Class Business

- Office hours
  - Instructors: Fri 10 am - 12 pm, starting 4/19
  - TA: Xinran Zhong, Tue 3-5 pm
  - email beforehand would be helpful

- Homework 1 due 4/26 Fri

- Follow Brian’s Bloch sim tutorial

- Final presentation date/time
  - 6/11 Tue and/or 6/13 Thu
  - conflicts? email instructors
Outline

• Gradient Echo (GRE)
• Rapid Gradient Echo
  - Balanced SSFP
  - Gradient-spoiled GRE
  - RF-spoiled GRE
• Comparison
• Extensions and Variations
• Applications
Gradient Echo

RF

θ

G_z

θ

TR

G_y

G_x

TE

ADC

T_2^* decay
Gradient Echo

- Gradient reversal on the readout axis forms the echo (vs. RF spin echo)
- A.k.a. gradient-recalled echo, gradient-refocused echo, field echo
- Flip angle $\theta$ typically $< 90^\circ$
- $M_{xy}$ has $T_2^*$ instead of $T_2$ decay
- Advantageous for fast 3D imaging
Gradient Echo

• Basic steps
  - RF excitation (flip angle $\theta$ and phase $\phi$)
  - Free precession (from $G$ and $\Delta B$)
  - $T_1$ and $T_2$ (or $T_2^*$) relaxation

• Steady state
  - “Dynamic equilibrium”
  - Established after initial transient state
  - $M_z$ and $M_{xy}$ remain the same, TR to TR
  - Need to meet certain conditions
Gradient Echo

- When $TR > 5 \cdot T_2^*$, $M_{xy}$ naturally “spoiled”
- To the board …
Gradient Echo

Steady-state signal equation:

\[ M_{xy,ss}(TE) = \frac{M_0 \sin \theta (1 - E_1)}{1 - \cos \theta E_1} e^{-\frac{TE}{T_2^*}} \]

Ernst angle:

\[ \theta_E = \cos^{-1}(E_1) \]

\[ E_1 = e^{-\frac{TR}{T_1}} \]
Gradient Echo

Ernst angle:

$\theta_E = 64^\circ$

$WM\ T_1 = 600\ ms,\ T_2 = 80\ ms$
Gradient Echo

• $T_1$-weighted image contrast
  - $M_{xy}$ gone at end of each TR
  - TE controls $T_2^*$ weighting

• Typical $T_2^* \sim 50$ ms
  - need TR $\sim 250$ ms for “natural” spoiling

• Reduce TR and maintain T1w contrast?
  - rapid GRE with appropriate spoiling
Rapid Gradient Echo

- Rapid imaging with TR $\ll T_2 < T_1$

- Steady state
  - Involves a mixture of $M_z$ and $M_{xy}$
  - Necessary and sufficient conditions:
    1. Constant RF flip angle $\theta$
    2. Constant TR
    3. Constant dephasing $\beta$ between RF pulses
    4. RF phase $\phi_n = a + bn + cn^2$

Gradient Echo

RF

$\theta$

long TR

$G_z$

$G_y$

$G_x$

ADC

...
Rapid Gradient Echo

\( RF \)

\( G_z \)

\( G_y \)

\( G_x \)

\( ADC \)

\( \theta, \phi \)

\( \theta, \phi \)

\( \theta, \phi \)

\( \theta, \phi \)

\[ \text{TR} \ll T_2 \]

Manage/utilize remaining \( M_{xy} \)
Balanced SSFP

RF

$\theta, \phi$

$G_z$

$G_y$

$G_x$

ADC
Gradient-spoiled GRE

RF

$G_z$

$G_y$

$G_x$

ADC
Gradient & RF-spoiled GRE

RF

\( \theta, \phi \)

\( G_z \)

\( G_y \)

\( G_x \)

ADC
## Rapid Gradient Echo

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cf. Table 14.1, *Handbook of MRI Pulse Sequences*

cf. “MRI Acronyms”, Siemens Healthcare
Balanced SSFP

RF

$G_z$

$G_y$

$G_x$

ADC
Balanced SSFP

• All gradients are balanced
  - $\beta$ from $G_x, G_y, G_z = 0$
  - $\beta$ only comes from $\Delta B$

• Typically use $\phi_n = n \cdot \pi$  ($\Delta \phi = \pi$)

• Typically use $TE = TR/2$
  - $M_{xy}$ actually has $T_2$ (not $T_2^*$) decay\(^1\)

• Contrast depends on $T_1$ and $T_2$

\(^1\)Ganter C, MRM 2006; 56:687-691
Balanced SSFP

• To the board …
Balanced SSFP

Steady-state signal equation \((\beta = 0)\):

\[
M_{xy,ss}(TE) = M_0 \sin \theta \frac{1 - E_1}{1 - (E_1 - E_2) \cos \theta - E_1 E_2} \sqrt{E_2}
\]

\[
E_1 = e^{-\frac{TR}{T_1}}
\]

\[
E_2 = e^{-\frac{TR}{T_2}}
\]

\[
\sqrt{E_2} = e^{-\frac{TE}{T_2}}
\]
Balanced SSFP

Steady-state signal equation ($\beta = 0$):

If $\text{TR} \ (3\text{-}5 \text{ ms}) \ll T_2$, $E_1 \sim 1\text{-}\text{TR}/T_1$ and $E_2 \sim 1\text{-}\text{TR}/T_2$:

$$M_{xy,ss}(\text{TE}) = \frac{M_0 \sin \theta}{(T_1/T_2)(1 - \cos \theta) + (1 + \cos \theta)} \sqrt{E_2}$$

$T_2/T_1$ contrast weighting

$$\theta_{max} = \arccos\left(\frac{T_1 - T_2}{T_1 + T_2}\right) \quad M_{xy,ss}(\theta_{max}) \sim \frac{M_0}{2} \sqrt\frac{T_2}{T_1}$$

When $T_1 = T_2$, $\theta_{max} = 90^\circ$, $M_{xy,ss} \sim 0.5 \ M_0$!
Balanced SSFP

SS signal as a function of flip angle:

- $\text{TR} = 5 \text{ ms}$
- $\Delta \phi = 0$
- $\beta = \pi$

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

SS signal as a function of off-resonance:

\[ TR = 5 \text{ ms} \]
\[ \Delta \phi = 0 \]

\[ T_1 = 1000 \text{ ms}, \ T_2 = 100, 200, 500, 1000 \text{ ms} \]
Balanced SSFP

SS signal as a function of off-resonance:

TR = 5 ms  \( \Delta f = \pm 100 \) Hz  
\( \Delta \phi = 0 \)

Recall \( \beta = 2\pi \Delta f \times TR \) and \( \Delta f = \gamma B / 2\pi \)

\( \beta = \pm \pi \) corresponds to \( \Delta f = \pm 1/(2 \ TR) \) Hz

TR = 5 ms: \( \Delta f = \pm 100 \) Hz  
TR = 2.5 ms: \( \Delta f = \pm 200 \) Hz
Balanced SSFP

SS signal as a function of off-resonance:

$\text{TR} = 2.5 \text{ ms}$

$\Delta \phi = 0$

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

SS signal as a function of off-resonance:

$$\Delta \phi = \pi$$

$$\Delta \phi$$ can shift the off-resonance response
Balanced SSFP

SS signal as a function of off-resonance:

$TR = 2.5 \text{ ms}$

$\Delta \phi = 0$

$T_1 = 1000 \text{ ms}$, $T_2 = 1000 \text{ ms}$
Balanced SSFP

Banding artifacts at 3 T:
Balanced SSFP

- Banding artifacts
  - bSSFP has freq-dep null bands
  - spatially varying field inhomogeneity
  - shim not perfect
  - worse at high field (e.g., 3 T vs 1.5 T)

- Mitigating banding artifacts
  - reduce TR
  - custom shim; shift center freq
  - phase cycling
Balanced SSFP

• Phase cycling - to the board ...
Balanced SSFP

- Removing banding artifacts
  - Multi-acquisition bSSFP (phase cycled)
  - Image reconstruction (rSoS, MIP, etc.)
Balanced SSFP

Transition to steady state:

\[ TR = 5 \text{ ms} \]
\[ \Delta \phi = \pi \]
\[ \theta = 60^\circ \]

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

Transition to steady state:

\[ \text{TR} = 5 \text{ ms} \]
\[ \Delta \phi = \pi \]
\[ \theta = 60^\circ \]

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

• Transient state
  - approach to steady state can take $5 \cdot T_1$
  - depends on sequence and tissue params
  - longer transition for larger $\theta$
  - artifacts and variable image contrast

• Catalyzation pulses
  - achieve smoother transition to steady state
  - simple approach: $\theta/2$ - TR/2 preparation
  - other sophisticated designs
Balanced SSFP

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

Scheffler et al., Eur Radiol; 13:2409-2418
Balanced SSFP

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

$\text{TR} = 5$ 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):

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

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

• Advantages
  - High SNR efficiency
  - $G_x$ and $G_z$ first moments nulled

• Challenges
  - Field homogeneity
  - TR
  - SAR
  - Catalyzation
  - Bright fat
Gradient-spoiled GRE

RF

$G_z$

$G_y$

$G_x$

ADC

SSFP-FID
Gradient-spoiled GRE

- End-of-TR gradient spoiler
  - typically on $G_x$ and/or $G_z$
  - Range of $\beta$ within each voxel
  - $M_{xy}$ is a complex sum of all spins

- Contrast depends on $T_1$ and $T_2$
Gradient-spoiled GRE

Steady-state signal equation:

\[
SSFP_{\text{FID}} = M_0 \frac{\sin \theta}{1 + \cos \theta} (1 - (E_1 - \cos \theta) f(E_1, E_2, \theta))
\]

\[
f(E_1, E_2, \theta) = \sqrt{\frac{1 - E_2^2}{(1 - E_1 \cos \theta)^2 - E_2^2(E_1 - \cos \theta)^2}}
\]

When \( TR \gg T_2 \):

\[
SSFP_{\text{FID}} \rightarrow M_0 \sin \theta \frac{1 - E_1}{1 - E_1 \cos \theta}
\]

same as ideally spoiled GRE
Gradient-spoiled GRE

SS signal as a function of flip angle:

*bSSFP*

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

SS signal as a function of off-resonance:

*bSSFP*

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

Transition to steady state:

$T_1 = 600 \text{ ms}, \ T_2 = 100 \text{ ms}, \ TE/TR = 2/10 \text{ ms}, \ \theta = 30^\circ$
Gradient-spoiled GRE

(reversed)

RF

$\theta$

$\theta$

$\theta$

Gz

Gy

Gx

ADC

SSFP-Echo
Gradient-spoiled GRE

(reversed)

Steady-state signal equation:

\[
SSFP_{\text{Echo}} = M_0 \frac{\sin \theta}{1 + \cos \theta} (1 - (1 - E_1 \cos \theta) f(E_1, E_2, \theta))
\]

\[
f(E_1, E_2, \theta) = \sqrt{\frac{1 - E_2^2}{(1 - E_1 \cos \theta)^2 - E_2^2 (E_1 - \cos \theta)^2}}
\]

When TR \ll T_1:

\[
\frac{SSFP_{\text{Echo}}}{SSFP_{\text{FID}}} \sim E_2^2 = e^{-2TR/T_2}
\]

higher \( T_2 \) contrast weighting than \( SSFP_{\text{FID}} \)
Gradient-spoiled GRE

SS signal as a function of flip angle:

*bSSFP*

Different T2/T1 ratios, df = 100 Hz

GRE (SSFP-Echo)

Different T2/T1 ratios, df = 50 Hz

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

- Image characteristics
  - no banding (averaged in voxel)
  - SSFP-FID: $T_2/T_1$ contrast
  - SSFP-Echo: more $T_2$ contrast
  - sensitive to motion / flow / diffusion

- When all gradients are balanced
  - SSFP-FID and SSFP-Echo coalesce
  - $T_2$ instead of $T_2^*$ weighting
  - Balanced SSFP!
Gradient & RF-spoiled GRE

RF

$\theta, \phi$

$G_z$

$G_y$

$G_x$

ADC
Gradient and RF-spoiled GRE

- RF spoiling (quadratic)
  - $\phi_n = \phi_{n-1} + n\phi_0 = (1/2)\phi_0(n^2 + n + 2)$
  - typically $\phi_0 = 50^\circ$ or $117^\circ$
  - ADC phase each TR also needs to match $\phi_n$

- $T_1$-weighted contrast
  - approaches contrast of ideally spoiled GRE
  - at expense of reduced SNR (removes T2w contributions)
Gradient and RF-spoiled GRE

Choice of RF phase increment:

\[ TR = 0.02T_1 = 0.02T_2, \alpha = 60^\circ \]

Ernst amplitude

Gradient and RF-spoiled GRE

SS signal as a function of flip angle:

**bSSFP**

Different T2/T1 ratios, df = 200 Hz

**Spoiled GRE**

Different T2/T1 ratios, df = 50 Hz

\( T_1 = 100, 200, 500, 1000 \text{ ms}, \ T_2 = 40 \text{ ms} \)
Gradient and RF-spoiled GRE

SS signal as a function of off-resonance:

**bSSFP**

Different T2/T1 ratios, $\theta = 60$ deg

**Spoiled GRE**

Different T2/T1 ratios, $\theta = 60$ deg

\[ T_1 = 100, 200, 500, 1000 \text{ ms} \quad T_2 = 40 \text{ ms} \]
Gradient and RF-spoiled GRE

Transition to steady state:

\[ T_1 = 600 \text{ ms}, \ T_2 = 100 \text{ ms}, \ TE/TR = 2/10 \text{ ms}, \ \theta = 30^\circ \]
Gradient and RF-spoiled GRE

- Image characteristics
  - no banding
  - $M_{xy}$ spoiled before next TR
  - T1w contrast with short TR
  - $\theta$ controls degree of $T_1$ contrast
  - TE controls degree of $T_2^*$ contrast
  - robust to motion
Rapid GRE - Comparison

bSSFP  Grad spoiled  RF spoiled

Hargreaves B, JMRI 2012; 36:1300-1313
Rapid GRE - Comparison

Flip angle

Hargreaves B, JMRI 2012; 36:1300-1313
## Rapid GRE - Comparison

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<td>T₁; T₂*</td>
<td>low</td>
</tr>
</tbody>
</table>

SS transition

cf. Hargreaves B, JMRI 2012; 36:1300-1313
Considerations

• Chemical shift

• Flow

• Diffusion
Extensions and Variations

- Partial echo
- Multi-echo
- Ultra-short TE
- Magnetization preparation
- Multiple steady states
Applications

• bSSFP
  - Cardiac
  - MRA
  - $T_2$-like imaging
  - fMRI
  - phase contrast
  - Mag-prep

Scheffler et al., Eur Radiol; 13:2409-2418
Applications

- SSFP-FID / Echo
  - $T_2$-like imaging (e.g., cartilage)
  - Bright fluid (bSSFP-like without banding)
  - Diffusion-weighted imaging (SSFP-Echo)
Applications

- Spoiled GRE
  - T1w imaging
  - $T_2^*$ BOLD fMRI
  - Susceptibility-weighted imaging (SWI)
  - Phase contrast
  - Thermometry
  - Time-of-flight MRA
  - Contrast-enhanced imaging
  - Mag-prep imaging
Thanks!

- **Web resources**
  - ISMRM 2010 Edu: Weigel, Bieri, Miller
  - ISMRM 2011 Edu: Weigel, Miller
  - ISMRM 2012 Edu: Miller, Bieri

- **Further reading**
  - Bernstein et al., Handbook of MRI Sequences
  - Haacke et al., Magnetic Resonance Imaging
  - Nishimura, Principles of MRI
  - pubmed.org
Thanks!

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  - Suba’s slides from M219 (2014)
  - Brian Hargreaves’s Bloch simulator

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