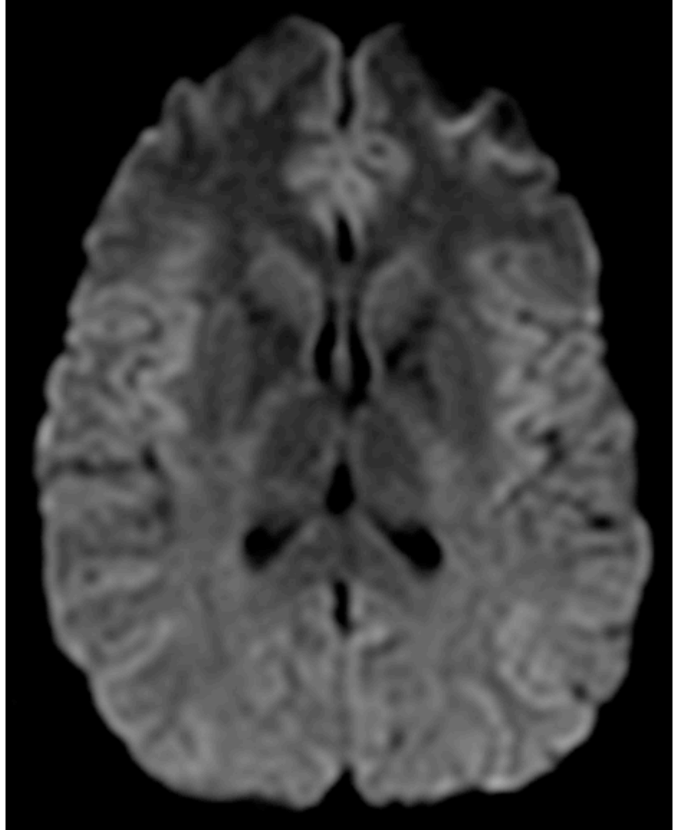
$$\mathrm{D} = -\frac{1}{b}\ln(S_{DWI} / S_o)$$

To calculate ADC, need one “b0” image.

Types of scanning:

- Diffusion Weighted Imaging (DWI)—average three orthogonal diffusion directions.
- Diffusion Tensor Imaging (DTI)—extract anisotropic properties of diffusion using at least six different directions.

Diffusion Example

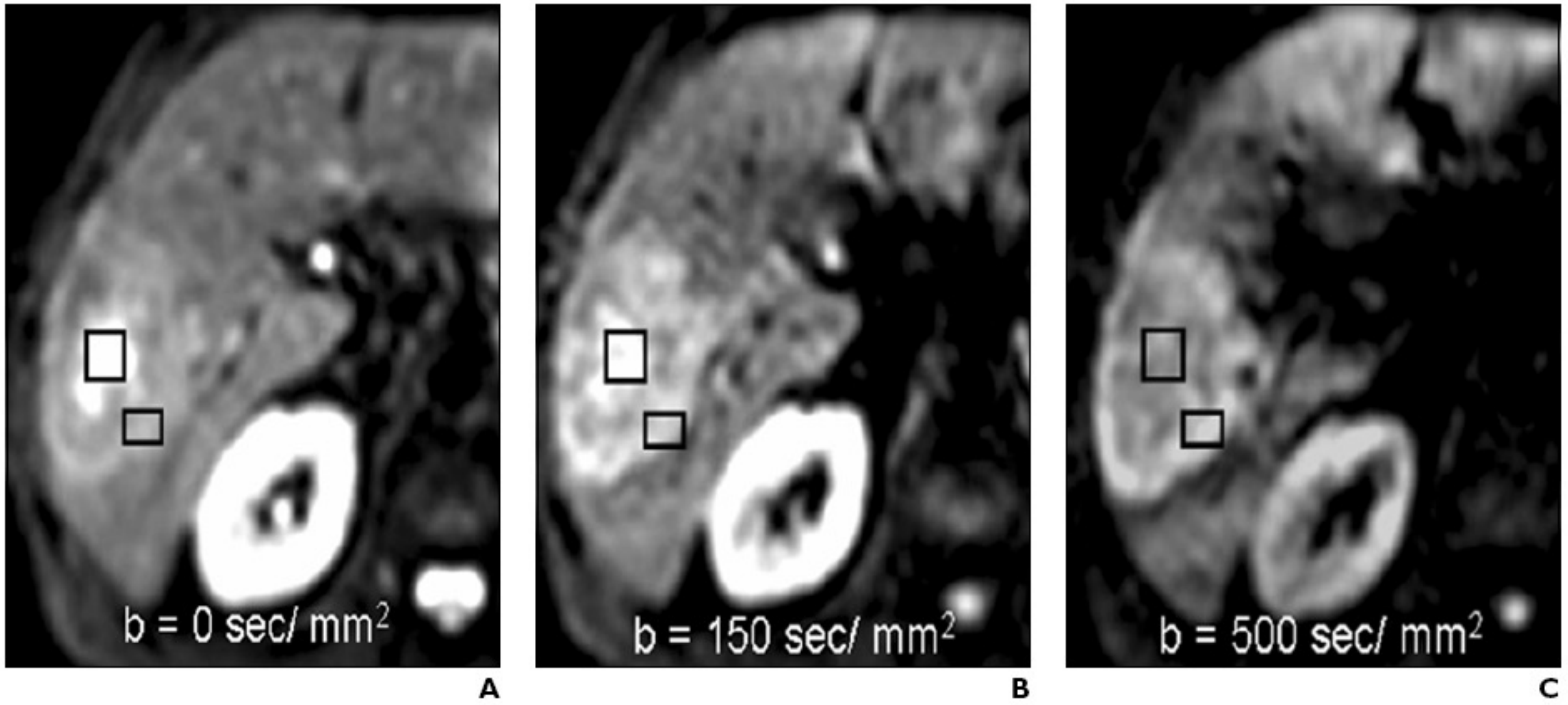


Diffusion is critical for cancer imaging.

Hypercellularity → restricted diffusion.

Necrosis → increased diffusion.

Pictures from Allison, et al. (MRI: Pulse Sequences RSNA web module)



55-yr old male with Liver Metastatis.

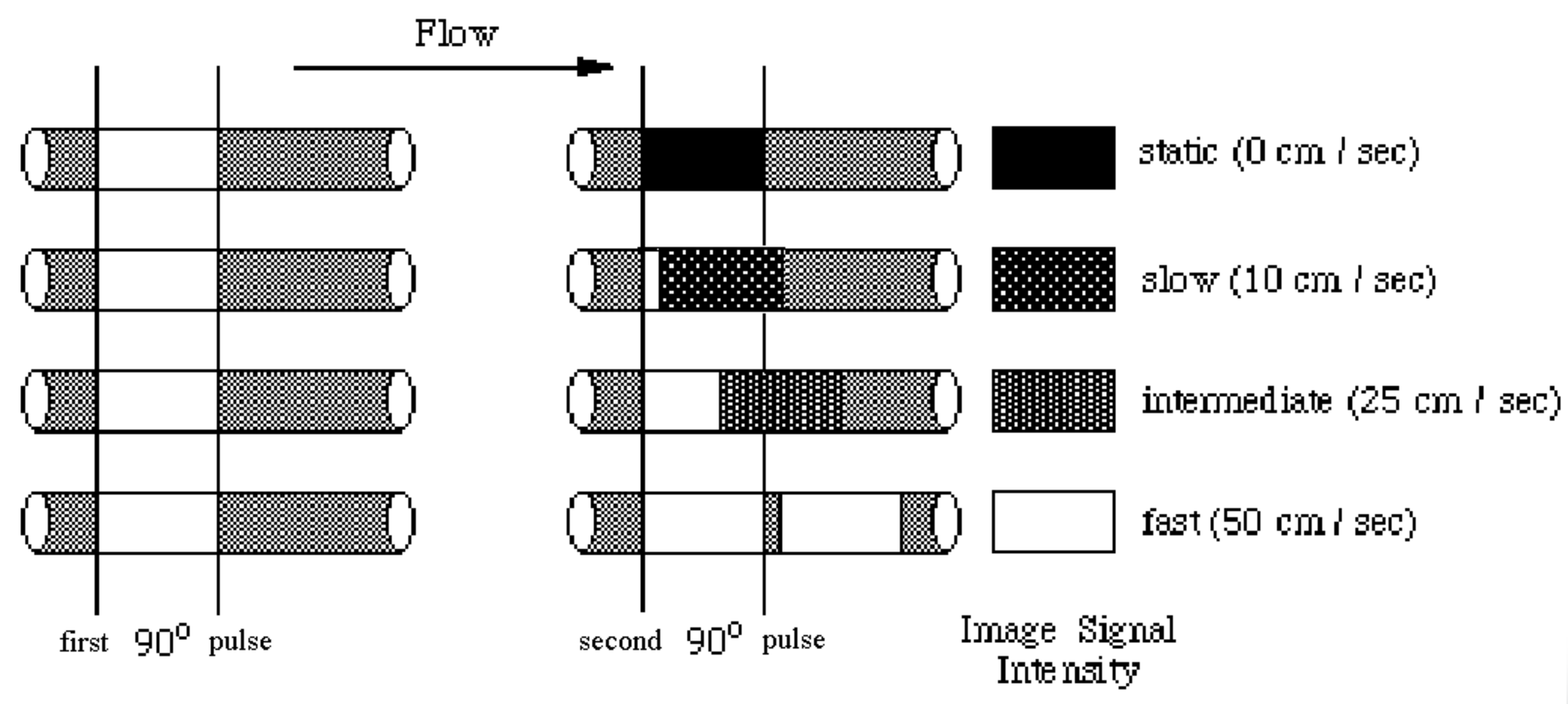
Necrosis (decrease as b increases) and cellular rim (increase as b increases) are shown in boxes.

Koh & Collins, AJR, 2007

MR Angiography (TOF)

Very short TRs – signal is saturated everywhere in slice unless it moved into slice before nth excitation.

Use of contrast agent and magnetization transfer can improve CNR.



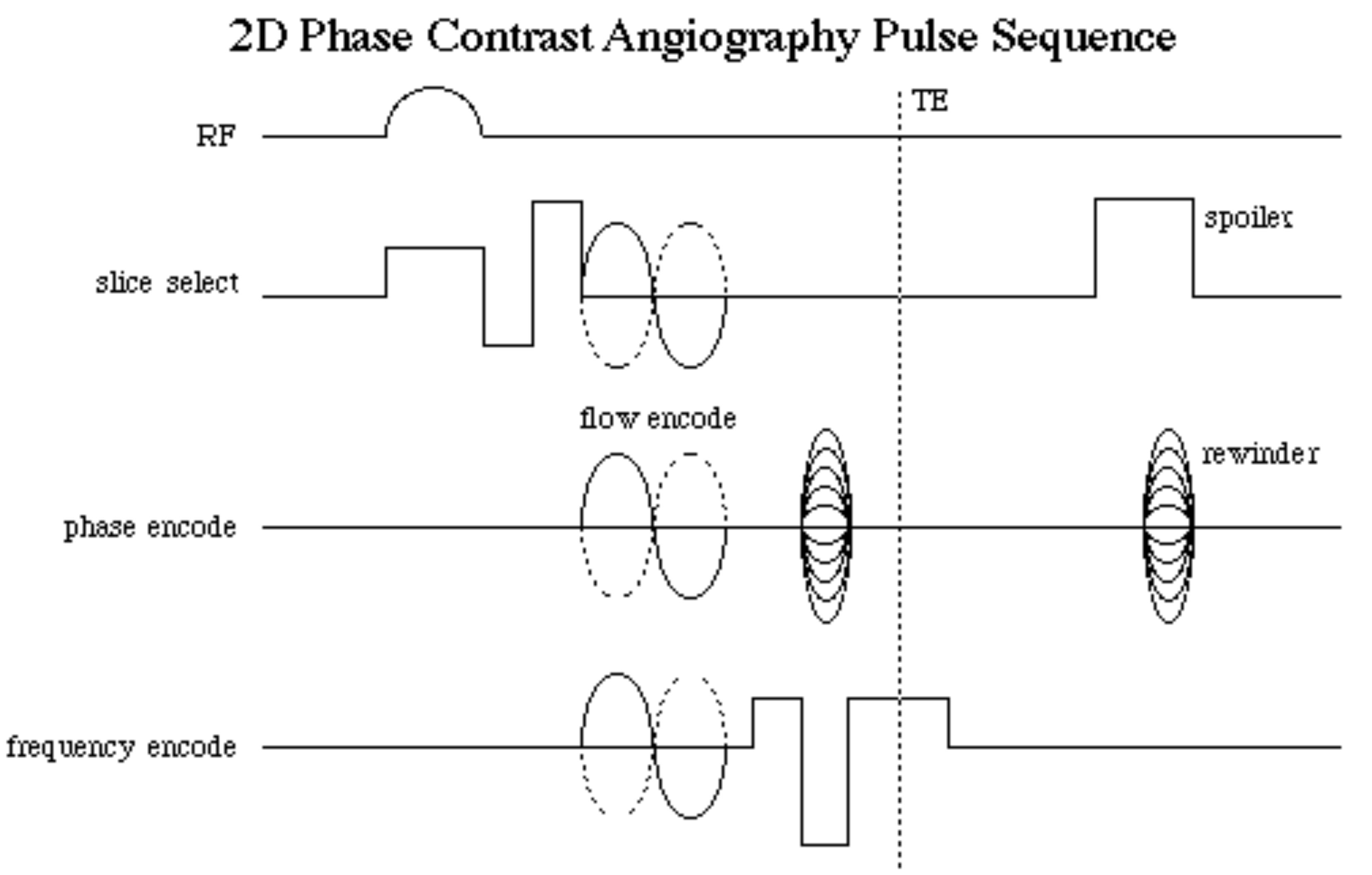
MR Angiography (PC-MRA)

Bipolar gradients (velocity encoding gradients – VENC) -- encode spin velocity as a phase change.

Similar to DWI sequence in function, but

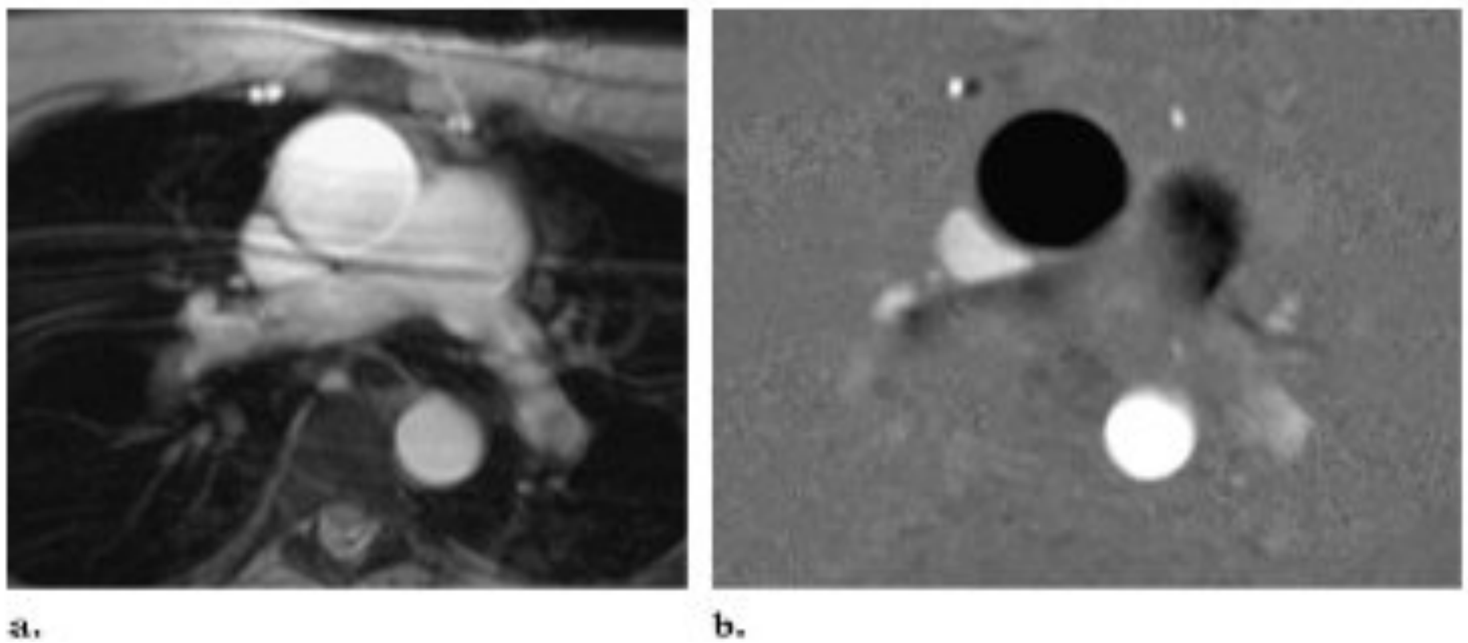
DWI → random motion introduces dispersion of phase.

Flow → directed motion introduces shift in phase.



Good technique for slow (venous flow) in small vessels (e.g. MRV).

MR Angiography Examples



Lotz, et al., 2002, Radiographics

Perfusion Imaging

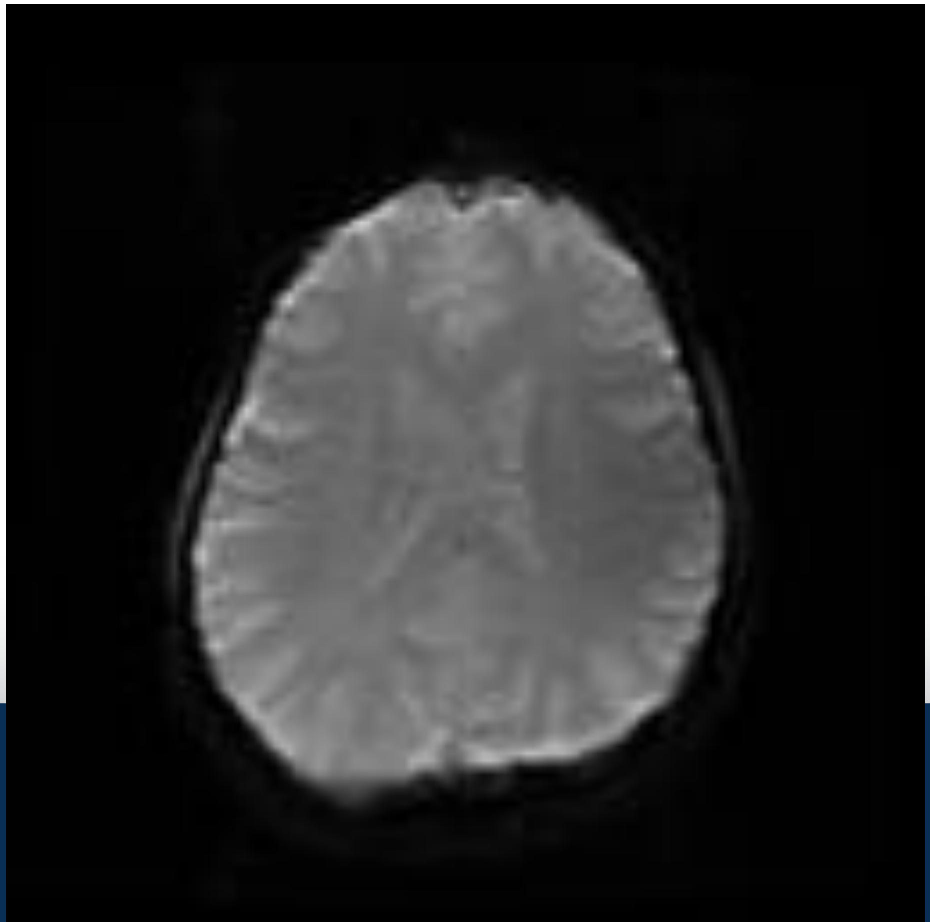
Various ways to image slow, sub-voxel flow.

Relative Speed:

Slow Diffusion → Perfusion → MRA ***Fast***

Three different types:

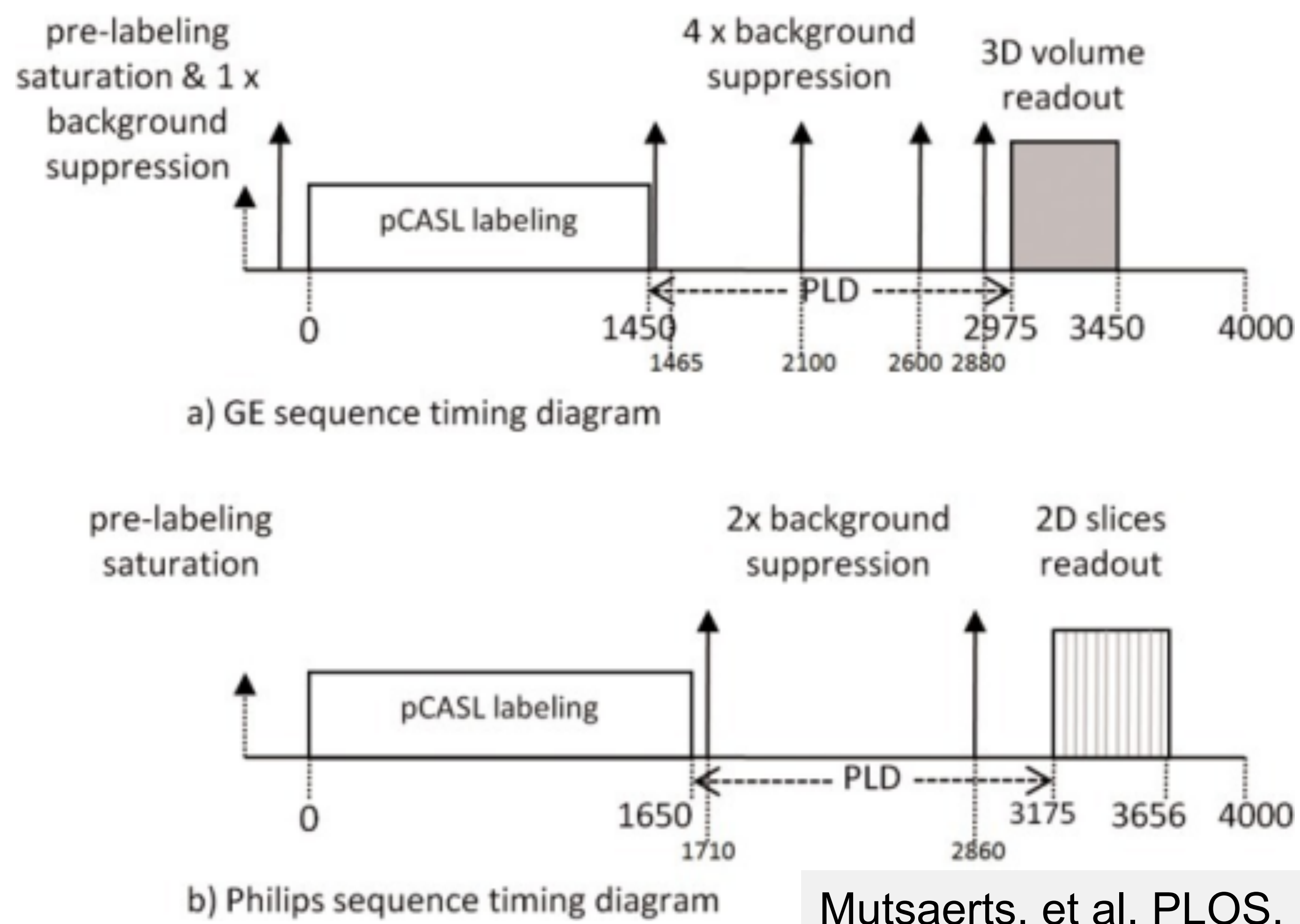
DCE- and DSC-MRI: Use GRE or EPI scans to examine T1W or T2*W of tissue as contrast agent washes through.



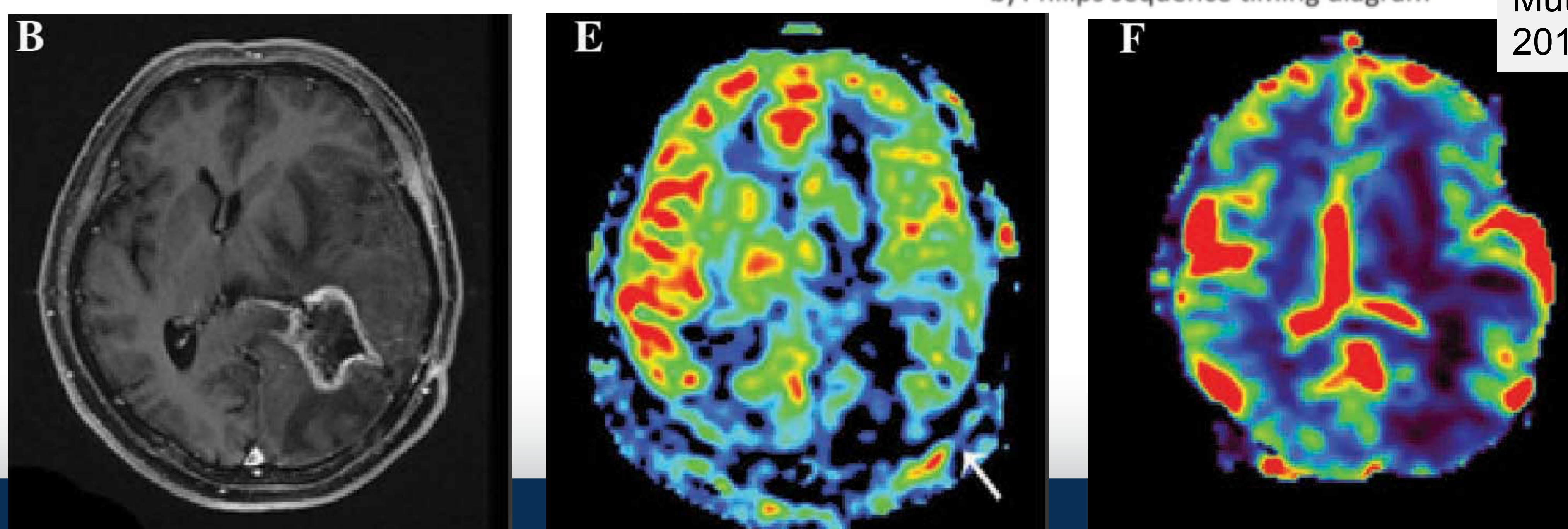
Perfusion Imaging

Arterial Spin Labeling (ASL): Two sets of T1W images are acquired, comparing local inflow of blood.

Blood is “labeled” in one series via inversion of spins in a layer outside of scan region. → CBF



Mutsaerts, et al. PLOS, 2014



Ye, et al. Experimental & Therapeutic Medicine, 2016

Susceptibility-Weighted Imaging (SWI)

Combines phase and magnitude images in a non-linear way.

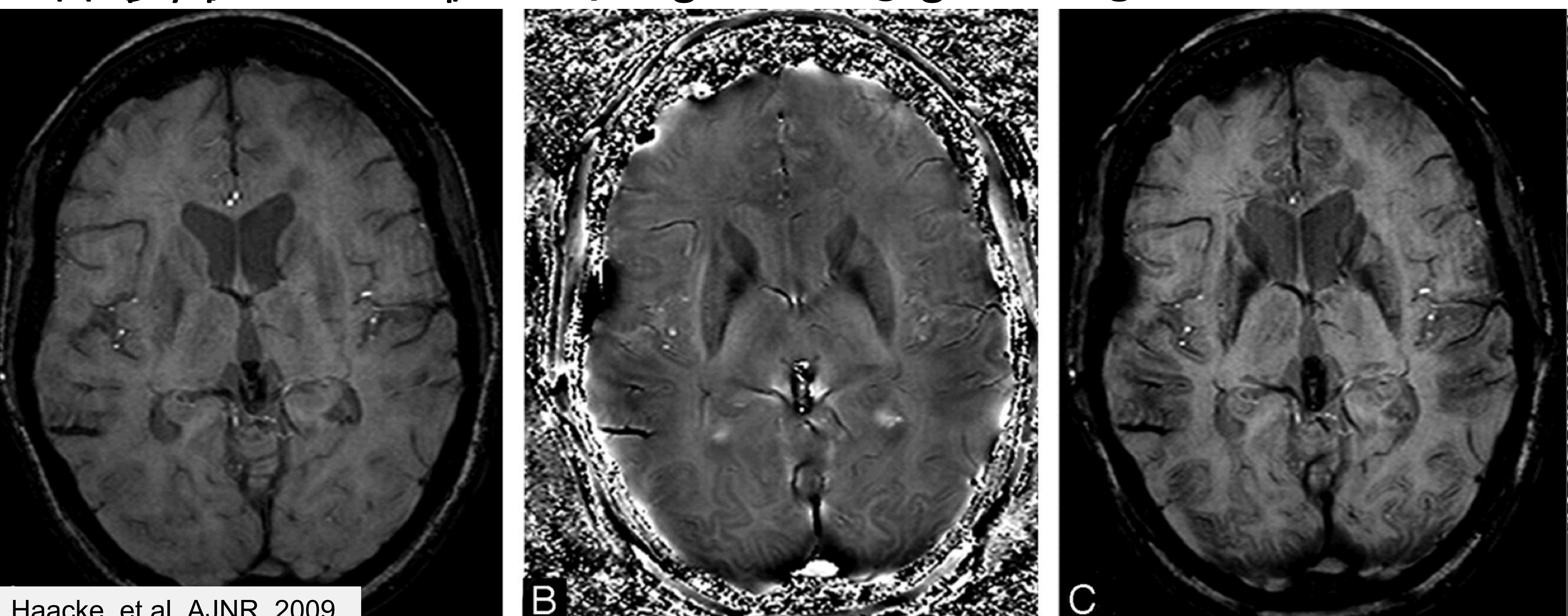
Process:

Collect images using a hi-res, PD-type of sequence.

High-pass filter the phase image.

Multiply processed phase image with magnitude.

Apply … regions are dark.



Haacke, et al. AJNR, 2009

Summary

- There are a multiplicity of different sequences.
- Many are hybrids of GE, SE, IR.
- Readout details play an important role in the image.
- Speed usually translates to some form of undersampling k-space if you avoid changing the contrast (TR).

Questions?