Lecture-8B — Spin-Echo Sequences
Practical Spin-Echo-Train Signals

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Learning Objectives

- Draw waveforms for a practical spin-echo-train sequence
- Explain the function of crusher gradients
- Explain the CPMG condition and why it is important
- Calculate the signal for reduced and variable refocusing angles
Spin-Echo Trains: Practical Concepts

- Reduced Refocusing
- Short Echo Spacings
- Crusher Gradients
- CPMG
- Stabilization
- Eddy-current correction

Practical spin-echo train sequences use reduced refocusing angles and crusher gradients.
Question 1

Why do we not play perfect 180º pulses?

- B1 is not uniform (dielectric, pulse profile, calibration, coil)
- Reducing flip angle reduces RF power deposition (SAR)
- Reducing flip angle can improve signal trade-offs
Spin Echo Formation: Reduced Refocusing Angle (120°)

A spin-echo will form with almost any refocusing angle.

\[ RF \]

90° \( y \) \hspace{1cm} 120° \( x \)

\[ \begin{align*}
M_x &+ M_y \\
\text{Will refocus!} &+ \text{Unaffected!}
\end{align*} \]
Spin Echo Train Simulation: epg_cpmg.m

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…

Using the EPG formalism, simulation of spin-echo trains is relatively easy: epg_cpmg.m
Coherence Pathways: 180° Spin Echo

With perfect 180° pulses, magnetization is fully refocused using low-order EPG states.
Coherences: Non-180° Spin Echo

When the refocusing pulse angle is reduced, higher-order EPG states and many coherence pathways exist.

Only $F_0$ produces a signal... other $F_n$ states are perfectly dephased.

When the refocusing pulse angle is reduced, higher-order EPG states and many coherence pathways exist.
Effect of Crusher Pulses - Eliminate Pathways

Crusher pulses limit which coherence pathways produce a signal at the echo.

Transverse (F)
Transverse, but no signal
Longitudinal (Z)

Only $F_0$ produces a signal... other $F_n$ states are perfectly dephased.
For fat-saturated spin-echo trains, fat recovers quickly. How does the recovering fat affect the signal in later echoes?

Any $F_0$ after an RF refocusing pulse is never refocused at an echo. Magnetization may accumulate, but does not affect the signal. (Note dashed states)
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)
  - $+90^\circ, +270^\circ, +90^\circ$
- Consider the “dephased” disc:
  - If the refocusing angle is lower, CPMG “corrects”
Example: CPMG

\[ Q_0 = [1;1;0]; \]
\[ Q_1 = \text{epg}_\text{grad}(Q0) \]
\[
\begin{array}{c}
0 & 1 \\
0 & 0 \\
0 & 0 \\
\end{array}
\]

\[ Q_2 = \text{RR}^*Q1 \]
\[
\begin{array}{ccc}
0.00 + 0.00i & 0.25 + 0.00i \\
0.00 + 0.00i & 0.75 + 0.00i \\
0.00 + 0.00i & 0.00 - 0.43i \\
\end{array}
\]

\[ Q_3 = \text{epg}_\text{grad}(Q2) \]
\[
\begin{array}{cccc}
0.75 + 0.00i & 0.00 + 0.00i & 0.25 + 0.00i \\
0.75 + 0.00i & 0.00 + 0.00i & 0.00 + 0.00i \\
0.00 + 0.00i & 0.00 - 0.43i & 0.00 + 0.00i \\
\end{array}
\]

\[ Q_4 = \text{epg}_\text{grad}(Q3) \]
\[
\begin{array}{cccccc}
0.00 + 0.00i & 0.75 + 0.00i & 0.00 + 0.00i & 0.25 + 0.00i \\
0.00 + 0.00i & 0.00 + 0.00i & 0.00 + 0.00i & 0.00 + 0.00i \\
0.00 + 0.00i & 0.00 - 0.43i & 0.00 + 0.00i & 0.00 + 0.00i \\
\end{array}
\]

\[ Q_5 = \text{RR}^*Q4 \]
\[
\begin{array}{cccccc}
0.00 + 0.00i & -0.19 + 0.00i & 0.00 + 0.00i & 0.063 + 0.00i \\
0.00 + 0.00i & 0.94 + 0.00i & 0.00 + 0.00i & 0.19 + 0.00i \\
0.00 + 0.00i & 0.00 - 0.11i & 0.00 + 0.00i & 0.00 - 0.11i \\
\end{array}
\]

\[ Q_6 = \text{epg}_\text{grad}(Q5) \]
\[
\begin{array}{cccccc}
0.94 + 0.00i & 0.00 + 0.00i & -0.19 + 0.00i & 0.00 + 0.00i & 0.06 + 0.00i \\
0.94 + 0.00i & 0.00 + 0.00i & 0.19 + 0.00i & 0.00 + 0.00i & 0.00 + 0.00i \\
0.00 + 0.00i & 0.00 - 0.11i & 0.00 + 0.00i & 0.00 - 0.11i & 0.00 + 0.00i \\
\end{array}
\]

In CPMG, the $F_1$ and $Z_1$ states add constructively at the refocusing pulse to $F_1$. 
Example: Non-CPMG

\[ \begin{align*}
\text{>> } Q_0 &= [i; -i; 0]; \\
\text{>> } Q_1 &= \text{epg\_grad}(Q_0) \\
0 &+i \\
0 &0 \\
0 &0 \\
\text{>> } Q_2 &= RR^*Q_1 \\
0.00 + 0.00i &0.00 + 0.25i \\
0.00 + 0.00i &0.00 + 0.75i \\
0.00 + 0.00i &0.43 + 0.00i \\
\text{>> } Q_3 &= \text{epg\_grad}(Q_2) \\
0.00 - 0.75i &0.00 + 0.00i &0.00 + 0.25i \\
0.00 + 0.75i &0.00 + 0.00i &0.00 + 0.00i \\
0.00 + 0.00i &0.43 + 0.00i &0.00 + 0.00i \\
\text{>> } Q_4 &= \text{epg\_grad}(Q_3) \\
0.00 + 0.00i &0.00 - 0.75i &0.00 + 0.00i &0.00 + 0.25i \\
0.00 + 0.00i &0.00 + 0.00i &0.00 + 0.00i &0.00 + 0.00i \\
0.00 + 0.00i &0.43 + 0.00i &0.00 + 0.00i &0.00 + 0.00i \\
\text{>> } Q_5 &= RR^*Q_4 \\
0.00 + 0.00i &0.00 - 0.56i &0.00 + 0.00i &0.00 + 0.06i \\
0.00 + 0.00i &0.00 + 0.19i &0.00 + 0.00i &0.00 + 0.19i \\
0.00 + 0.00i &-0.54 + 0.00i &0.00 + 0.00i &0.11 + 0.00i \\
\text{>> } Q_6 &= \text{epg\_grad}(Q_5) \\
0.00 + 0.19i &0.00 + 0.00i &0.00 - 0.56i &0.00 + 0.00i &0.00 + 0.06i \\
0.00 - 0.19i &0.00 + 0.00i &0.00 + 0.19i &0.00 + 0.00i &0.00 + 0.00i \\
0.00 + 0.00i &-0.54 + 0.00i &0.00 + 0.00i &0.11 + 0.00i &0.00 + 0.00i \\
\end{align*} \]

In non-CPMG, the \( F_1 \) and \( Z_1 \) states add destructively at the refocusing pulse to \( F_{-1} \).
Intuition: Stabilization Pulse

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

The stabilization pulse makes the odd and even echoes more consistent (Hennig, 2000)
Example: CPMG (Same as before!)

>> Q0 = [1;1;0];
>> Q1 = epg_grad(Q0)

0     1
0     0
0     0

>> Q2 = RR*Q1

0.00 + 0.00i   0.25 + 0.00i
0.00 + 0.00i   0.75 + 0.00i
0.00 + 0.00i   0.00 - 0.43i

>> Q3 = epg_grad(Q2)

0.75 + 0.00i   0.00 + 0.00i   0.25 + 0.00i
0.75 + 0.00i   0.00 + 0.00i   0.00 + 0.00i
0.00 + 0.00i   0.00 - 0.43i   0.00 + 0.00i

>> Q4 = epg_grad(Q3)

0.00 + 0.00i   0.75 + 0.00i   0.00 + 0.00i   0.25 + 0.00i
0.00 + 0.00i   0.00 + 0.00i   0.00 + 0.00i   0.00 + 0.00i
0.00 + 0.00i   0.00 - 0.43i   0.00 + 0.00i   0.00 + 0.00i

>> Q5 = RR*Q4

0.00 + 0.00i  -0.19 + 0.00i  0.00 + 0.00i  0.063 + 0.00i
0.00 + 0.00i  0.94 + 0.00i  0.00 + 0.00i  0.19 + 0.00i
0.00 + 0.00i  0.00 - 0.11i  0.00 + 0.00i  0.00 - 0.11i

>> Q6 = epg_grad(Q5)

0.94 + 0.00i   0.00 + 0.00i  -0.19 + 0.00i  0.00 + 0.00i  0.06 + 0.00i
0.94 + 0.00i   0.00 + 0.00i   0.19 + 0.00i  0.00 + 0.00i  0.00 + 0.00i
0.00 + 0.00i   0.00 - 0.11i  0.00 + 0.00i  0.00 - 0.11i  0.00 + 0.00i

In CPMG, the $F_1$ and $Z_1$ states add constructively at the refocusing pulse to $F_1$. 
Example: CPMG (with Stabilization)

\[
\begin{align*}
Q_0 &= [1;1;0]; \\
Q_1 &= \text{epg\_grad}(Q0) \\
Q_2 &= \text{RR1\_Q1} \\
Q_3 &= \text{epg\_grad}(Q2) \\
Q_4 &= \text{epg\_grad}(Q3) \\
Q_5 &= \text{RR\_Q4} \\
Q_6 &= \text{epg\_grad}(Q5)
\end{align*}
\]

The stabilization pulse brings the odd and even echoes to similar amplitudes, and maintains low-order EPG states.
Spin Echo Train Results

- Varying $\alpha_\phi$ refocusing pulses, 10ms echo spacing

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

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

Examples of CPMG, non-CPMG, and stabilized CPMG in two reference frames
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 maintains spins in lower-order EPG states
Modulated Refocusing Angles

- Variable flip-angles with CPMG
- Different schemes to “optimize” signal over echo train
- AUC vs SAR vs flatness vs “extended” exponential

Modulating the refocusing train will alter the echo-train signal. (Mugler 2000)
Phase Correction

• Eddy-current variations are a problem
  – Between refocusing pulses eddy currents are the same - less problematic
  – 90°-180° eddy currents differ, causing loss of the 90° phase difference for CPMG
  – Oscillation over echo train causes ghosting

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

Hinks, 1993

No Phase Correction

Phase Correction
Hyperechoes

- Symmetry around $180^\circ_y$:
  - $R_z(\beta) R_y(180^\circ) R_z(\beta) = R_y(180^\circ)$
  - $R_\phi(\alpha) R_y(180^\circ) R_\phi(-\alpha) = R_y(180^\circ)$
- The following reduces to $R_x(180^\circ)$,
  - *with $\phi$ defined w.r.t $x$
    ( $\alpha_1, \phi_1$ ), ( $\alpha_2, \phi_2$ ), … ( $\alpha_N, \phi_N$ ), ( $180^\circ, 0$ ), ( $-\alpha_N, -\phi_N$ ), …, ( $-\alpha_2, -\phi_2$ ), ( $-\alpha_1, -\phi_1$ )
Hyperecho Example

The time-reversed, conjugate-phase and opposite refocusing angles lead to a hyperecho.

Random $\alpha$, $\varphi$. $N=4$

Phase Diagram (epg_cpmg)
Summary

- CPMG: Refocusing pulses “self-correct” $90^\circ_y, \alpha_x, \alpha_x, \alpha_x, \ldots$ or $90^\circ_x, -\alpha_x, \alpha_x, -\alpha_x, \ldots$
- Stabilization Pulse: First refocusing pulse balances echoes
- Non-CPMG: Signal oscillates and decays quickly
- CPMG allows reduced, variable refocusing angles
- Eddy-current-induced phase can disrupt CPMG
- Hyperechoes enable reversal of reduced-refocusing-angle effects
How are spin-echo sequences related to gradient echo sequences?