Quantitative MRI

Ryan M. Kalmoe
Department of Radiology, University of Minnesota

Advisor: Dr. Gregory Metzger
Department of Radiology, University of Minnesota
Center for Magnetic Resonance Research

University of Minnesota
Objectives

- Distinguish the differences between qualitative and quantitative magnetic resonance imaging
- Understand basics of fitting data to generate maps quantifying relaxation constants and apparent diffusion coefficients (ADC)
- Present an anthropomorphomic body phantom with quantitative prostate insert
  - Results from investigating sources of variance
  - Identify applications of the quantitative phantom
Background

- Quantitative Magnetic Resonance Imaging (qMRI): maps of meaningful physical or chemical variables that can be measured in physical units and compared between tissue regions and among subjects[^1]
  - Most clinical acquisitions are NOT quantitative

- **Advantages:**
  - Increase sensitivity and specificity of MRI
  - Detect and monitor subtle changes in global parameters

- **Disadvantages:**
  - Many quantities have multiple dependencies (acquisition, $B_1^+$, ...)
  - Requires more QA for reliable measurements
Background

Example: A typical T2-weighted sequence yields an image with voxel values proportional to the signal intensities of the other voxels in the image.

- Quantitatively tells us very little.

T2 data often fitted to a simple exponential curve:

\[ S(TE) = M_0 e^{-\frac{TE}{T2}} \]

*Requires multiple TEs!*
A single image is sufficient depending on your goal.

But what if instead of a quantitative weather forecast, say a high of 30°F and 18” of snow, you had something vague such as:

“It will be cold with lots of precipitation.”

In Minnesota and Wisconsin, without an other reference, you wouldn’t know if you need an umbrella or a blizzard warning!
Instead of looking for regions of hypointensity to diagnose cancer, ranges of T2 values have been established after registering surgically removed tissue with corresponding slices from multiparametric study[2].

How do we know that the measured T2’s are accurate?
Purpose and Significance

- Develop an anthropomorphic body phantom with NIST-traceable standards to:

  1) Better understand the sources of variability in qMRI measurements
  2) Harmonize results of qMRI studies
  3) Develop QA as systems are upgraded and new acquisition methods are introduced
Materials and Methodology

- Phantom designed in collaboration with manufacturer (High Precision Devices, Boulder, CO) each comprising three sections

  - Wings are approximately 4.3L
  - Center is approximately 7.5L
    - Total Volume ~16L
    - 40x19x30cm (WxHxL)
  - Body phantom filled with saline (4.0 g/L) providing body matched conductivity*
  - Interchangeable tube currently supports two endorectal coil designs (solid and balloon)

*Not currently matched for permitivity
Materials and Methodology

- Rotatable prostate mimic positioned in center of body phantom
- T2 vials filled with MnCl₂
- T1 vials filled with NiCl₂
- ADC vials filled with PVP
- Resolution phantom on end
Materials and Methodology

- T1 measurements performed using two sequences
  - Variable Flip Angle (VFA) method used clinically, uses spoiled gradient echo (SPGR) with flip angles = $2^\circ, 5^\circ, 10^\circ, 15^\circ$
    - Total scan time = 6:16
  - Variable Inversion Recovery (VIR) is the “golden standard” for T1 mapping, uses spin-echo inversion recovery (SE-IR) with TI = 22, 30, 40, 75, 100, 125, 150, 250, 500, 1000, 1500ms
    - Total scan time = 94:58
Materials and Methodology

- T1 Fitting
  - Variable Flip Angle (VFA) fitted to:
    
    \[
    S(\alpha) = M_0 \frac{(1-e^{-\frac{TR}{T_1}})}{(1-e^{-\frac{TR}{T_1}}\cos(\alpha)}) \sin(\alpha)
    \]

- Variable Inversion Recovery (VIR) fitted to:
  
  \[S(TI)= M_0 e^{-\frac{T_1}{T_1}}\]

*VIR Fitting often has various correction factors applied*
Materials and Methodology

- T2 measurements performed using two sequences
  - Variable Echo Time (VTE) method used clinically, uses turbo spin echo (TSE) with echo times = 30, 71, 107, 144ms
    - Total scan time = 9:52
  - Spin Echo Multi-Contrast (SE_MC) method has lower resolution, but faster scan time
    - Total scan time = 7:21
Materials and Methodology

- T2 Fitting
  - Data from both sequences fitted to:
    \[ S(TE) = M_0 e^{-\frac{TE}{T_2}} \]

So what is the difference between the TSE and the SE_MC acquisitions?
- TSE is 4 separate scans each with a single echo time
- SE_MC is a single scan that samples independent \( k \)-spaces using consecutive echoes in a pulse train
Materials and Methodology

- ADC measurements performed with the following sequence
  - Diffusion weighted imaging (DWI) with 2D selective RF pulse (i.e. ZOOMIT) and b-values = 0, 50, 400, 800, 1200
  - Generic DWI sequence with GRAPPA R2 enabled in the AP direction

- Data was fitted to the following exponential curve:
  \[
  \frac{M}{M_0} = e^{-b*ADC}
  \]
Materials and Methodology

- The following considerations were made during scanning:
  - Phantoms to be used were left overnight in the scanner room
  - The default position of the prostate mimic was “12 o’clock”
  - Temperatures were recorded at the beginning of the study and at the end to correct ADC values (~3% per degree Celsius)
  - Set-up was performed by a single operator
  - The following sources of variation were investigated:
    - Sequence
    - Scanner
    - Coil Configuration / Phantom Orientation
    - Time
Results: Sequences

The clinically used VTE sequence consistently overestimates T2 by approximately 10%. This is likely due to the presence of a stimulated echo. The SEMC demonstrates excellent agreement with target T2 values.
Results: Sequences

VFA T1 mapping sequences are highly dependent upon B1⁺. The VIR sequence lacked a sufficiently long TR to accurately map Vials 1 and 2.
Results: Sequences

Vial 1 (0% PVP) suffers from insufficient SNR leading to significant variance in ADC values.
When the phantom mimic is rotated 180 degrees, there is a noticeable shift in estimated values for vials 2, 4, and 5.
Results: Coil Configuration / Orientation

The rotation exhibits a more dramatic shift in values with the inclusion of a solid endorectal coil.
Results: Time

Shorter T2 values demonstrated a higher average deviation from the target value, illustrating the difficulty in measuring short T2s.
The first 3 days had an incorrect power calibration. They are not included in the variability trends but are included to demonstrate the value of the phantom for verifying measurement parameters.
Results: Time

ADC measurements were among the most consistent and accurate.
Conclusions

- An anthropomorphic body phantom with quantitative prostate mimic has been demonstrated to:
  - Explore sources of variability in qMRI studies, identifying variation amongst different sequences, system variability over time, and coil configuration and phantom orientation
    - Can be used to harmonize results of various qMRI studies
  - Serve as a useful quality assurance tool to verify system parameters and protocols
Additional Applications: MRF

Magnetic Resonance Fingerprinting (MRF) is a method to simultaneously generate a quantitative map of multiple parameters (T1, T2, etc.) in one time-efficient acquisition.\[^{3}\]

- Each type of tissue has a unique signal evolution due to deliberate variations in acquisition parameters of a balanced steady-state free-precession sequence.
  - Not limited to a single set of parameters being varied.
- Match signals to a pre-defined dictionary generated from first principles

Analogous to the forensics matching of fingerprints.
# Results: MRF

<table>
<thead>
<tr>
<th></th>
<th>T2 Vials (ms)</th>
<th>T1 Vials (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Matched</td>
<td>Reference</td>
</tr>
<tr>
<td></td>
<td>193.09</td>
<td>129.38</td>
</tr>
<tr>
<td></td>
<td>278.1</td>
<td>190.9</td>
</tr>
<tr>
<td>T2</td>
<td>T1</td>
<td>T2</td>
</tr>
<tr>
<td></td>
<td>1374.7</td>
<td>996.7</td>
</tr>
<tr>
<td></td>
<td>1989</td>
<td>1454</td>
</tr>
</tbody>
</table>

- **Matched** values are for the experimental samples, **Reference** values are for the control samples.
Additional Applications: UHF Relaxometry

Quantitative multiparametric model of prostate cancer at 3T is attempted to be translated to higher field strengths (i.e. 7T, 10.5T)

- T1 and T2 values vary based on field strength
- ADC values are largely independent of field strength
Results: UHF Relaxometry @7T

7T ADC Map ($10^{-6} \text{ mm}^2/\text{s}$)

ADC Vials ($10^{-6} \text{ mm}^2/\text{s}$) @ 20° C

<table>
<thead>
<tr>
<th></th>
<th>7T Measured</th>
<th>3T Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>7T Measured</td>
<td>2043 ± 28</td>
<td>2055</td>
</tr>
<tr>
<td></td>
<td>1597 ± 11</td>
<td>1594</td>
</tr>
<tr>
<td></td>
<td>1212 ± 9.1</td>
<td>1197</td>
</tr>
<tr>
<td></td>
<td>874 ± 14</td>
<td>838</td>
</tr>
<tr>
<td></td>
<td>572 ± 16</td>
<td>546</td>
</tr>
<tr>
<td></td>
<td>377 ± 31</td>
<td>332</td>
</tr>
<tr>
<td></td>
<td>856 ± 12</td>
<td>838</td>
</tr>
</tbody>
</table>
Results: UHF Relaxometry @7T

<table>
<thead>
<tr>
<th>T2 Vials (ms)</th>
<th>7T Measured</th>
<th>3T Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>193.1 ± 2.6</td>
<td>125.1 ± 1.5</td>
<td>278.1</td>
</tr>
<tr>
<td>193.1 ± 2.6</td>
<td>125.1 ± 1.5</td>
<td>190.9</td>
</tr>
<tr>
<td>94.0 ± 1.6</td>
<td>63.1 ± 1.6</td>
<td>133.3</td>
</tr>
<tr>
<td>63.1 ± 1.6</td>
<td>43.8 ± 1.6</td>
<td>96.9</td>
</tr>
<tr>
<td>43.8 ± 1.6</td>
<td>34.1 ± 2.3</td>
<td>64.1</td>
</tr>
<tr>
<td>34.1 ± 2.3</td>
<td>21.9 ± 3.1</td>
<td>46.42</td>
</tr>
<tr>
<td>21.9 ± 3.1</td>
<td></td>
<td>32</td>
</tr>
</tbody>
</table>
Results: UHF Relaxometry @10.5T

\[ M = M_0 \cdot e^{-t/T_2} \]
Results: UHF Relaxometry @10.5T

\[ M_z = |a + b \cdot e^{-t/T_1}| \]

Slice 1/1
Acknowledgements

- University of Minnesota
  - Greg Metzger
  - Xiaoxuan He
  - Arcan Ertük

- High Precision Devices
  - Elizabeth Mirowski

- Funding
  - NCI R01 CA155268
  - NIBIB P41 EB015894
  - DOD W81XWH-15-1-0477
  - MN-REACH
References

