Spin-Echo Sequences

- Spin Echo Review
- Echo Trains
  - Applications: RARE, Single-shot, 3D
  - Signal and SAR considerations
- Hyperechoes?
Spin Echo Review

- Static Dephasing: \( \frac{1}{T2} = \frac{1}{T2^*} + \frac{1}{T2'} \)
- Spin echo “rephases” magnetization
- Spin echoes can be repeated
Motivation: Spin Echo Imaging

• Probably over 75% of clinical MRI
Spin Echo: $T_2$ and $T_2^*$ Decay

The Spin Echo

Courtesy of Kim Butts Pauly
Multi-Echo Trains: RARE, TSE, FSE

Hennig 1986
Echo Train Imaging

RF

Signal

$k_y$

$k_x$

$PD$-weighted $k$-space

$T_2$-weighted $k$-space
Spin-Echo Contrast Variations

T1-weighted  Proton Density  T2-weighted

(Coronal shoulder images showing rotator cuff tear)
Interleaved T$_1$-weighted Imaging

\textbf{RF}

\textbf{$G_z$}

\textbf{$G_y$}

\textbf{$G_x$}

\textbf{Signal}  \hspace{1cm} Slice 1  \hspace{1cm} Slice 2  \hspace{1cm} Slice 1  \hspace{1cm} Slice 2
Single-Shot FSE (SSFSE, HASTE)

Entire image acquired in single echo train

• Lower resolution
• Significant echo-train blurring
• Robust to motion
3D Spin Echo Train Methods

- Originally quite long
- Extended echo-trains help
- Phase-encode orders vary $k_y$ and $k_z$ modulation
- No interleaving(!)
Spin Echo Variations - Summary

• 2D Interleaved:
  • Single-echo
  • Echo-train PD or T2 (FSE, RARE, TSE)
  • STIR, FLAIR, Fast-recovery options
• Single-shot (SSFSE, HASTE)
• 3D: (Cube, SPACE, VISTA)
Spin-Echo Signals

- Basics: T2 decay models, EPG
- Reduced refocusing angles
  - CPMG
  - Pseudo-steady-states
- Modulated refocusing angles
Spin-Echo Signals - Warmup!

• Why do we not play perfect 180º pulses?
  - $B_1$ is not uniform (dielectric, pulse profile, calibration, coil)

• Reducing flip angle reduces RF power deposition (SAR)
• Reducing flip angle can increase signal trade-offs
Spin Echo Train Example

- Simulate
  1. 90° excitation

Repeat:
  2. Relaxation and crusher gradient
  3. Refocusing pulse
  4. Relaxation and crusher gradient
  5. Signal at spin echo

- Vary refocusing angle and/or phase…

epg_cpmg.m
Review: Spin-Echo Coherence Pathways

Only $F_0$ produces a signal… other $F_n$ states are perfectly dephased.
Effect of Crusher Pulses - Eliminate Pathways

Only $F_0$ produces a signal… other $F_n$ states are perfectly dephased.
Crushers Review Question

For fat-saturated spin-echo trains, fat recovers quickly. How does the recovering fat affect the signal in later echoes? No signal!

Any $F_0$ after an RF pulse is never refocused at an echo. Magnetization may accumulate, but does not affect the signal. Note dashed states.
Intuition: Stabilization Pulse

- Often use reduced refocusing angles
  - $90_x$, $-120_x$, $120_x$, $-120_x$, ...
- Consider the “on-resonant” spins
  - $90_x$, $-150_x$, $120_x$, $-120_x$, ...

(Hennig 2000)
Standard CPMG Sequence... FAST!

RF

G_z

G_y

G_x

Signal

90° Refoc. Refoc. Refoc. Refoc. ...

4-8ms!
CPMG Sequences

• Most spin-echo train sequences use CPMG

• CPMG = Carr Purcell Meiboom Gill
  • $90_x, 180_y, 180_y, 180_y, ...$
  • $90_x, -180_x, 180_x, -180_x, ...$ (alternate ref. frame)

• Consider the “dephased” disc:
  • If the 180 angle is lower, CPMG “corrects”
Spin Echo Train Results

- Repeated with $\alpha \varphi$ refocusing pulses, 10ms echo spacing

(see epg_echotrain.m)

3rd line uses 90-150-120-120
4th line uses 90-120-120-120

(Hennig J et al. 2000; 44: 938)
Intuition: CPMG

- $90_y$, $180_x$, $180_x$, ...

- Viewed from x axis (●) = spin after $90^\circ$ tip

- Even echoes “correct” for imperfect $180^\circ$ pulse

\[ M_y \]

\[ M_z \]

\[ 90^\circ_y \text{ - dephase} \]

\[ 180^\circ_x \text{ - dephase} \]

\[ 180^\circ_x \text{ - dephase} \]

\[ M_z \]

\[ M_z \]

\[ M_z \]

\[ M_z \]

\[ M_z \]

\[ M_z \]

\[ M_z \]
CPMG
CPMG: Effect of Phase

- Compares $90^\circ - \pi/2 - \alpha_\phi$ for $\phi=[0,\pi]$ and $\alpha=105^\circ$
- CPMG ($\phi=0$) shown for reference
CPMG: EPG States

- Compare $90^\circ_x - \alpha_x$ to $90^\circ_x - \alpha_y$
- F/Z states on 2nd spin-echo after perfect $90^\circ$ pulse
Pseudo-Steady States

- Reduced flip angles
- “Stabilization” pulse
TRAPS

- Transition to Pseudo-steady-states
- Enhance signal at k-space center (sequential $k_y$)

Hennig 2003
Modulated Refocusing Angles

- Variable flip-angles with CPMG
- Different schemes to “optimize” signal over echo train
- “optimize” varies(!)
- AUC vs SAR vs flatness?

![Graphs showing modulated flip-angle echo train]
Modulated Refocusing Angles: XETA

- “Extended” exponential -- Busse 2006
- $T_2$ contrast with extended echo train
Phase Correction

• Eddy-current variations are a problem
  • Between refocusing pulses eddy currents are the same - so less problematic
  • 90-180 eddy currents differ, causing loss of the 90° phase difference for CPMG

• Linear corrections by modifying $G_x$ and $G_z$ areas

Hinks, 1993
SSFP vs Fast Spin Echo

bSSFP

FSE
Spin-Echo vs Balanced SSFP

- RARE is bSSFP with high-flip angles and crushers
- 90-TE/2 pulse is like the $\alpha/2$-TR/2 pulse
  - But steady-state is eliminated by crushers
  - Transient state is imaged
cTIDE: “Continuous Transition into Driven Equilibrium”

- Start with 90° pulse.
- Ramp down from 180° to $\alpha$
- Looks a lot like modulated spin-echo train
- Usually acquire data during pseudo steady state

RF

-90° +

+ − + − + − + − −α α

Acquisition

....
Off-resonance Behavior of TIDE

a) bSSFP
b) N=80
c) N=5
d) N=2
(90° - 90°+α/2 - α...)

(Courtesy of Jurgen Hennig, Univ. of Freiburg)
Spin-Echo Trains: Additional Points

- J-coupling: Relaxation mechanism in fat
  - Rapid refocusing decreases relaxation rate, so fat is brighter on FSE/RARE than SE
- MT: Interleaved multislice
  - Slice-selective pulses are off-resonance to others
  - MT saturation effect - suppresses some signals
- More...?
Spin-Echo Sequences

• Basic spin echo

• Echo-trains: RARE, FSE, TSE
  • Efficient T2 and PD contrast
  • Extreme cases: SSFSE/HASTE
  • 3D Echo trains

• Signal considerations
  • CPMG / Reduced refocusing angles
  • Modulated echo trains