Class Business

- Final project
  - start thinking
  - come to office hours
  - discussion in class next Thu
  - 6/7 9am-12pm and 6/8 3pm-6pm

- Homework 1 due 4/26 Thu

- Homework 2 due 5/4 Fri
Outline

- Rapid GRE
  - gradient and RF-spoiled GRE

- RARE (aka FSE, TSE)

- Pulse sequence simulations
  - MATLAB Bloch simulations
  - Homework 2
Why RARE (TSE)?

• Basic spin echo (SE) MRI is slow
  - TR on the order of 500 - 5000 ms
  - Data acquisition of one k-space line per TR, readout duration of 10 ms or less
  - Could acquire more lines before complete $T_2$ decay of $M_{xy}$
RARE (TSE) MRI

• Rapid Acquisition with Relaxation Enhancement (RARE)\(^1\), aka Fast Spin-Echo (FSE) or Turbo Spin-Echo (TSE)

• Has virtually replaced SE for multiple clinical applications, esp. T2w imaging

• Challenging at high field (≥ 3 T)

\(^1\)Hennig J et al., MRM 1986
Spin Echo

90°  180°

τ  τ

$T_2$ decay

TE = 2τ

TR

SE
Spin Echo

• Image contrast
  - Based on TE, TR
  - T1w, T2w, PDw
  - Can augment with prep pulses

• Scan time
  - $T_{SE} = N_{pe} \times TR$
  - TR = 1000 ms, $N_{pe} = 256$: $T_{SE} = 4+ \text{ min}$
  - usually combined with 2D multislice acq
Multi-echo Spin Echo

90°  180°  180°  180°

τ τ 2τ 2τ

$T_2$ decay

$TE_1 = 2\tau$  $TE_2 = 4\tau$  $TE_3 = 6\tau$

Can perform $T_2$ mapping.
RARE (Turbo Spin Echo)
Carr-Purcell-Meiboom-Gill conditions

- ensure echoes only occur at desired positions in the sequence, and
- signals at each position have the same phase

\[ 90^\circ_x - \tau - 180^\circ_y - 2\tau - 180^\circ_y - 2\tau - 180^\circ_y \ldots \]

Constant phase accrual between pulses

- Same area for crusher pairs
- Phase encode rewinder
CPMG Conditions

• When satisfied
  - SE and STE coincide (same phase)
  - secondary SE and FID are crushed

• Moving spins can violate CPMG
TSE Sequence Params

- Echo train length (ETL)
- Echo spacing (ESP)
- Number of shots ($N_{\text{shot}}$)
- Effective TE ($T_{E\text{eff}}$)

ESP = $2\tau$

$90^\circ_x$  $180^\circ_y$  $180^\circ_y$  $180^\circ_y$  ...

$T_{E\text{eff}}$

$\text{ETL}$

$\text{TR}$  $x$  $N_{\text{shot}}$
TSE Sequence Params

- **ETL typically 4-16**
  - Can’t be too high, due to $T_2$ decay

- **ESP typically <10 ms**
  - Must accommodate RF, gradients, ADC
  - Short ESP facilitates high ETL

- **Example**: readout until $S = 0.2 \ S_0$
  - $S = S_0 \ * \ exp(-t/T_2)$; assume $T_2 = 100$ ms
  - $t = 160.9$ ms
  - ESP = 8 ms; ETL = 20
  - ESP = 4 ms; ETL = 40
2D RARE Sequence

Bernstein et al., Handbook of MRI Pulse Sequences, Ch 16.4
2D RARE Sequence

Interleaved 2D Multi-Slice Acquisition

Bernstein et al., Handbook of MRI Pulse Sequences, Ch 16.4
3D RARE Sequence

Bernstein et al., Handbook of MRI Pulse Sequences, Ch 16.4
TSE Scan Time

- **Scan time**
  - Recall $T_{SE} = N_{pe} \times TR_{SE}$
  - $N_{shot} = N_{pe} / ETL$
  - $T_{TSE} = N_{shot} \times TR_{TSE} = (T_{SE} / ETL) \times (TR_{TSE} / TR_{SE})$

- **Example**: 2D single slice
  - $N_{pe} = 256; ETL = 16; N_{shot} = 16$
  - $TR = 1000 \text{ ms}: T_{TSE} = 16 \text{ sec}$

- **Example**: 3D volume
  - $N_{pe} = 256*256; ETL = 32; N_{shot} = 2048$
  - $TR = 1000 \text{ ms}: T_{TSE} = 34 \text{ min}$
TSE Image Contrast

- $\text{T}_\text{E}_{\text{eff}}, \text{TR}$
  - T1w, T2w, PDw
  - PE ordering affects $\text{T}_\text{E}_{\text{eff}}$

Bernstein et al., Handbook of MRI Pulse Sequences, Ch 16.4
FIGURE 16.48  By using different echoes to sample the k-space center, considerably different image contrast can be obtained from a RARE sequence. (a) $T_1$-weighted image with $TE = 11$ ms, $TR = 480$ ms, and $N_{etl} = 8$. (b) Moderately $T_2$-weighted image with $TE = 77$ ms, $TR = 4000$ ms, and $N_{etl} = 16$. (c) Heavily $T_2$-weighted image with $TE = 176$ ms, $TR = 4000$ ms, and $N_{etl} = 16$. 

Bernstein et al., Handbook of MRI Pulse Sequences, Ch 16.4
TSE Image Contrast

• Dual-echo PDw+T2w in same TR
• Mag-prep modules (IR, SR, FS, etc.)
• Inherent flow suppression
  - only static spins see multiple 180s
  - “dark/black blood” imaging
TSE Image Contrast

- Bright fat
  - J-coupling of protons in lipids (CH$_3$-CH$_2$-); $f_{CS} \sim 25$ Hz, $f_J \sim 7$ Hz @ 1.5 T
  - $S = S_0 \times \exp(-t/T_2) \times \cos(n_{\text{ech}} \pi f_J \text{ESP})$
  - Shortening of apparent $T_2$ (in SE)

- J-coupling negligible when $\text{ESP} \leq 1/[2 \sqrt{f_{CS}^2 + f_J^2}] \sim 20$ ms @ 1.5 T
- In TSE, short ESP avoids attenuation by J-coupling, thus brighter fat signal
TSE Image Contrast

Spin Echo

Turbo Spin Echo

Bright Fat

¹Henkelman R et al., JMRI 1992
• Magnetization transfer
  - MT effect
  - multiple refocusing pulses in TSE
  - off-resonance excitation in other slices; can lead to MT-induced signal loss
TSE Advantages

- Image contrast very similar to SE
- Robust to off-resonance effects (SE)
- Much faster scan than SE
TSE Challenges

- Blurring; edge enhancement; ghosting;
  - attention to PE ordering and ETL

*Bernstein et al., Handbook of MRI Pulse Sequences, Ch 16.4*
TSE Challenges

$T_2$ blurring (PE) in single-shot TSE

Bernstein et al., Handbook of MRI Pulse Sequences, Ch 16.4
TSE Challenges

- RF power deposition increased
  - Specific Absorption Rate (SAR) W/kg; SAR $\propto \theta^2 (B_0)^2$
  - use reduced refocusing flip angles, e.g., $\theta = 130^\circ$ instead of $180^\circ$
Extensions and Variations

- Partial echo
- Multi-echo
- Mag-prep
Extensions and Variations

• Partial Fourier
  - Sample \(~\text{half of } k\)-space data, reconstruct assuming Hermitian symmetry (real-valued MR images)
  - reduce refocusing pulses, reduce SAR
  - better control of $T\text{E}_{\text{eff}}$

• Parallel imaging
  - Undersample $k$-space data, reconstruct using information from multiple coils
  - reduce refocusing pulses, reduce SAR
Related Sequences

• TSE + non-Cartesian trajectories
  - radial, rings, spiral, cylinders, etc.

• TSE-Dixon to separate bright fat

• Half-Fourier acquired single-shot turbo spin echo (HASTE)

• Variable flip angle 3D TSE (SPACE, CUBE, etc.) to manage SAR, ETL
Related Sequences

Gradient And Spin Echo (GRASE)\textsuperscript{1}, aka Turbo gradient spin echo (TGSE)

\textsuperscript{1}Oshio K et al., MRM 1991

Bernstein et al., Handbook of MRI Pulse Sequences, Ch 16.2
Clinical Applications

- The bread and butter sequence!
  - Brain
  - Body
  - Cardiac
  - Musculoskeletal
  - and more ...
More About TSE

- FID, SE, secondary SE, Stimulated Echoes (STE) ...

- Practical conditions
  - Reduced refocusing pulse angles
  - Non-uniform slice profiles
  - $B_1$ inhomogeneity
Summary

• RARE (Turbo Spin Echo)
  - efficient use of $M_{xy}$
  - shares robustness of SE
  - core clinical sequence
  - challenges with SAR

• Multiple RF pulses $\rightarrow$ multiple echoes
  - generalized view of MR pulse sequences

• EPG next week!
Pulse Sequence Simulations
Outline

• Bloch Equation Simulations
  - basic operations (matrix form)
  - MATLAB implementation
  - examples: rapid GRE
  - homework
Bloch Simulation

- Bloch Equations
  - RF excitation
  - $T_1, T_2$ decay
  - free precession
  - gradient pulse
Bloch Simulation

Rotation:

\[ R_x(\theta) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \theta & \sin \theta \\ 0 & -\sin \theta & \cos \theta \end{bmatrix} \]

\[ R_y(\theta) = \begin{bmatrix} \cos \theta & 0 & -\sin \theta \\ 0 & 1 & 0 \\ \sin \theta & 0 & \cos \theta \end{bmatrix} \]

\[ R_z(\theta) = \begin{bmatrix} \cos \theta & \sin \theta & 0 \\ -\sin \theta & \cos \theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \]

\[ \text{function } R_x=\text{xrot(phi)} \]
\[ R_x = [1 \ 0 \ 0; \ 0 \ \cos(\text{phi}) \ -\sin(\text{phi}); \ 0 \ \sin(\text{phi}) \ \cos(\text{phi})]; \]

Nishimura, Principles of MRI, Ch. 2
Hargreaves, MATLAB Bloch Simulator
Bloch Simulation

Free precession:

\[ R_z(\omega_0 t) = \begin{bmatrix}
\cos \omega_0 t & \sin \omega_0 t & 0 \\
-\sin \omega_0 t & \cos \omega_0 t & 0 \\
0 & 0 & 1
\end{bmatrix} \]

Nishimura, Principles of MRI, Ch. 2
Bloch Simulation

General Rotation:

\[ R_{\{\varphi, \xi\}}(\theta) = R_z(-\varphi)R_y(-\xi)R_z(\theta)R_y(\xi)R_z(\varphi) \]

Nishimura, Principles of MRI, Ch. 2
Bloch Simulation

Relaxation + Free Precession:

\[ M(t) = e^{-t/T_2} \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix} e^{-t/T_2} + e^{-t/T_1} \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} R_z(\Delta \omega t)M(0) + \begin{bmatrix} 0 \\ 0 \\ M_0(1 - e^{-t/T_1}) \\ AM(0) + B \end{bmatrix} \]

Hargreaves, MATLAB Bloch Simulator
Bloch Simulation

- Transient state; steady state
- Different seq/tissue params
- Brian’s MATLAB Bloch sim tutorial
Bloch Simulation

- **Example 1**: Gradient Echo (long TR)
  - xrot.m, yrot.m, zrot.m, throt.m
  - freeprecess.m
  - Sim_SatRecovery.m

- add gradient rewinders / spoilers, RF phase cycling to simulate rapid GRE sequences
Bloch Simulation

- **Example 2**: Balanced SSFP
  - xrot.m, yrot.m, zrot.m, throt.m
  - freeprecess.m
  - sssignal.m
  - BalancedSSFP_freqresp.m
  - consider different flip angle, $T_1$, $T_2$
  - change TR and look at freq response
Bloch Simulation

- Homework 2, part 1A
  - Steady state for bSSFP, SSFP-FID and SSFP-Echo
Gradient-spoiled GRE

SS signal as a function of off-resonance:

*bSSFP*

$T_1 = 1000 \text{ ms}$, $T_2 = 100, 200, 500, 1000 \text{ ms}$

GRE (SSFP-FID)
Gradient-spoiled GRE

SS signal as a function of flip angle:

*bSSFP*

Different T2/T1 ratios, df = 100 Hz

GRE (SSFP-FID)

Different T2/T1 ratios, df = 50 Hz

$T_1 = 1000 \text{ ms}$, $T_2 = 100, 200, 500, 1000 \text{ ms}$
Gradient-spoiled GRE

SS signal as a function of flip angle:

- **bSSFP**
- **GRE (SSFP-Echo)**

Different T2/T1 ratios, df = 100 Hz

Different T2/T1 ratios, df = 50 Hz

\[ T_1 = 1000 \text{ ms}, \ T_2 = 100, 200, 500, 1000 \text{ ms} \]
Bloch Simulation

- Homework 2, part 1B
  - Transition to steady state for bSSFP
  - Catalyzation schemes
Balanced SSFP

Transition to steady state:

TR = 5 ms
Δφ = π
θ = 60°

$T_1 = 600\, ms$, $T_2 = 100\, ms$
Balanced SSFP

Transition to steady state:

TR = 5 ms
$\Delta \phi = \pi$
$\theta = 60^\circ$

$T_1 = 600 \text{ ms}, T_2 = 100 \text{ ms}$
Balanced SSFP

Transition to steady state ($\theta/2 - TR/2$ prep):

- $TR = 5$ ms
- $\Delta \phi = \pi$
- $\theta = 60^\circ$

$T_1 = 600$ ms, $T_2 = 100$ ms
Balanced SSFP

Transition to steady state ($\theta/2 - TR/2$ prep):

- TR = 5 ms
- $\Delta\phi = \pi$
- $\theta = 60^\circ$

$T_1 = 600\ ms$, $T_2 = 100\ ms$
Balanced SSFP

- Linear ramp-up catalyzation
  - initial train of $\theta \cdot [1:N]/N$ (same TR)
  - Example:
    $\theta = 60^\circ$, $N = 5$
    ramp up pulses $\theta_{lin} = [12^\circ, 24^\circ, 36^\circ, 48^\circ, 60^\circ]$
Homework 2

- Pulse Sequence Simulations
  - 1. Bloch: Steady state comparison, bSSFP transient state and catalyzation
  - 2. EPG: SSFP-FID, RF-spoiled GRE

- Due 5 pm, Fri, 5/4 by email
  - PDF and MATLAB code
Thanks!

- **Web resources**
  - ISMRM 2010 Edu: Miller, Weigel
  - ISMRM 2011 Edu: Miller, Weigel

- **Further reading**
  - Bernstein et al., Handbook of MRI Sequences
  - Haacke et al., Magnetic Resonance Imaging
  - Hennig, JMR 1988; 78:397-407
Thanks!

• Acknowledgments
  - Brian Hargreaves

• Next lecture
  - EPG and MATLAB demo

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