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 $B_1$. 
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 $\omega_0 = \gamma B_0$
RF pulse properties

- **On- / off- resonant:** $\omega_{\text{rf}} = \neq \omega_{\text{o}}$

- **Flip angle:** tipping effect of the RF pulse

- **Frequency response:** Fourier transform of $B_1(t)$

- **Bandwidth:** within which spins are considered on-resonant

(E. Mark Haacke, *et al.* 1999)
Types of RF pulse

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

![Excitation diagram](image1)
![Refocusing diagram](image2)
![IR diagram](image3)

(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: $T_{\text{sinc}} = 5.12\text{ms}$ w/ 4 zero crossing $\Rightarrow$ BW $\approx 780\text{Hz}$
  - **Non-selective (hard):**
    Very broad BW, e.g. rectangular pulse
    Example: $T_{\text{rect}} = 100\mu\text{s}$ $\Rightarrow$ BW $\approx 12100\text{Hz}$
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 (T₁ρW)
  - 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, $G$

$$\omega_2 = B_0 - Gx_2$$
$$\omega_1 = B_0 + Gx_1$$

Spatial field distribution
Ideally to be spatially linear

Diagram symbol
(gradient lobe)
Generating Gradient pulse
Gradient pulse properties

- Arbitrary lobe shape, slew rate and $G_{\text{max}}$ 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

\[ t_X = t_{X'} \]

\[ t = t_{RF} \neq t_{RF}' \]

\[ X \quad t \quad = \quad X \quad t \quad = \quad X \quad t \]

\[ X \quad t \quad = \quad X \quad t \]

\[ RF \quad \]

\[ X \quad t \quad \neq \quad X \quad t \]
Types of gradient pulses

- Gradient lobe shapes
  - Trapezoid (most commonly used)
  - 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 $G_{\text{max}}$ 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/)

\[ B(x) \]

\[ \text{FOV} \]
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
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 0\textsuperscript{th} 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)

\[ SNR/\text{voxel} \propto \frac{\Delta x \Delta y \Delta z \sqrt{N_{acq}}}{\sqrt{\frac{BW_{read}}{N_x N_y N_z}}} \]
Sequence examples

Hmmm, something's not practically right

3D GRE

2D Spin Echo

(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: $\pi$ pulse not strictly $\pi$

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**RARE (Fast Spin Echo)**

(Berstein, et al. 2004)
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 shrinks 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
- 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