Advanced Medical Imaging Techniques and Applications: *Spin Echo / Gradient Echo Imaging*

2018 Fellows’ Lecture Series
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Assistant Professor of Radiology
Magnetic Resonance Research Labs

Location: UCLA Medical Center, Room 1621C

2018 Fellows’ Lecture Series
Advanced Medical Imaging Techniques & Applications

Mondays at 7:15am in the Ronald Reagan UCLA Medical Center (Room 1621C)

07/23/2018 - Spin Echo / Gradient Echo Imaging (Dr. Sung)
07/30/2018 - Parallel Imaging (Dr. Hu)
08/06/2018 - Perfusion and Diffusion Imaging (Dr. Ellingson)
08/13/2018 - Motion Artifacts / Compensation (Dr. Wu)
08/20/2018 - Fat / Water Imaging (Dr. Wu)
08/27/2018 - Medical Imaging Informatics (Dr. Hsu)
09/03/2018 - Holiday (Labor Day)
09/10/2018 - MR Spectroscopy (Dr. Thomas)
$T_1$ & $T_2$ Relaxation

$T_1$ Relaxation

Decay Time [ms]

Fraction of $M_0$

- Fat: 260ms
- Liver: 500ms
- CSF: 2400ms
T₁ Relaxation

• Longitudinal or spin-lattice relaxation
  – Typically, (10s ms) < T₁ < (100s ms)
• T₁ is long for
  – Small molecules (water)
  – Large molecules (proteins)
• T₁ is short for
  – Fats and intermediate-sized molecules
• T₁ increases with increasing B₀
• T₁ decreases with contrast agents

T₁ Contrast

<table>
<thead>
<tr>
<th>Signal</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short Repetition</td>
<td><img src="image1.png" alt="Image" /></td>
</tr>
<tr>
<td>Long Repetition</td>
<td><img src="image2.png" alt="Image" /></td>
</tr>
</tbody>
</table>

- White/Gray Matter
- CSF
**T<sub>2</sub> Relaxation**

- Transverse or spin-spin relaxation
  - Molecular interaction causes spin dephasing
  - Typically, T<sub>2</sub> < (10s ms)
- Increasing molecular size, decrease T<sub>2</sub>
  - Fat has a short T<sub>2</sub>
- Increasing molecular mobility, increases T<sub>2</sub>
  - Liquids (CSF, edema) have long T<sub>2</sub>s
- Increasing molecular interactions, decreases T<sub>2</sub>
  - Solids have short T<sub>2</sub>s
- T<sub>2</sub> relatively independent of B<sub>0</sub>
T2 Contrast

T1 and T2 Values @ 1.5T

<table>
<thead>
<tr>
<th>Tissue</th>
<th>T1 [ms]</th>
<th>T2 [ms]</th>
</tr>
</thead>
<tbody>
<tr>
<td>gray matter</td>
<td>925</td>
<td>100</td>
</tr>
<tr>
<td>white matter</td>
<td>790</td>
<td>92</td>
</tr>
<tr>
<td>muscle</td>
<td>875</td>
<td>47</td>
</tr>
<tr>
<td>fat</td>
<td>260</td>
<td>85</td>
</tr>
<tr>
<td>kidney</td>
<td>650</td>
<td>58</td>
</tr>
<tr>
<td>liver</td>
<td>500</td>
<td>43</td>
</tr>
<tr>
<td>CSF</td>
<td>2400</td>
<td>180</td>
</tr>
</tbody>
</table>
Spin Echo Imaging

Free Induction Decay

RF

90°

T$^*_2$ and gradients lead to rapid FID dephasing

Signal

FID
RF Signal
Spin Echo

90° 180°

FID Spin Echo
Record by computer.

T₂* and gradients lead to rapid FID dephasing
Reversible components rephase
T₂* and gradients lead to additional dephasing

RF Signal
Spin Echo

90° 180° TR

FID Spin Echo
Record by computer.
Spin Echo - Refocusing

How do you adjust the TR?
How do you adjust the TE?

Spin Echo - Contrast
Spin Echo Contrast

$$A_{Echo} \propto \rho \left( 1 - e^{-TR/T_1} \right) e^{-TE/T_2}$$

Longer TR minimizes T1 contrast
Short TE minimizes T2 contrast

Intermediate TR maximizes T1 contrast
Intermediate TE maximizes T2 contrast

Spin Echo Parameters

<table>
<thead>
<tr>
<th></th>
<th>TE</th>
<th>TR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spin Density</td>
<td>Short</td>
<td>Long</td>
</tr>
<tr>
<td>T₁-Weighted</td>
<td>Short</td>
<td>Intermediate</td>
</tr>
<tr>
<td>T₂-Weighted</td>
<td>Intermediate</td>
<td>Long</td>
</tr>
</tbody>
</table>
Spin Echo Contrast

**Spin Density**
- Short

**T1-Weighted**
- Short
- Intermediate

**T2-Weighted**
- Intermediate
- Long

**TR**
- Short
- Intermediate
- Long

**TE**
- Short
- Intermediate
- Long

Images Courtesy of Mark Cohen

Spin Echo

**TE**
- Short
- Intermediate
- Long

**TR**
- Short
- Intermediate
- Long

Excitation Pulse

Refocusing Pulse

Echo

TE=12ms

Spin Echo: TR=6500ms (ETL=12)
Spin Echo

TE=12ms
TE=47ms

Spin Echo: TR=6500ms (ETL=12)

TE=12ms  TE=47ms  TE=106ms

Spin Echo: TR=6500ms (ETL=12)
Spin Echo

Excitation Pulse

Refocusing Pulse

Echo

TR

TE

90°

180°

90°

Excitation Pulse

Spin Echo: TR=6500ms (ETL=12)

TE=12ms

TE=47ms

TE=106ms

TE=153ms

TE=235ms
Turbo Spin Echo (TSE) / Fast Spin Echo (FSE)

Spin Echo

RF

\[ 90° \]

\[ 180° \]

\[ \text{TE} \]

\[ \text{TR} \]

\[ 90° \]

\[ \text{GSlice} \]

\[ \text{GPhase} \]

\[ \text{GReadout} \]

\[ \text{Signal} \]
Spin Echo

Wasted Time

Turbo Spin Echo (TSE)
T$_2$-weighted TSE

RF

Signal

Proton Density Weighted TSE

RF

Signal

PD vs $T_2$-weighted TSE

Proton Density Weighted

- Good cartilage signal
- Good cartilage/fluid contrast
- Late-Echo Blurring

$T_2$-weighted

Summary for TSE

- Pros:
  - Fast, high SNR
  - Less sensitive to B0 inhomogeneity

- Cons:
  - $T2$ weighting varies in k-space
  - RF power limits speed, particularly at 3T

- Multi-echo acquisitions accelerate imaging, but single-shot methods are probably overkill
Gradient Echo Imaging

Gradient Echo Sequences

• Spoiled Gradient Echo
  – SPGR, FLASH, T1-FFE

• Balanced Steady-State Free Precession
  – TrueFISP, FIESTA, Balanced FFE
Principal GRE Advantages

• Fast Imaging Applications
  – **Why?** Can use a shorter TE/TR than spin echo
  – **When?** Breath-held, realtime, & 3D volume imaging

• Flexible image contrast
  – **Why?** Adjusting TE/TR/FA controls the signal
  – **When?** Characterize a tissue for diagnosis

• Bright blood signal
  – **Why?** Inflowing spins haven’t “seen” numerous RF pulses
  – **When?** Cardiovascular & angiographic applications

• Low SAR
  – **Why?** Imaging flip angles are (typically) small
  – **When?** When heating risks are a concern

Principal GRE Advantages

• Quantitative
  – **Why?** Multi-echo acquisition are practical.
  – **When?** Flow quantification & Fat/Water mapping

• Susceptibility Weighted Imaging
  – **Why?** No refocusing pulse.
  – **When?** $T_2^*$-weighted (hemorrhage) imaging

• Reduced Slice Cross-talk
  – **Why?** SE hard to match slice profile of 90° & 180°
  – **When?** Little or no slice gap for 2D multi-slice

• More...
Principal GRE Disadvantages

• Off-resonance sensitivity
  – Why? No refocusing pulse
    • Field inhomogeneity, Susceptibility, & Chemical shift

• $T_2^*$-weighted rather than $T_2$-weighted
  – Why? No re-focusing pulse
    • Spin-spin dephasing is not reversible with GRE

• Larger metal artifacts than SE
    • Large field inhomogeneities aren’t corrected with GRE

Basic Gradient Echo Sequence

- FID Decay due to
  - $T_2$ decay
  - Spin dephasing
Basic Gradient Echo Sequence

- FID Decay due to
  - T2 decay
  - Spin dephasing
- Gradients accelerate spin dephasing
- Gradients can undo gradient induced spin dephasing
Basic Gradient Echo Sequence

- FID Decay due to
  - T2 decay
  - Spin dephasing

- Gradients accelerate spin dephasing

- Gradients can undo gradient induced spin dephasing
Basic Gradient Echo Sequence

Gradient Echoes & Contrast
Contrast depends on tissue’s \( \rho \), \( T_1 \) and \( T_2^* \).

\[
A_{echo} \propto \frac{\rho(1 - e^{-TR/T_1})}{1 - \cos \alpha e^{-TR/T_1}} \sin \alpha e^{-TE/T_2^*}
\]

Contrast adjusted by changing TR, flip angle, and TE.

### Gradient Echo Parameters

<table>
<thead>
<tr>
<th>Type of Contrast</th>
<th>TE</th>
<th>TR</th>
<th>Flip Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spin Density</td>
<td>Short</td>
<td>Long</td>
<td>Small</td>
</tr>
<tr>
<td>( T_1 )-Weighted</td>
<td>Short</td>
<td>Intermediate</td>
<td>Large</td>
</tr>
<tr>
<td>( T_2^* )-Weighted</td>
<td>Intermediate</td>
<td>Long</td>
<td>Small</td>
</tr>
</tbody>
</table>
**T₂*-weighted Gradient Echo Imaging**

Susceptibility Weighting (darker with longer TE)
Bright fluid signal (long T₂* is "brighter" with longer TE)

Images Courtesy of Brian Hargreaves

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**Gradient vs Spin Echo Contrast**

**Gradient Echo Parameters**

<table>
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<tr>
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<th>TE</th>
<th>TR</th>
<th>Flip Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spin Density</td>
<td>&lt;5ms</td>
<td>&gt;100ms</td>
<td>&lt;10°</td>
</tr>
<tr>
<td>T₁-Weighted</td>
<td>&lt;5ms</td>
<td>&lt;50ms</td>
<td>&gt;30°</td>
</tr>
<tr>
<td>T₂*-Weighted</td>
<td>&gt;20ms</td>
<td>&gt;100ms</td>
<td>&lt;10°</td>
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**Spin Echo Parameters**

<table>
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<th>Flip Angle</th>
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<tbody>
<tr>
<td>Spin Density</td>
<td>10-30ms</td>
<td>&gt;2000ms</td>
<td>90+180</td>
</tr>
<tr>
<td>T₁-Weighted</td>
<td>10-30ms</td>
<td>450-850ms</td>
<td>90+180</td>
</tr>
<tr>
<td>T₂-Weighted</td>
<td>&gt;60ms</td>
<td>&gt;2000ms</td>
<td>90+180</td>
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Gradient Echoes & Flip Angle

Spoiled GRE & Ernst Angle

\[ \alpha_{Ernst} = \arccos \left( e^{-\frac{TR}{T_1}} \right) \]

Produces the largest MRI signal for a given TR and T_1

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Spoiled GRE & Ernst Angle

Fat
Muscle
Contrast

MRI Signal [A.U.]

Flip Angle

10°  20°  30°  40°  50°  60°  70°  80°  90°

Spoiled GRE & Ernst Angle

High Muscle Signal
High Fat Signal

1°  5°  10°  20°

30°  45°  60°  90°

Highest Contrast
Relaxation - True or False?

1. $T_2^* > T_2 > T_1$

2. Long $T_1$s appear bright on a $T_1$-weighted image

3. Short $T_2$s appear dark on a $T_2$-weighted image
Relaxation - True or False?

1. $T_1(\text{CSF}) > T_1(\text{Gray Matter})$

2. $T_2(\text{Liver}) < T_2(\text{Fat})$

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Spin Echoes - True or False?

1. The 90-180 pair is the hallmark of the spin echo sequence.
2. The 180 pulse is an inversion pulse.
3. Spin echoes are ultrafast sequences that provide \( T_1 \) or \( T_2^* \) weighted images.
Spin Echoes - True or False?

1. Long TE and long TR for T2-weighted.
2. Short TE and short TR for T1-weighted.
3. Spin echoes are low SAR sequences.

\[ A_{Echo} \propto \rho \left( 1 - e^{-TR/T_1} \right) e^{-TE/T_2} \]

Longer TR minimizes T1 contrast
Short TE minimizes T2 contrast
Gradient Echo Imaging...

Gradient echo imaging is great for everything except:

A. $T_2^*$-weighted imaging.

B. $T_2$-weighted imaging.

C. True 3D imaging.

D. Real time imaging.

Yes. GRE can be a $T_2^*$-weighted sequence.

No. GRE can not be $T_2$-weighted

Yes! GRE is a fast sequence

Yes! GRE is a fast sequence
Gradient Echo Imaging...

A. ...is great for T₂ imaging

B. ...works well for imaging near metal implants

C. ...is a fast acquisition technique

D. ...is insensitive to off-resonance effects

---

Gradient Echo Imaging...

A. ...is great for T₂ imaging
   GRE is sensitive to T₂*, whereas SE is sensitive to T₂

B. ...works well for imaging near metal implants
   Metal causes large distortions for which SE is useful

C. **...is a fast acquisition technique**
   Yes! The TE/TR are typically quite short compared to SE

D. ...is insensitive to off-resonance effects.
   GRE is sensitive to B₀ inhomogeneity, chemical shift and susceptibility shifts
In Gradient Echo Imaging Always...

A. Use the highest available flip angle.

B. Calculate and use the Ernst angle.

C. Use a flip angle for maximum contrast.
Gradient vs. Spin Echo

Which image is a gradient echo image?

A. Spin Echo
B. Gradient Echo

Images Courtesy of Brian Hargreaves

Gradient vs. Spin Echo

Both are T1-weighted
Spin Echo has higher SNR (longer TR)
GRE has shorter TE (meniscus/tendon is brighter)

Images Courtesy of Brian Hargreaves
Thanks

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Images/Slide Courtesy of
Daniel Ennis, Ph.D.
Brian Hargreaves, Ph.D.