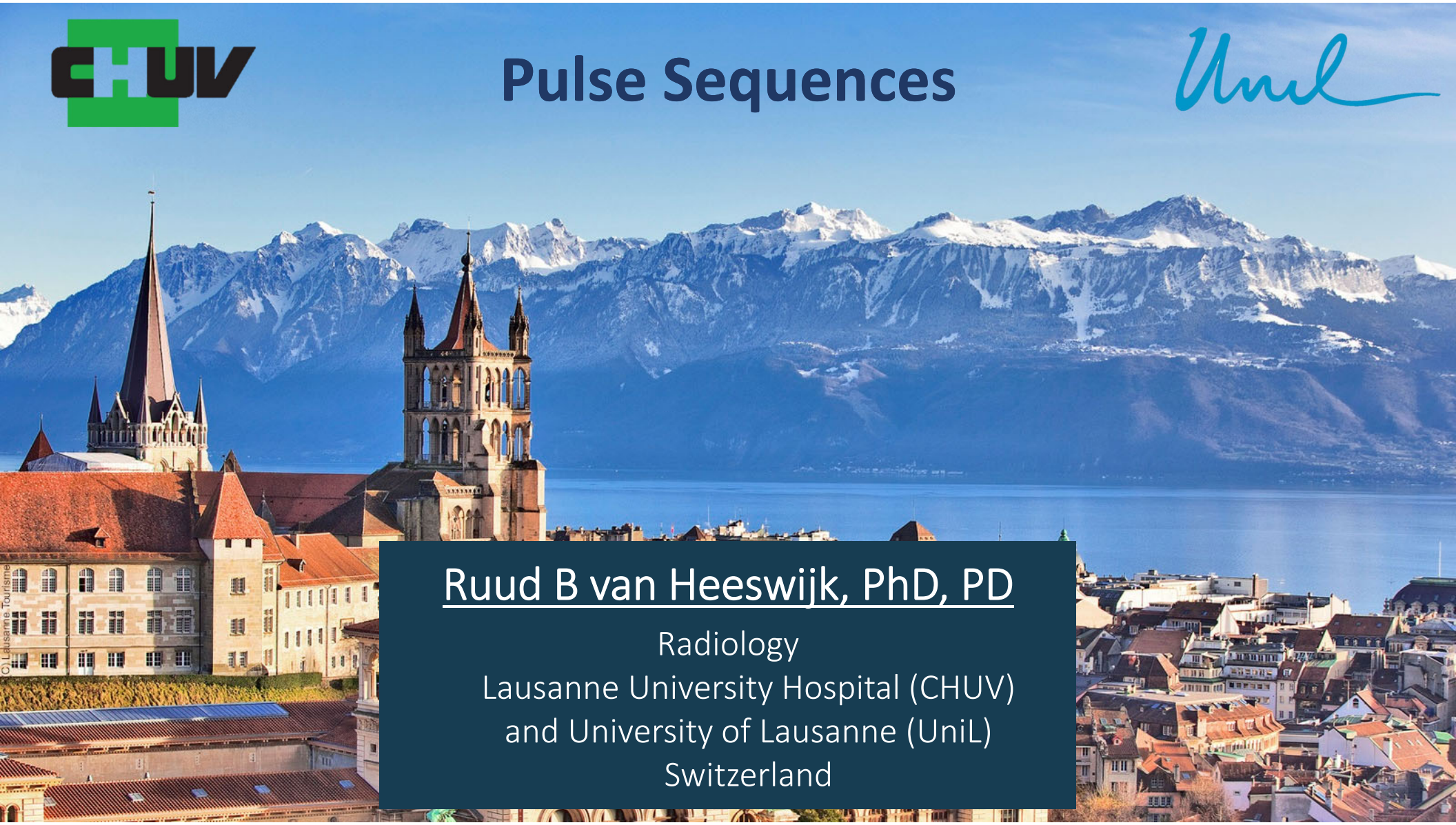
Pulse Sequences



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and University of Lausanne (UniL)
Switzerland

Overview

- Refresher on k-space encoding
- Spin echo and derivatives
- Gradient echo and derivatives
- Flow

k-Space encoding refresher

k-Space encoding

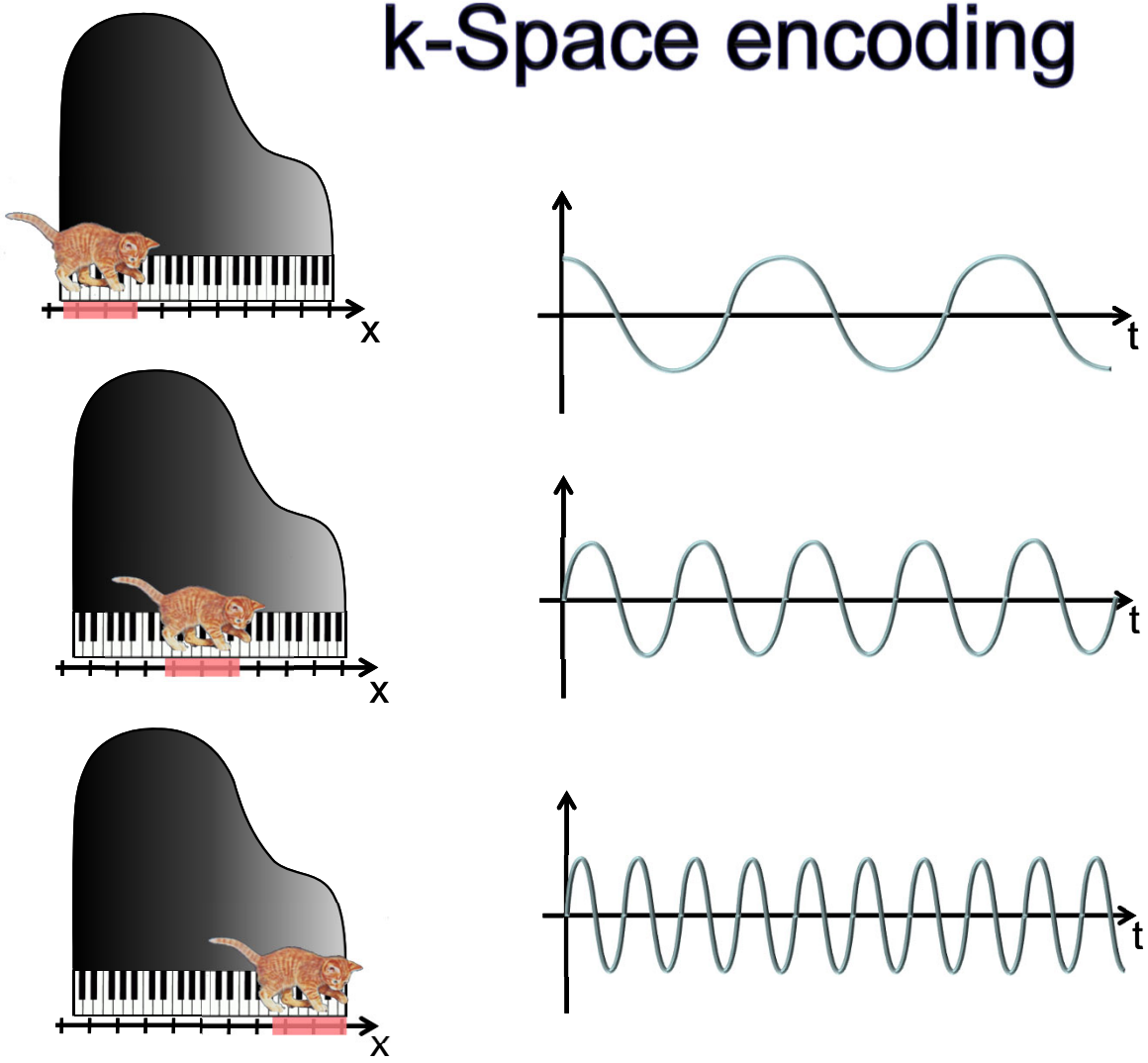
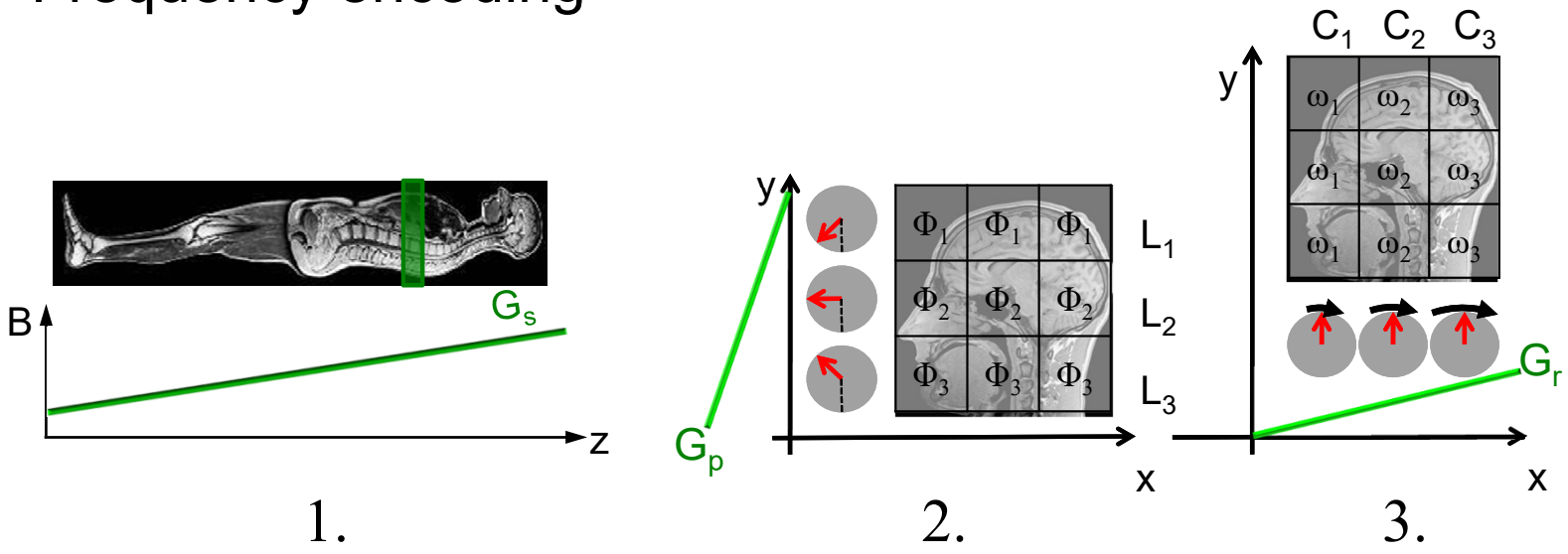
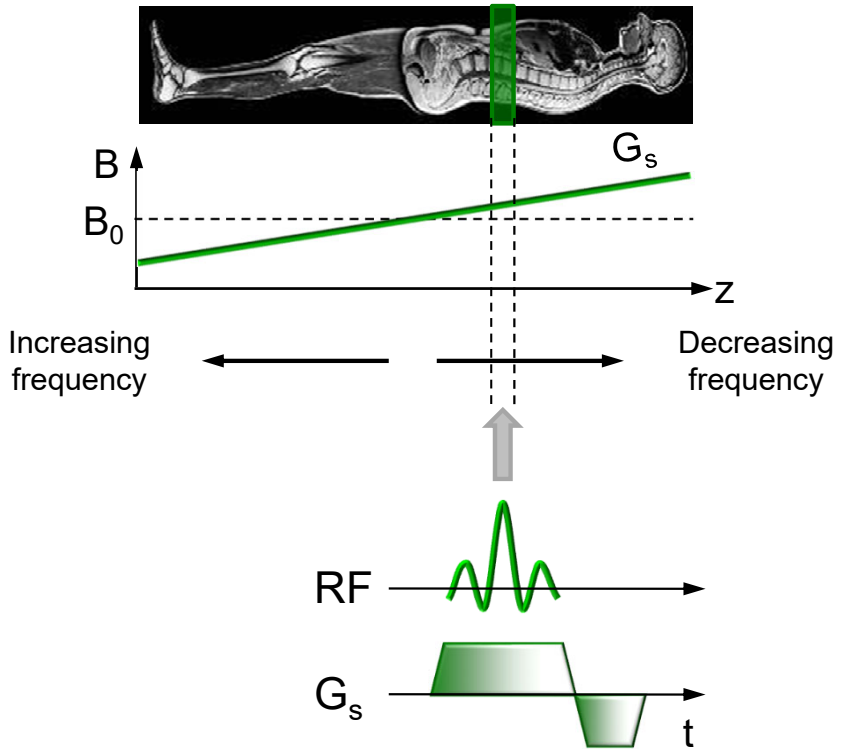


Image Acquisition

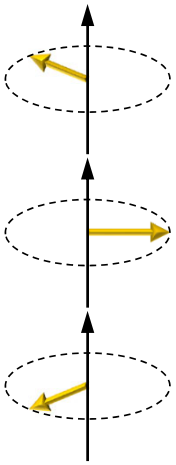
- MR signal spatial localization
  1. Selection of an image slice
  2. Phase encoding
  3. Frequency encoding

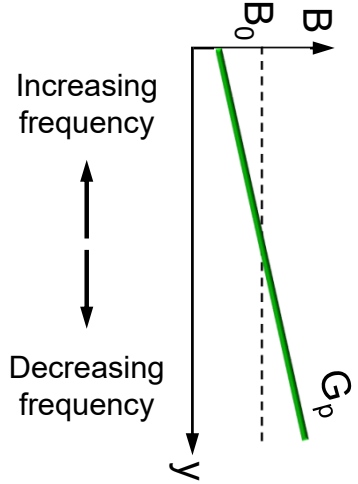


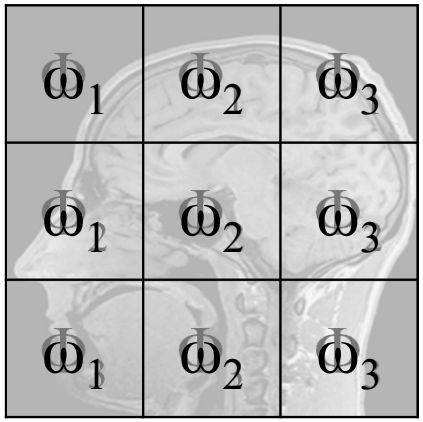
Selection of an Image Slice

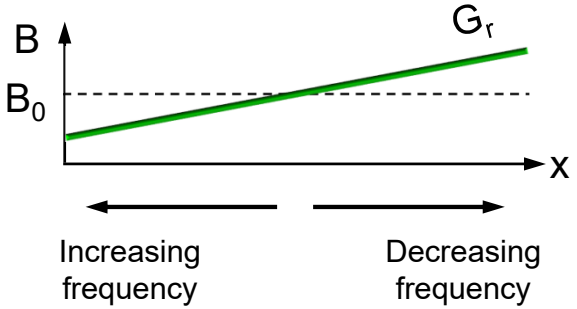


Phase and Frequency Encoding









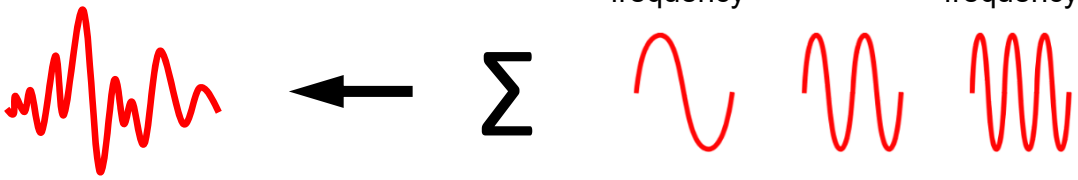
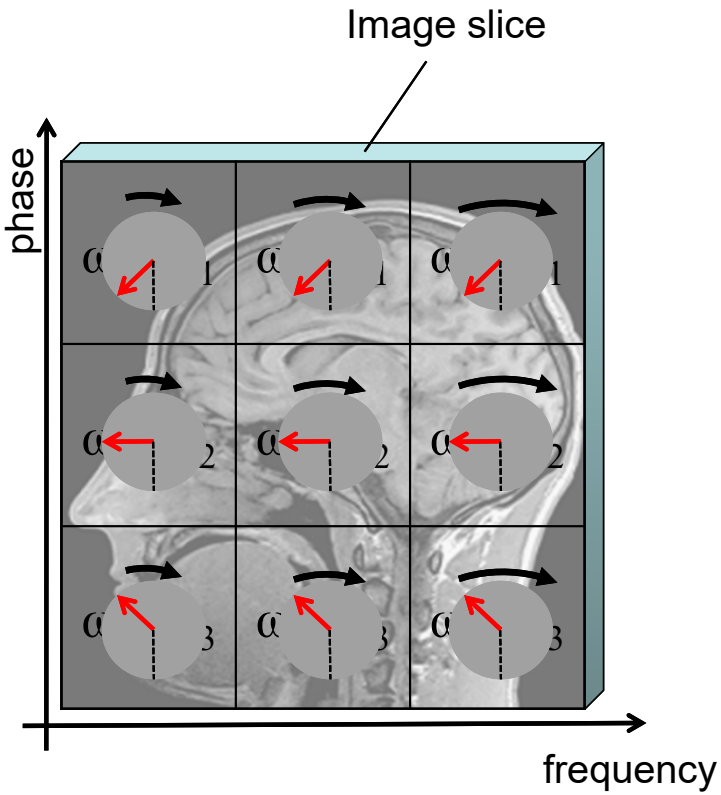


Image Acquisition



Separation of Frequencies (Image Reconstruction)

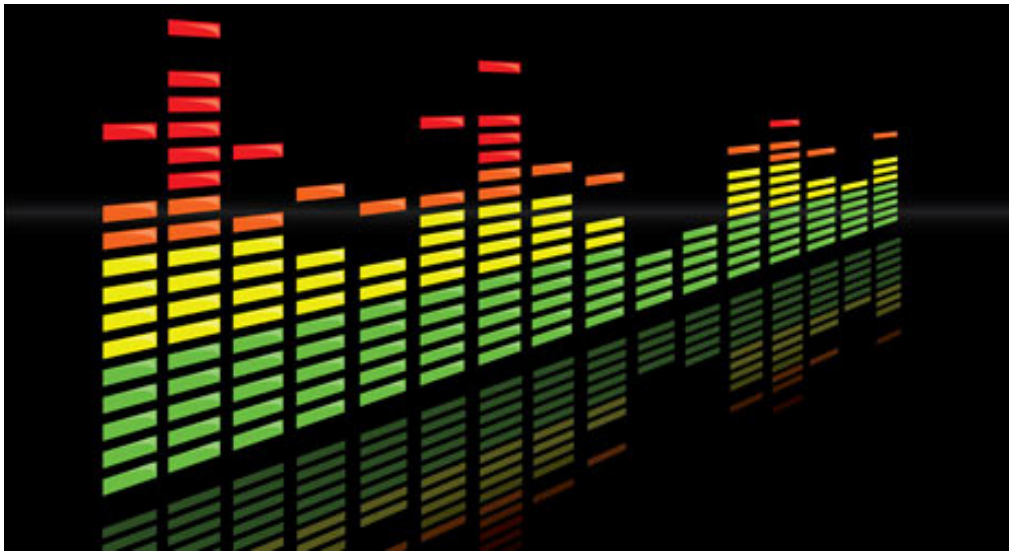
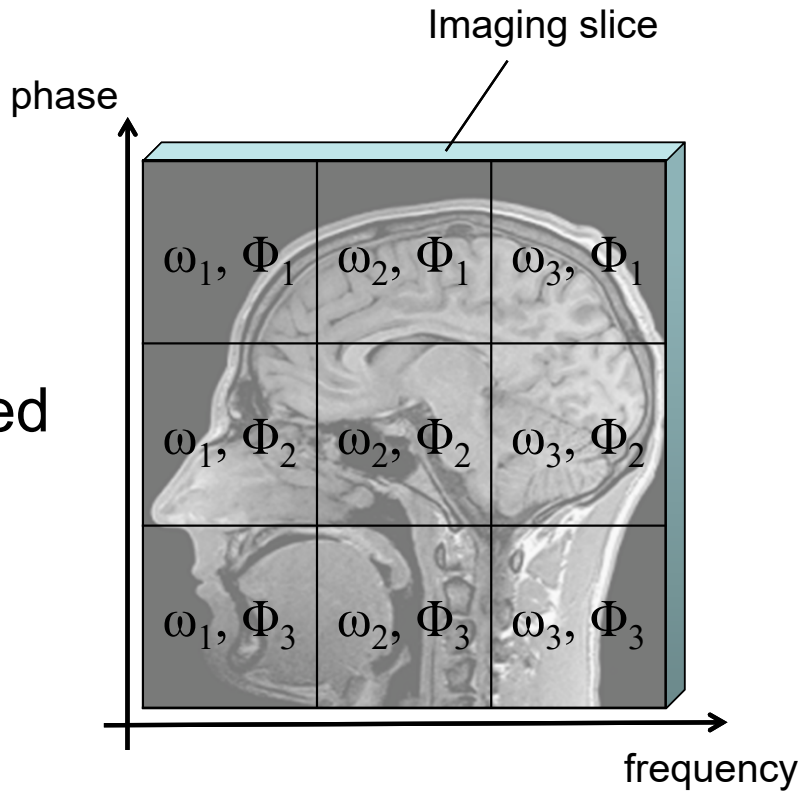


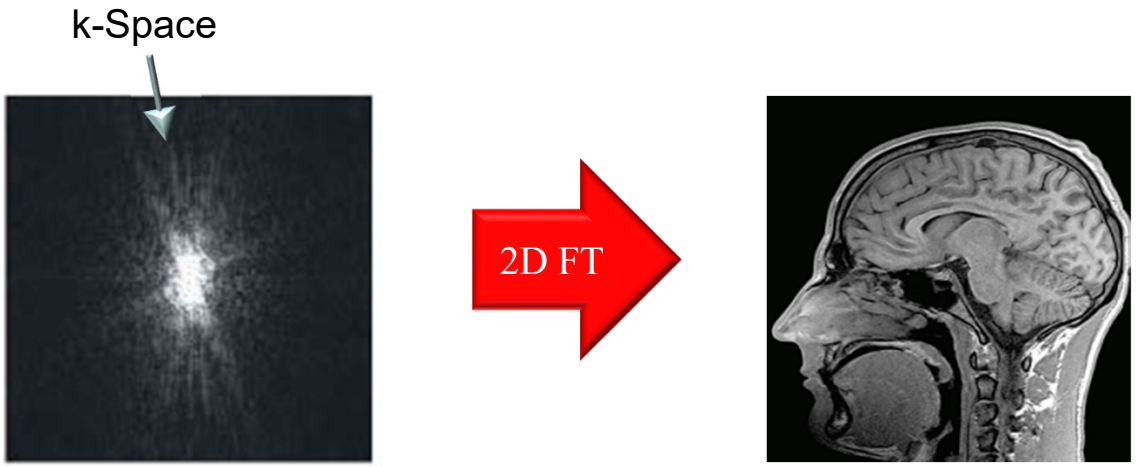
Image Reconstruction

- An image is encoded line by line in « k-space ».
- At each step, the phase encoding gradient is increased to acquire a new line.
- Typically, images use 256 different phase shifts.



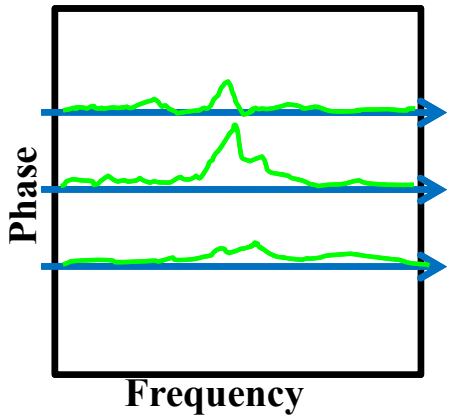
k-Space & Image Reconstruction

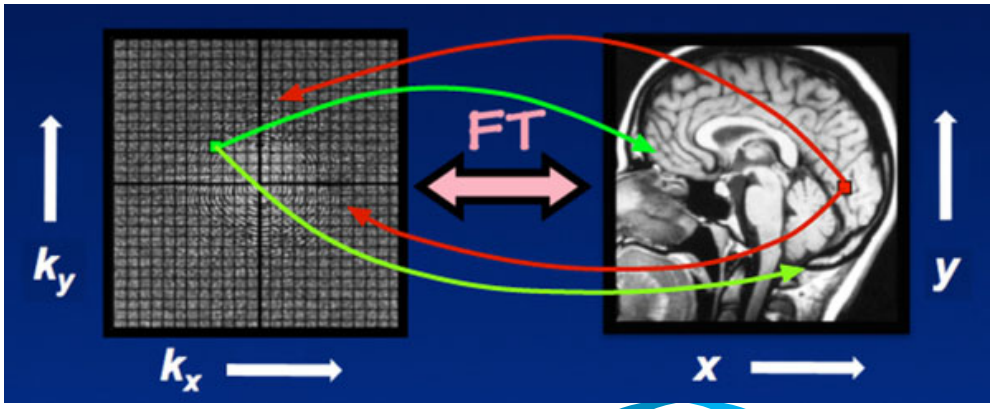
- A two-dimensional Fourier transformation of this matrix results in the reconstruction of the image.

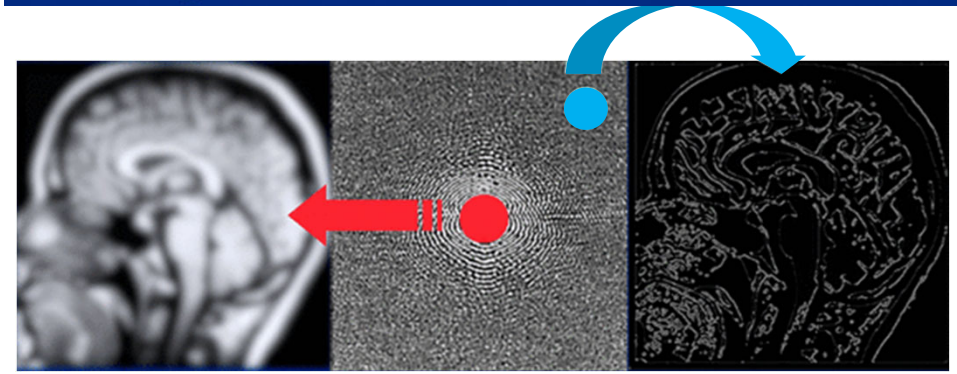


k-Space versus image space

- Each point in k-space has information on the entire image and vice versa





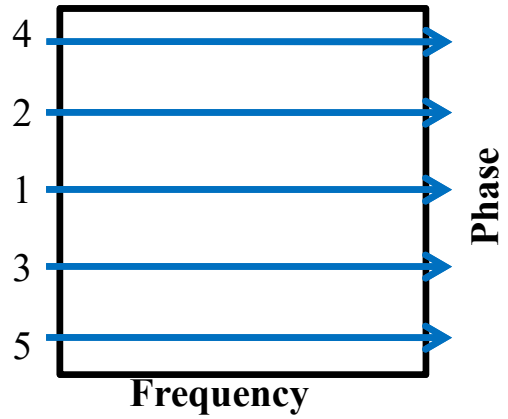


mriquestions.com

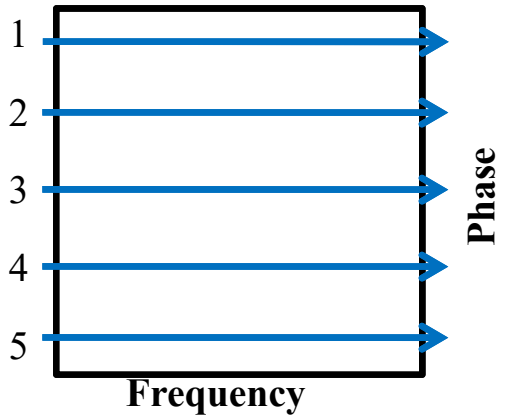
To play with this yourself:
Apple Store: k-Space Odyssey (Haselhoff)
Play Store: k-Spapp (Springorum)

Centric versus Linear Sampling

- What line to sample first?
- Influences contrast and eddy currents

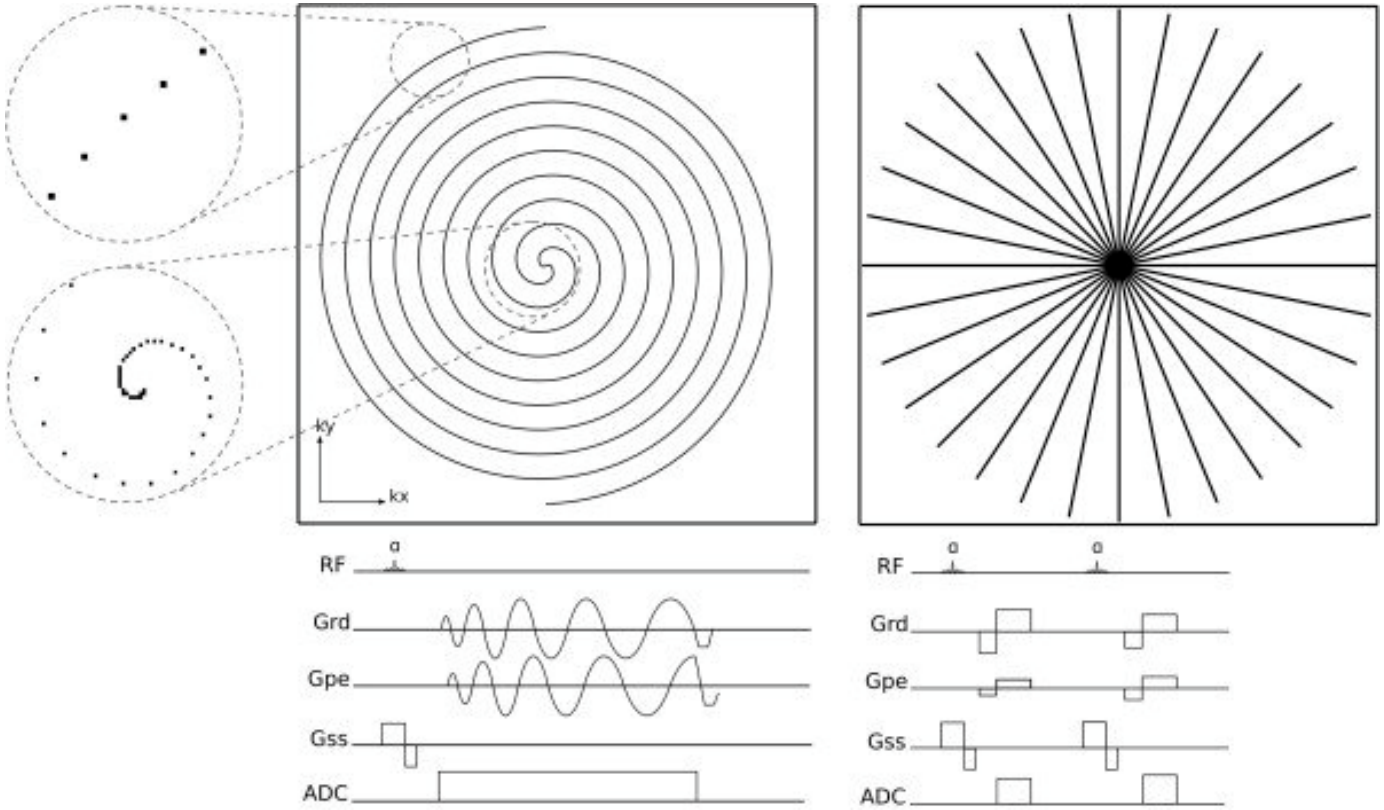


Centric



Linear

Non-Cartesian Sampling: 2D

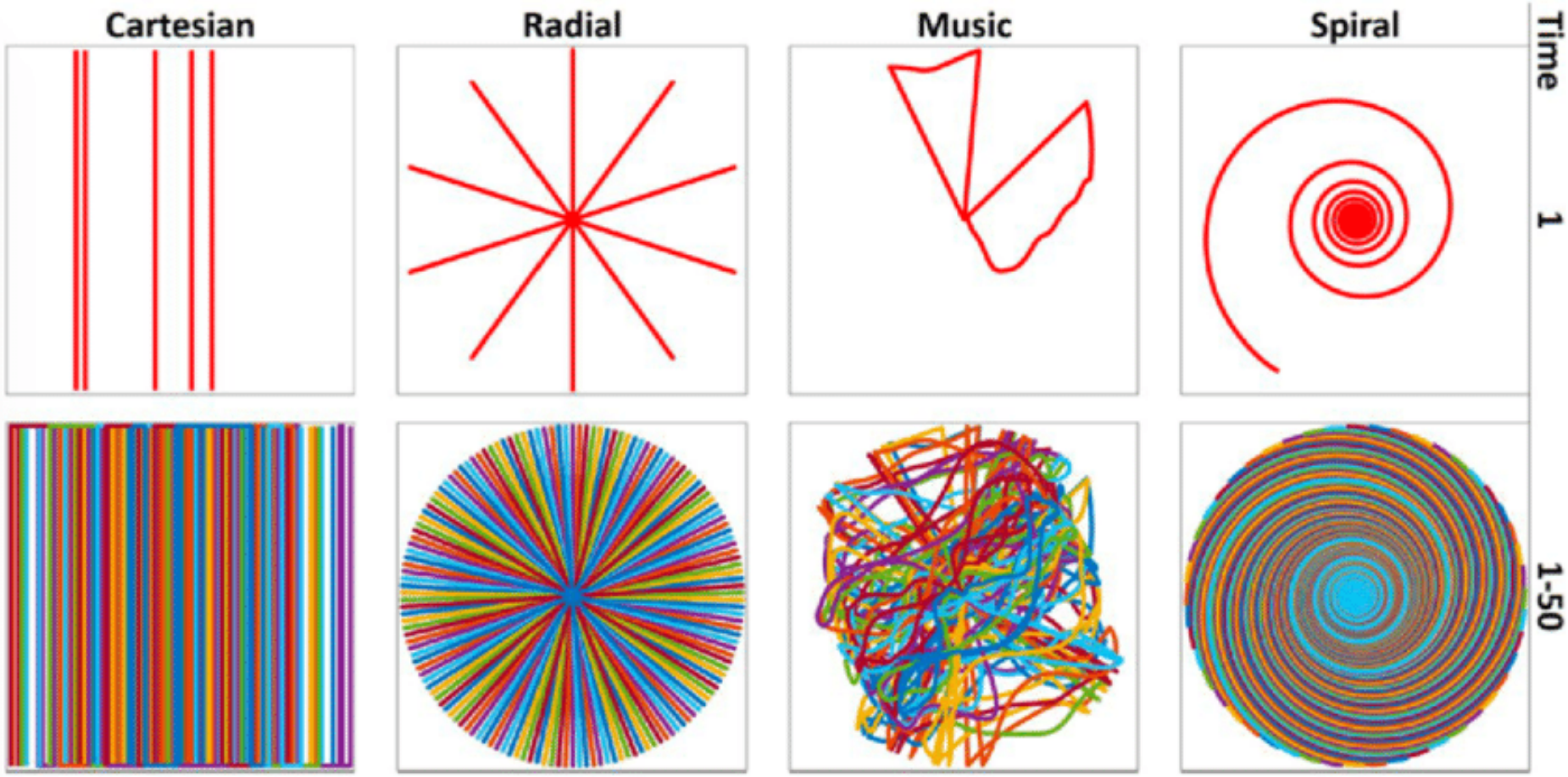


Spiral

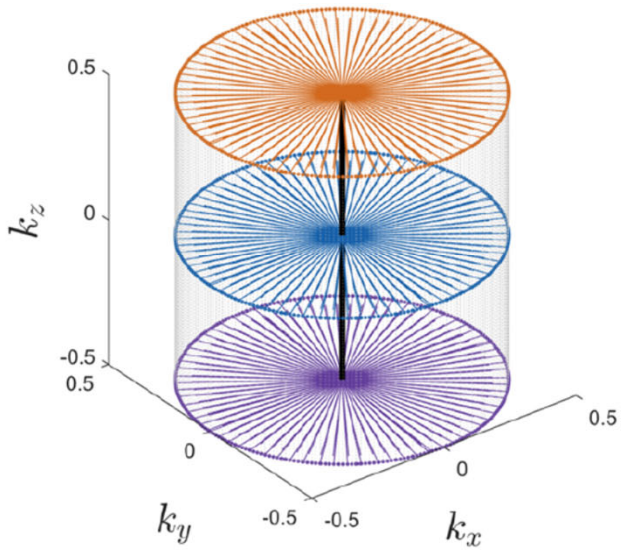
Radial

Ferreira et al. J Cardiov Magn Res (2013)

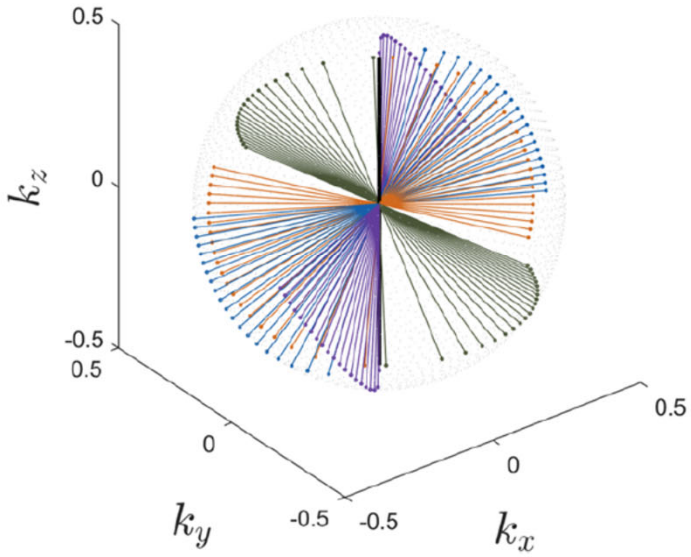
Randomized 2D k-Space Sampling



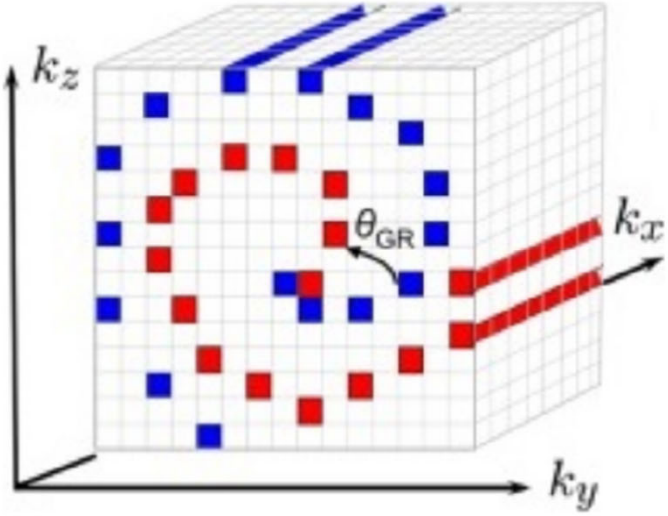
Non-Cartesian Sampling: 3D



3D Radial-Cartesian hybrid



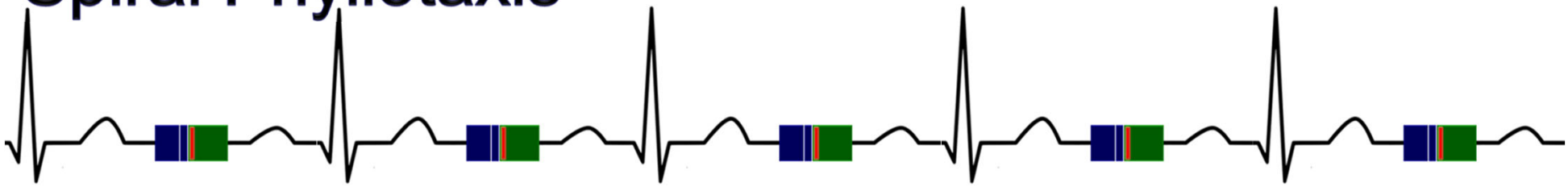
3D radial (spiral phyllotaxis)

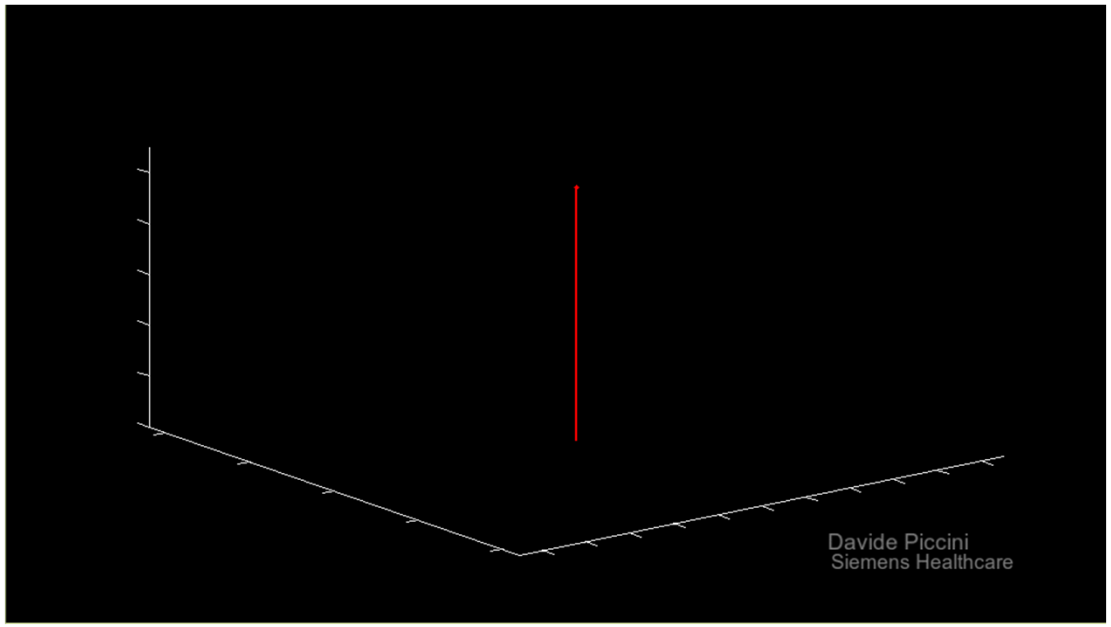


3D Cartesian (pseudo-spiral)

Menchón-Lara et al. Insights into Imaging (2019)

Spiral Phyllotaxis



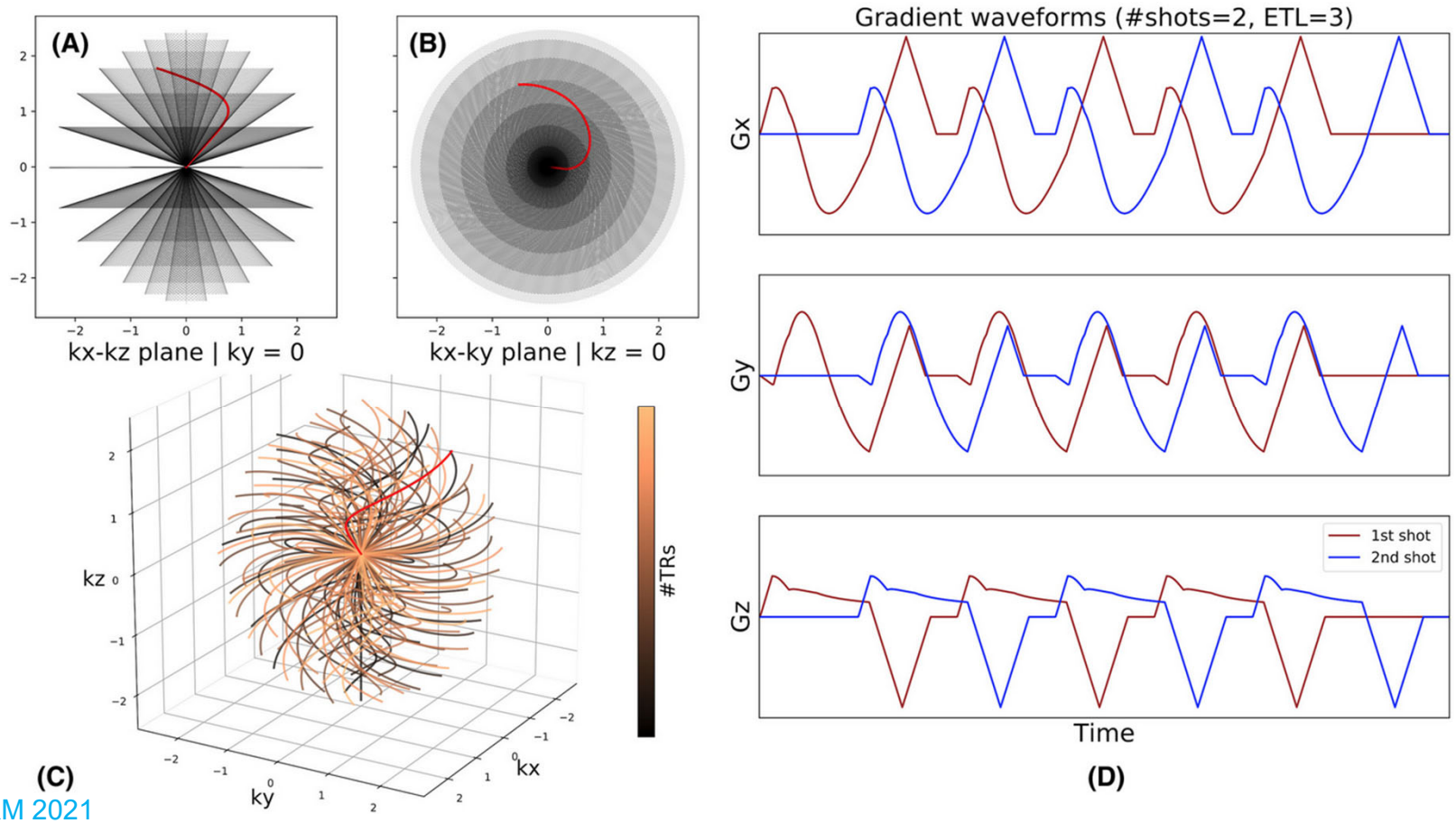


3D radial trajectory with a segmented spiral phyllotaxis pattern

Slide courtesy of Davide Piccini, Siemens Healthcare and CHUV

Piccini et al, Magn Reson Med 66 (2011)

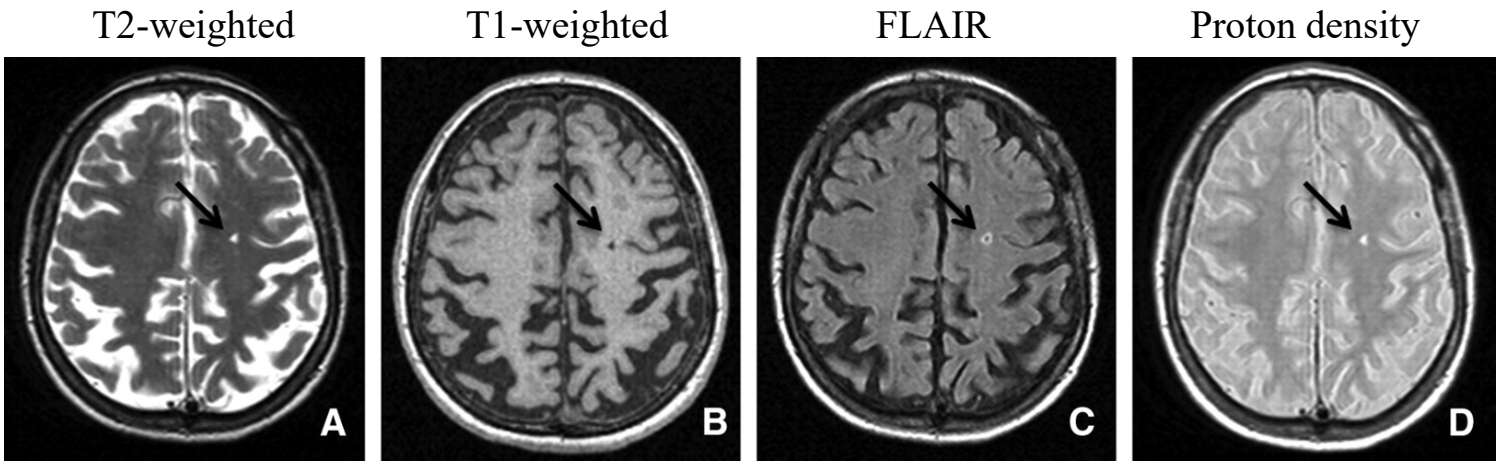
Non-Cartesian Sampling: 3D Cones



Kee et al. MRM 2021

Spin echoes

MR pulse sequences

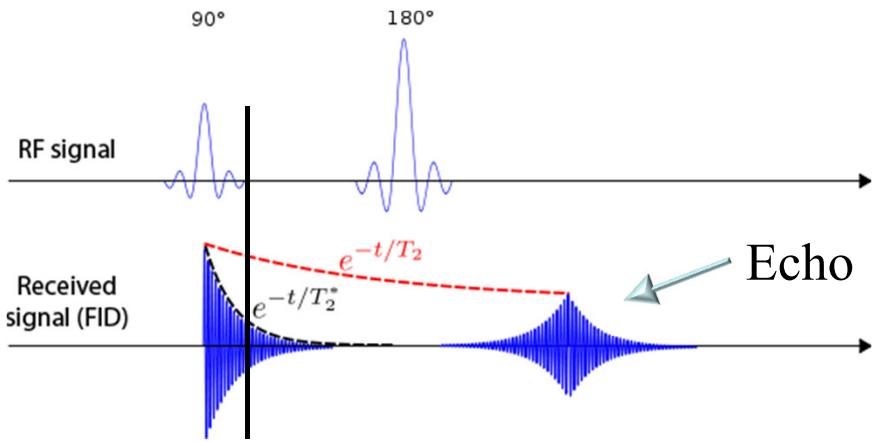


This example shows four images of the same subject anatomy that were acquired with different MR pulse sequences. As a result, the images have different image contrasts

Zhu et al. Stroke. 2011;42:1140-1145

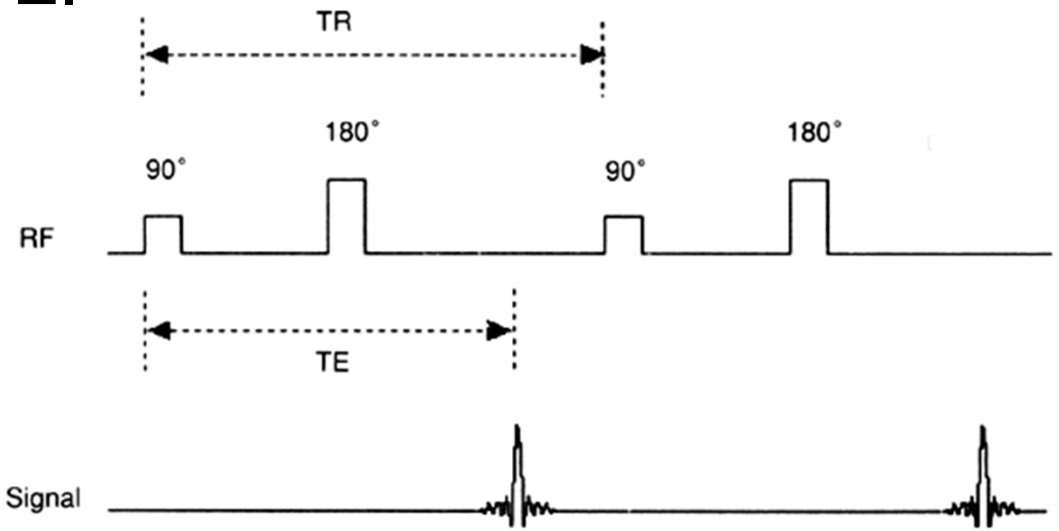
Echoes

- For MR imaging, it is more common to generate and measure the MR signal in the form of an **echo**
- Pulse sequences used to generate echoes: **spin echo** and **gradient echo**



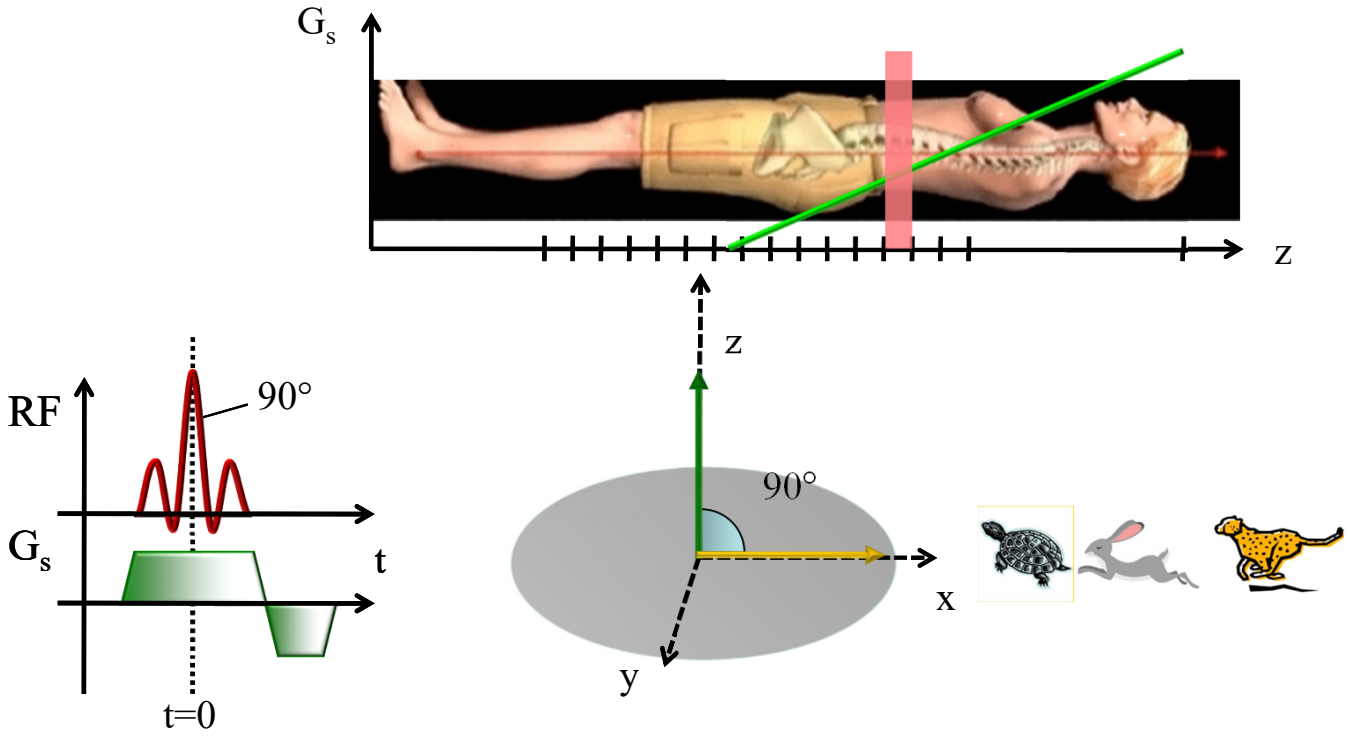
Spin Echo Sequence

- After the 90° excitation pulse, a 180° refocusing RF pulse is played out
- The 180° pulse must be applied at time TE/2 for the echo to occur at time TE.



Spin Echo Sequence

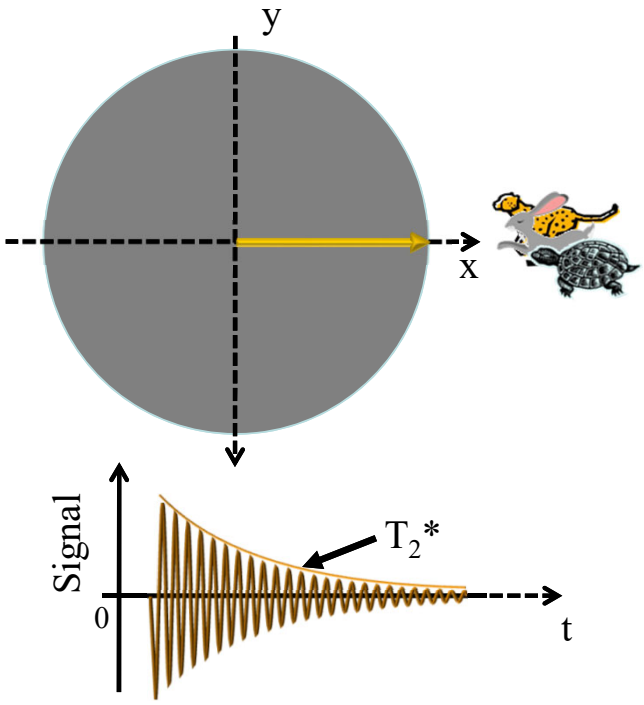
1) Slice selection at t=0 (RF excitation pulse 90°).

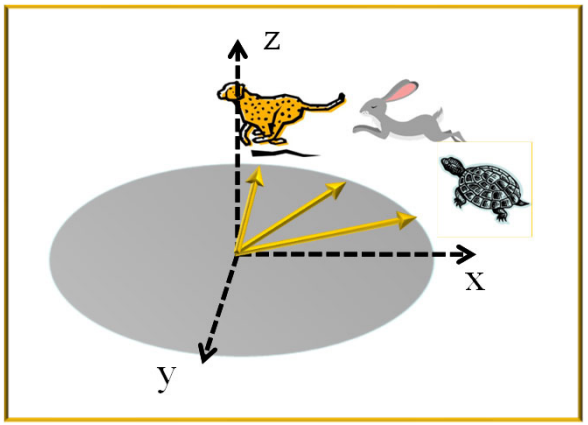


Spin Echo Sequence

2) Spin de-phasing

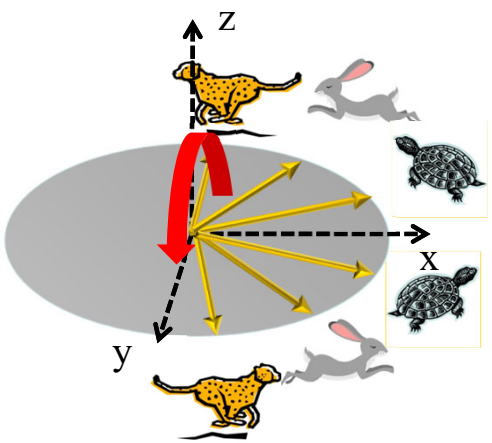
– transverse relaxation: T_2^* decay during TE/2.

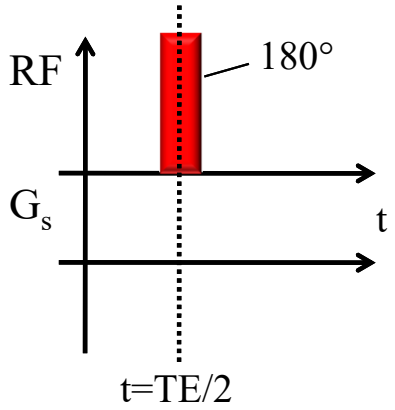




Spin Echo Sequence

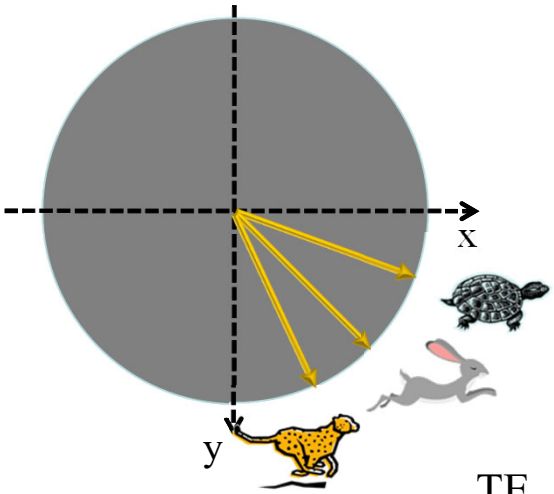
3) 180° refocusing RF pulse at t=TE/2.

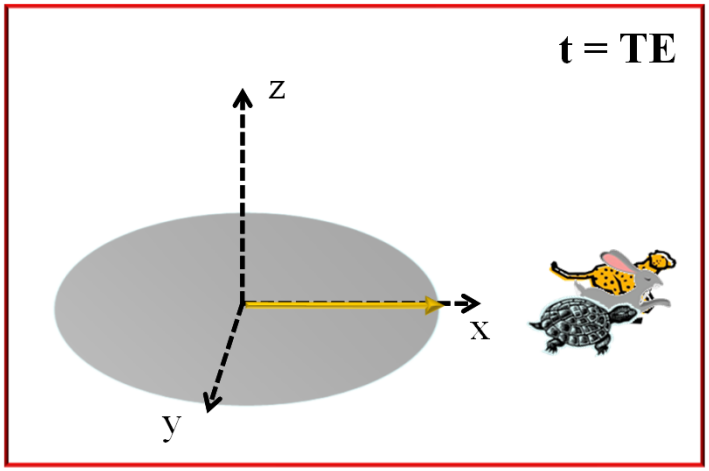


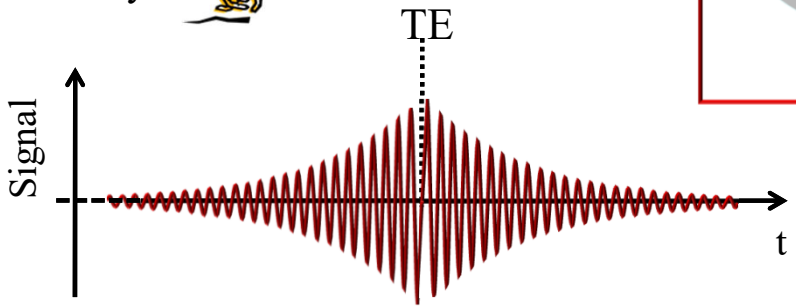


Spin Echo Sequence

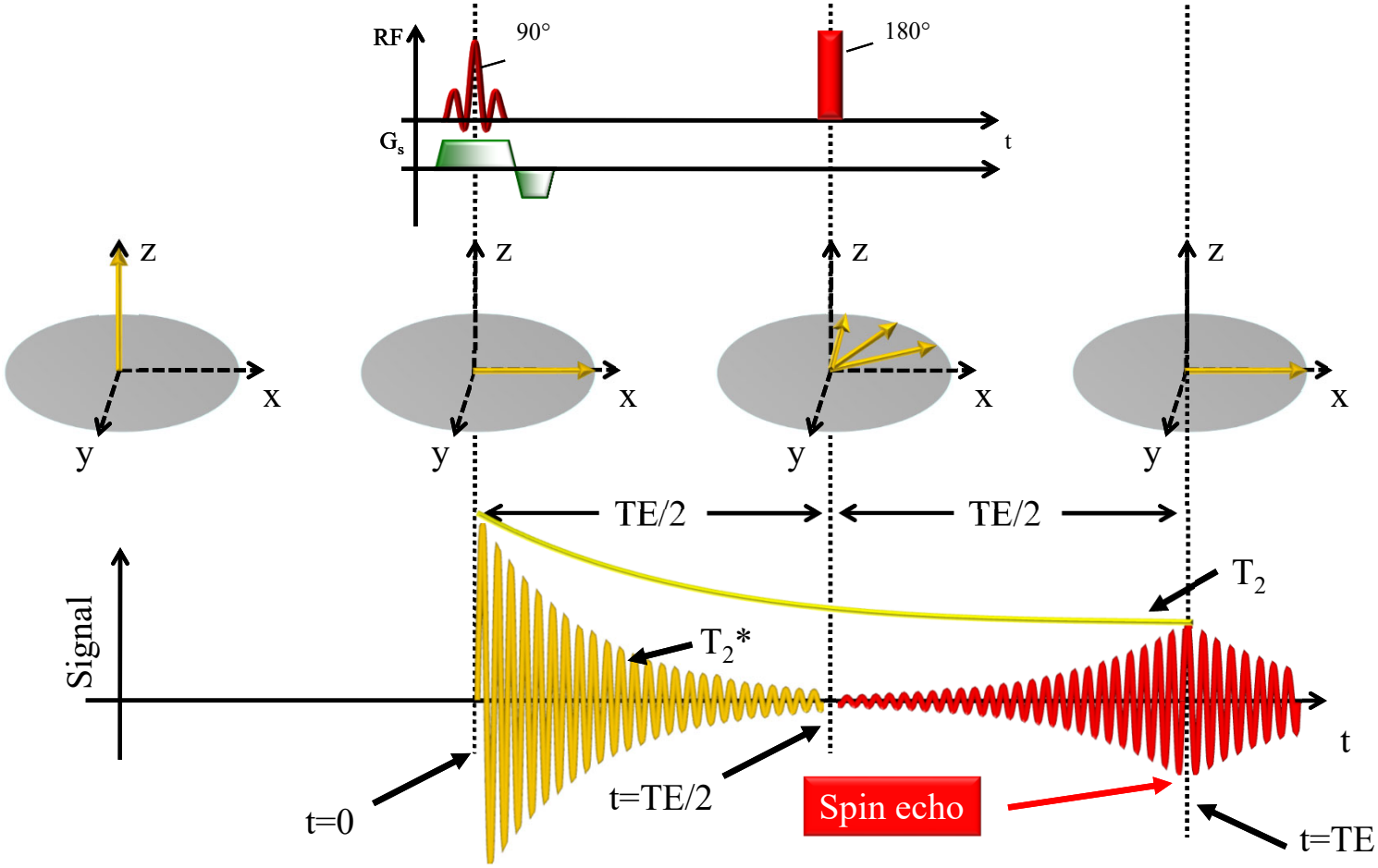
4) Spin echo at t=TE.



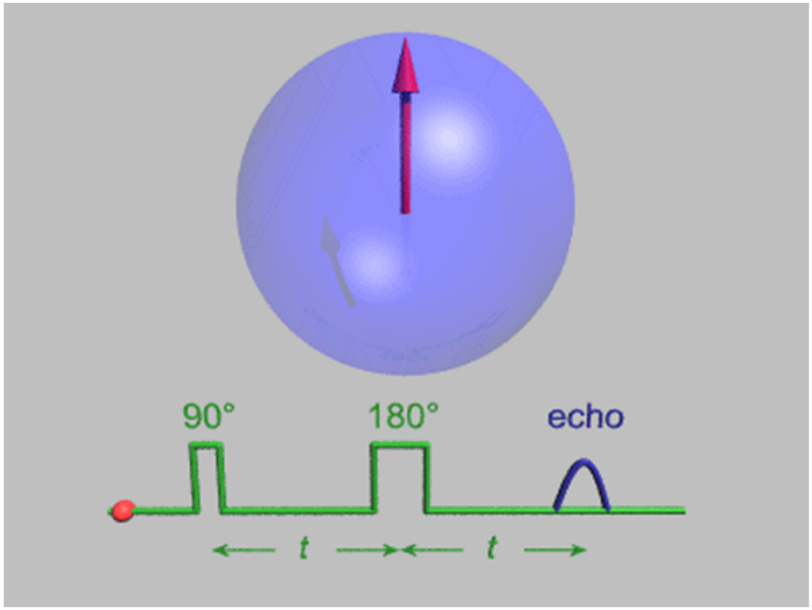




Spin Echo Sequence

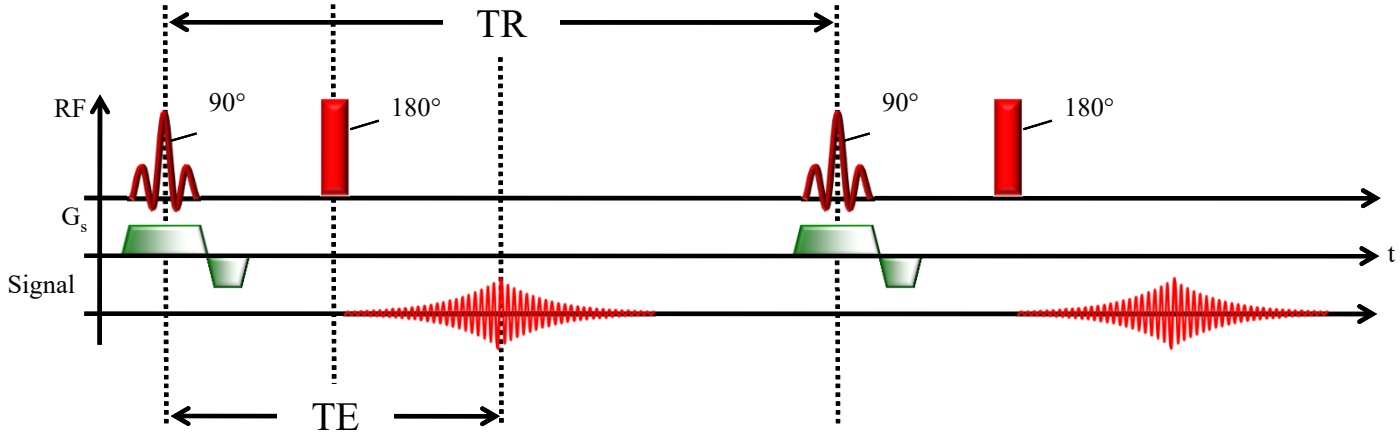


Spin Echo Sequence

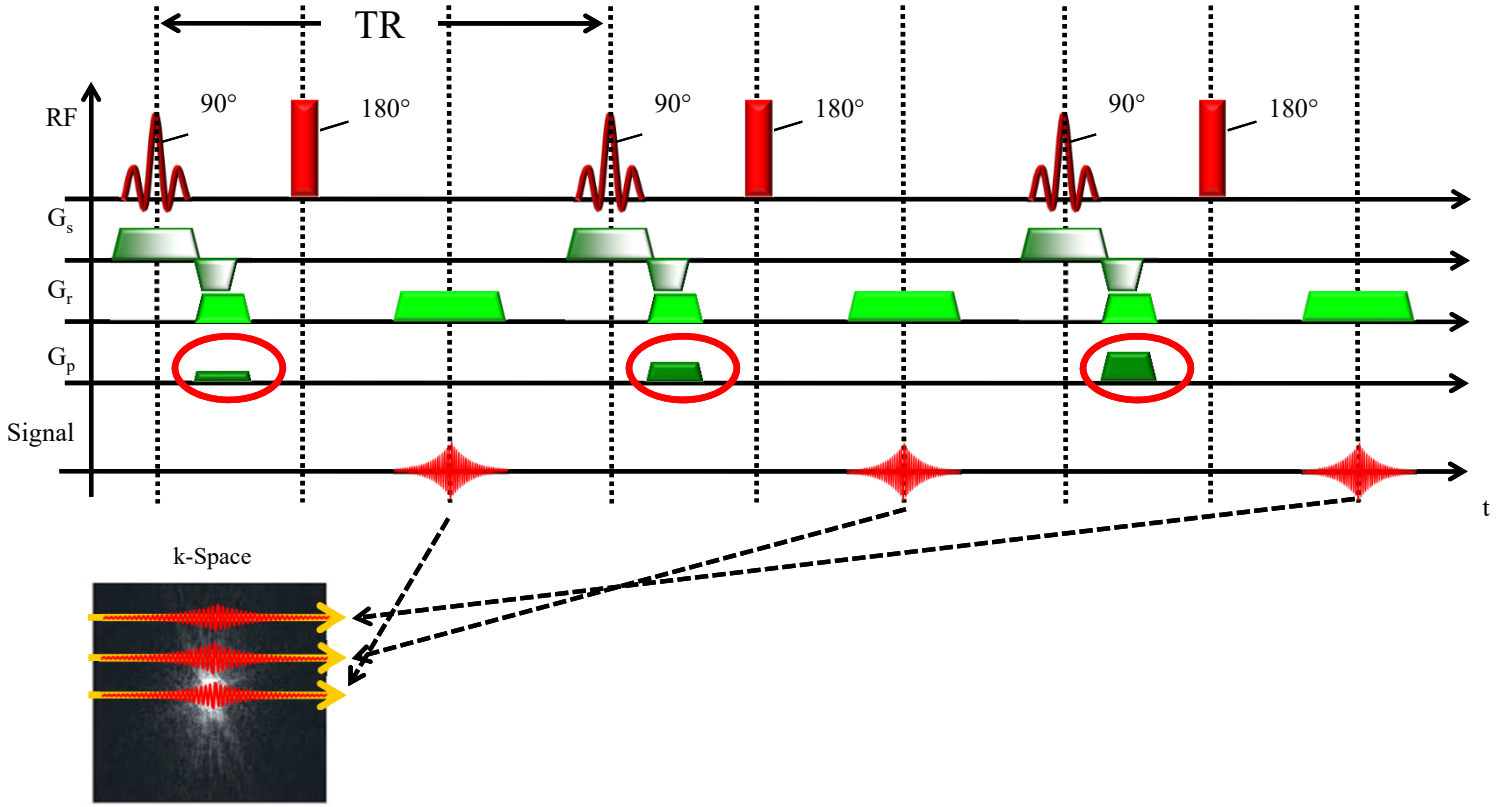


Spin Echo Sequence

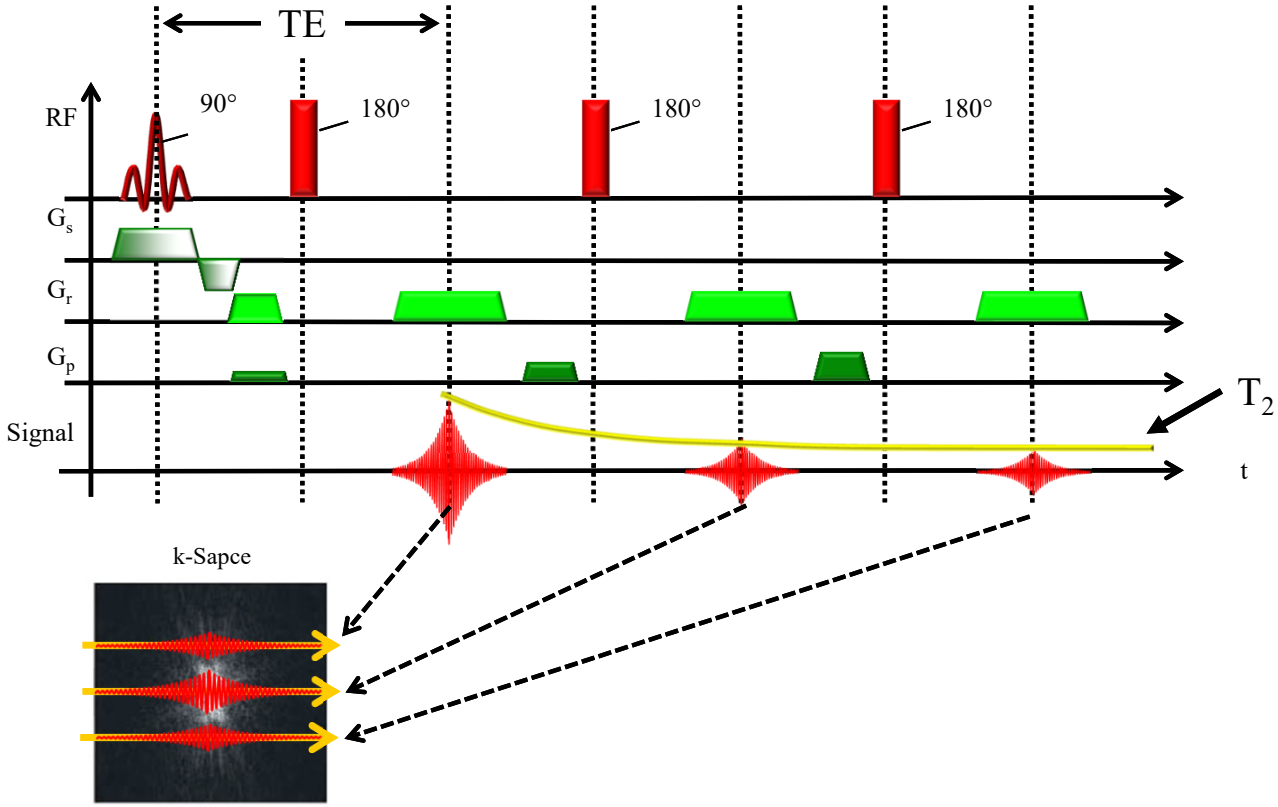
- Repetition time TR and echo time TE



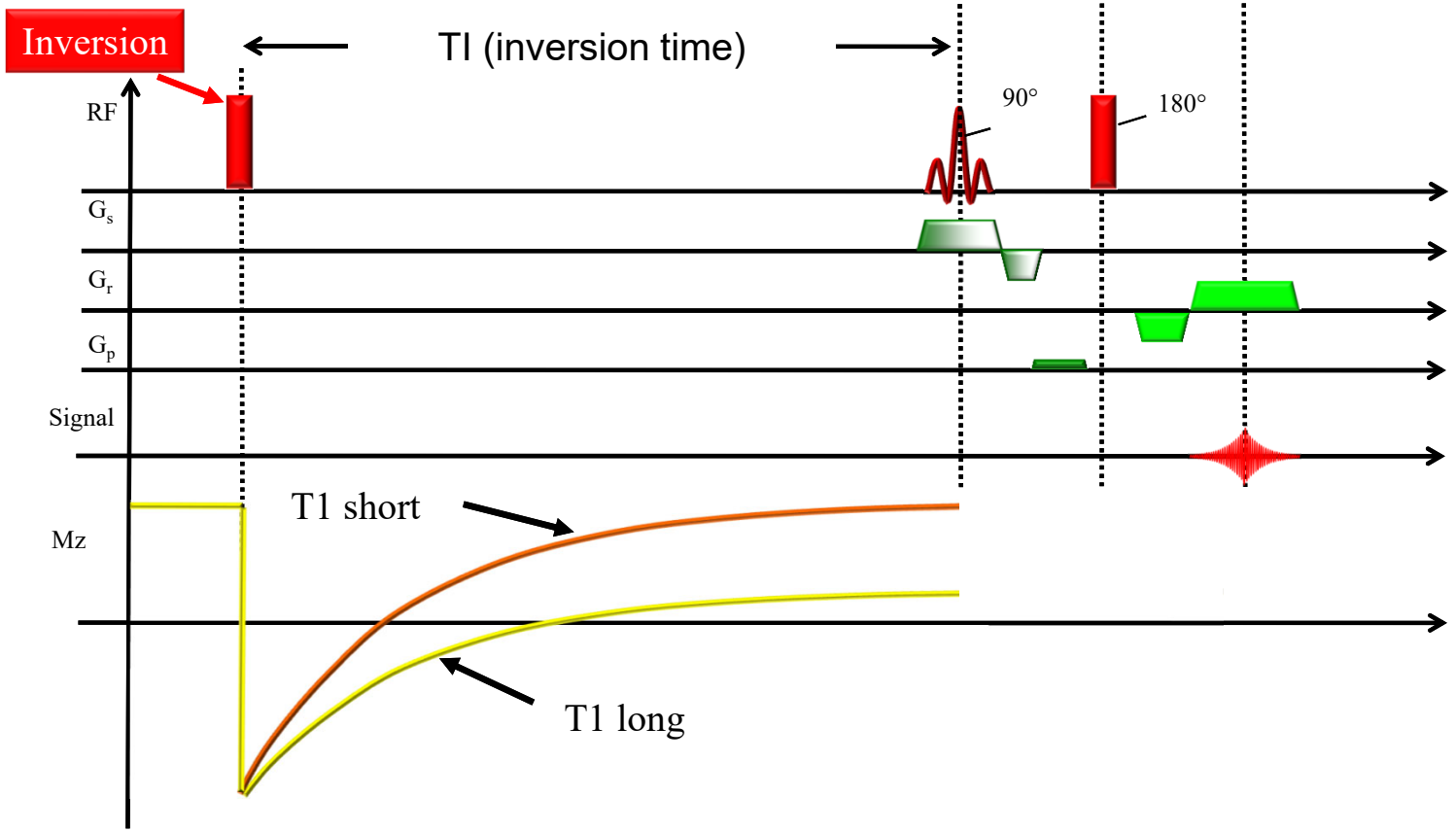
k-Space Filling with SE



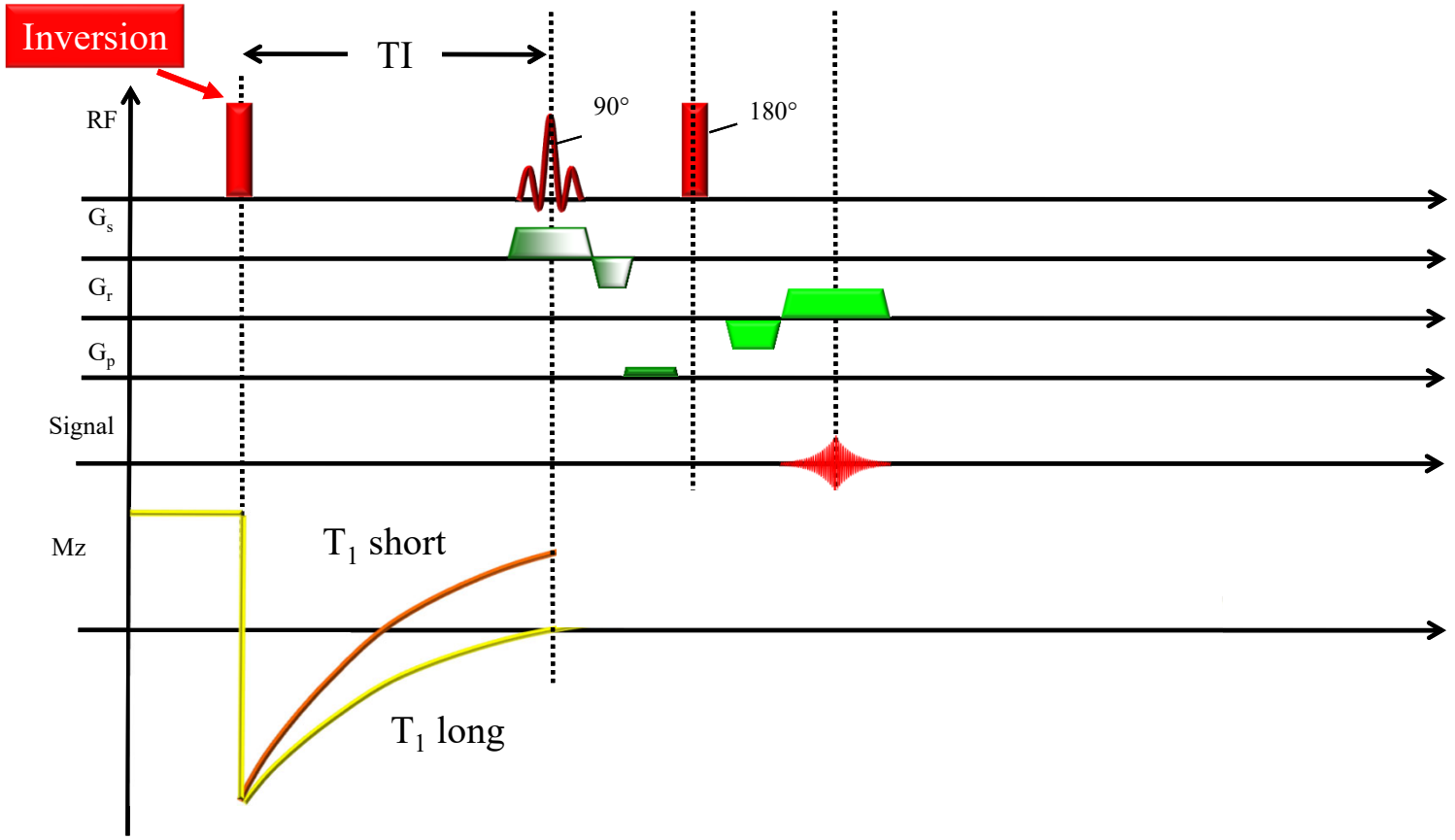
k-Space Filling with **Turbo** Spin Echo



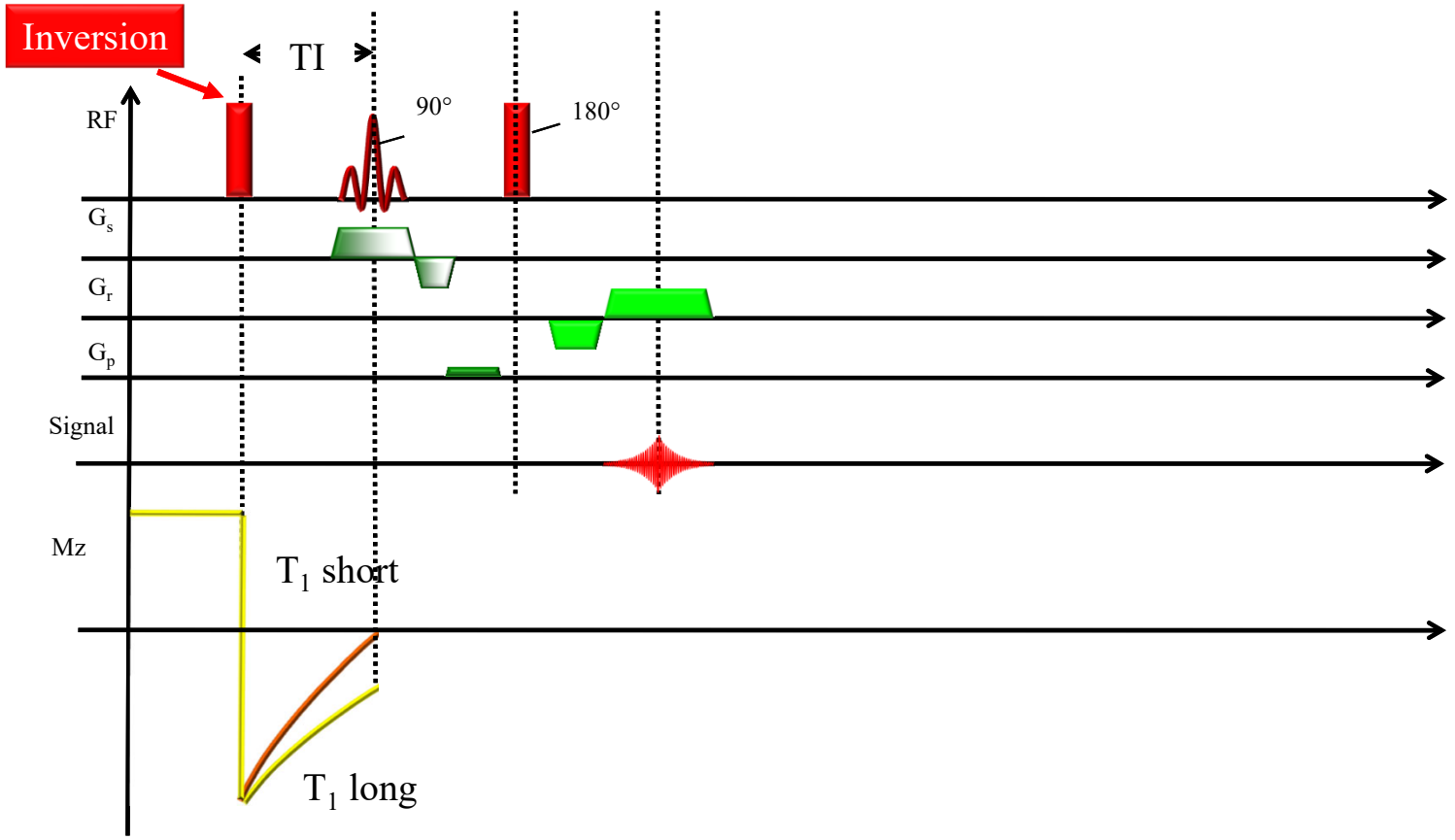
Inversion Recovery Preparation



Inversion Recovery Preparation

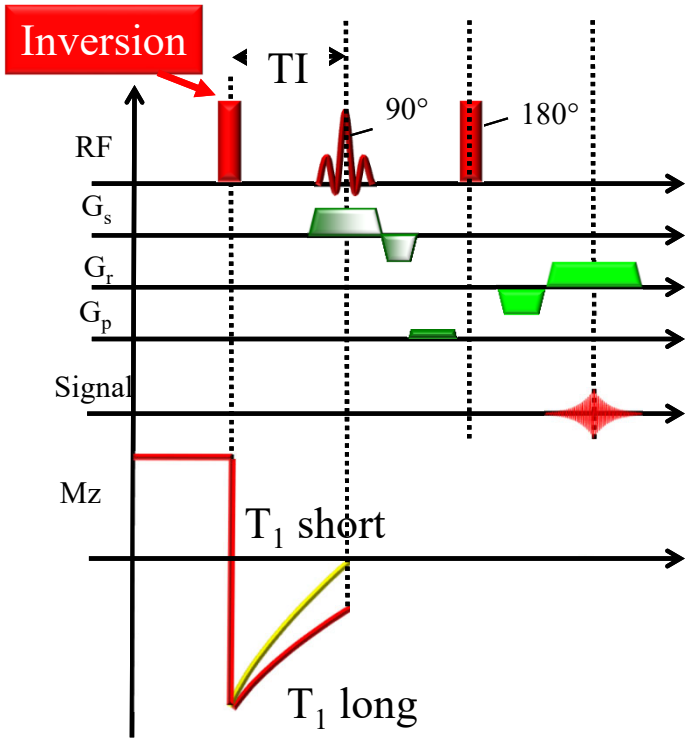


Inversion Recovery Preparation



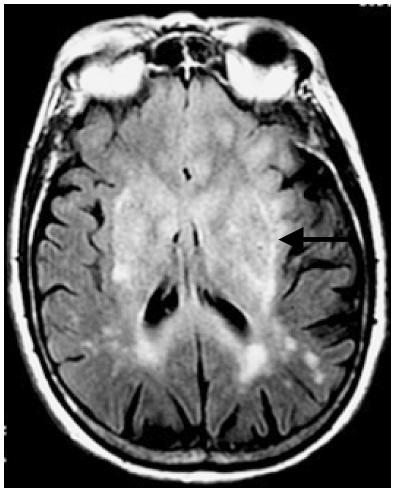
Example - STIR

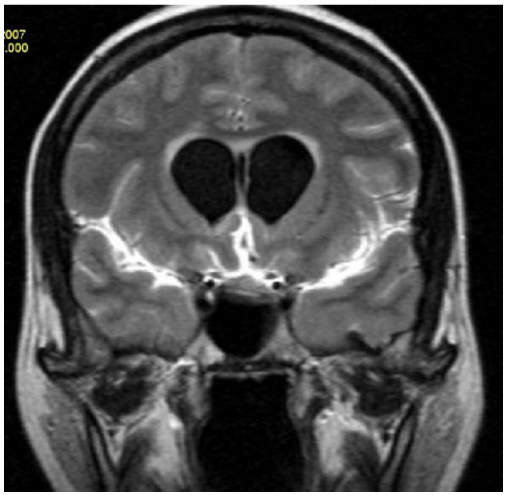
- Short-TI Inversion Recovery
- TSE with non-selective IR
- Short TI (usually 160-180 ms at 1.5T) to suppress fat
- Non-selective IR = robust, but inverts everything (so not post-Gd)



Example - FLAIR

- Fluid-Attenuated Inversion Recovery
- IR-TSE with TI chosen such that liquids (CSF, urine, blood, etc.) signals pass through zero





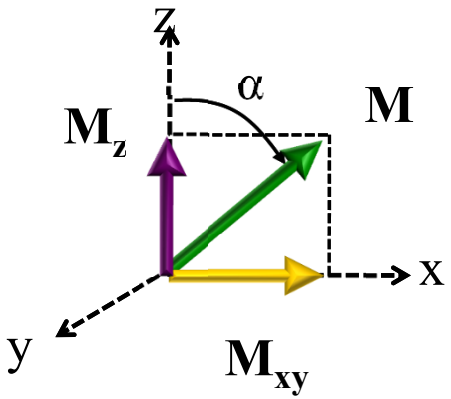
Wikipedia.org

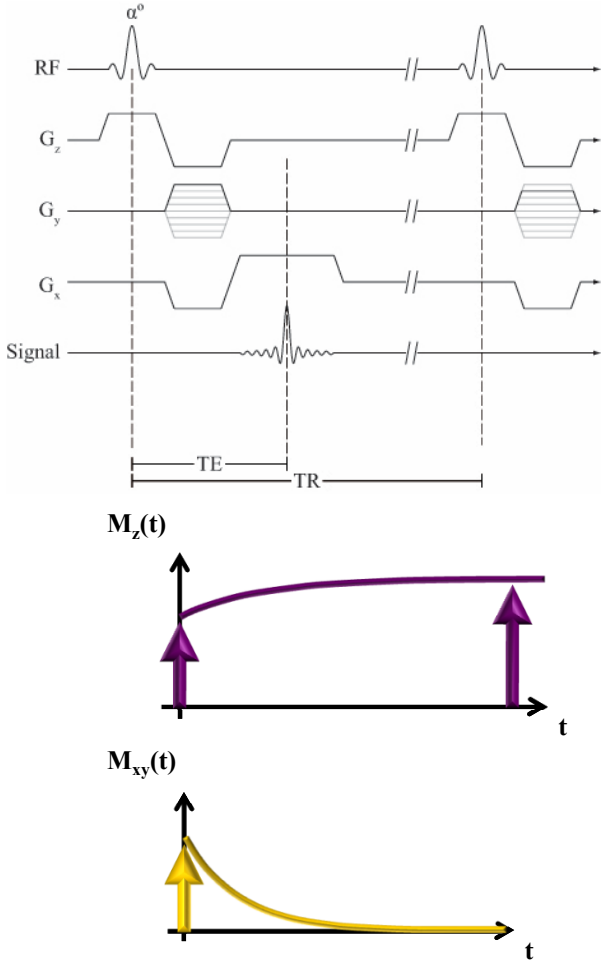
Spin Echo Sequence Summary

1. **t=0**: Slice selection and excitation with a 90° RF pulse and slice selection gradient G_s.
2. Spatial encoding with phase (G_p) and frequency (G_r) encoding gradients (line selection in k-space matrix).
3. **t=TE/2**: 180° refocusing RF pulse.
4. **t=TE**: refocus the spin with readout gradient to measure the MR signal (spin echo).
5. **t=TR**: repeat sequence to encode another k-space line.



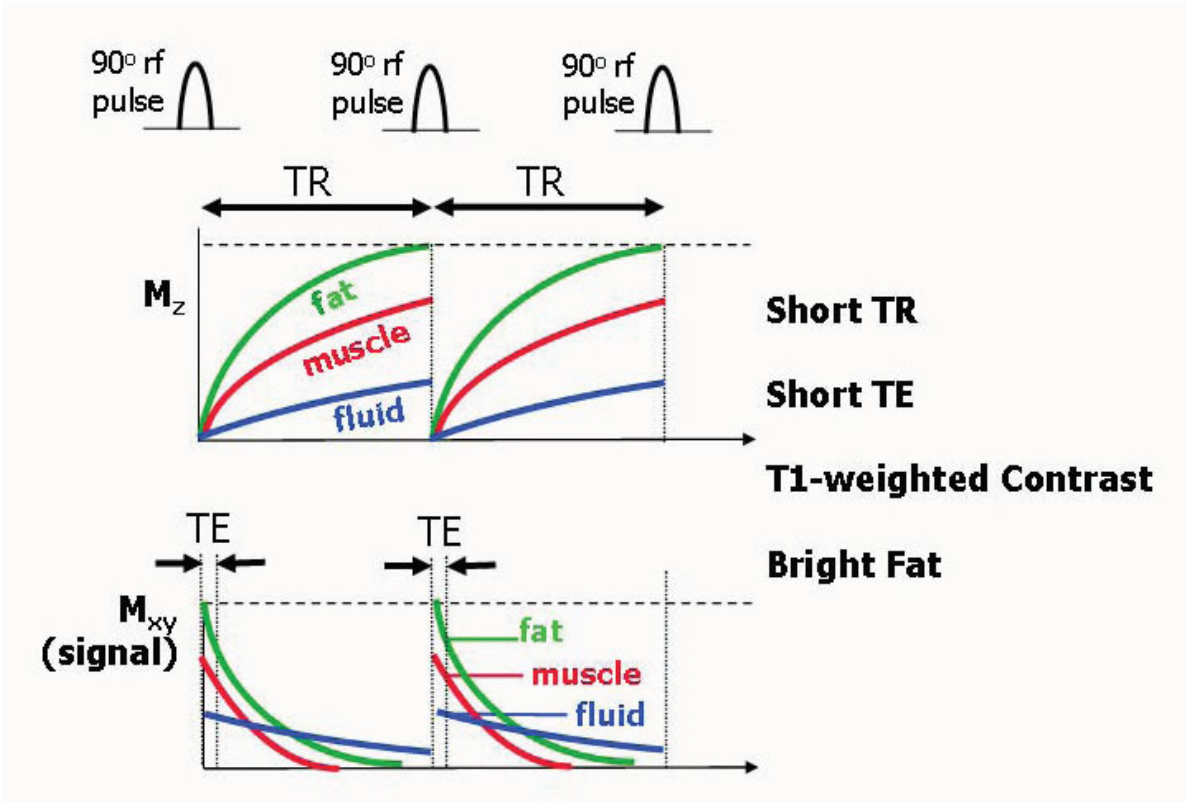
Image Contrast



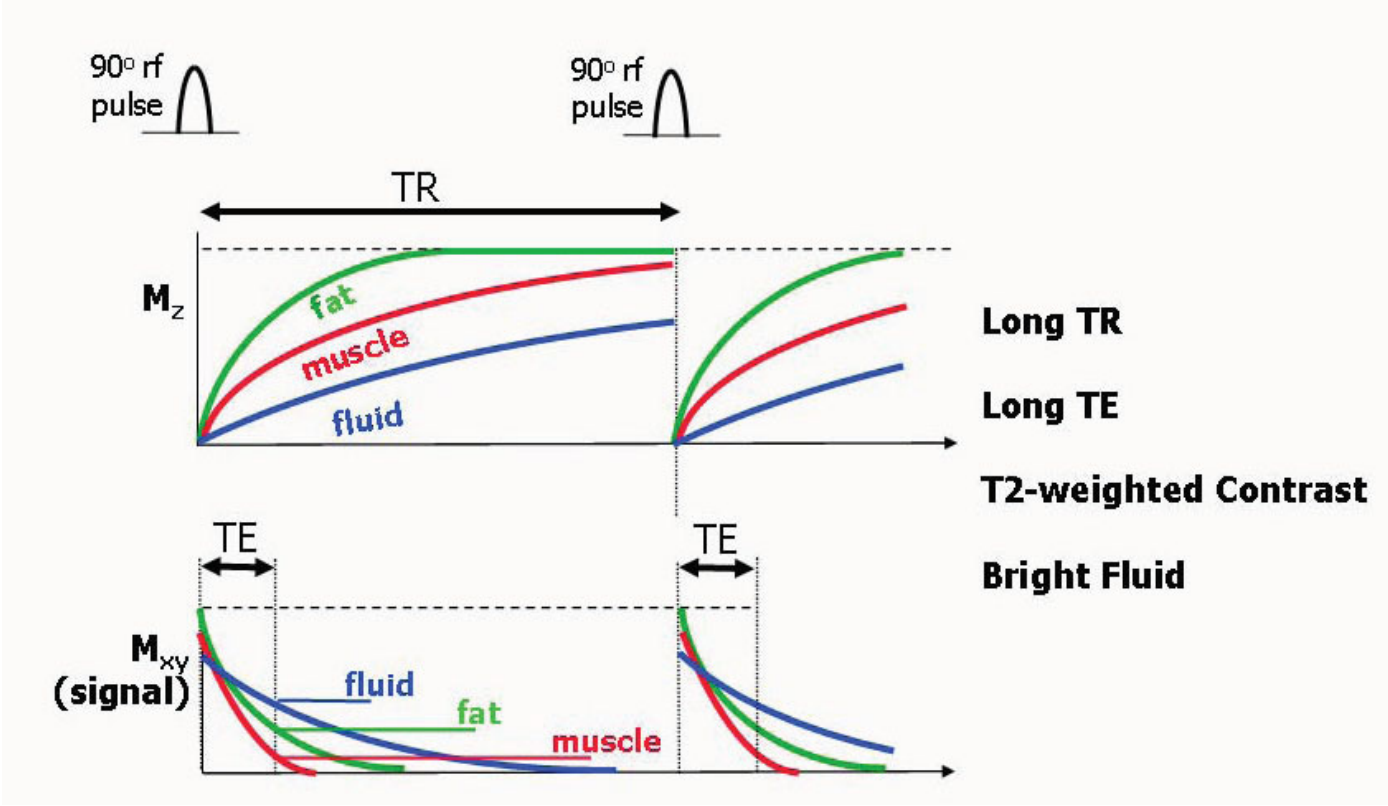


- Long TRs minimize T_1 effects, since all tissues have time to **fully recover** between excitations
- Short TEs minimize T_2 effects, since there is little time for T_2 decay differences **to appear**

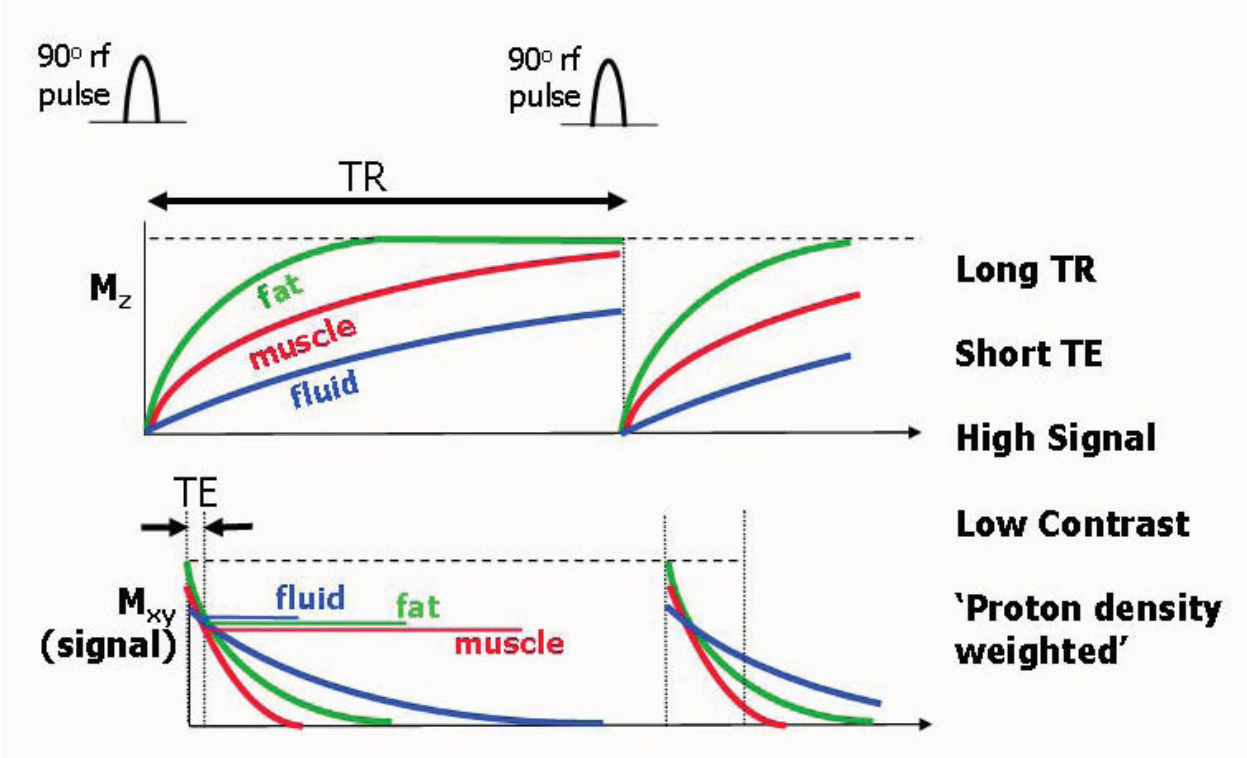
T_1-Weighted Contrast



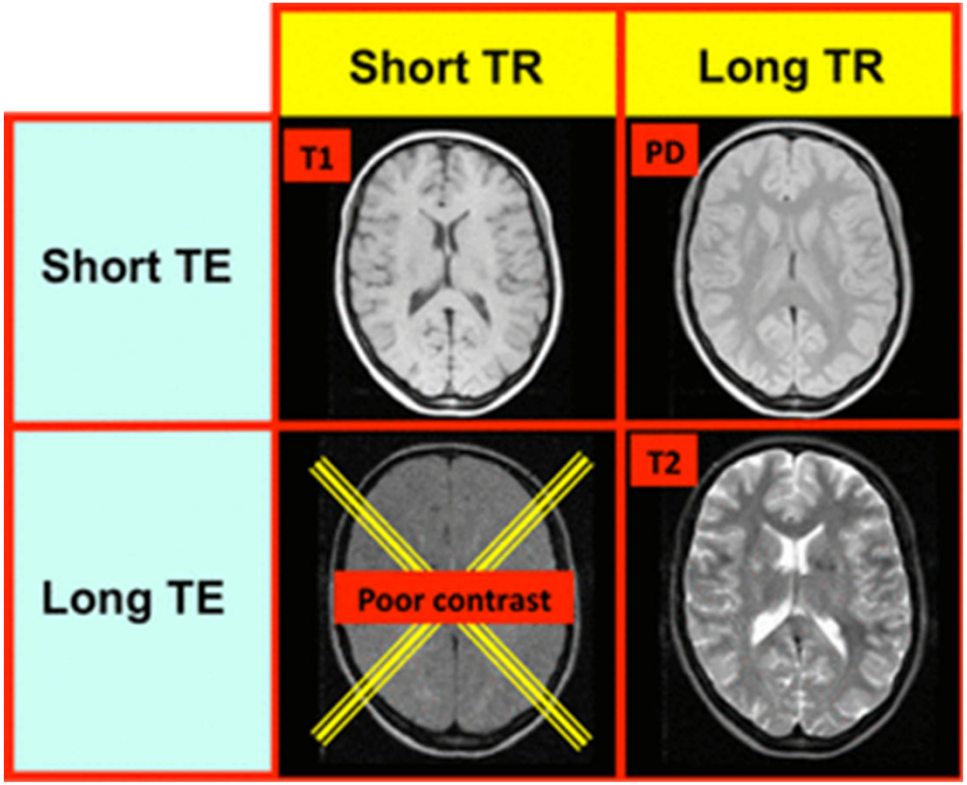
T_2-Weighted Contrast



Proton Density-Weighted Contrast

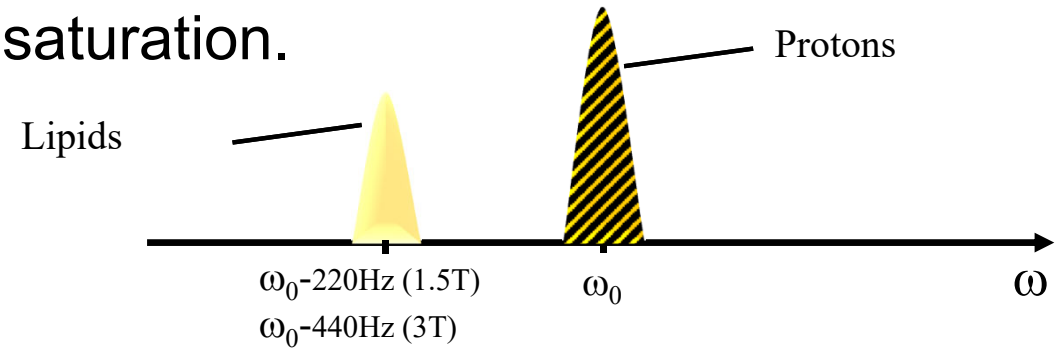


TE vs TR

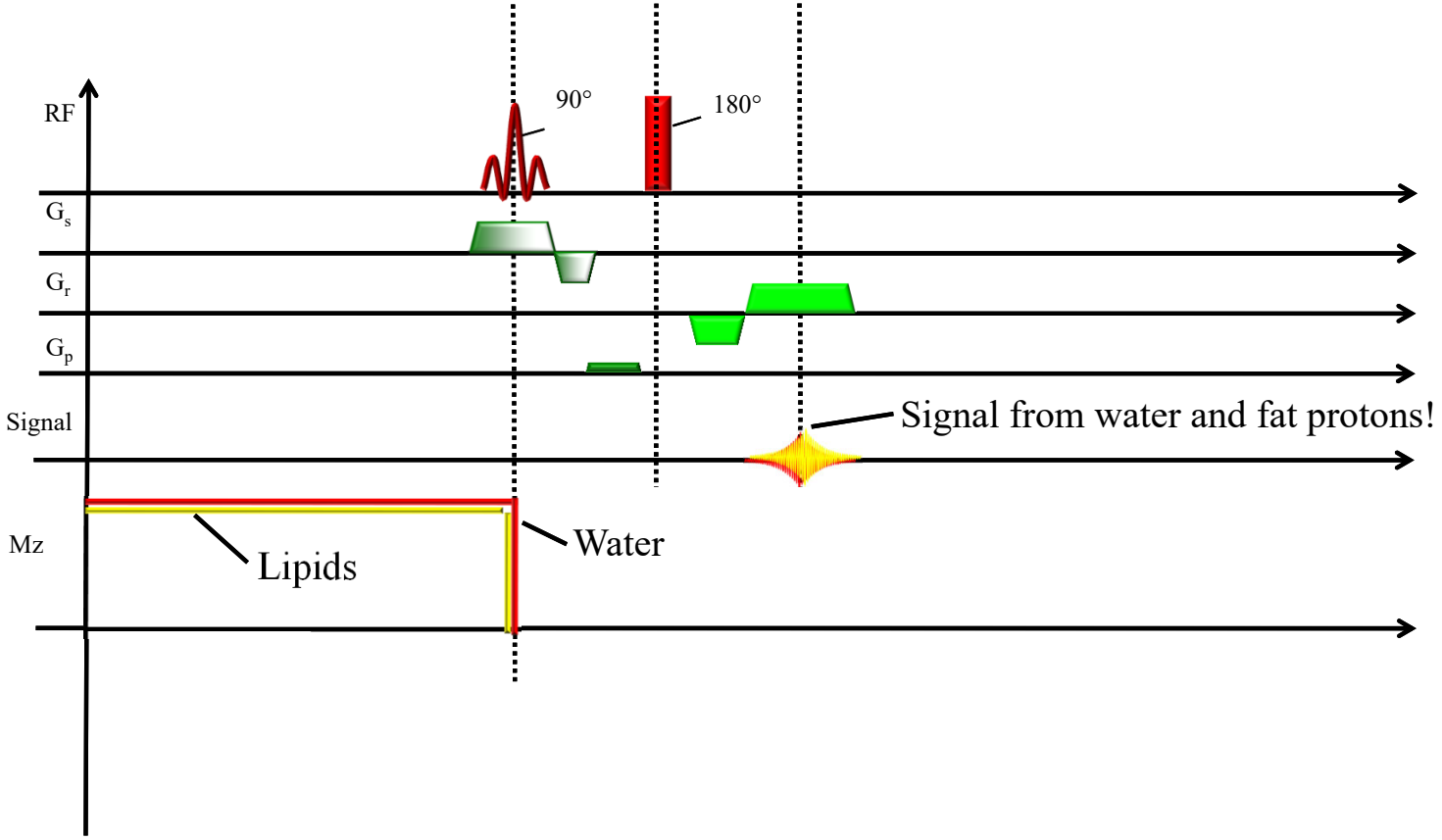


Fat Signal Suppression

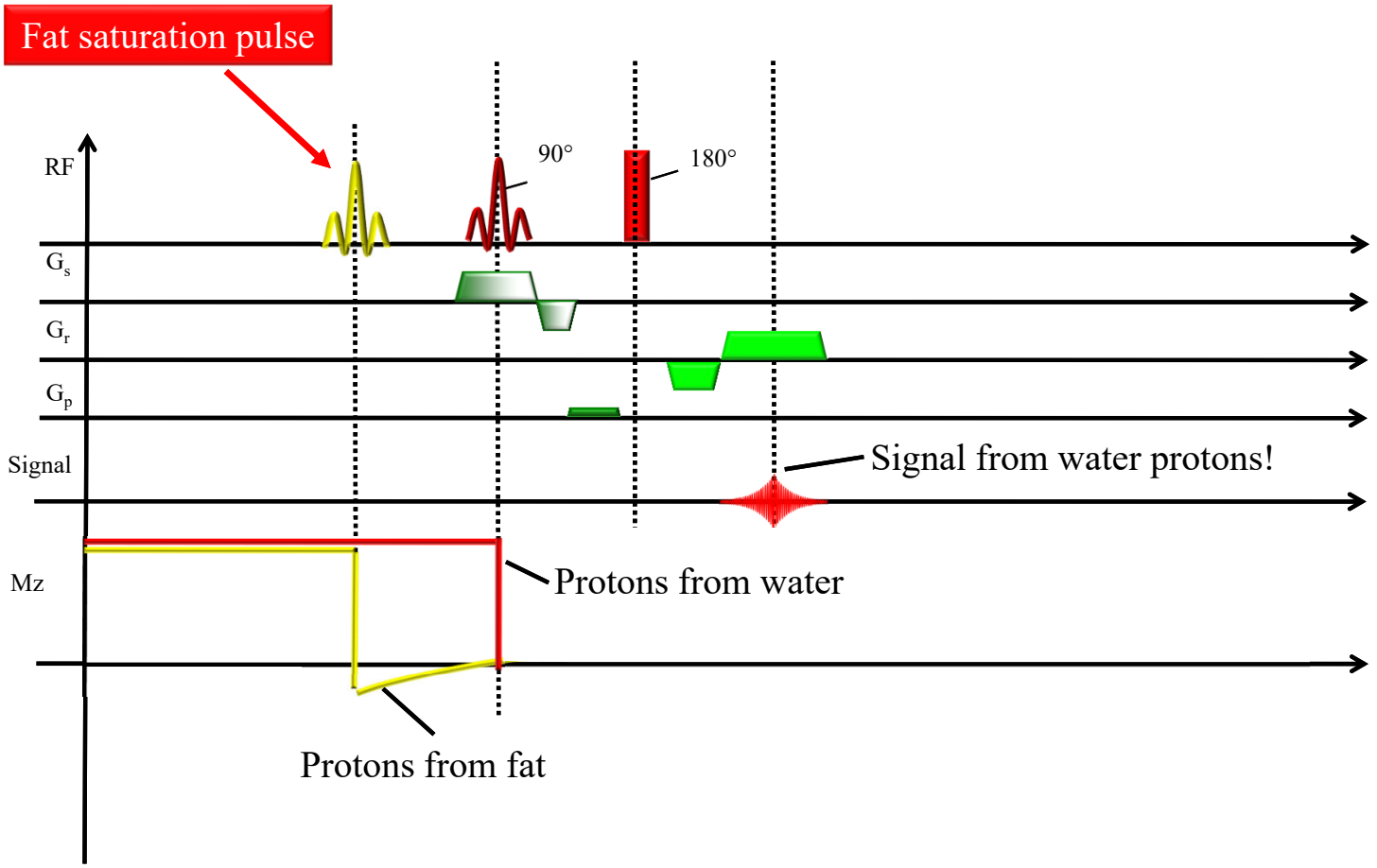
- Fat signal suppression techniques are used to suppress the signal from adipose tissue.
- Lipid protons and hydrogen protons from water have a small difference in resonance frequency , which is related to the different electronic environments.
- This so-called chemical shift allows frequency-selective fat saturation.



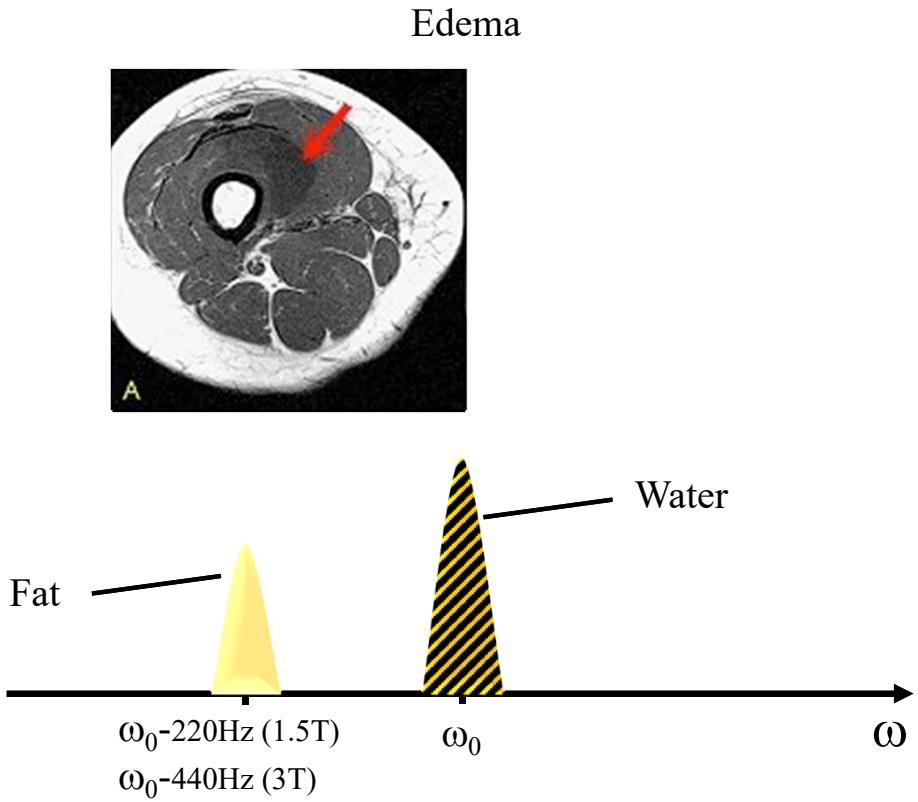
Without Fat Saturation Pulse



With Fat Saturation Pulse



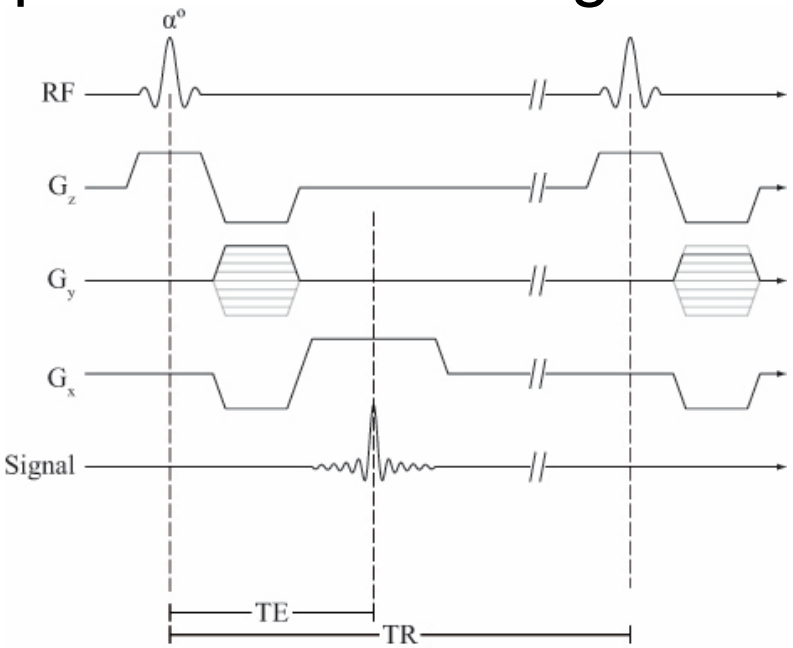
Fat Saturation



Gradient echoes

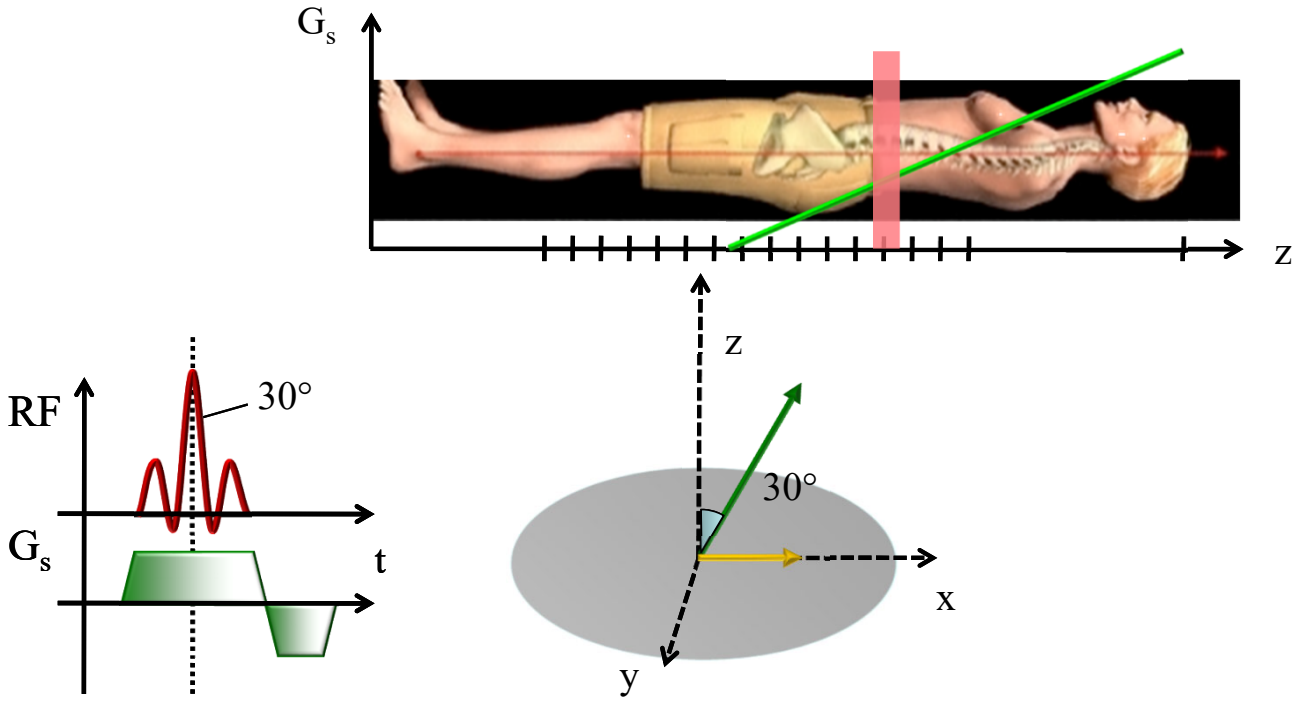
Gradient Echo Sequence

- An RF excitation pulse (less than 90°) is followed by a controlled application of **magnetic field gradients** to de- and refocus the spins and create a gradient echo.

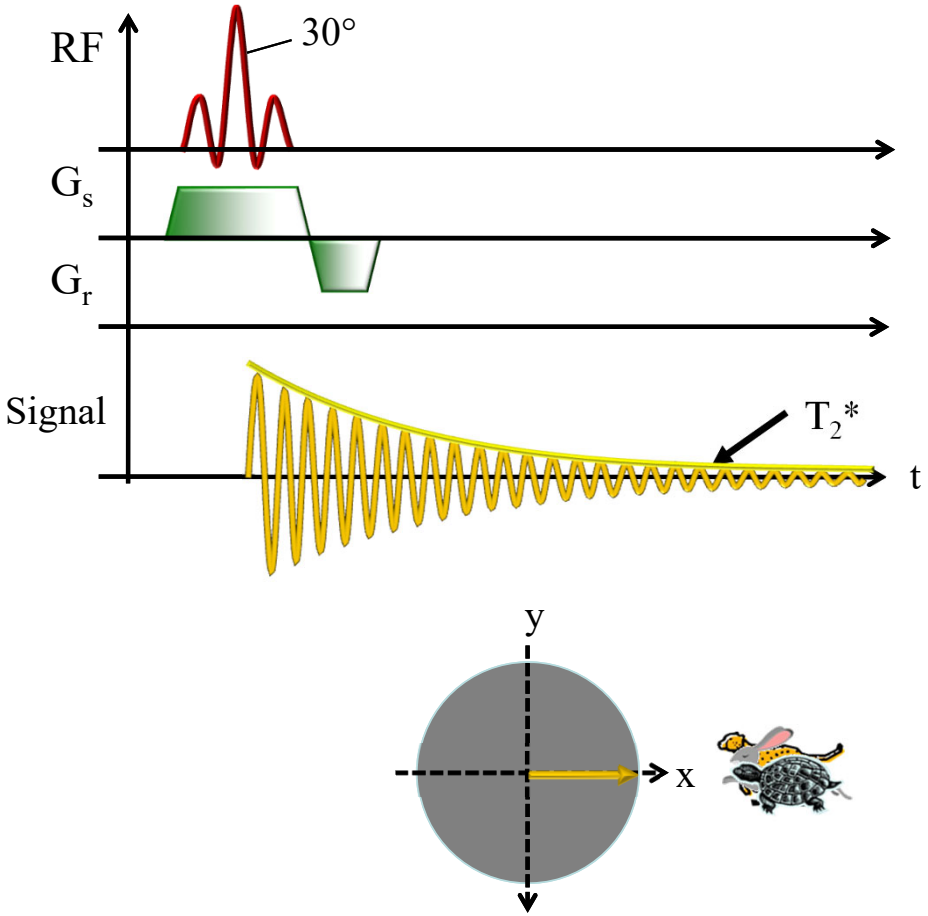


Gradient Echo Sequence

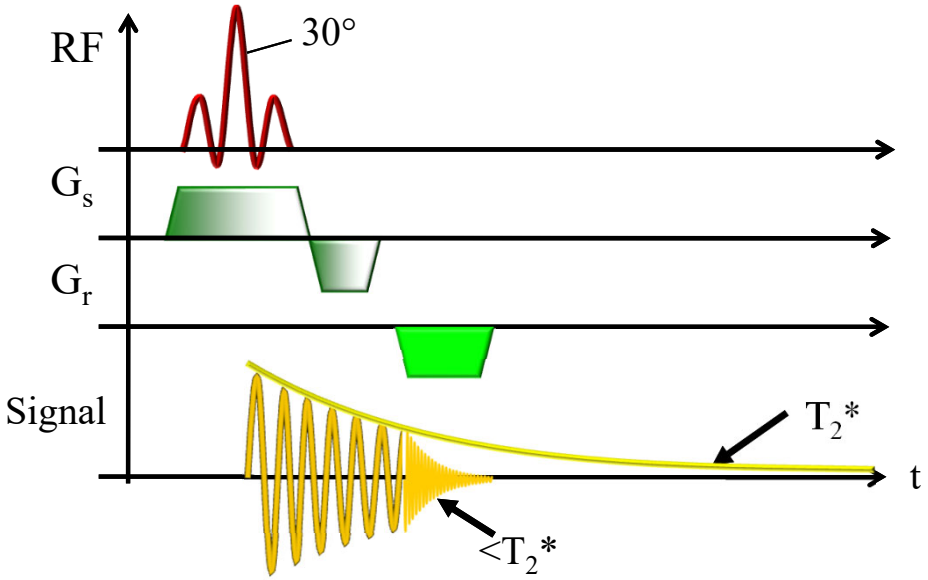
1) Slice selection at t=0 (RF excitation pulse <90°).

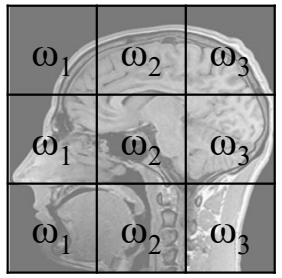


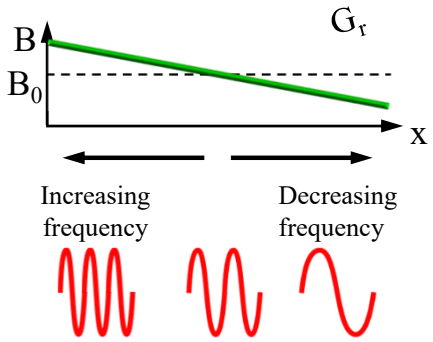
Gradient Echo Sequence



Gradient Echo Sequence

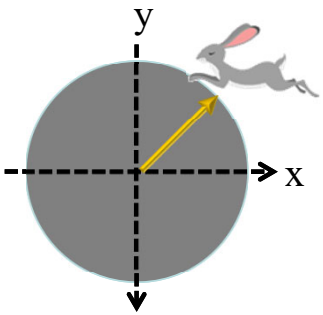




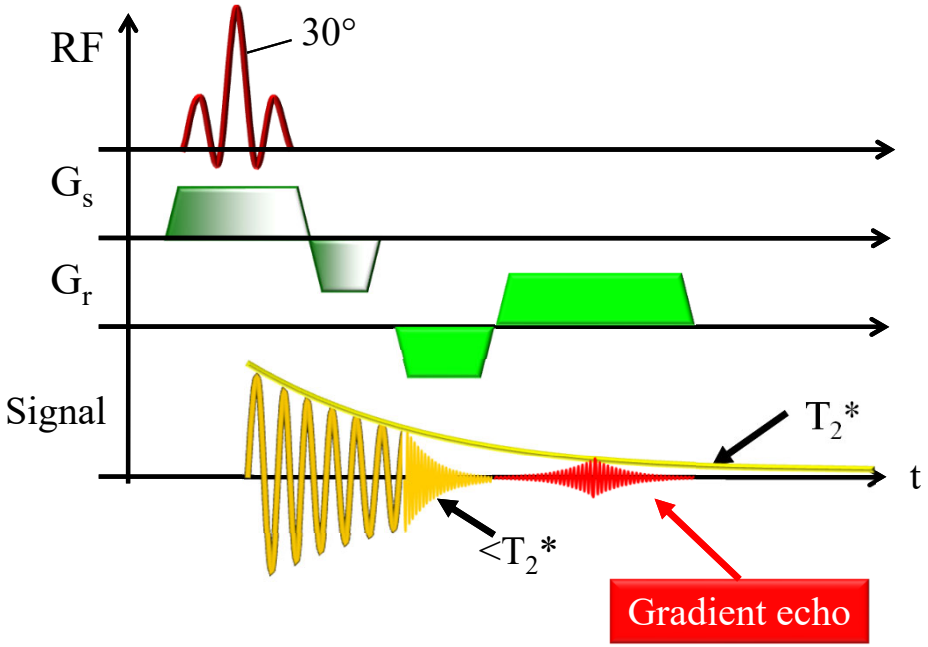


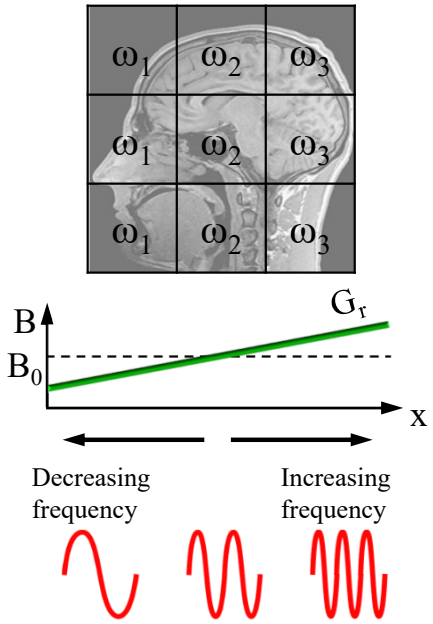
2) Spin de-phasing

– Transverse relaxation: <<T_2*, accelerated by readout gradient G_r).

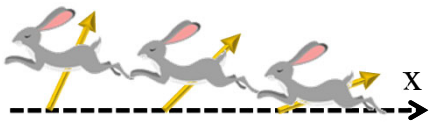


Gradient Echo Sequence



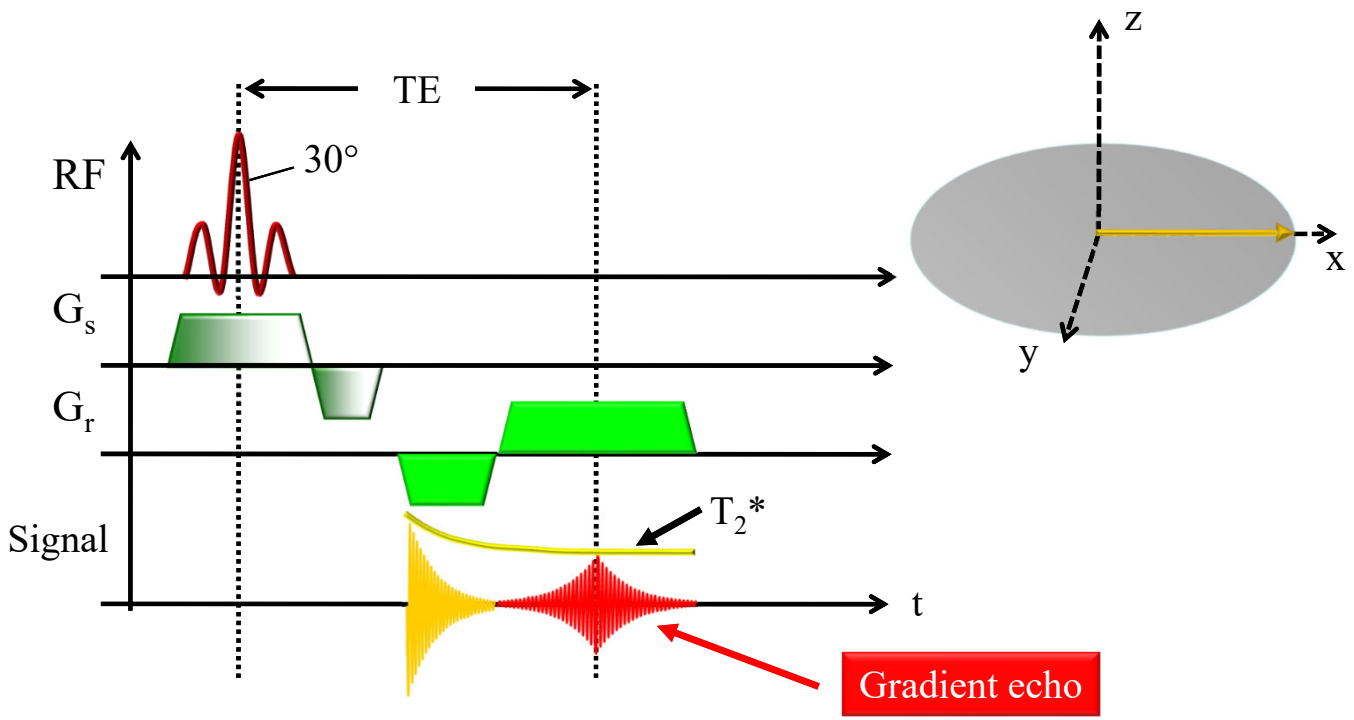


3) Refocusing of the spins with bipolar gradient.



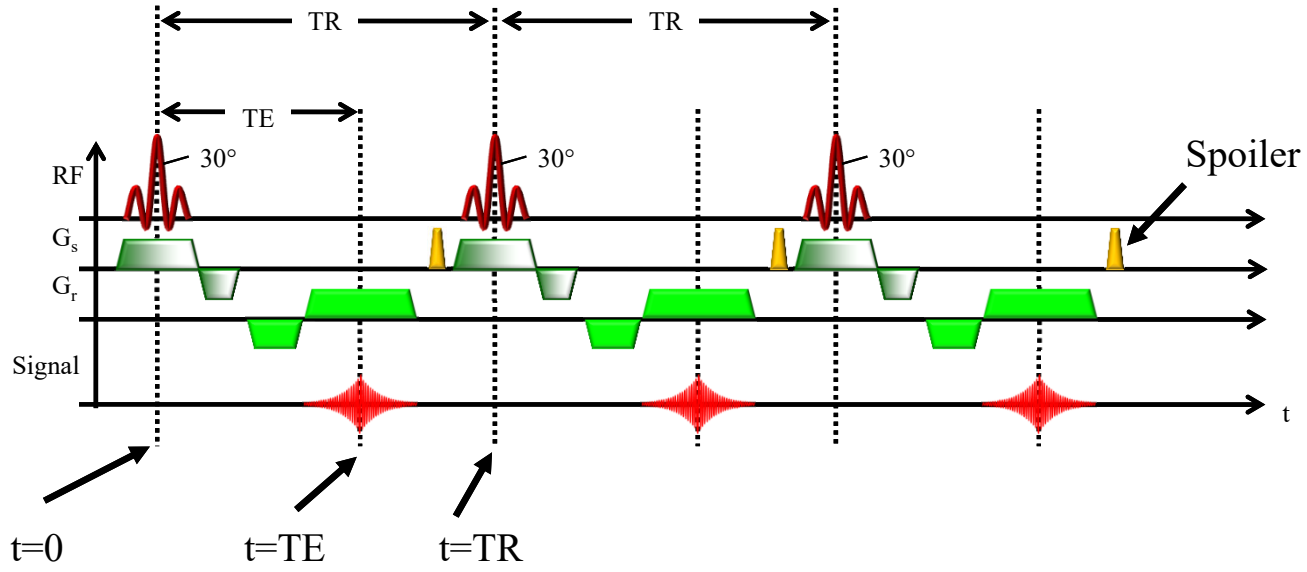
Gradient Echo Sequence

- Gradient echo at time TE

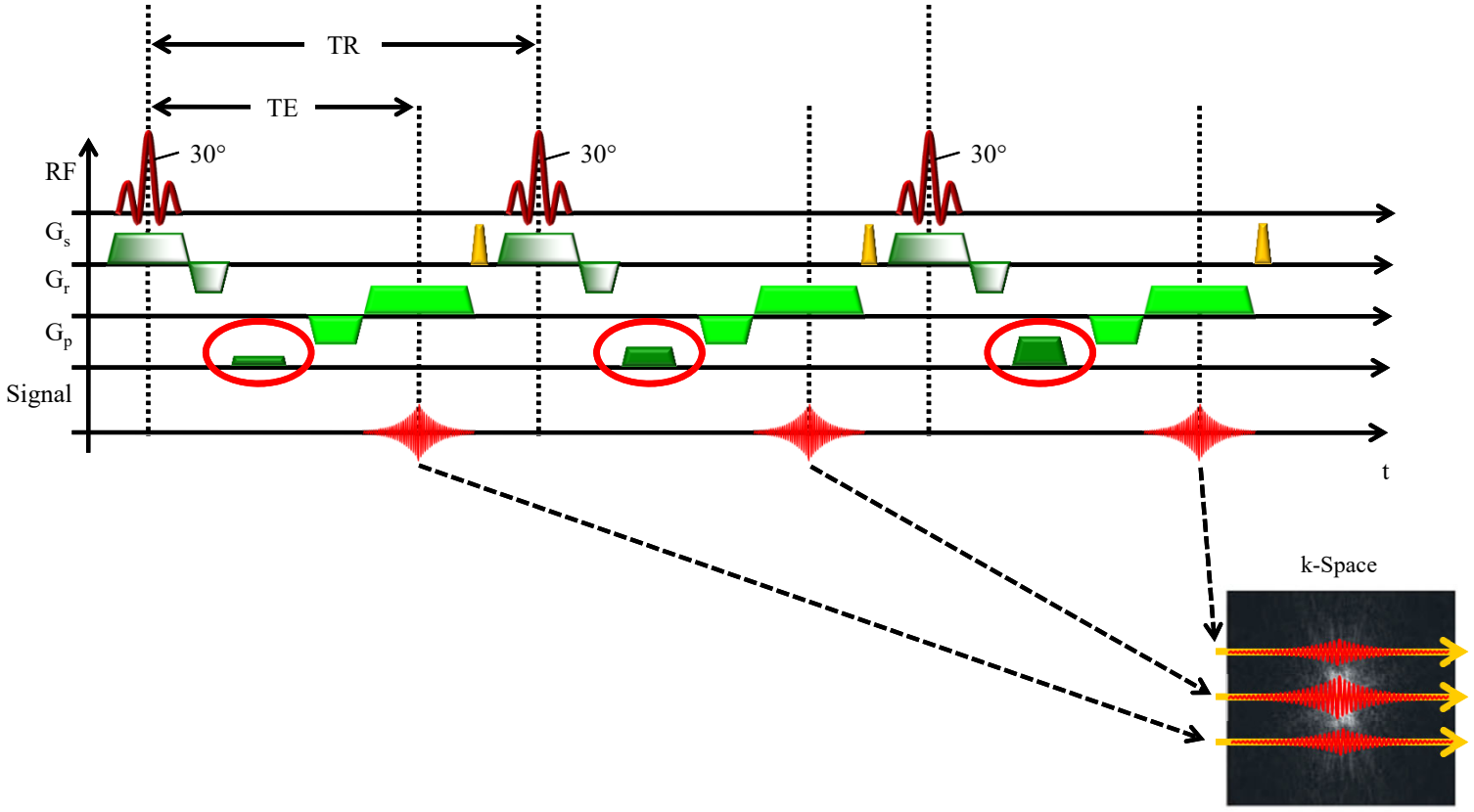


Gradient Echo Sequence

- Repetition time TR



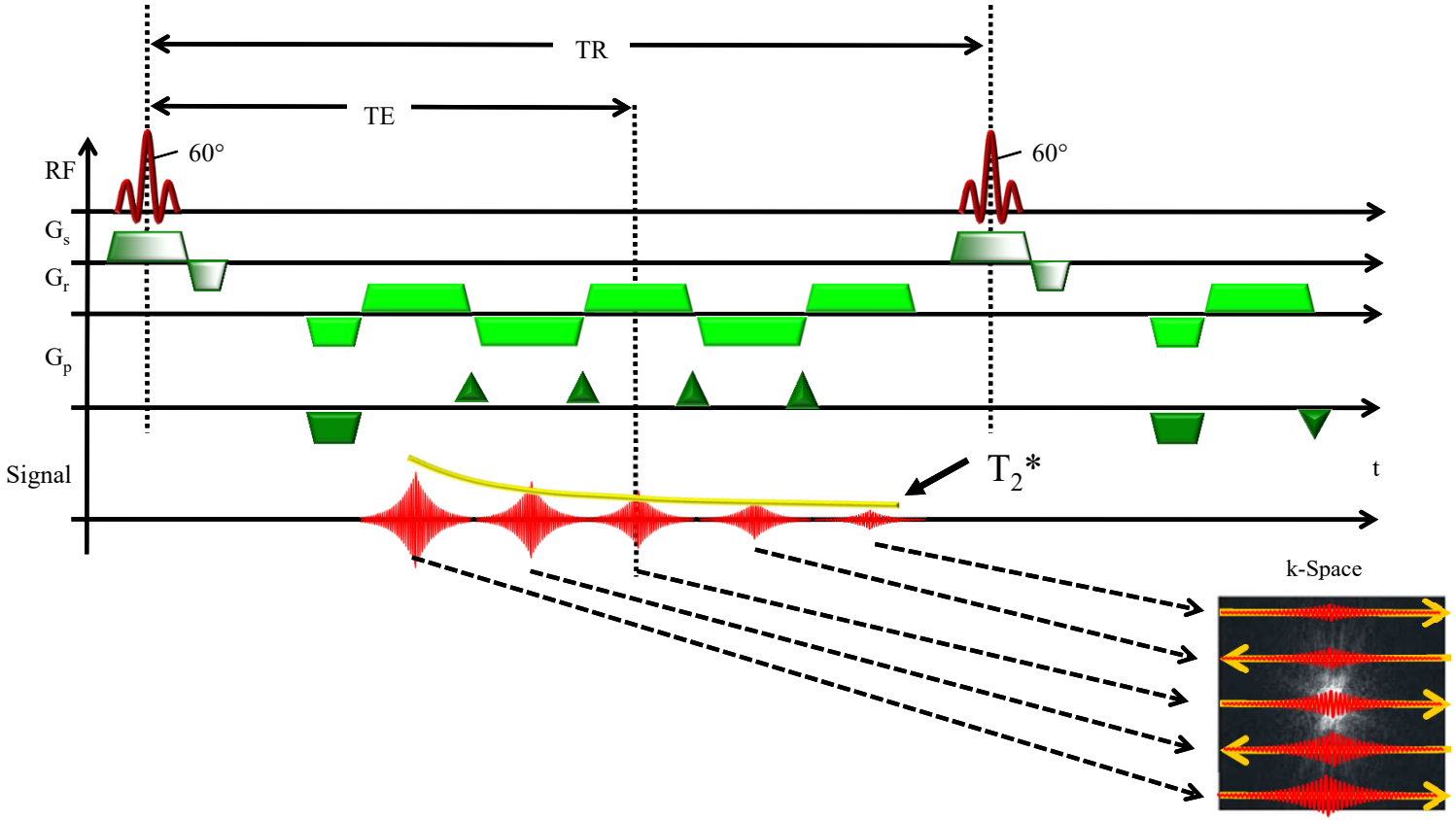
k-Space Filling with GRE Sequence



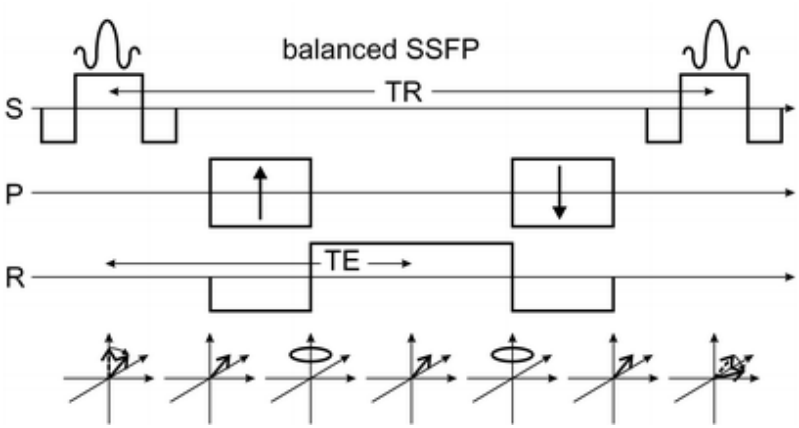
Gradient Echo Sequence Summary

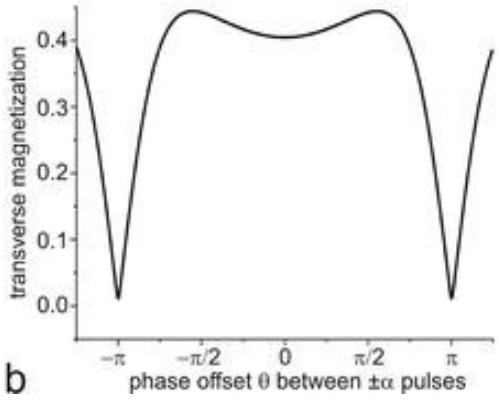
- 1.) t=0: Slice selection and excitation with a <90° RF pulse and slice selection gradient G_s.
- 2.) Spatial encoding with phase (G_p) and frequency (G_r) encoding gradients (line selection of k-space matrix).
- 3.) t=TE: Refocus spins readout gradient to measure the MR signal (gradient echo).
- 4.) t=TR: Repeat sequence to encode another k-space line.

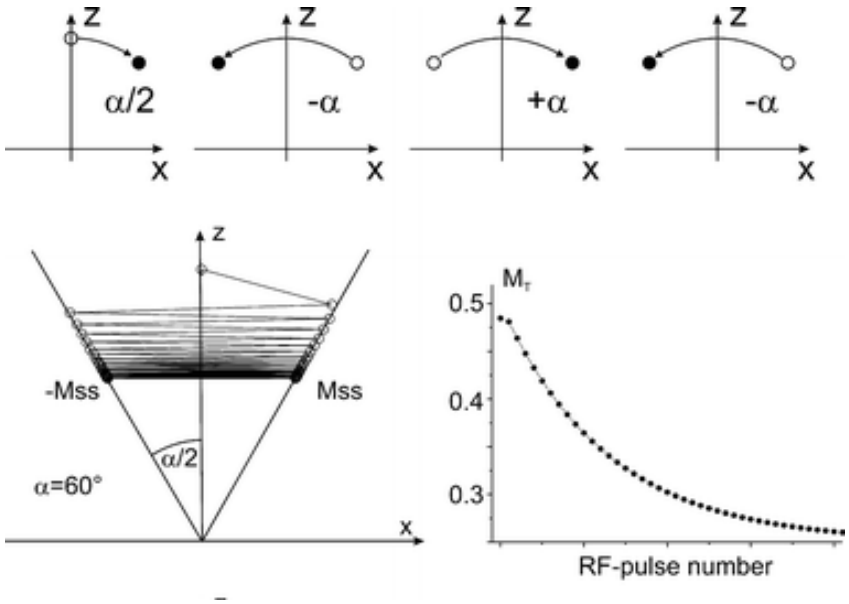
Echoplanar Imaging (EPI)



Balanced steady-state free precession (bSSFP)



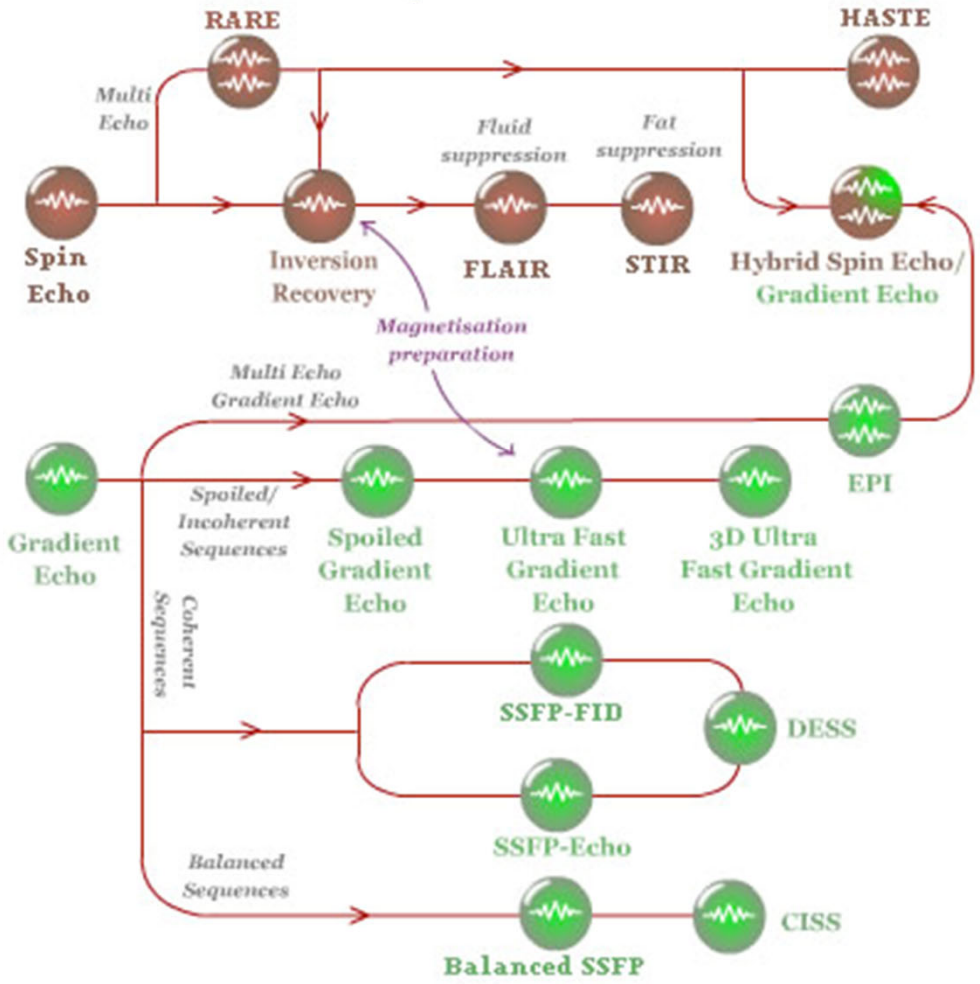




- Everything balanced – no need to dephase
- Allows for high flip angle
- Dark rim artifacts in inhomogeneities

Scheffler & Lehnhardt. Eur Radiol 2003

Families of Pulse Sequences



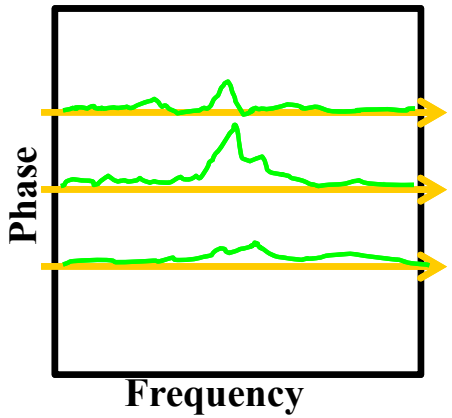
Families of Pulse Sequences

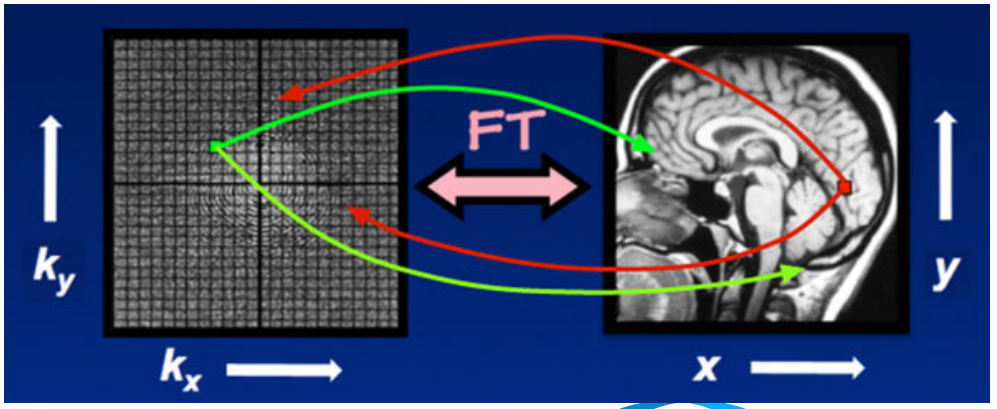
Sequence	Siemens	GE	Philips	Hitachi	Toshiba
Generic Gradient Echo	GRE	GRE	FFE	GE	FE
RF-Spoiled GRE	FLASH	SPGR	T1-FFE	RSSG	T1-FFE
Coherent GRE with "FID" Refocusing	FISP	GRASS	FFE	SARGE (SG)	FE
Coherent GRE with "Echo" Refocusing	PSIF	SSFP	T2-FFE	TRSG	SSFP
Coherent GRE with Balanced "FID/Echo" Refocusing	True FISP	FIESTA	Balanced FFE	BASG	True SSFP
Coherent Balanced GRE using Dual-excitation	CISS	FIESTA-C	---	PBSG	---
Coherent Double GRE using Combined "FIDs" & "Echoes"	DESS	MENSA	---	---	---
Spoiled GRE using Combined Multiple FIDs	MEDIC	MERGE	M-FFE	---	---
Ultrafast GRE	TurboFLASH (2D) MP-RAGE (3D)	Fast GRE BRAVO (3D)	TFE 3D T1-TFE	RGE (2D) 3D-GEIR	Fast FE
Spoiled 3D GRE Variants	VIBE	FAME/LAVA	THRIVE	TIGRE	3D QUICK
GRE Plus SE with Combined Signal	TGSE	---	GRASE	---	Hybrid EPI

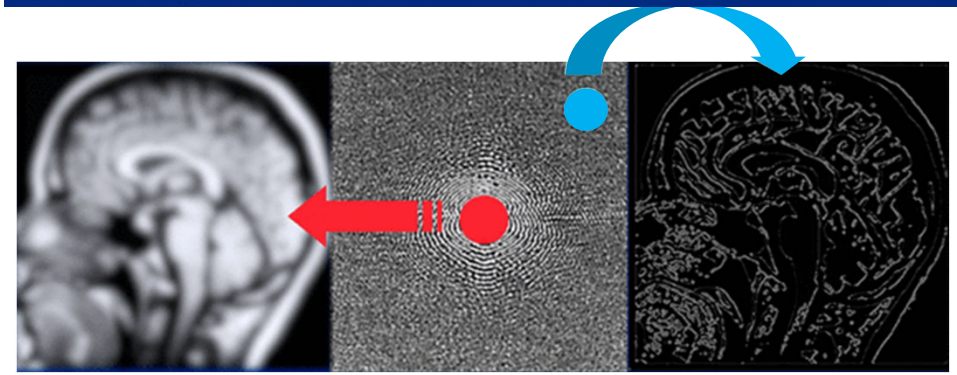
Search online for "Siemens MRI acronyms" for an overview

k-Space versus image space

- Each point in k-space has information on the entire image and vice versa





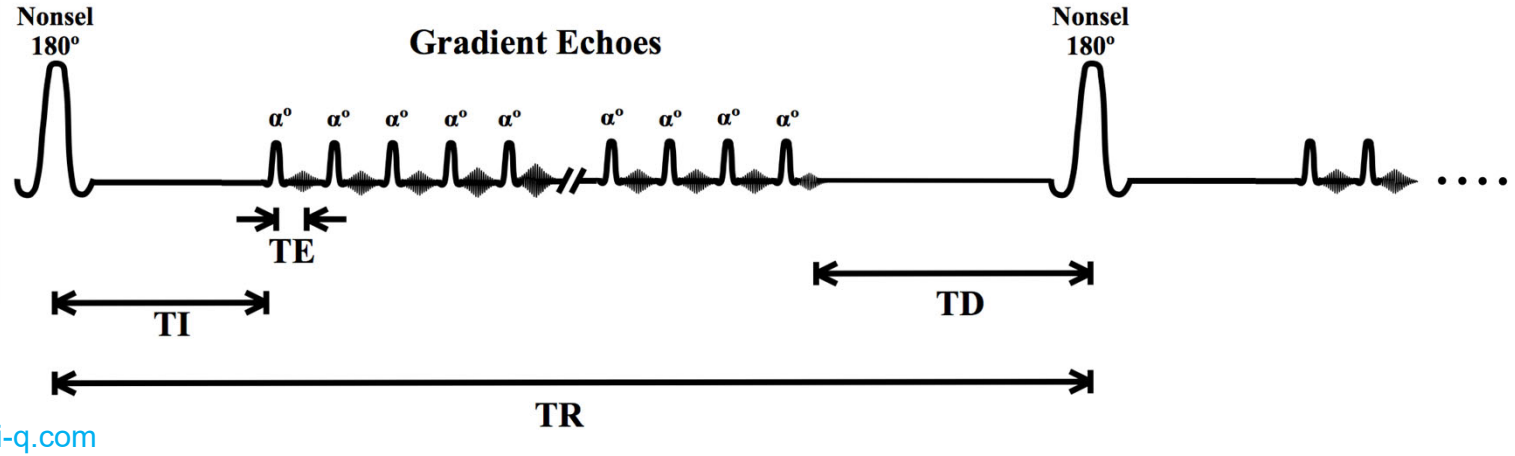


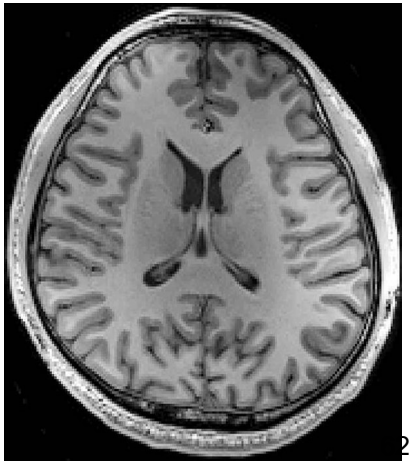
mriquestions.com

To play with this yourself:
Apple Store: k-Space Odyssey (Haselhoff)
Play Store: k-Spapp (Springorum)

MP-RAGE

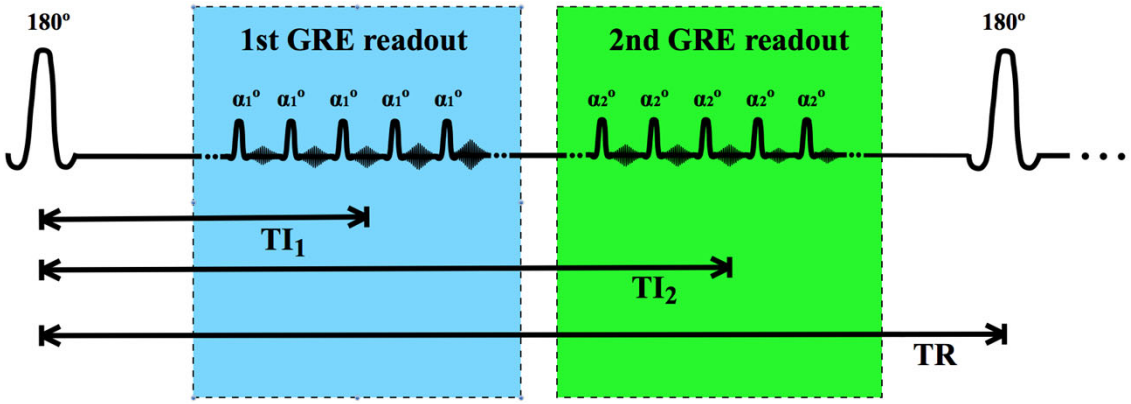
- Magnetization Prepared - RApid Gradient Echo
- T_1 weighted
- non-selective (180º) inversion pulse (medium *TI* of 600-900 ms)
- Series of GRE readouts at short *TE's* (2-4 ms) and small flip angles (5- 12º)
- Long repetition time (*TR*) of approximately 2000 ms are typical





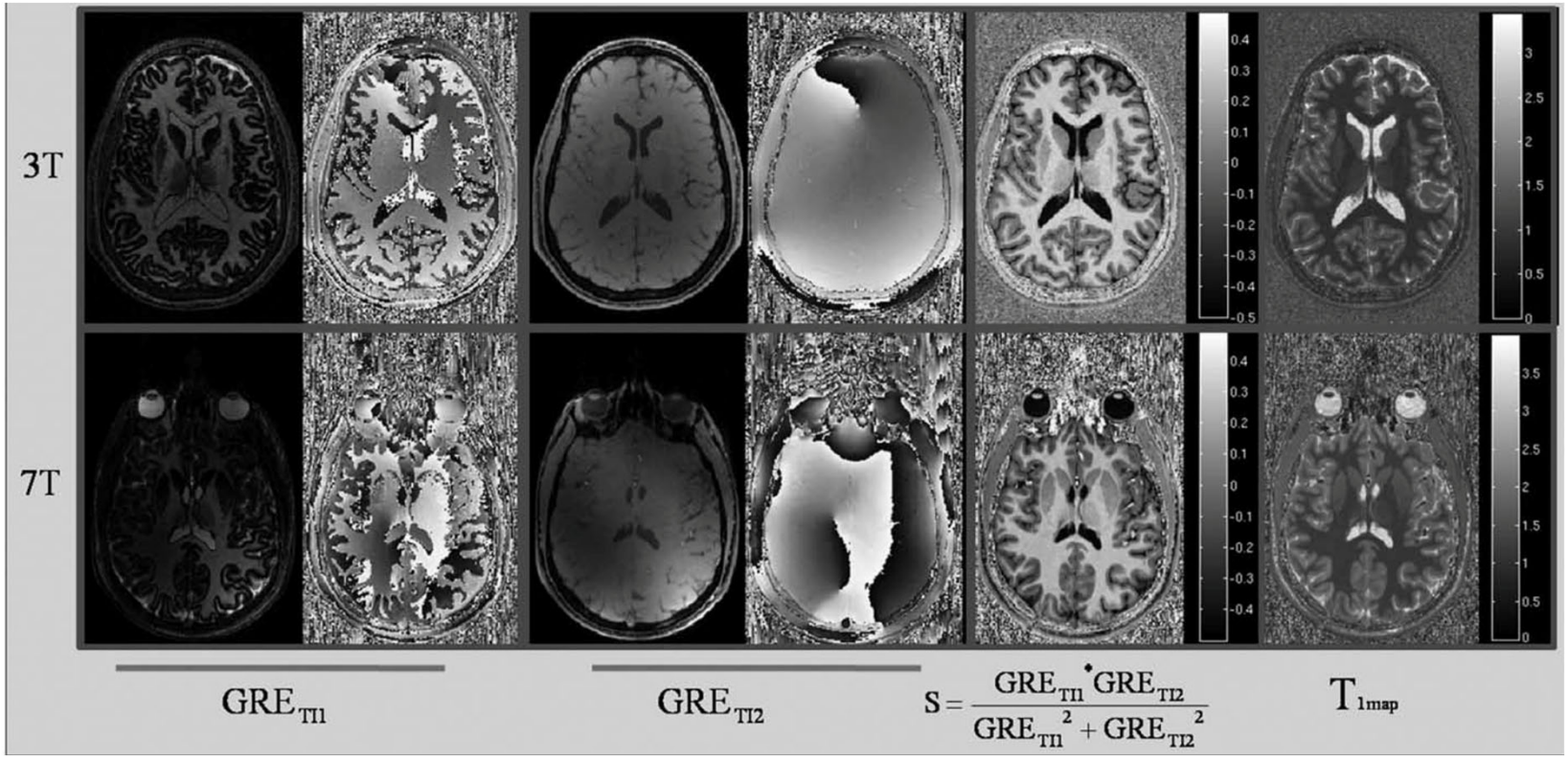
MP2RAGE

- Two GRE readouts between each inversion pulse
- First inversion time (*TI1*) ~700 ms → T1w image with the gray matter nulled
- Second inversion time (*TI2*) is long (~2500 ms)
- Multiply and normalize both images for unbiased contrast: $MP2RAGE = \frac{GRE_{TI1} \cdot GRE_{TI2}}{GRE_{TI1} + GRE_{TI1}}$



Marques et al. Neuroimage 2010

MP2RAGE



Marques et al. Neuroimage 2010

Take home messages

TLDR

In general:

- **Spin echo** is robust, slow, and high-SNR
- **Gradient echo** is fast, sensitive and lower-SNR

Also:

- **Contrast** can be tailored to your liking through timing
- **Preparation modules** can be added to your liking
- Just **look up** any new acronym you come across, it will be a GRE or SE variant in the end