Musculoskeletal MRI: Physical Principles

Brian Hargreaves, PhD
Radiological Sciences Laboratory
Stanford University
bah@stanford.edu
http://rsl.stanford.edu/hargreaves/

Challenges
• Signal to noise ratio (SNR)
• Spatial Resolution and volume coverage
• Scan Time
• Diagnostic Contrast

Outline
• Technical Factors:
  • SNR
  • Contrast
• Sequences
  • Spin echo sequences
  • Gradient echo sequences
  • Rapid sequences

SNR
SNR is the major limitation for musculoskeletal MRI

Factors Influencing SNR

\[
SNR \propto Voxel Volume \cdot \sqrt{T_{acq}}
\]

• Proportionality depends on:
  • Polarization or Field strength
  • RF coil
  • Pulse sequence and parameters
  • Subject size and position
  • Receive Electronics (Ideally insignificant)

SNR vs Resolution vs Scan Time

High SNR
High Resolution (Small Voxels) Short Scan Time

Low SNR High SNR
Musculoskeletal MRI: Physical Principles

SNR and Field Strength

- 1.5T
- 3.0T

Sagittal $T_2$ RARE: SNR Ratio = 1.65

SNR and Receive Coils

- Transmit/Receive
- Quadrature
- Phased Array
- Surface

Phased-Array vs Linear Coil

- Phased Array Coil
- Linear Extremity Coil

Phased array coils have brightness variations, but higher SNR

SNR and Subject Size/Position

- 90 kg Subject
- 50 kg Subject

Smaller Background Noise
Higher Signal near Coil Element

SNR and Pulse Sequence

- 2D $T_1$, Spin Echo
- 3D Gradient Echo

Sequences and parameters affect SNR (and contrast)

SNR Points

- Increasing SNR is a tradeoff:
  - Increases scan time
  - Limits voxel size (resolution)
- SNR also depends on:
  - Field strength
  - RF Coil
  - Pulse Sequence
  - Subject size and positioning

... but we also care about contrast
Basic Contrast Mechanisms

- Proton Density (PD)
- Relaxation ($T_1$ or $T_2$)
- Fat suppression
- Magnetization Transfer
- Diffusion
- Flow-sensitive

Relaxation

- Magnetization returns exponentially to equilibrium:
  - Longitudinal recovery time constant is $T_1$
  - Transverse decay time constant is $T_2$
- Relaxation and precession are independent.

$T_2$ Contrast

- Short Echo-Time
- Long Echo-Time

$T_1$ Contrast

- Short Repetition
- Long Repetition

$T_2/T_1$ Contrast

- Some recovery and some residual signal
- Common in rapid imaging sequences
- Contrast can be adjusted with flip angle
- Can provide $T_2$-like contrast efficiently in 3D

Cartilage and Surrounding Tissue

- Bone Marrow
- Muscle
- Cartilage
- Fluid


Brian A. Hargreaves,
Stanford University Radiology
**Fat Suppression**

- Fat Suppression allows:
  - Improved dynamic range
  - Improved contrast
  - Reduced chemical shift artifact

- Common methods:
  - Fat saturation (CHESS)
  - Spectral-spatial excitation
  - Dixon or IDEAL
**Fat Suppression for Contrast**

- $T_1$ Spin Echo
- PD Spin Echo (Fat Sat)

**Fat Suppression for Contrast**

- PD FSE
- Fat-Sat PD FSE

Coronal Wrist

*Radial cyst was otherwise iso-intense with fat*

---

**Fat Saturation**

- Chemically-selective excitation
- Spoiler gradient
- Normal imaging sequence

**Spectral-Spatial Excitation**

- Excite only water
- Shorter than fat-saturation

(Hardy 1998)

---

**IDEAL Fat/Water Separation**

- Multiple TEs
- Least Squares Inversion

Field Map Estimate

**Fat Suppression Summary**

- CHESS
  - Saturates fat based on chemical shift
- Spectral-Spatial
  - Excites only water
  - Shorter than CHESS
- Dixon or IDEAL
  - Separates fat/water in reconstruction
  - Efficient and robust to field inhomogeneity
  - Does not improve dynamic range

---

Brian A. Hargreaves,
Stanford University Radiology
Musculoskeletal MRI: Physical Principles

Pulse Sequences

- Excitation
- Reception
- Recovery

Gradient Echo

Spin Echoes

- Start with transverse magnetization
- Dephasing from frequency variations
- 180º excitation "flips" spins
- Rephasing to a spin echo

Spin Echo Sequences

- $T_1$-weighted spin echo (SE)
  - Short TR, Short TE
- PD-weighted RARE
  - (FSE, TSE, RARE)
  - Long TR, Short TE
- $T_2$-weighted RARE
  - (FSE, TSE, RARE)
  - Long TR, Long TE

Brian A. Hargreaves,
Stanford University Radiology
**Musculoskeletal MRI: Physical Principles**

**T\(_1\)-weighted Spin Echo**

- \(90^\circ\) RF pulse
- \(180^\circ\) RF pulse
- \(90^\circ\) RF pulse

**T\(_1\) and T\(_2\) Images**

- **T\(_1\)** SPGR
- **T\(_2\)** FSE

**T\(_2\) Contrast**

- Delayed acquisition / different signal decay rates
- Always trade **SNR** for **contrast**
- Long TR makes 3D imaging difficult

**T\(_2\) Weighted RARE (TSE, FSE)**

- \(90^\circ\) RF pulse
- \(180^\circ\) RF pulse
- \(180^\circ\) RF pulse

**Proton Density Weighted RARE**

- \(90^\circ\) RF pulse
- \(180^\circ\) RF pulse
- \(180^\circ\) RF pulse

*Fluids are suppressed on T\(_1\)-weighted images*
Musculoskeletal MRI: Physical Principles

**PD vs $T_2$-weighted RARE**
- Proton Density Weighted
- $T_2$-weighted
- Good cartilage signal
- Good cartilage/fluid contrast
- Late-Echo Blurring
- Low cartilage signal
- Good cartilage/fluid contrast

**Driven Equilibrium**
- RARE with a “tip-up” pulse (Becker 1969, Shoup 1972)
- Shortens TR
- 2D and 3D versions
  - (FRFSE, DRIVE, RESTORE)
  - $M_{xy}$
  - $M_z$

**3D DEFT (FRFSE, DRIVE, RESTORE)**
- 3D (here) and 2D implementations
  - (FRFSE, DRIVE, RESTORE)
- 5 minute scan time (Hargreaves 1999)

**Gradient Echo Sequences**
- RF-Spoiled: (SPGR, T1-FFE, FLASH)
- GRE: Gradient-spoiled (GRE, FFE, TFE)
- Balanced SSFP (FIESTA, TrueFISP, Balanced FFE)
  - Numerous variations for fat suppression
    (FEPR, Fat-Sat SSFP, Water-only SSFP, IDEAL, …)
- DESS: Dual echo steady state (Hardy 1996)

**2D vs 3D Slab Imaging**
- 2D Multislice
- 3D Slab
- Shorter scan times
- Efficient when TR is long and all slices can be interleaved
- Usually Higher SNR
- Continuous coverage
- Better for image reformat

**3D Pulse Sequence**
- RF, $G_x$, $G_y$, $G_z$, Acq.
SNR: 2D vs 3D

- All parameters identical, except 2D/3D
- 3D effectively averages over volume

RF-Spoiled Gradient Echo

3D SPGR with Fat Saturation

- Long scan times
- Moderate SNR efficiency
- High cartilage, low fluid signal
- Most commonly used for cartilage segmentation (Eckstein, et al.)

3D SPGR and GRE (3.0T)

SPGR (T₁-weighted) and GRE (T₂/T₁-weighted)

Fluid is dark on T₁-weighted images, but bright on T₂/T₁

Reeder 2005

Balanced SSFP
Musculoskeletal MRI: Physical Principles

"Gradient Echo" Sequences

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

Balanced SSFP "Dark Bands"

- Dark bands occur at certain resonant frequencies
- Position can depend on center frequency / phase cycling

Balanced SSFP Variations

<table>
<thead>
<tr>
<th>PD-FSE</th>
<th>FS-SSFP</th>
<th>SPGR</th>
<th>LCSSFP</th>
<th>FEMR</th>
</tr>
</thead>
<tbody>
<tr>
<td>2:04</td>
<td>1:04</td>
<td>5:11</td>
<td>1:48</td>
<td>1:48</td>
</tr>
</tbody>
</table>

(Hargreaves 2003)

SPGR and IDEAL SSFP

3D-FS-SPGR (9:40) | IDEAL SSFP (3:40)

Reeder 2003

Summary

- SNR: Field, coils, sequence, positioning
- Contrast: PD, $T_1$, $T_2$ weighted
- Fat suppression techniques
- Spin echo or RARE sequences:
  - 2D multislice, robust
- Gradient echo sequences:
  - RF-spoiled, GRE, balanced SSFP, DESS
  - 3D, moderate-to-high SNR
  - Mixed contrast

Acknowledgements

Richard M. Lucas Foundation | Garry Gold
National Institutes of Health | John Pauly
GE Healthcare | Chris Beaulieu
               | Dwight Nishimura
               | Scott Reeder
               | Misung Han
               | Jean Brittain
               | Ann Shimakawa
               | Thomas Andriacchi