Principles of MRI
EE225E / BIO265

Image Contrast

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**IMAGE CONTRAST**

So far assumed

\[ \mathbf{M}(0) = [0, 0, M_0]^T \]

Sample is fully relaxed \( T_R \gg 3T_1 \)

In practice this is seldom true

\[ I(x,y) = f^*(p, T_1, T_2, \Theta, T_R, T_E) \]

Image

Physical parameters

Instrumental parameters

Tissue has inherent variability in \( T_1, T_2, \Theta \)

What to emphasize is
Question

• What is the difference between the images?
Answer

- Both T1-weighted

spin-echo

gradient-echo

Meniscus (short TE)

Lower SNR
Spin-Echo Properties

- Robust to off-resonance effects
- Excellent Contrast

You -- Get cervical, thoracic and lumbar T2 weighted Fast Spin-Echo MRIs
Spin-Echo Properties

- Robust to off-resonance effects
- Excellent Contrast

but...

- SAR limitations (high-power RF)
- Long scan times, and long echo-time
- Mostly multi-slice 2D
- Artifacts/long scan-time in 3D

Gradient-echo: Fast, short TE, often 3D
Spin-Echo Pulse Sequence

Excitation

Refocusing

180°

TE~10+ ms

Acquisition

Spin-Echo+

Gradient-Echo
Gradient-Echo Pulse Sequence

No Refocusing!

- RF
- Gz
- Gy
- Gx
- A/D

Gradient-Echo
Gradient-Echo Pulse Sequence

- RF
- Gx
- Gy
- Gz
- A/D

**TE ~ 1+ ms**

Gradient-Echo
MRI is all about contrast......
Contrast Knobs: GRE Variations

- Spoiling (sequence)
- RF: Flip / Phase
- Timing (TR, TE)
- Preparation Sequence

Flip/Phase

Spoiling

No preparation

Fat-saturation
Assumptions

• \( m(x,y,t) \) is a function of time

• Approximation:
  - when analyzing \( I(x,y) \), assume \( m(x,y,t=TE) \)

• Consider:
  - \( T1 > TR > 3T2 \)
  - Later: \( TR < 3T2 \)
Review Magnetization Dynamics

- RF Excitation
- Free-precession/ (gradient induced)
- Relaxation
SATURATION RECOVERY

RF

90

90

90

90
Very Long TR: Full Relaxation

- $M_{xy}$ decays completely before next RF
- $M_z$ recovers fully before next RF
- Full signal after RF
Long TR: T1-Weighting

- $M_{xy}$ decays completely before next RF
- $M_z$ partially recovers before next RF
- T1-weighted signal after RF
1st TR usually not used
STEADY-STATE SIGNAL: \[ M_0 (1 - e^{-\frac{TR}{T_1}}) \]

*IMAGE IS!*

\[ I(x,y) = k \rho(x,y) \left[ 1 - e^{-\frac{TR}{T_1(x,y)}} \right] \]

\[ T_1 = 0 \]

\[ T_{1\rho} < T_1 \]

\[ I(x,y) \equiv k \rho(x,y) \frac{TR}{T_1(x,y)} \]

\[ T_{1\rho} = T_0 \]

\[ I(x,y) = k \rho(x,y) \left[ 1 - e^{-\frac{TR}{T_1(x,y)}} \right] e^{-\frac{TR}{T_2}} \]
SPIN-ECHO VERSION

RF

$M_0$

$M_z$

$||M_{xy}||_0$

$||M_{xy}||$

$90$

$180$

TR

TE

$T_2^*$

$T_2$
If $TE < T_1$

$$I(x,y) = k_p(\alpha, y) \left[ 1 - e^{-\frac{TE}{T_1}} \right] e^{-\frac{TR}{T_1}}$$

**Proton Density:**
- $TE$ short $\ll T_2$
- $TR$ long $\gg T_1$

$$I \equiv k_p(\alpha, y)$$

**T₁ Weighting:**
- $TE$ short $\ll T_2$
- $TR \sim T_1$

$$I \equiv k_p C_1 e^{-\frac{TR}{T_1}}$$

($T_1 = 4000 ms, TE = 15 ms$ @ 1st Brain)

**T₂ Weighting:**
- $TR$ long $\gg T_2$
- $TE \sim T_2$

$$I \equiv k_p e^{-\frac{TE}{T_2}}$$

($TR = 2500 ms, TE = 90 ms$ @ Brain)

$T_1$ - Anatomy

$T_2$ - Lesion Sensitive
Let \( E_t = e^{-\frac{TR}{T_1}} \)

\[
M^{-}_2 = M^{+}_2 e^{-\frac{TR}{T_1}} + (1 - e^{-\frac{TR}{T_1}})M_0
\]

\[
M^{-}_0 = M^{+}_0 E_t + M_0 (1 - E_t)
\]

And

\[
M^{+}_2 = M^{-}_2 \cos \Theta
\]

In steady-state

\[
M^{-}_2 = M^{-}_2 \cos \Theta E_t + M_0 (1 - E_t)
\]

\[
M^{-}_2 (1 - \cos \Theta E_t) = M_0 (1 - E_t)
\]

\[
M^{-}_0 = \frac{M_0 (1 - E_t)}{1 - \cos \Theta E_t}
\]

\[
M^{+}_2 = \frac{M_0 (1 - E_t) \sin \Theta}{1 - \cos \Theta E_t}
\]
$I(x,y) = k \rho (x,y) \frac{(1-E_1(x,y)) \sin \theta}{1-\cos \theta E_1(x,y)} e^{-\frac{FE}{12\gamma}}$

WHAT IS $\theta$ THAT MAX SIGNAL

$\theta$ SMALL, SIN $\theta$ SMALL, NO SIGNAL

$\theta$ LARGE, $M_2$ SMALL, NO SIGNAL

OPTIMUM:

$\theta_E = \cos^{-1} E_1 = \cos^{-1} \left( e^{-\frac{7\pi}{14}} \right)$

[ERNEST ANGLE]
Example:

\[ \text{TR}=9T1, \; \Theta_E = 68.4^\circ \]

Optimum \[ M_{xy}^+ \]

\[ M_{xy}^+ = M_0 \sqrt{\frac{1-E_1}{1+E_1}} \]

\text{Optimum signal not contrast}
After $q_0$, $M_2 = 0$

At $\textcircled{5}$

$$M_2 = 1 - e^{-\frac{(TR-TI)}{T_1}}M_0$$

At $\textcircled{6}$

$$M_2 = -M_0 \left( 1 - e^{-\frac{(TR-TI)}{T_1}} \right)$$

At $\textcircled{7}$

$$M_2 = -M_0 \left( 1 - e^{-\frac{(TR-TI)}{T_1}} \right) e^{-\frac{-TT}{T_1}} +$$

$$+ \left( 1 - e^{-\frac{-TT}{T_1}} \right) M_0 =$$

$$= -M_0 e^{-\frac{-TT}{T_1}} + M_0 e^{-\frac{-TR}{T_1}} + M_0 + M_0 e^{-\frac{-TT}{T_1}}$$

$$M_2 = M_0 \left( 1 - 2e^{-\frac{-TT}{T_1}} + e^{-\frac{-TR}{T_1}} \right)$$
\[
I(x,y) = k_0(x,y) \left[ 1 - 2e^{-\frac{TE}{T_1(x,y)}} + e^{-\frac{TR}{T_1(x,y)}} \right] e^{-\frac{TE}{T_2(x,y)}}
\]

IR GIVES
1) GREATER $T_1$ CONTRAST (ALMOST TWICE)
2) NULL SPECIFIC TISSUE
   - FAT $\Rightarrow$ STIR $T_1 = 250$ ms
   - CSF $\Rightarrow$ FLAIR $T_1 = 2000$ ms

NULL TIME:
\[
1 - 2e^{-\frac{TI}{T_1}} + e^{-\frac{TR}{T_1}} = 0
\]
\[
TI = -T_1 \log \left[ \frac{1 + e^{-\frac{TR}{T_1}}}{2} \right]
\]

$TR >> T_1$
\[
TI \approx -T_1 \log \frac{1}{2} = 0.693 T_1
\]
Example: Fat MULLING

$T_1$ of fat $\approx 260 \text{ ms}$, $TR = 900$

$TI = -260 \log \left(1 + \frac{5000}{500}\right) = 167 \text{ ms}$
Minor Stroke
Short TR Steady-State Imaging

• $M_{xy}$ persists before next RF
• May have shifted in phase
• Adds/Subtracts from next signal

• makes a HUGE difference on image contrast
Balanced SSFP

True-FISP, FIESTA, balanced FFE, BASG

- Do nothing at the end
- Balanced Gradients

Oppelt 1986, Duerk 1997
Balanced SSFP

- High steady-state signal
- T2/T1 mixed contrast
- Sensitive to off-resonance

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Balanced-SSFP Dark Bands

- Must limit precession
  - Short TR
- Limits resolution

Freeman 1971
Balanced-SSFP Cardiac Imaging

- Fast (TR=2-5ms)
- Good contrast
- Flow-compensated
Gradient Spoiling

- Reduce sensitivity to off-resonance by Spoiling Mxy before next RF

FFE, FISP, GRASS, GRE, FAST, Field Echo

Spin distribution across slice
Question

- Does gradient spoiling eliminates transverse signal at the end of TR?

Spin distribution across slice

First TR

Steady State
• No, its an average of balanced-SSFP but....
• No dark bands
• Lower signal than balanced-SSFP
• Reduced contrast
Gradient Spoiled vs Balanced SSFP

(Courtesy of Krishna Nayak, USC Electrical Engineering)
RF Spoiled Imaging

- Goal: Pure T1 contrast with short TR
- Fast, 3D T1-Weighted imaging
- Need to “Zero” Mxy at the end of TR

SPGR, FLASH, T1-FFE, RF-spoiled FAST

Frahm 1987, Zur 1991
RF Spoiling

- The Trick:
  - Quadratic Phase Increment of RF
  - Effectively “Random” angle RF every TR
  - Spoiled magnetization has random phase and does not add

- Low SNR!
RF Spoiled Contrast Enhanced MR

Pre-Contrast SPGR

Post-Contrast SPGR
RF Spoiled Dynamic Contrast MR

Enhancement over Time

Repeated 6-second breath holds, 10 seconds apart
32 slices using 3x accelerated imaging
### Gradient Echo Sequence Comparison

<table>
<thead>
<tr>
<th>Sequence</th>
<th>Balanced SSFP</th>
<th>Gradient Echo</th>
<th>RF-Spoiled</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Spoiling</strong></td>
<td>None</td>
<td>Gradient</td>
<td>RF + Gradient</td>
</tr>
<tr>
<td><strong>Transverse Magnetization</strong></td>
<td>Retained</td>
<td>Averaged</td>
<td>Cancelled</td>
</tr>
<tr>
<td><strong>Contrast</strong></td>
<td>$T_2/T_1$</td>
<td>$T_2/T_1$</td>
<td>$T_1$</td>
</tr>
<tr>
<td><strong>SNR</strong></td>
<td>High (but Banding)</td>
<td>Moderate</td>
<td>Lower</td>
</tr>
</tbody>
</table>

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Quiz I

Here are a balanced SSFP and RF-Spoiled post-contrast image. Which is the image on the left?

1) RF-Spoiled Post Gd
2) Balanced SSFP
Quiz I

2) Balanced SSFP
   Bright Fluid (T2-like)

1) RF Spoiled post Gd
   T1 contrast, enhanced wall
**Image Comparison**

**Identify the images shown (Same TR, TE, Flip)**

<table>
<thead>
<tr>
<th></th>
<th>RF Spoiled</th>
<th>Balanced SSFP</th>
<th>Gradient Spoiled</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>RF Spoiled</td>
<td>Balanced SSFP</td>
<td>Gradient Spoiled</td>
</tr>
<tr>
<td>2</td>
<td>Gradient Spoiled</td>
<td>RF Spoiled</td>
<td>Balanced SSFP</td>
</tr>
<tr>
<td>3</td>
<td>RF Spoiled</td>
<td>Gradient Spoiled</td>
<td>Balanced SSFP</td>
</tr>
</tbody>
</table>
Image Comparison

- Same TR, TE, flip angle
- Differences: Signal, Contrast, Dark-Bands

3) RF Spoiled  Gradient Spoiled  Balanced SSFP
Contrast Knobs: GRE Variations

- Spoiling (sequence)
- RF: Flip
- Timing (TR, TE)
- Preparation Sequence
Flip Angle in Gradient Echo Sequences

Does increasing the flip angle increase signal?
1) Yes: Signal always increases with flip angle.
2) No: Signal decreases as flip angle increases
3) Sometimes: The signal peaks at a specific flip angle
Flip Angle in Gradient Echo Sequences

Does increasing the flip angle increase signal?
1) Yes: Signal always increases with flip angle.
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Flip Angle Selection

Blood

- Signal vs. Flip Angle

Muscle

- Signal vs. Flip Angle

Ernst Angle

Buxton 1990
Flip Angle Selection?

The best flip angle to use is found by:
1) Maximizing the image SNR
2) Maximizing contrast between certain tissues
3) Both 1 and 2
Flip Angle Selection?

The best flip angle to use is found by:

3) Both 1 and 2: maximizing SNR and contrast (CNR)
Flip Angle Examples

RF-Spoiled

Best?

Gradient Spoiled

Balanced SSFP

5°  10°  20°  30°  40°  50°  Best?
Contrast Knobs: GRE Variations

- Spoiling (sequence)
- RF: Flip / Phase
- Timing (TR, TE)
- Preparation Sequence
Echo Time (TE) Considerations

- **Longer TE:** \( T2^* \) weighting (BOLD, Perfusion)
  - BOLD Imaging for fMRI
  - \( T2^* \)-weighted perfusion

- **Short TE**
  - Reduced flow/motion sensitivity
  - Reduced \( T2^* \) weighting

- **In-phase and Out-of-phase TE**
  - Water/Fat cancellation, Dixon Imaging
Dixon-Based Imaging

RF

Signal

Water

Fat

Fat

Water
Liver Imaging

In-Phase

Out-of-Phase

Water

Fat
Question

Gradient spoiled images - which is opposed phase?

1) Left

2) Right
Gradient Spoiling: TE Effects

Left adrenal lesion with signal loss on opposed phase imaging – Diagnosis Benign Adenoma

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Contrast Knobs: GRE Variations

- Spoiling (sequence)
- RF: Flip / Phase
- Timing (TR, TE)
- Preparation Sequence
Preparation Options

- Fat Saturation
- Inversion - Recovery
- Myocardial Tagging
- T2-prep
- Magnetization Transfer

Imaging Sequence:

Mag Prep  ...  Mag Prep
Fat Saturation Example

Not Fat-Sat RF-Spoiled

Fat Sat RF-Spoiled
Cardiac: bSSFP and IR-RF-Spoiled

Balanced SSFP

IR-Prep RF-Spoiled
Summary

- Spoiling (sequence)
- RF: Flip / Phase
- Timing (TR, TE)
- Preparation Sequence

Flip/Phase

Spoiling

No preparation

Fat-saturation
Summary and Acronyms

• RF spoiled
  SPGR, FLASH, T1-FFE, RF-spoiled FAST

• Balanced SSFP
  True-FISP, FIESTA, balanced FFE, BASG

• Gradient spoiled
  FFE, FISP, GRASS, GRE, FAST, Field Echo

• Vendor acronyms are confusing -- Demand that they tell you what it really is...!

• Acronym source: mr-tip.com
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