Chapter 26
Sequence Design, Artifacts and Nomenclature

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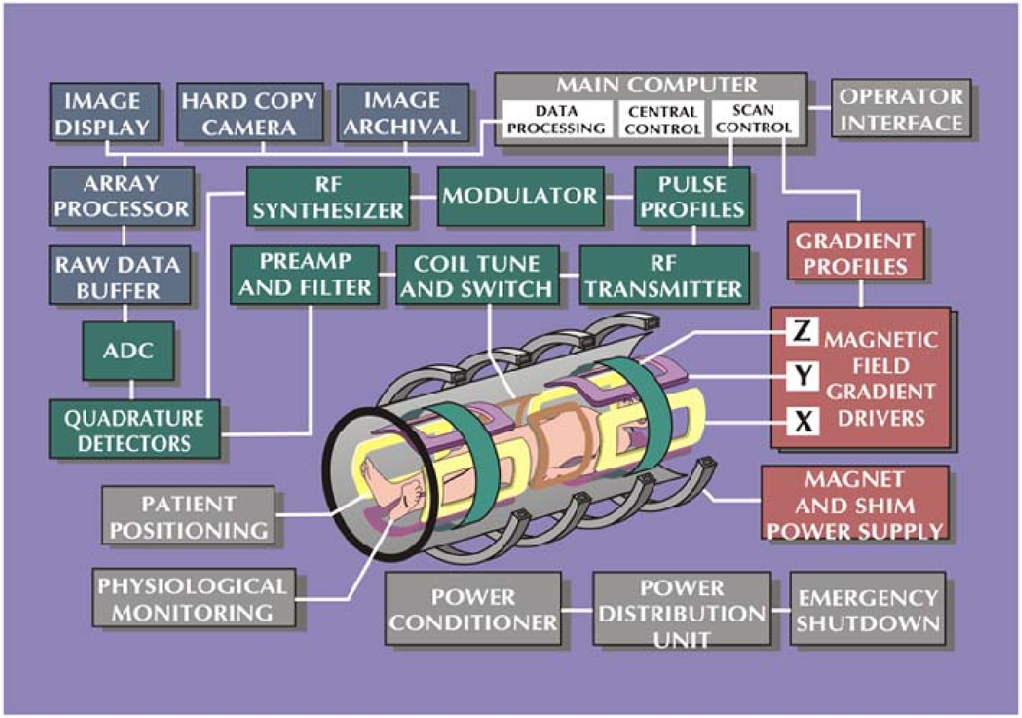
- **Previous classes:**
  - RF pulse, Gradient, Signal Readout
  - Gradient echo, spin echo, inversion recovery, etc
  - K-space concept, filling trajectory and phase consistency
- **Today's content**
  - MR sequence components
  - Sequence design and imaging parameters, how it is actually done
  - Tricks and artifacts
  - Sequence examples and nomenclature

MRI sequence 1, 2, 3 (literally)

- Essential MRI Sequence components:
  - RF pulse
  - Gradient
  - ADC
- Peripheral
  - Patient positioning
  - Imaging processor
  - Etc

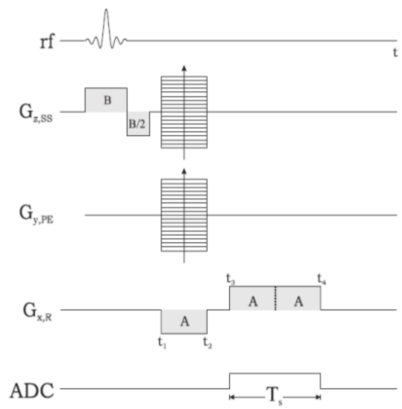


MRI sequence 1, 2, 3 (literally)

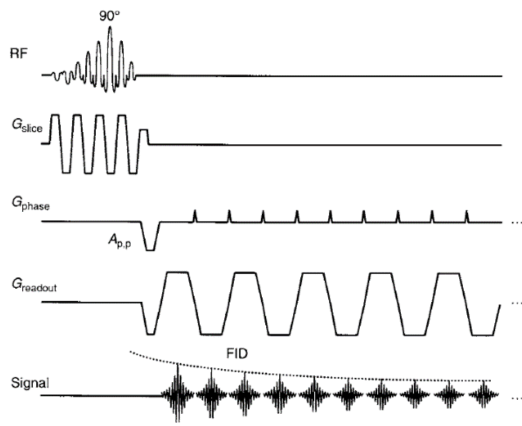
- Sequence functionalities
  - Signal excitation
  - Signal preparation/manipulation/ modulation
  - Signal acquisition

- What is a MR sequence?

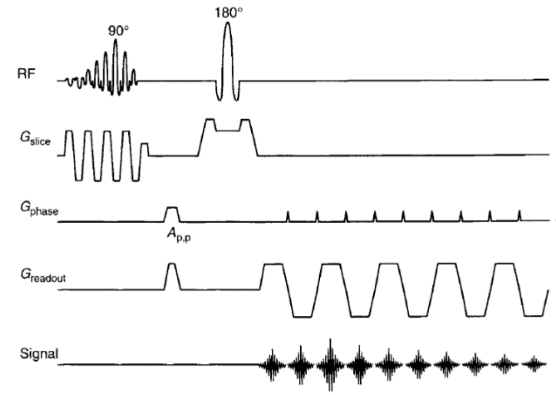
Sequence examples



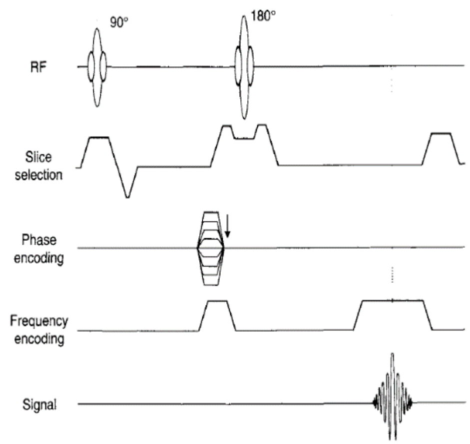
3D GRE



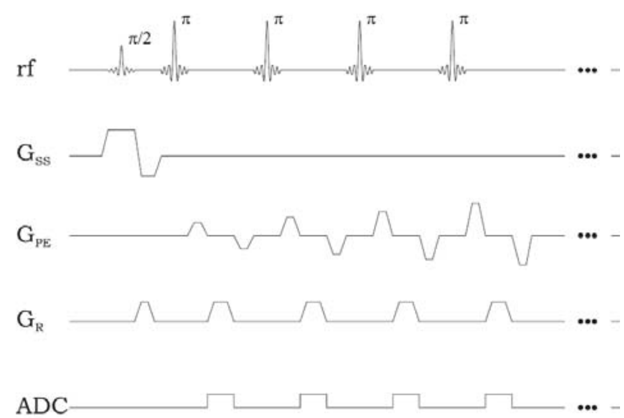
GRE-EPI



SE-EPI



2D Spin Echo



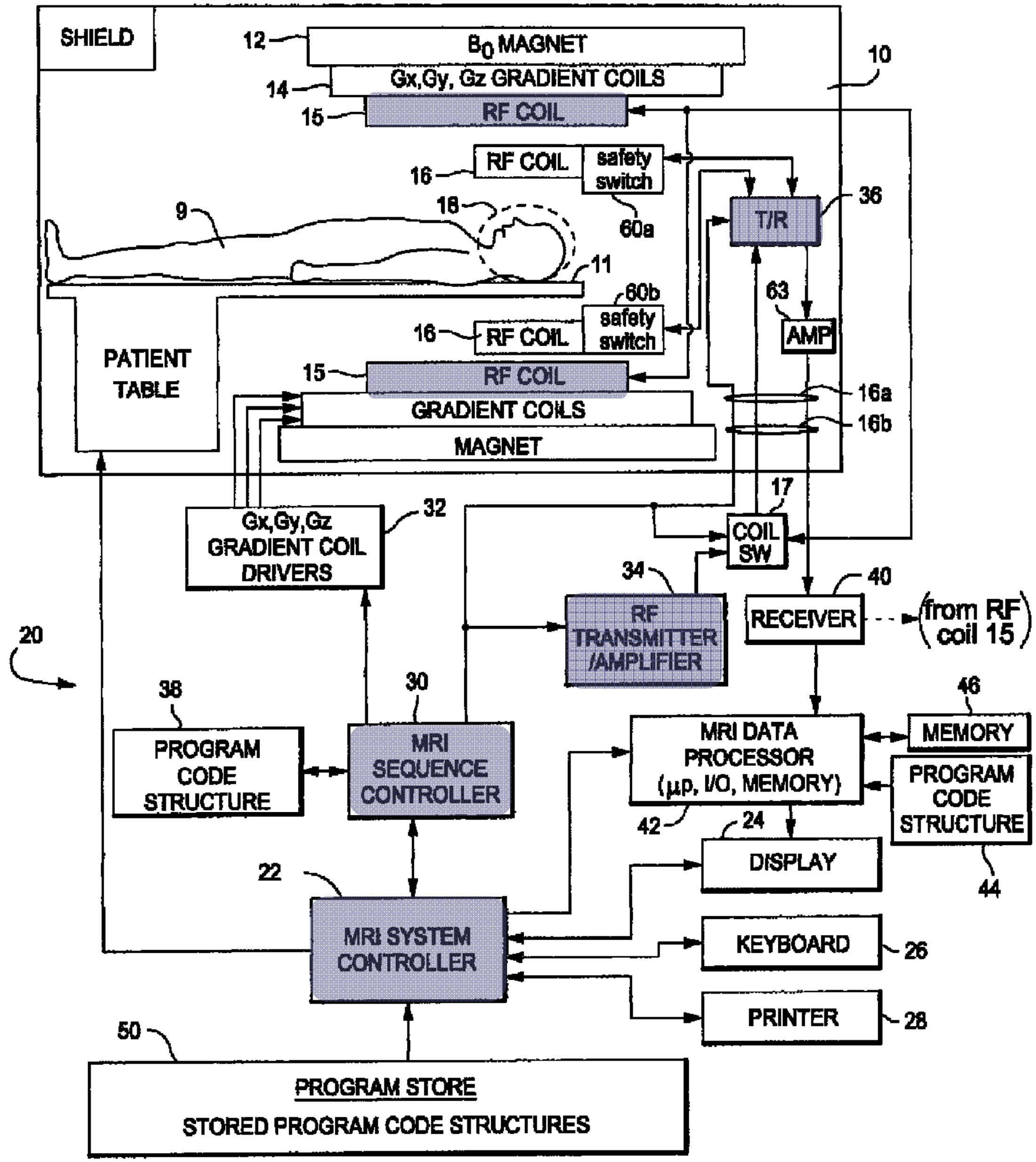
RARE (Fast Spin Echo)

(Berstein, *et al.* 2004)

(E. Mark Haacke, *et al.* 1999)

Generating RF pulse

An ideal RF pulse creates a spatially homogeneous electromagnetic field, denoted as B1



Patent US826949

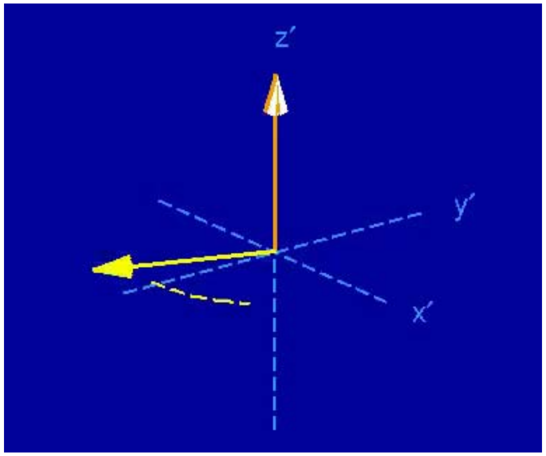
Using RF pulse to create M_{xy}

- Basic Bloch Equation

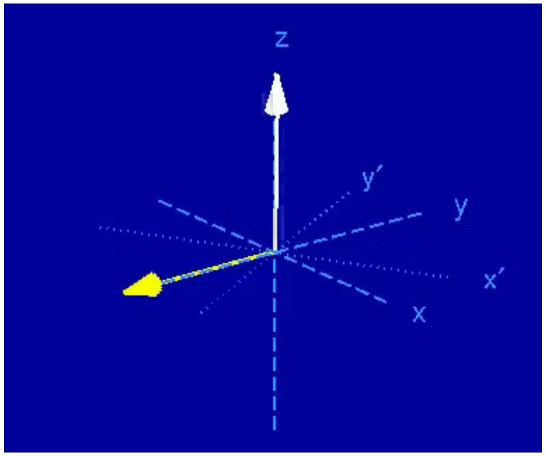
$$\frac{d\vec{M}}{dt} = \gamma\vec{M} \times \vec{B}_{ext}$$

i.e. M precesses around any external magnetic fields

- A RF pulse creates an electromagnetic field, i.e. B_1 field, with frequency also of $\omega_o = \gamma B_o$



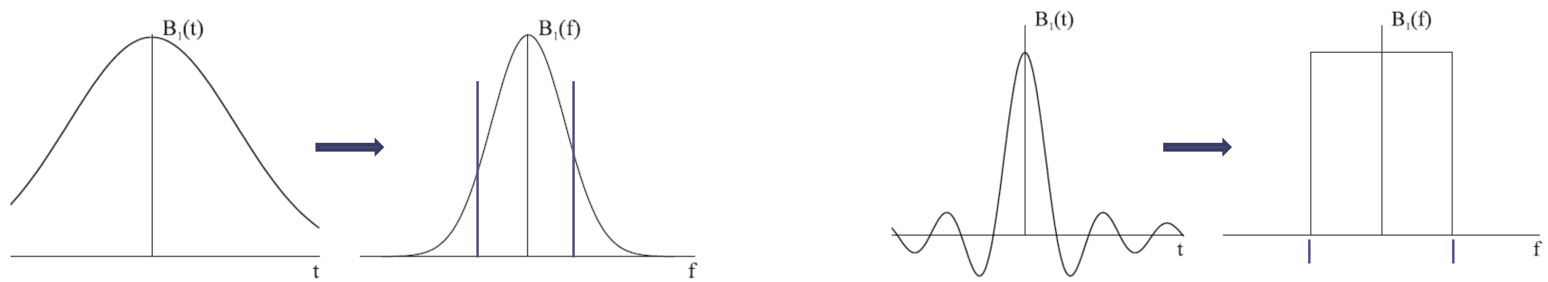
Lab Frame



Rotating Frame

RF pulse properties

- On- / off- resonant: $\omega_{rf} =/\neq \omega_o$
- Flip angle: tipping effect of the RF pulse
- Frequency response: Fourier transform of $B_1(t)$

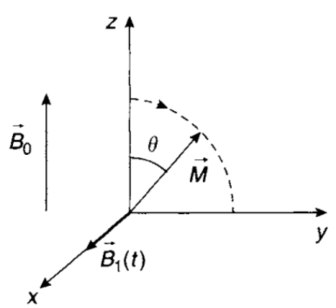


(E. Mark Haacke, *et al.* 1999)

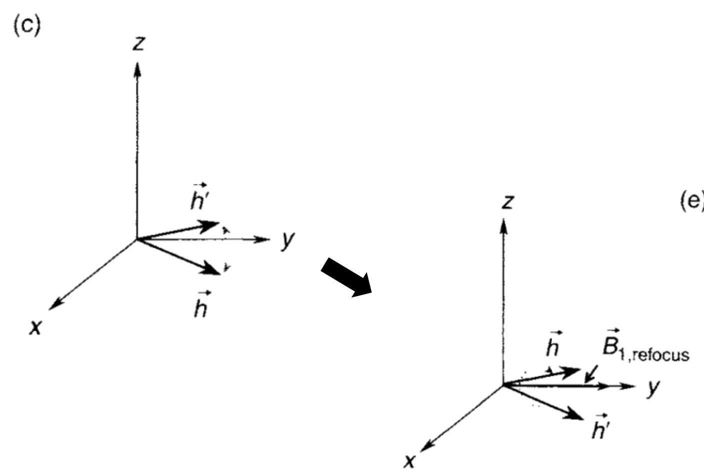
- Bandwidth: within which spins are considered on-resonant

Types of RF pulse

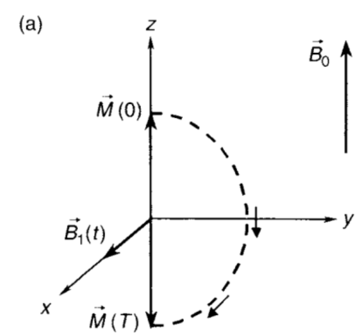
- Functionality
  - Excitation (needed for all; $\theta=0\text{-}\pi/2$)
  - Refocusing (for spin echo; $\theta=\pi/2\text{-}\pi$)
  - Inversion (IR; for T1W, tissue nulling; $\theta=\pi$)



Excitation



Refocusing

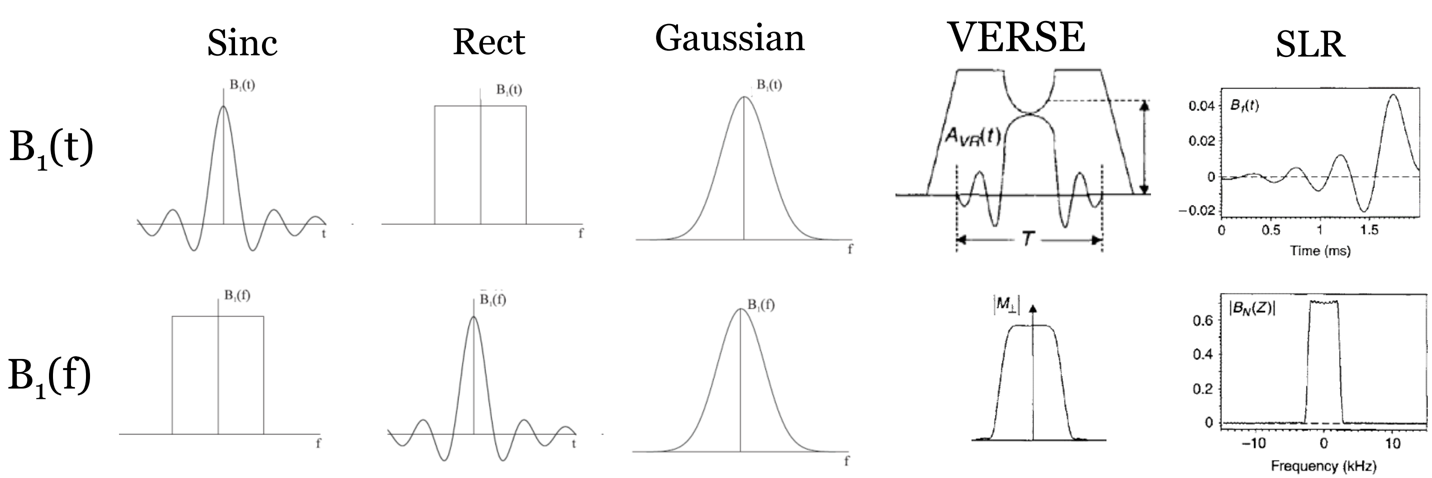


IR

(Berstein, *et al.* 2004)

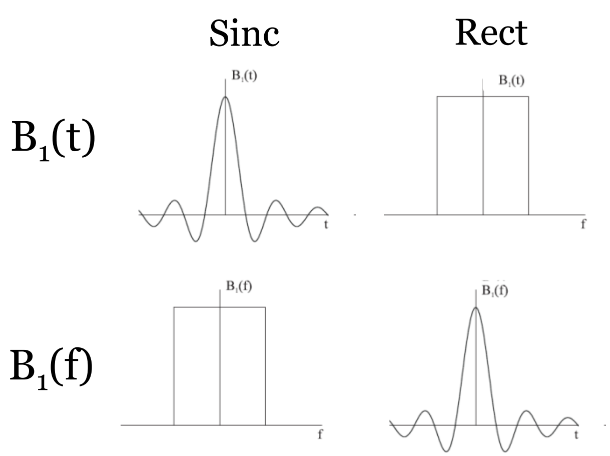
Types of RF pulse

- Temporal shape. i.e. $B_1(t)$
  - Sinc (widely used for spatially selective imaging)
  - Rectangular (non-selective excitation or IR)
  - Gaussian (Saturation, MTC)
  - VERSE (variable rate selective excitation)
  - Composite pulses (SLR)
  - etc…



Types of RF pulse

- Selectivity
  - Selective (soft):
    Narrow BW with well defined frequency response, e.g. sinc pulse
    Example: T_{sinc} = 5.12ms w/ 4 zero crossing => BW ≈ 780Hz
  - Non-selective (hard):
    Very broad BW, e.g. rectangular pulse
    Example: T_{rect} = 100µs => BW ≈ 12100Hz



Types of RF pulse

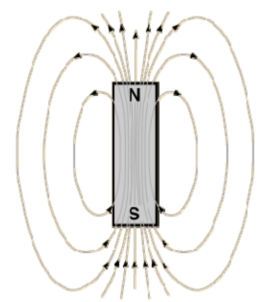
- Special purpose RF pulses
  - Selective excitation/saturation pulse (water or fat)
  - MTC (Magnetic transfer contrast, reduce signal of certain tissue via off-resonant effects. e.g. in MRA)
  - TONE pulse (spatially varied flip angle for MRA)
  - SPSP pulses (spatial-spectral selective)
  - Spin Lock pulse ($T1\rho W$)
  - Adiabatic pulses (uniform response over non-uniform B1 field)

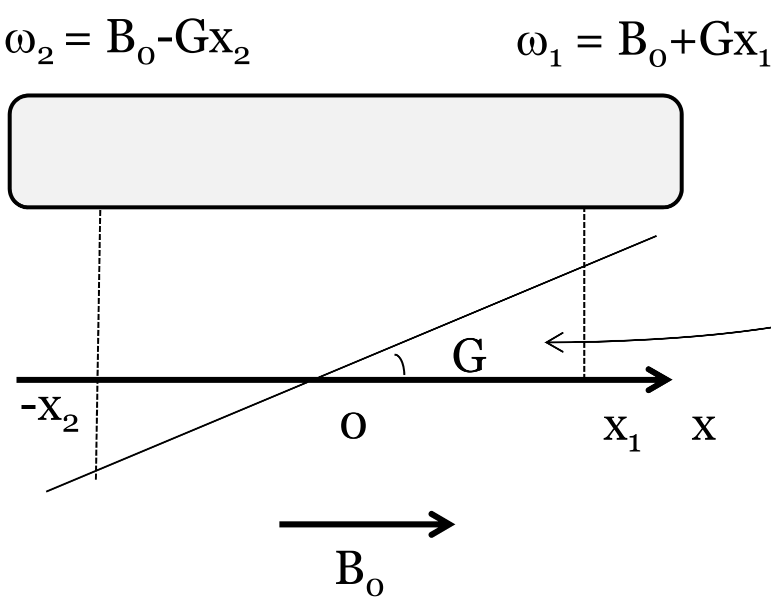
RF pulse consideration

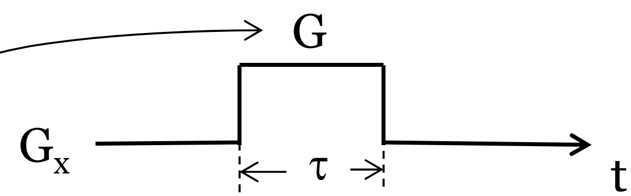
- Small flip angle approximation (single pulse)
- Specific Absorption Rate (SAR) of RF power deposition, increase at higher flip angle/fields
- B_1 field uniformity/ dielectric effects, worse at higher fields
- Frequency response profile
- Application specific (2D,3D/contrast mechanism/ safety/ selectivity…)

Magnetic Gradient

- Definition
  Spatially varying magnetic field, G



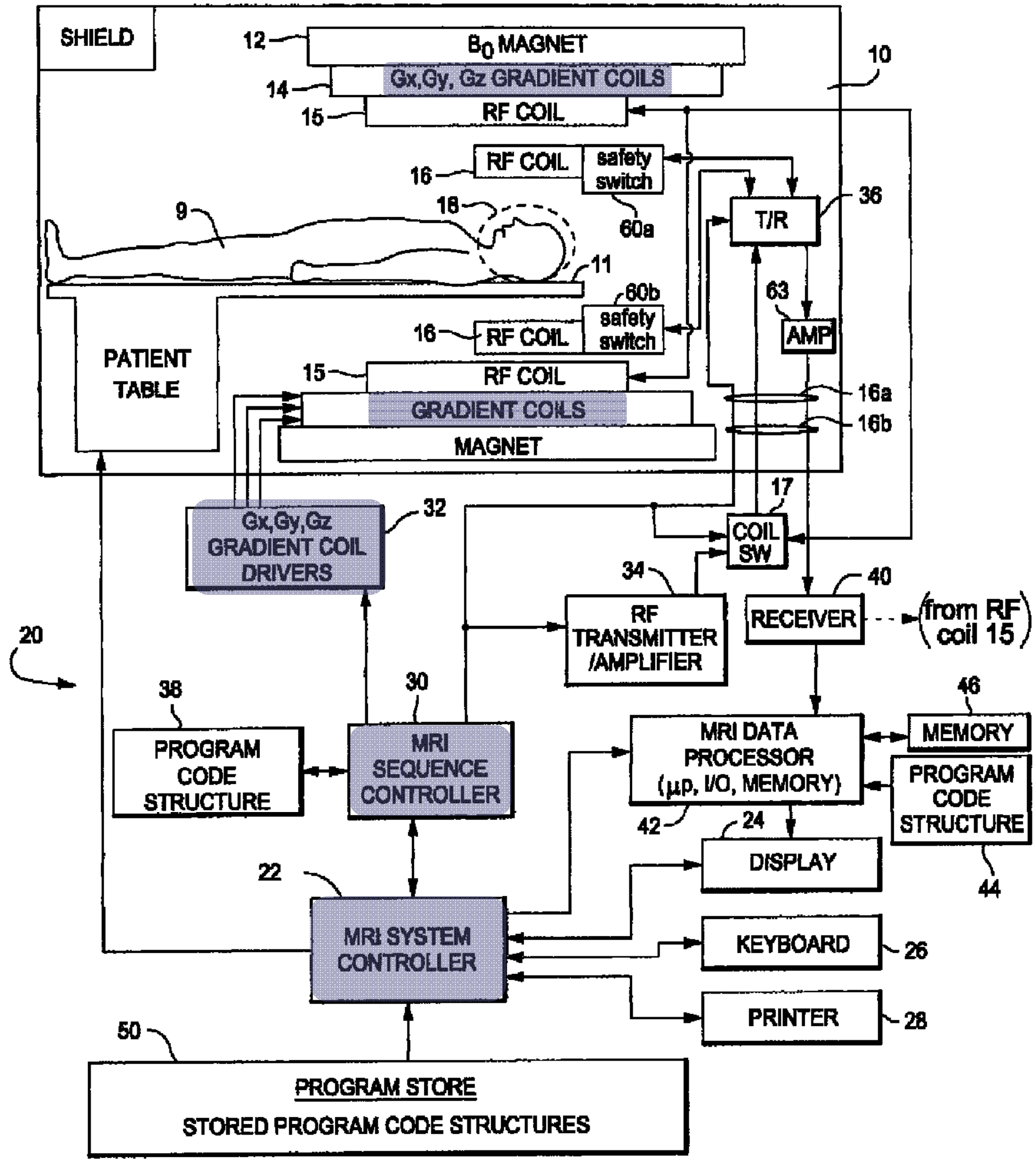




Spatial field distribution
Ideally to be spatially linear

Diagram symbol
(gradient lobe)

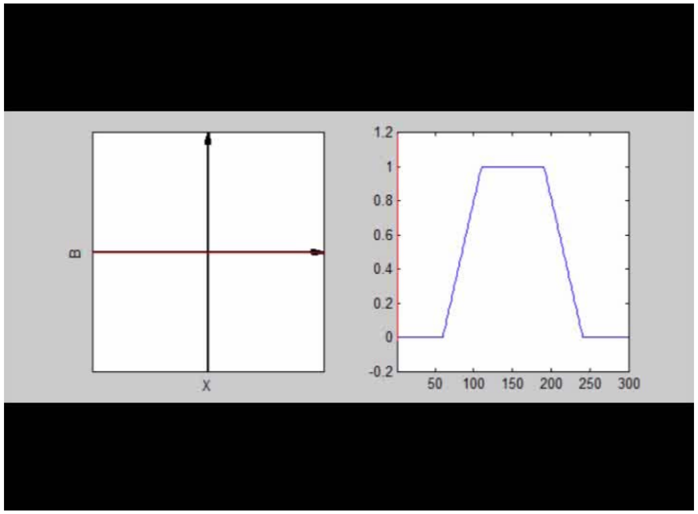
Generating Gradient pulse

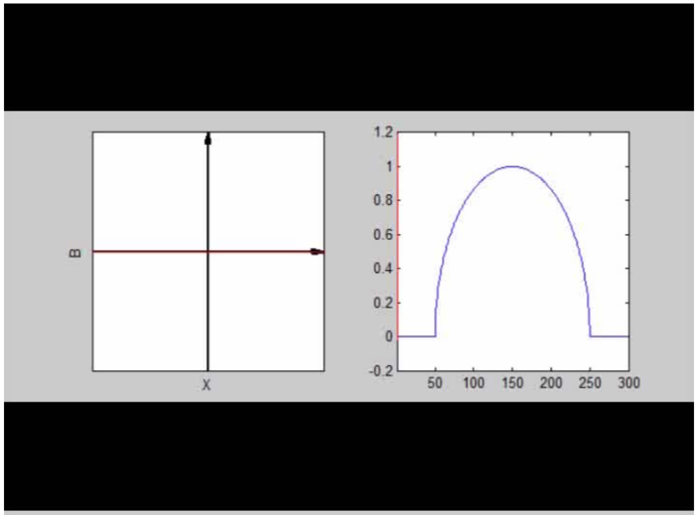


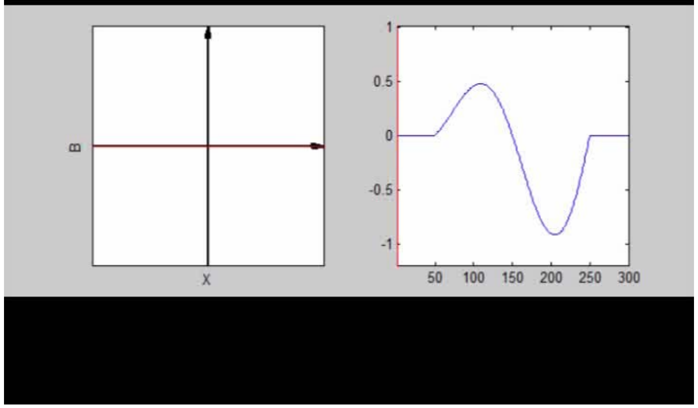
Patent US826949

Gradient pulse properties

- Arbitrary lobe shape, slew rate and G_{max} limited by hardware
- Field variation should be spatially linear at any time

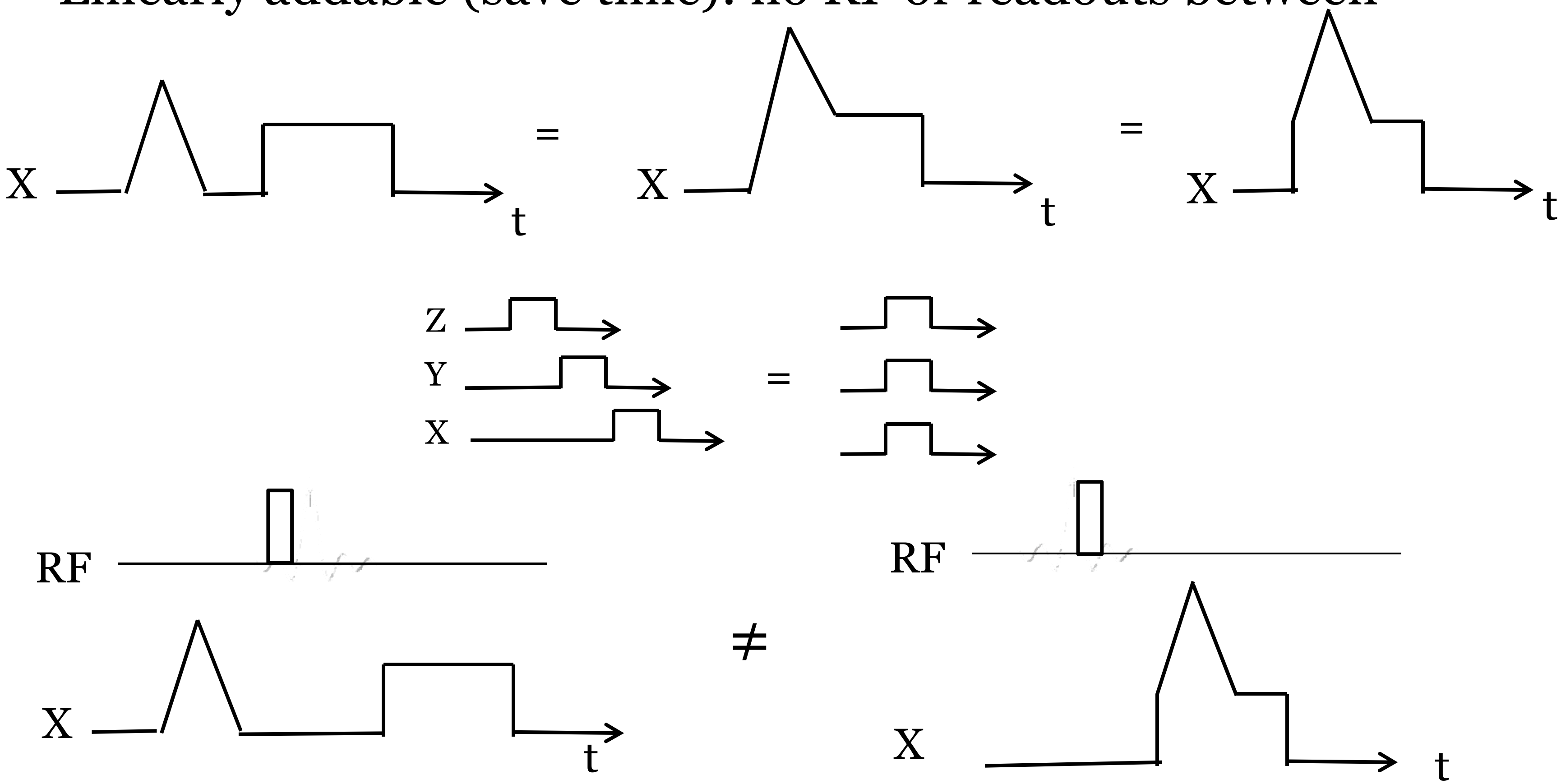






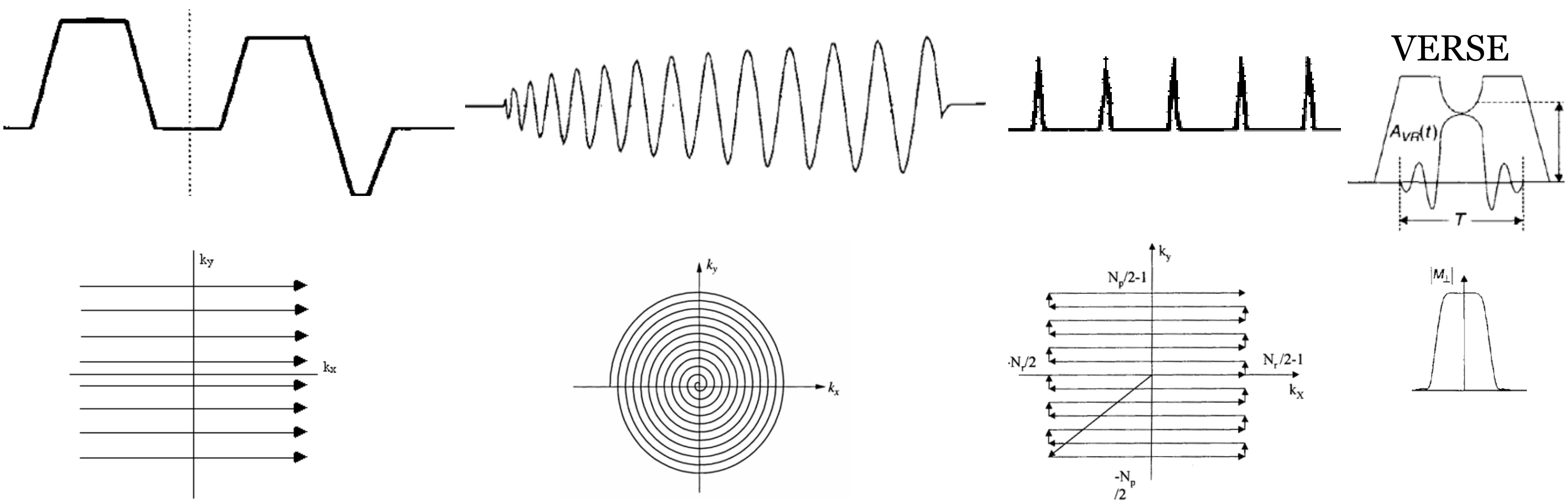
Gradient pulse properties

- Directionality
- Affects only the M_{xy} by itself alone
- Can affect M in any state when used with RF pulse
- Linearly addable (save time): no RF or readouts between



Types of gradient pulses

- Gradient lobe shapes
  - Trapezoid (most commonly use)
  - Spiral (special readout)
  - Triangle, or blips (EPI phase encoding)
  - Special gradient (e.g. VERSE)

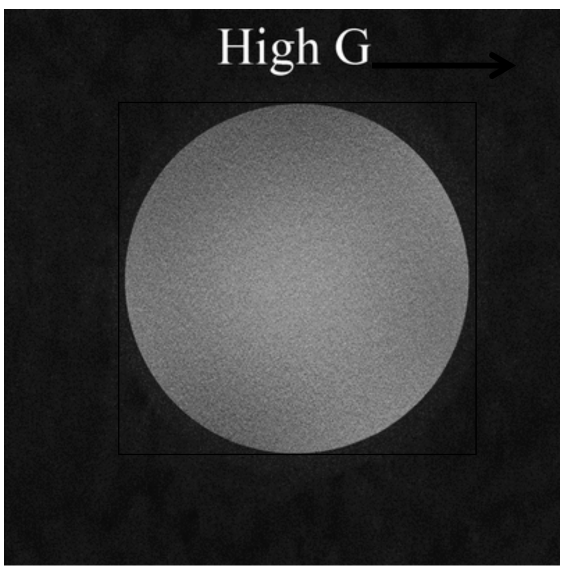


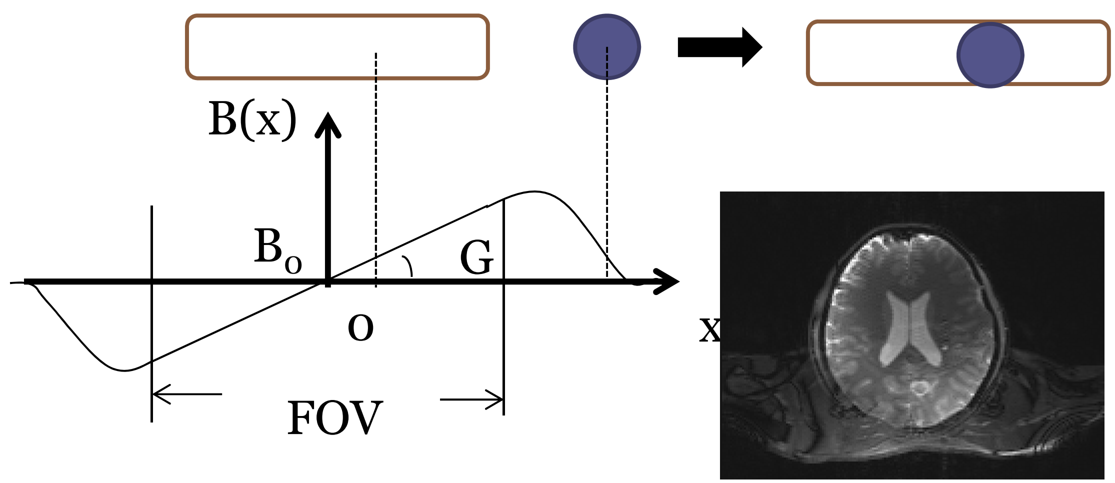
Gradient categories

- Functionality
  - Readout/ Phase encoding/ Slice selection
  - Pre-phase/ Dephase / Rephase
  - Spoiler / Crusher /field compensation (e.g. z-shimming)
- Imaging contrast related gradients
  - Flow compensation/encoding/dephasing
  - Diffusion gradients
  - etc

Gradient design consideration

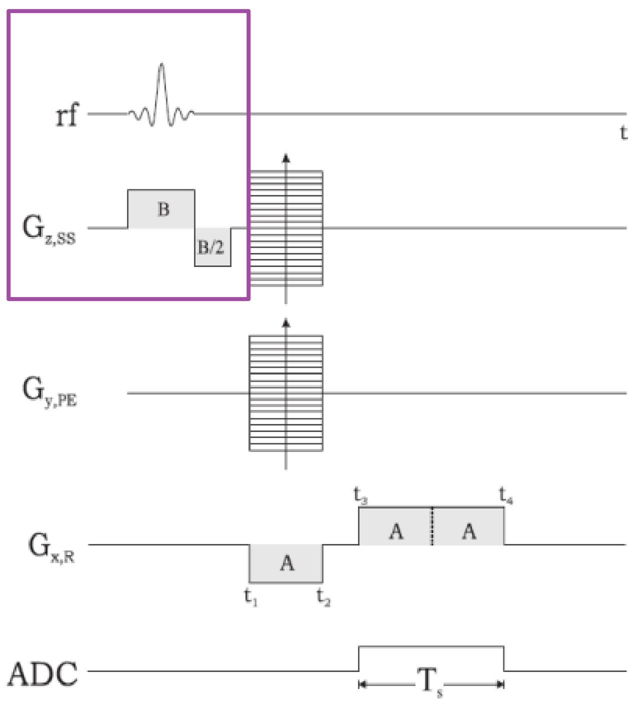
- Slew rate and G_{max} limited by gradient amplifier
- Fast/strong gradients lead to nerve stimulation, physical vibration, acoustic noise
- Eddy currents and image distortion
- Spatially limited linearity, lead to 'third arm artifacts'
- Application specific (image contrast/efficiency/)

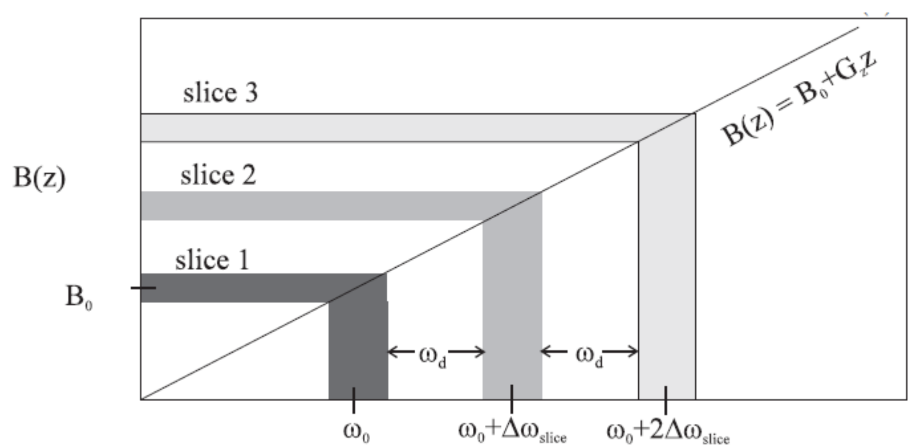




Slice (slab) select gradient

- Translate spectral selectivity of the RF pulse to spatial selectivity
- Used for excitation, SE refocusing, IR
- 0th moment (of the SS part) must be 0 before ADC turns on

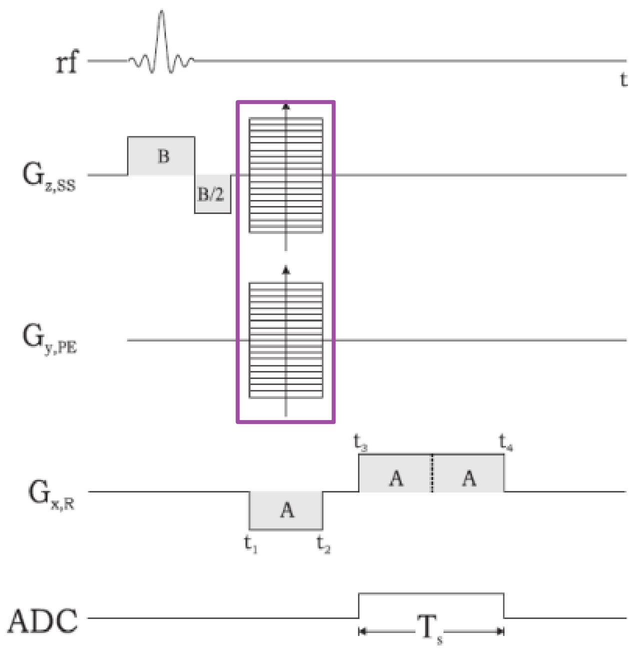




(b)

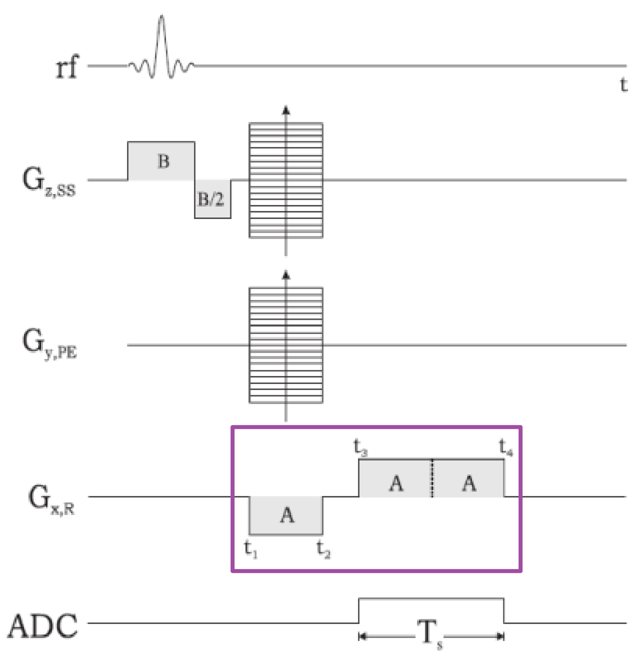
Phase encoding gradient

- Represented as PE table in seq diagram
- PE reordering (ascending, center-out, etc), effects and restriction
- Affects minimal TE

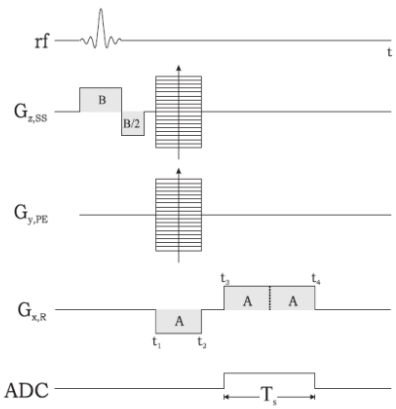


Readout gradient

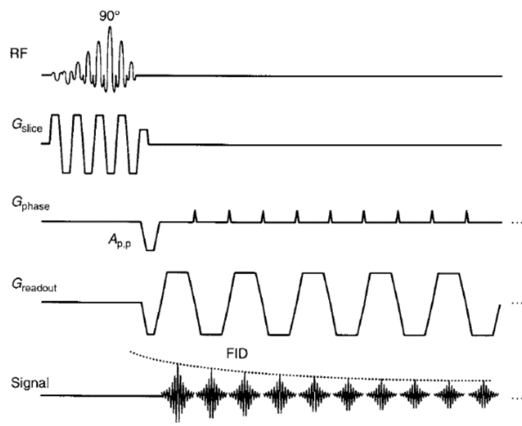
- Combined with ADC to collect freq encoded signal
- Echoes take place when 0th moment becomes 0 again
- Sampling rate $\Delta t = \frac{1}{\gamma G_{RO} L_{RO}} = \frac{1}{BW}$
- ADC sampling duration T_s=N/BW



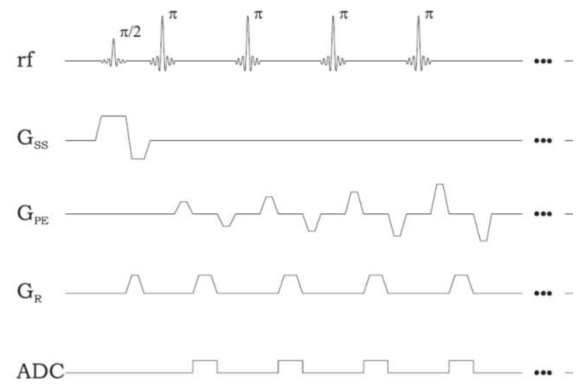
Sounds of MRI



3D GRE



GRE-EPI



RARE (Fast Spin Echo)

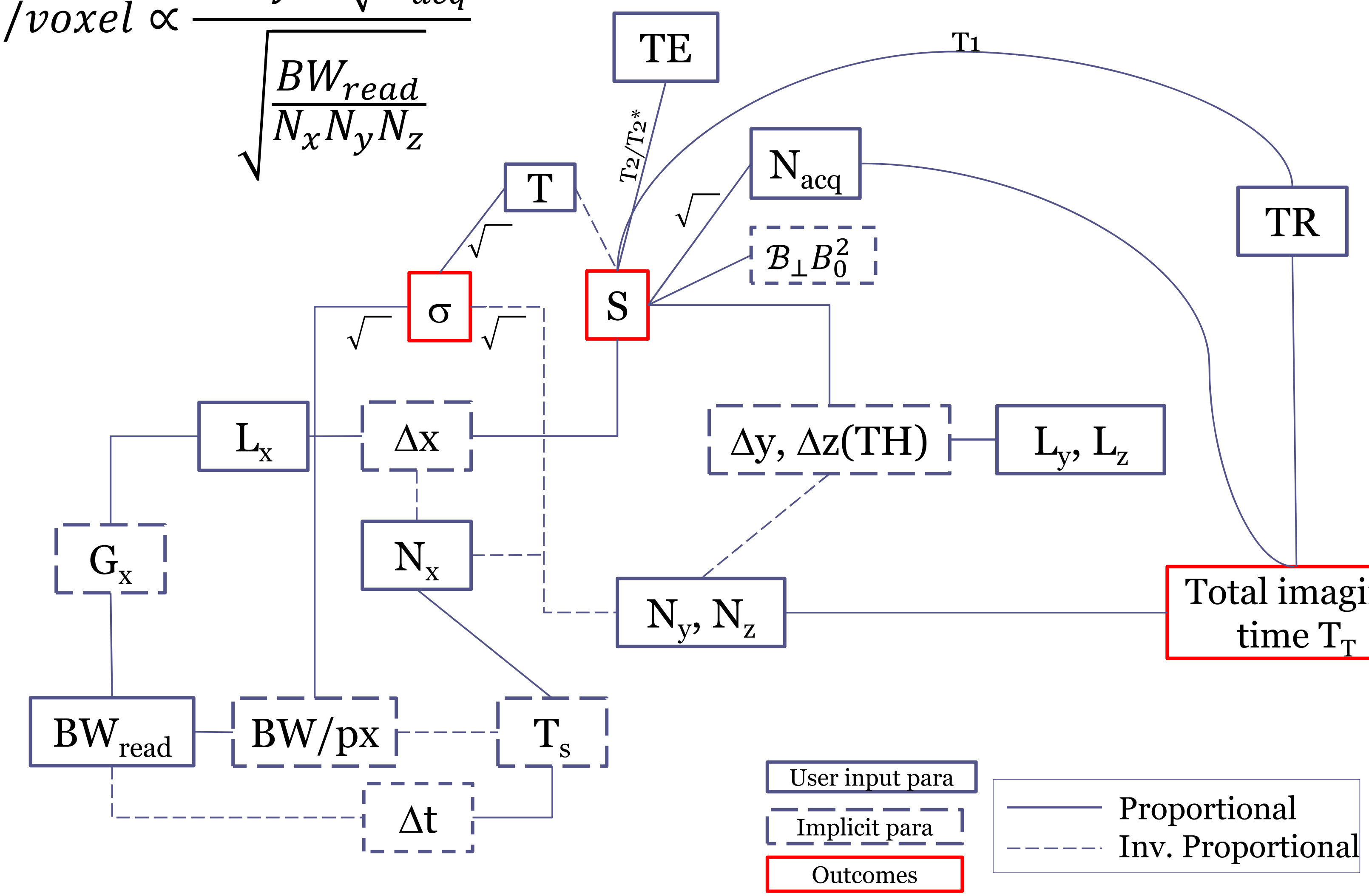
Just for fun

Practical consideration of MR sequence programming

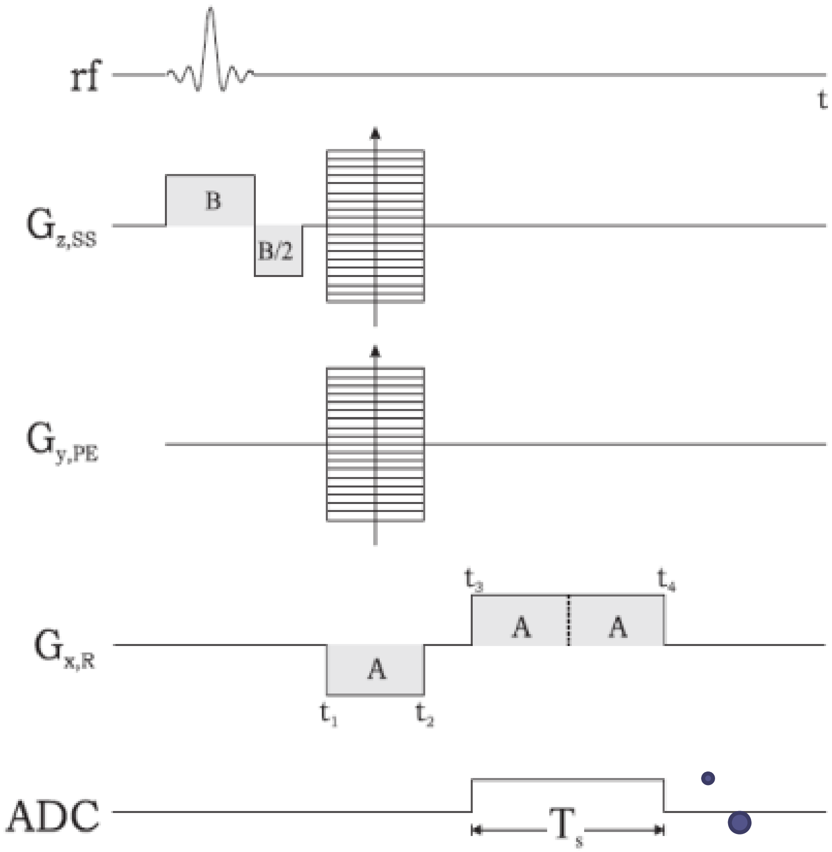
- Before the programming
  - Know the exact goal and major restrictions & potential problems
  - Draft up the sequence diagram
- During programming (apart from the inevitable coding works)
  - Timing; Timing; Timing
  - Consistency/interaction between parameters
  - Simulation and thorough checking on everything
- Debugging & optimization
  - Testing and use deduction to find the cause of problems (artifact, execution failure, etc)
  - Optimize sequence design and imaging parameters

Imaging parameter dependence (revisit)

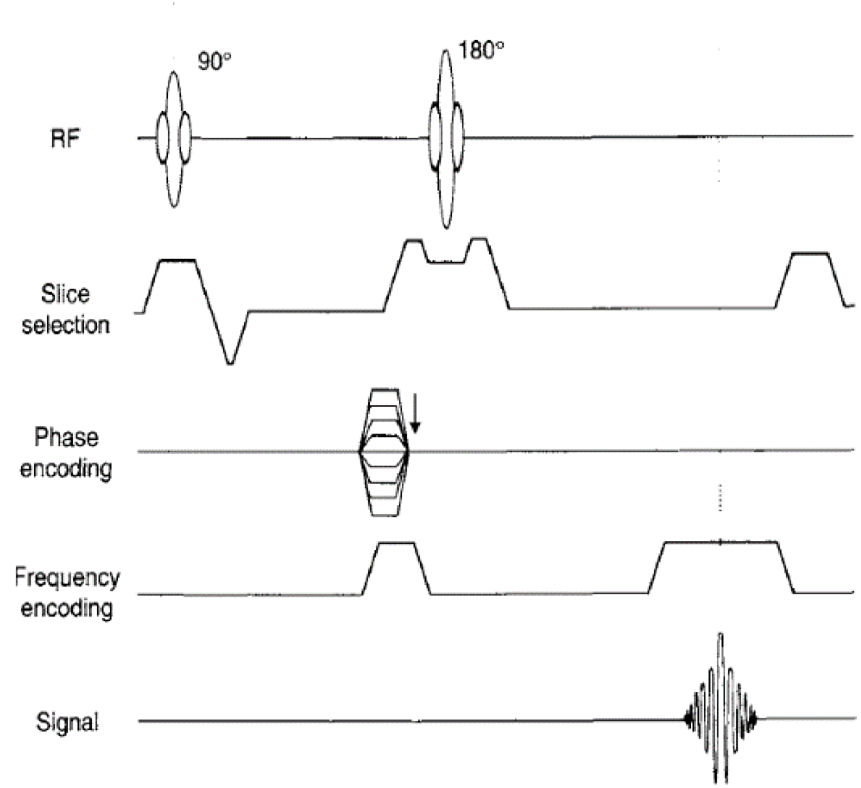
$$SNR/voxel \propto \frac{\Delta x \Delta y \Delta z \sqrt{N_{acq}}}{\sqrt{\frac{BW_{read}}{N_x N_y N_z}}}$$



Sequence examples



3D GRE



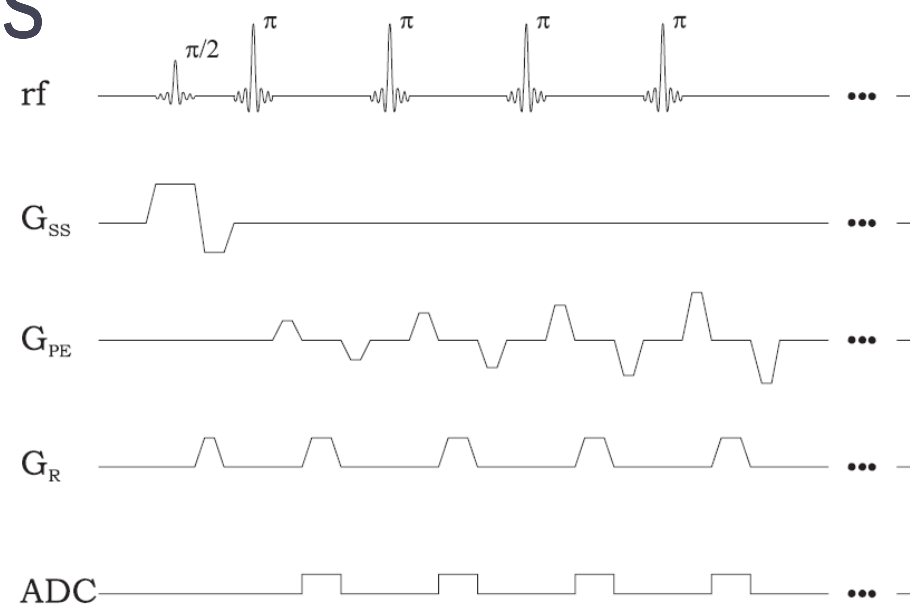
2D Spin Echo

Hmmm, something's not practically right

(Berstein, *et al.* 2004)

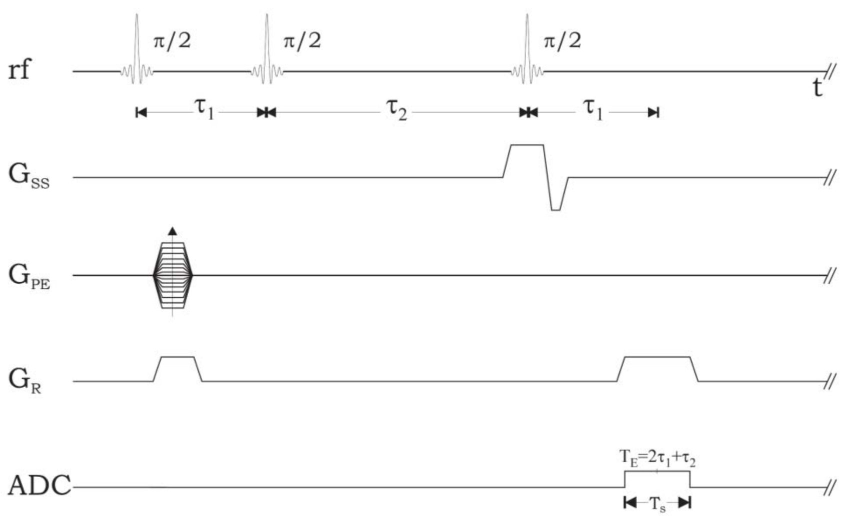
Sequence examples

1. What is the practical error in this diagram?
2. CPMG RF phase alternation scheme needed (90x/180y/180y/180y…)
3. Consideration: π pulse not strictly π



RARE (Fast Spin Echo)

(Berstein, *et al.* 2004)

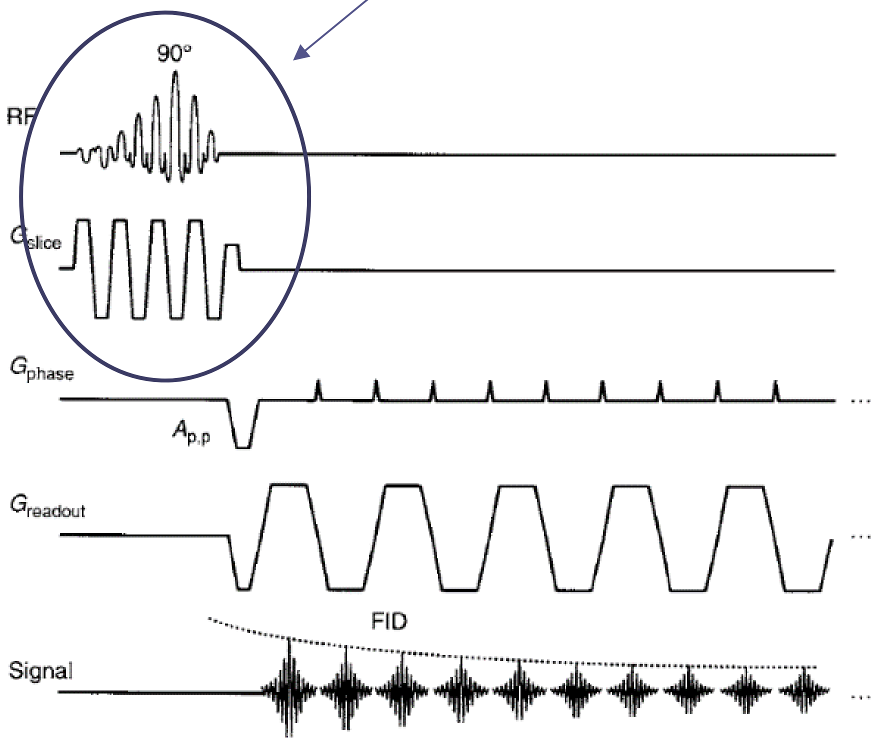


Stimulated echo

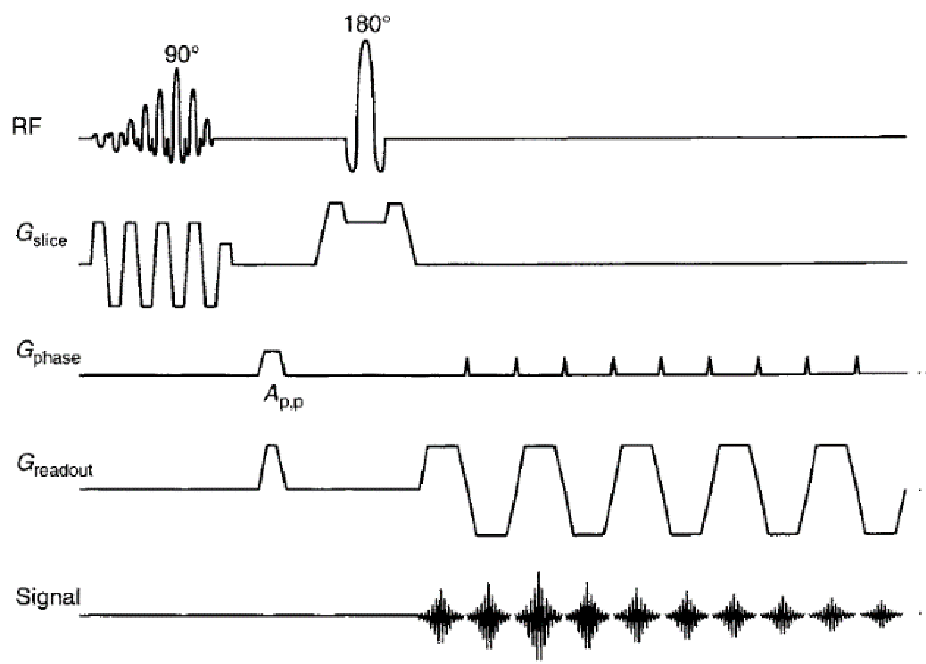
Fig. 26.13

Sequence examples

SPSP pulse



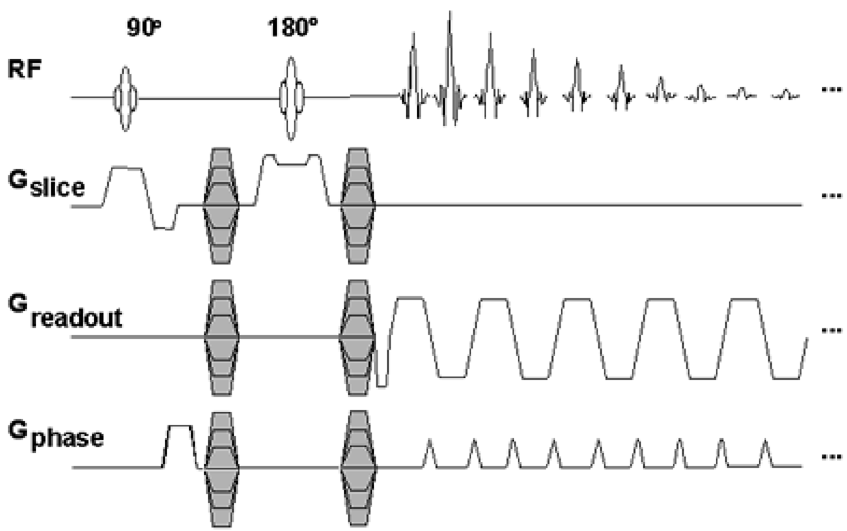
GRE-EPI



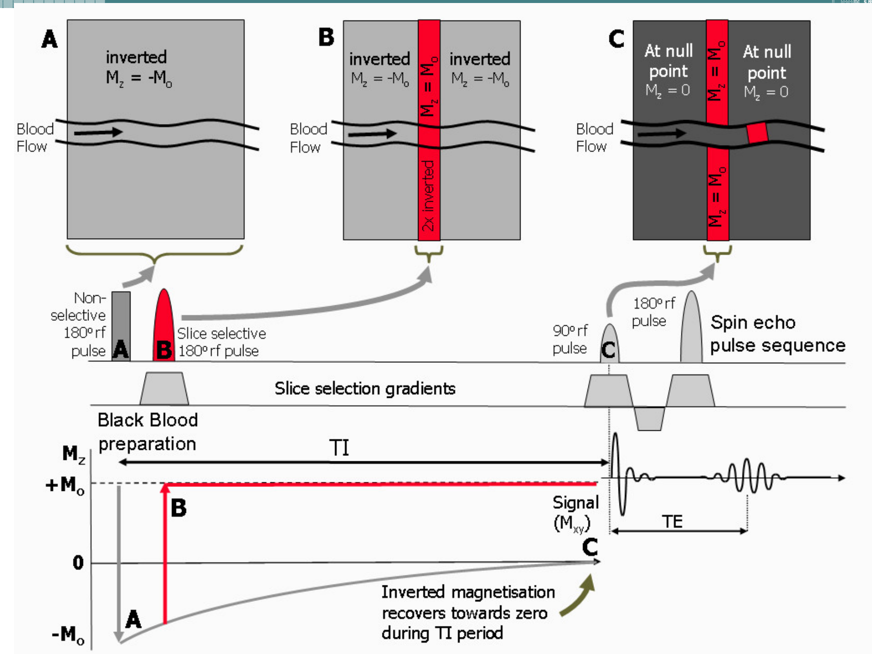
SE-EPI

(Berstein, *et al.* 2004)

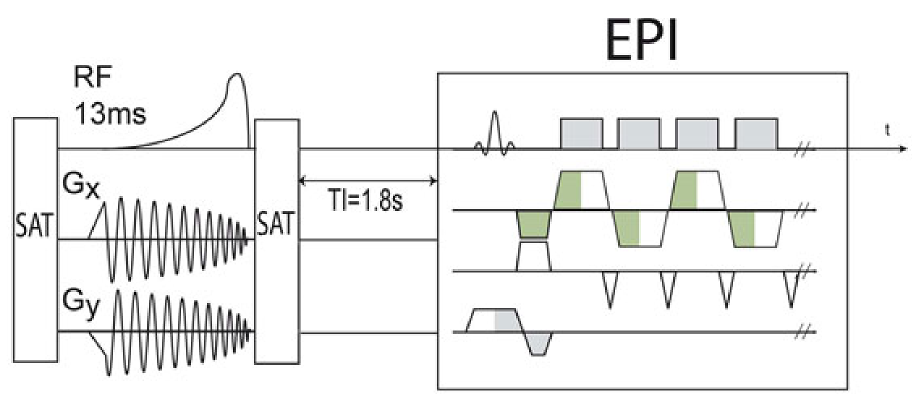
Sequence examples



DTI with S-T diffusion gradients



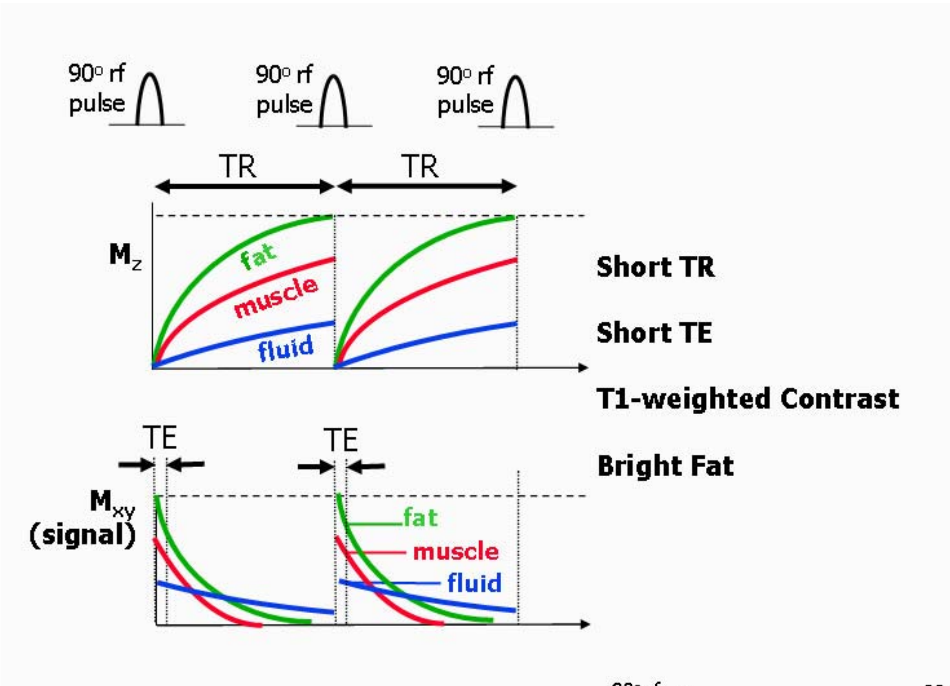
Double IR for black blood imaging
(Ridgway, JCMR, 2010)

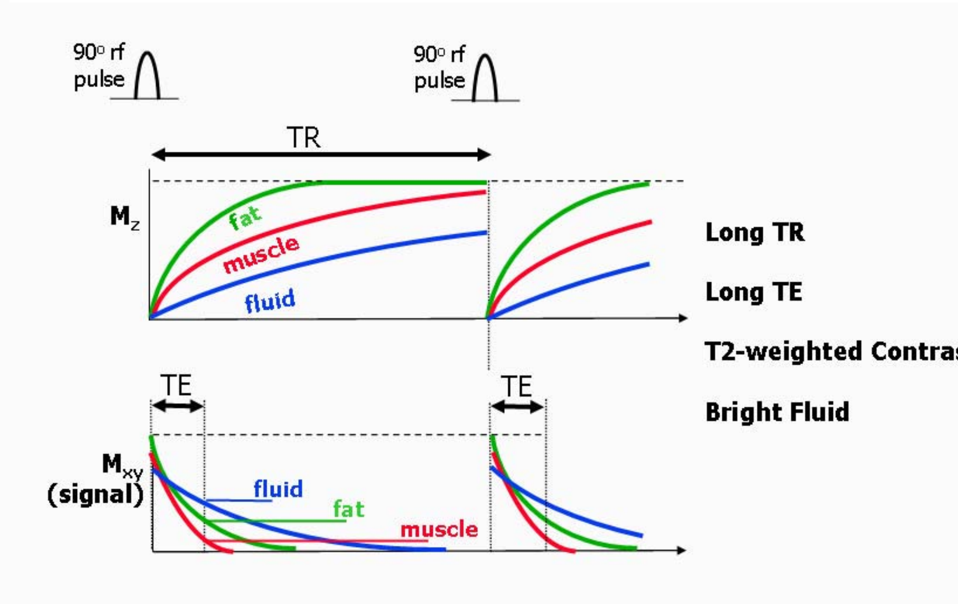


ASL

(Konstandin et al, 2009)

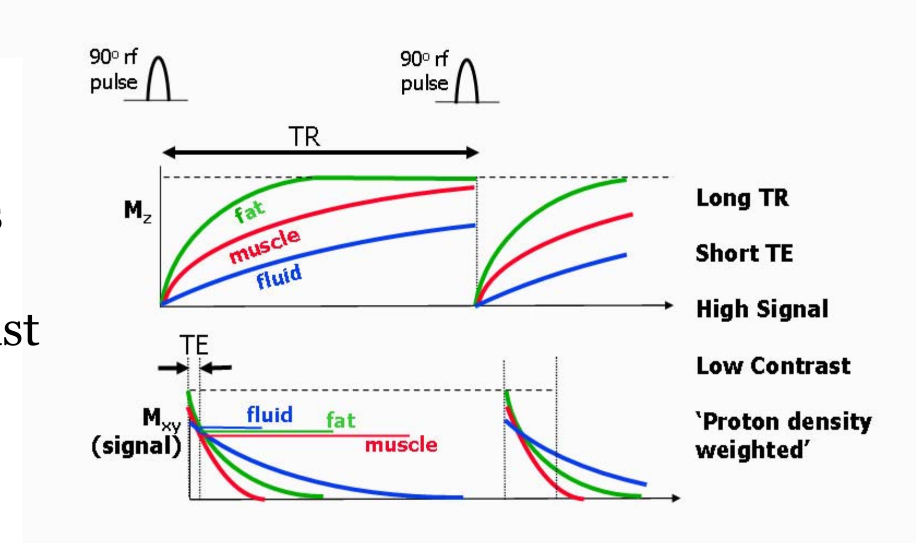
Sequence examples





Same sequence
Different parameters

Different image contrast

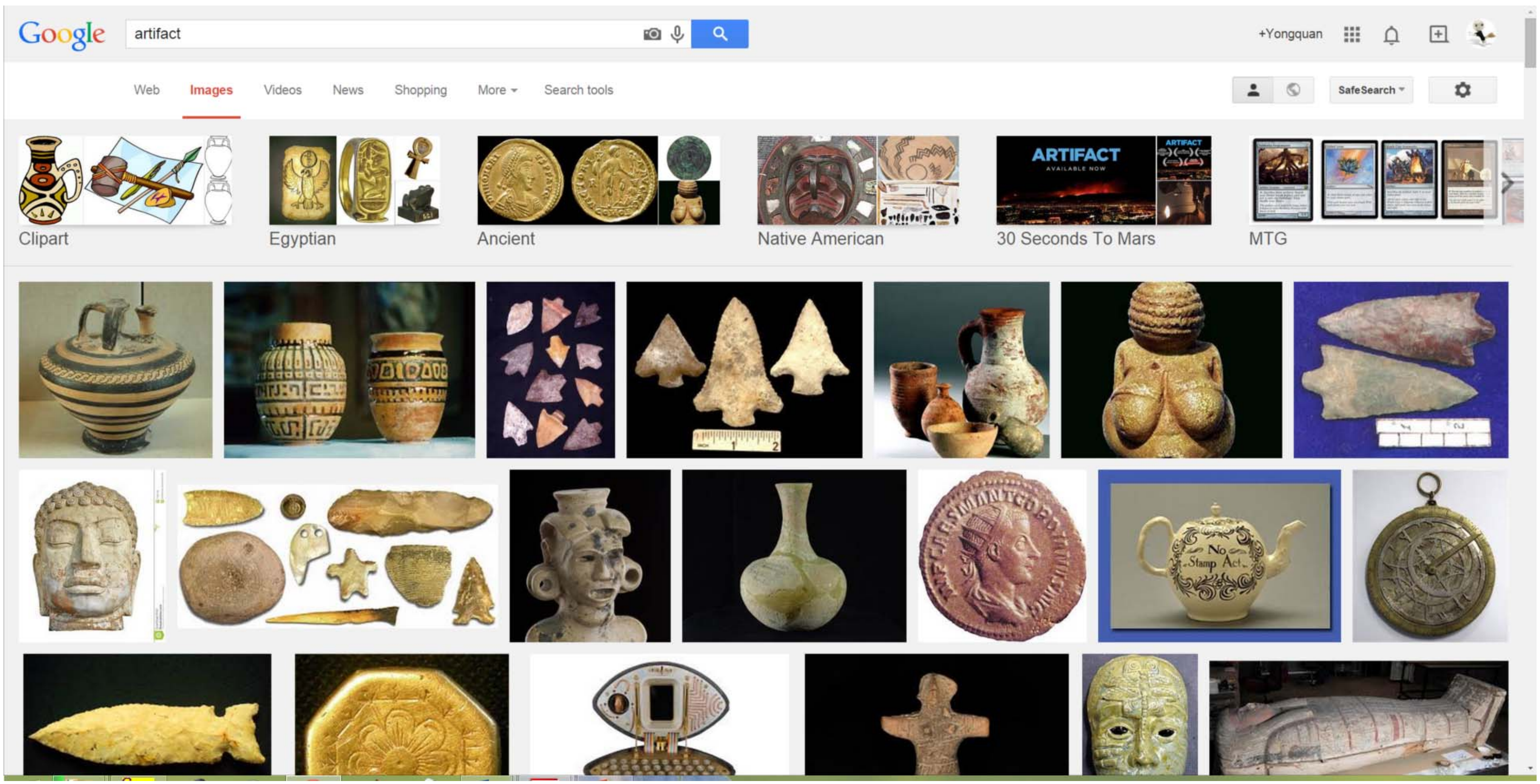


(Ridgway, JCMR, 2010)

Artifacts (or Artefacts)

- A simple object (such as a tool or weapon) that was made by people in the past
- An accidental effect that causes incorrect results

Webster Dictionary



Artifacts

An image artifact is any feature which appears in an image which is not present in the original imaged object.

- Joseph P. Hornak

Bright line artifact/Chemical shift/crossover/
DC artifact/distortion artifact/flow artifact/ghosting/
line artifact/misregistration/motion artifact/ blurring/
Gibb's ringing (truncation) /starring artifact/ streamlining artifact/ susceptibility artifact/ zebra stripe (phase aliasing)/ zipper artifact/spikes artifact…

(Above appeared in the Green Book)

But there are still many more out there…

Magic angle artifact/data clipping/ T2 shine through/ Partial volume/ inflow/outflow/ FOV wrapping/ third arm artifact/ RF interference…

And carelessness artifacts

Source of artifacts

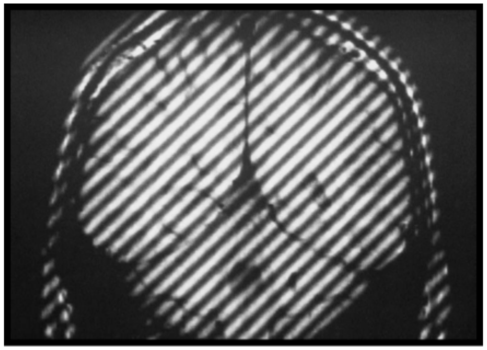
- Hardware/electronic components
- Environmental effects
- Physiological effects (heart beat, respiration, motion, blood flow…)
- Implants or hygiene
- Operational error
- Protocol settings/Sequence design/ signal processing
- Mysterious sources

How to treat Artifacts

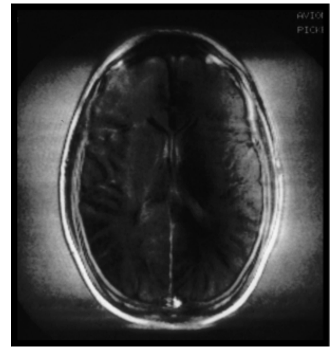
- Artifacts are inevitable, some being significant while others subtle, but most artifacts can be removed or alleviated or identified

- Apart from ruining the images, artifacts can actually be useful
  - As 'symptoms' for diagnosis of the underlying source
  - Forming new contrast mechanism: DWI, BOLD, PCFQ
  - Maybe bad for some sequence but good for others
  - They can be used for fun in some rare cases

Some routine artifacts

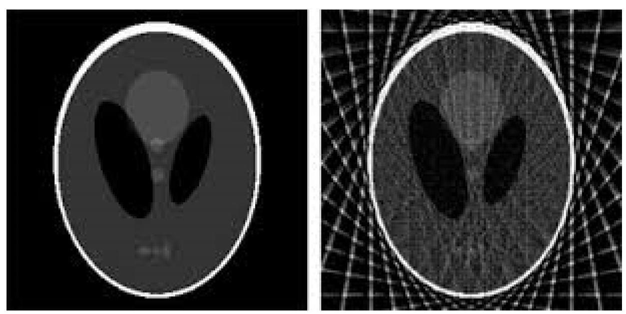

Spikes

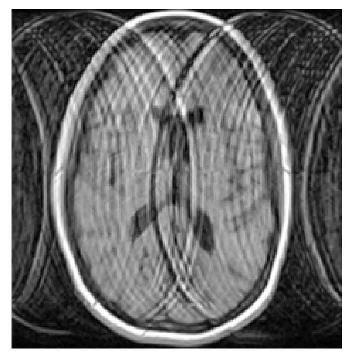

Central point artifact

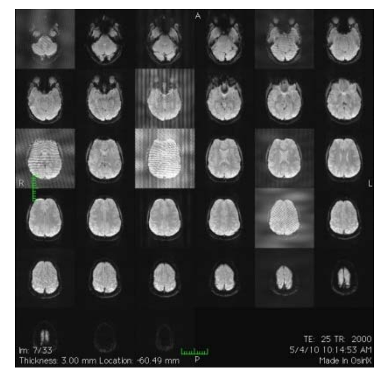

Data clipping


Aliasing

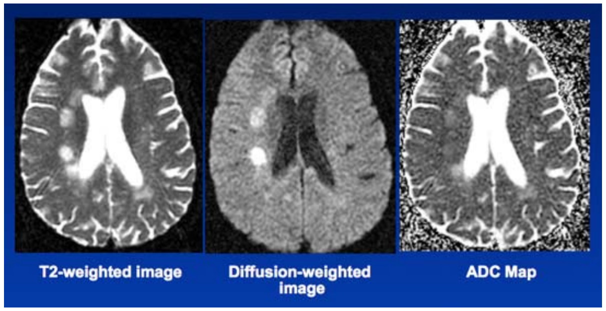

CUSP artifact


Radial recon artifact

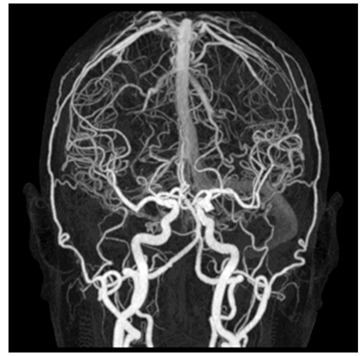

Motion artifact


Random RF
interference

Some subtle artifacts

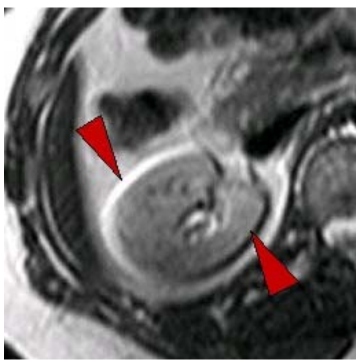


T2 shrine through in DWI

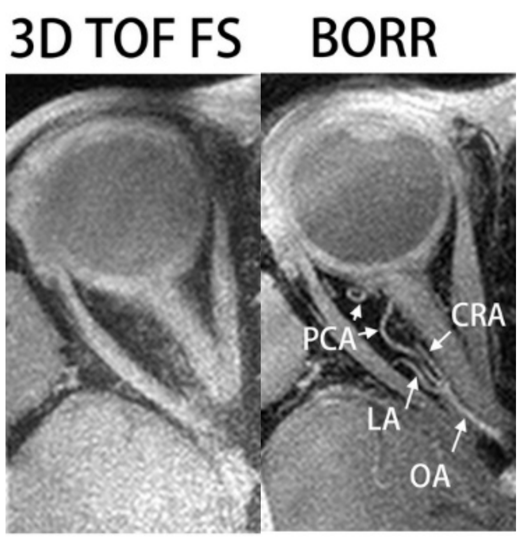


Venous contamination
in CEMRA

Parallel recon, g-factor

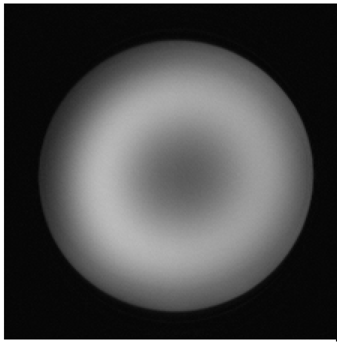


Chemical shift

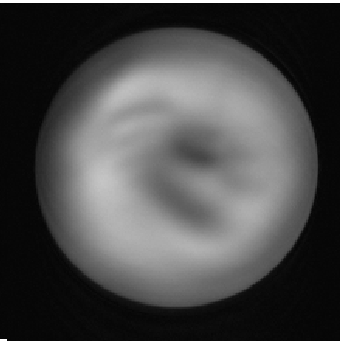


FatSat
power leakage

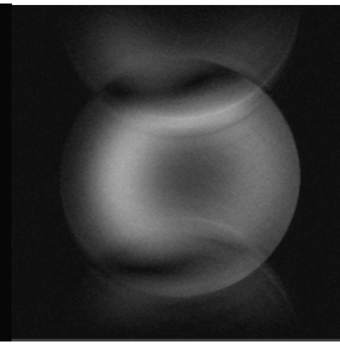
My artifact collections



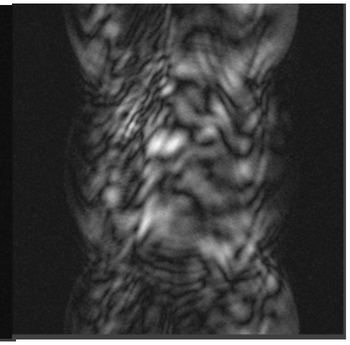
Dielectric effects



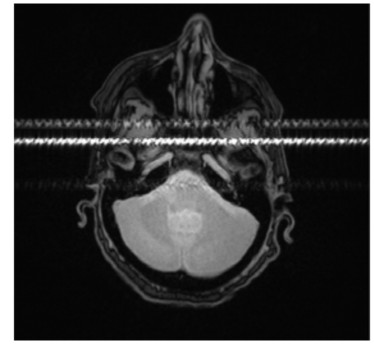
Unsettled liquid



Eddy current
from Nav

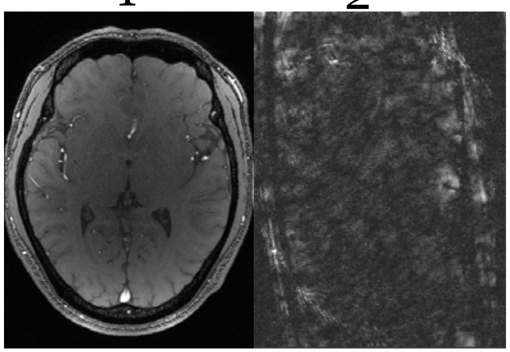


Eddy current
+ unsettled liquid

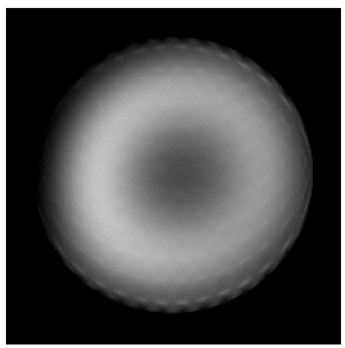


Zipper (RF) artifact

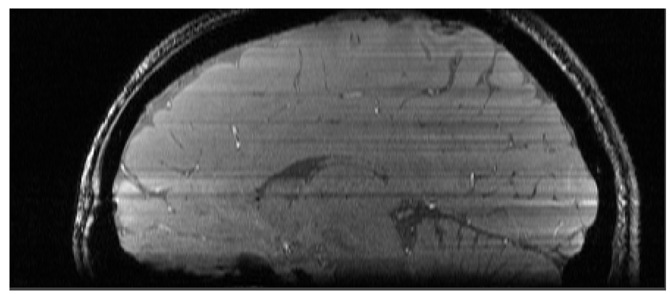
1st 2nd



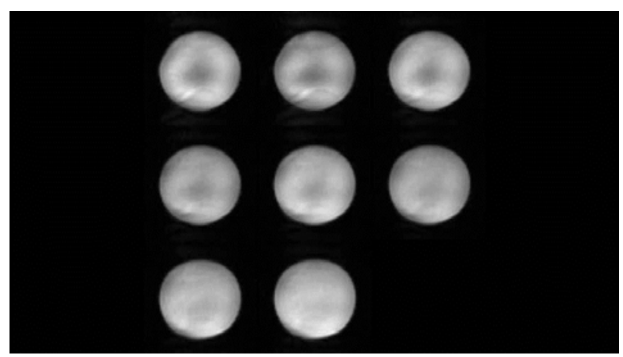
Double echo
unbalanced gradients



Signal pathway
interference in TSE



Possible random
RF interference



Temporally
varying artifact

Homework

Try to find out the cause and solution for several types of MRI artifacts

Next Session

Review on SNR, resolution, imaging parameters and image contrast. (Mainly Chaps 15-20)

Q & A discussion