Optimizing and Troubleshooting MRI Scanning for Radiation Therapy

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Disclosure

• Dr. Gach owns common shares in ViewRay Inc., the manufacturer of WashU's MRI Guided Radiotherapy System.

• WashU has Master Research Agreements with Siemens, ViewRay, and Philips and may receive research funding or support from these vendors.
Agenda

Introduction:
- Workflow
- Priorities

Optimization:
- Acquisition Tradeoffs
- Metal Artifact Reduction
- Low Field MRI for MRIgRT

Troubleshooting:
- Image RT-facts
- Diagnostics

Educational Goal: Introduce some issues and solutions for MRI-based RT.
WashU Clinical MRI Systems

Radiation Oncology:
- MRI Sim: Philips 1.5 T Ingenia with HIFU (R5.1.7) Sonalleve
- MR-RT: ViewRay $^{60}$Co MRIdian 0.35 T (VB19)→MRI Linac
  ViewRay MRI Linac 0.35 T (VB19)

Mallinckrodt Institute of Radiology:
- Diagnostic Radiology: Siemens 1.5 & 3 T MRIs
- Center for Clinical Imaging Research (CCIR):
  - Siemens mMR 3 T (PET/MRI, VB20→VE11)
  - Siemens 3 T Trio (VB17)→Prisma 3 T VE11
  - Siemens 1.5 T Avanto (VB17)→Vida 3 T VEA
- Neuroimaging & Human Connectome (East Building):
  - Siemens 3 T Prisma (VD13→VE11)

**Takeaway: Every MRI is unique. Solutions must be customized.**
WU Image-Guided Radiotherapy Workflow

Diagnosis & Referral

CT Simulation

MRI Simulation

Image Fusion

Dose Planning

Treatment Delivery

Pre-Treatment Images

Treatment

Image Matching

IGRT Images

Treatment Review

Yes

Adjust Treatment?

No

Treatment Complete

Treatment Complete

Department of Radiation Oncology Division of Medical Physics

Washington University School of Medicine in St. Louis
MRI-based RT Priorities

1. Precise tumor and OAR delineation
2. Electron density determination
   A. Fusion with CT
   B. MRCAT
3. Motion management (Simulation and Treatment)
   A. Artifact suppression
   B. Motion characterization
   C. Motion compensation (gating, compression, treatment boundary)
4. Adaptation for changes in anatomical structural (e.g., bladder, bowel)
5. Patient comfort and safety
6. Determination of delivered "actual" dose
7. Tumor response assessment
What's Really Important?

Things that tend to be OK:
- Gradient nonlinearities.
- $B_0$ field shim.
- Eddy currents.

Things that tend to be problems:
- Patient compliance (e.g., motion) and size.
- Tissue interaction with fields: Shim and susceptibility.
- SNR, CNR, and RF coil performance.
- Patient Safety:
  - Specific absorption rate (SAR) and patient heating.
  - Metal.

What I want: *In vivo* measurement/correction of geometric distortions.*

*e.g., JC Lau et al., Neuroimage in press.*
Optimization
Is 3D T1W TSE better than MPRAGE for detecting lesions?

After Gd Administration

3D T1W MPRAGE
(TE/TR: 6.7/12 ms
0.8x0.8x0.8 mm, 8°)

3D T1W TSE+SPIR
(mVISTA)
(TE/TR: 24/700 ms
0.8x0.8x0.8 mm)

NN Kammer et al., Eur Radiol 26:1818-1825 (2016)
3D vs. 2D T1Ws (1.5 T)

**3D TSE**
- TE/TR: 10/500 ms
- 1x1x1.2 mm, 819 Hz/Pixel
- TA: 318 s, 2 Avgs

**2D TSE**
- TE/TR: 15/732 ms
- 1x1x3 mm, 115 Hz/Pixel
- TA: 274 s, 1 Avg

**3D MPRAGE**
- TE/TR: 4/8 ms, 8°
- 1x1x1.2 mm, 190 Hz/Pixel
- TA: 429 s, 1 Avg

(Poor Flow Comp)

Different Patient

**Takeaway:** Benefit of 3D TSE appears small.
Benefits of increasing receiver bandwidth:
1. Minimizes chemical shift artifacts
   - Ideally rBW >3.5 ppm/pixel.
2. Minimizes geometric distortion
3. Reduces acquisition time

Disadvantages of increasing receiver bandwidth:
1. SNR drops.
2. Stress on hardware.
3. Echo interference?
ViewRay (0.35 T): Cardiac Imaging TrueFISP

1502 Hz/pixel, 5/8 Fourier, GRAPPA 2, TR: 2 ms, TE: 0.86 ms

501 Hz/pixel, 5/8 Fourier, GRAPPA 2, TR: 2 ms, TE: 0.86 ms

103 ms/image

160 ms/image

MUTROG044

Takeaway: Slowing down may improve image quality.
Respiratory Motion (1.5 T)

Coronal 3D Fast Gradient Recalled Echo (T₁ weighted)

Free-Breathing  Breathhold  Navigator-Echo Gating
Motion: 2D vs. 3D

2D: Displacements between slices.
- Even with respiratory gating/triggering.
- Not good for treatment planning.

3D: Motion gets averaged into volume.
- Artifacts may affect all slices.
Motion Compensation - Philips MultiVane (1.5 T)

2D TSE T2W  
TE/TR: 0.1/12 s

2D MultiVane T2W  
TE/TR: 0.11/4 s

2D TSE T2W  
TE/TR: 0.1/1.9 s

2D MultiVane T2W  
TE/TR: 0.11/4 s

7-18-2017: First day after MV installation
Single-Breathhold 3D Acquisitions
Can We Simulate 0.35 T at 1.5 T?

The Target:
VR 3D Sim
T2/T1 TrueFISP
0.35 T
1.5x1.5x5 mm

3D T2W ViewTSE
(1.6x1.6x3 mm resolution)
rBW: 285 Hz/pixel
TE/TR: 71/326 ms
60 Slices/Slab
TA: 21 s/image

3D T1W Dixon VIBE
(1.6x1.6x5 mm resolution)
TE1/TE2/TR: 3/5/6 ms
rBW: 677 Hz/Pixel
70 Slices/Slab
TA: 17 s

3D bTFE Fat Suppressed
(1.6x1.6x6 mm resolution)
TE/TR: 2/4 ms
rBW: 1603 Hz/Pixel
50 Slices/Slab
TA: 23 s

3D T1W WAVE (MagPrep)
(1.6x1.6x4 mm resolution)
TE/TR: 4/8 ms
rBW: 722 Hz/Pixel
60 Slices/Slab
TA: 21 s

Takeaway: Need $T_1$ and $T_2$ values to optimize sequences.
Commercial MRI-Guided Radiotherapy
Elekta Unity
MRI-Linac (1.5 T)
Why MRIgRT?

Why High Field? More Signal

The NMR Signal is proportional to the net magnetization:

\[
\text{Signal} = \text{B}_0 \times 10 \text{ out of 1 million protons will be in the ground state (3 T, 310 K).}
\]
Why Low Field?

Pros:
- Electron return effect minimally impacted by magnetic field.
- Reduced inhomogeneities, susceptibilities, and geometric distortion.
- SAR does not restrict duty cycle & pulse amplitudes.
- Shorter $T_1$ can lead to shorter TRs and faster acquisitions.
- High CNR in TrueFisp.
- Reduced safety concerns (Lorentz/Lenz) for implants.
- Negligible chemical shift.

Cons:
- SNR and image resolution are constrained.
- Cannot saturate fat signal.

ViewRay

- 3D Simulation and 2D real-time imaging use TrueFISP
  - Balanced steady-state free precession (bSSFP)
  - \( T_2/T_1 \) weighted contrast. High CNR at low field.
  - Popular for cardiac MRI
  - Short TE and TR
  - Lower SAR than TSE
  - Vulnerable to field inhomogeneities
- Other sequences can be run in MRI-only mode.
- MRI uses Siemens hardware and software (IDEA/ICE).

**ViewRay (0.35 T)**

**3D Simulation**
- TE/TR: 1.6/3.8 ms, 1.5 mm resolution
- >500 Hz/pixel, > 17 s
- 6/8 Fourier, GRAPPA 2, FA: 60°

**2D Cine**
- TE/TR: 1/2 ms
- 6/8 Fourier, GRAPPA 2, 3.5 mm resolution
- 2 Avgs, >1000 Hz/pixel
- 0.25 s/avgd image, FA: 60°
2D TrueFISP vs. Field Strength

0.35 T
2D TrueFISP
(2.5x2.5x5 mm resolution)
rBW: 300 Hz/pixel
TE/TR: 2/4 ms
TA: 0.4 s/image

1.5 T
2D bTFE
(2.5x2.5x5 mm resolution)
rBW: 1417 Hz/pixel
TE/TR: 1/3 ms
TA: 0.3 s/image

MUTROG050
(No Distortion Correction)

MUTROG080
Why Radial Trajectory for Fast Imaging?

Pros:
● Can optimize temporal resolution by updating k-space using moving window.
● Can get quality images despite undersampling.
● Less sensitive to motion than Cartesian.

Cons:
● Reconstruction is more complicated than Cartesian.
● Reconstruction time may preclude real-time reconstruction.
● Need $\pi/2$ times higher number of k-space samples vs. Cartesian to avoid undersampling.
● Parallel imaging may be more challenging.
● Vulnerable to field inhomogeneities and gradient errors.
ViewRay (0.35 T) Radial TrueFISP

Healthy Volunteer (3 mm Resolution)

Arrhythmia Patient (2.5 mm Resolution)

0.17 s/image, 112 Radial lines, Flip angle: 110°
MRI-Based Brachytherapy
1.5 T
Brachytherapy MRI Priorities

1. Tumor delineation
2. Implant delineation
3. Fiducial marker delineation

Per Perry Grigsby MD
Visualizing the Tumor (1.5 T)

- 2D Proton Density
  - 2.5 mm thick

- 2D DWI-TSE ADC Map
  - 5 mm thick

- 2D T2W
  - 5 mm thick

- 2D TSE

- 2D EPI
Image Denoising

PDW  T2W

(courtesy of Deshan Yang)
Suppressing Metal Artifacts

- Use spin echo acquisitions
- Increase receiver bandwidth
- Use wide bandwidth RF excitations
- Use metal artifact reduction sequences
  - View angle tilting
  - Z-shimming
- Change readout axis
- Avoid high-field systems (e.g., 3 T)

2) B. Hargreaves et al., AJR 197:547-555 (2011).
Philips O-MAR

- New product.
- Comes in slice encoding for metal artifact correction (SEMAC) or metal artifact reduction sequence (MARS) versions.
  - SEMAC addresses in-plane and through-plane artifact.
  - MARS addresses in-plane artifact.
- Can be selected with most weightings (PD, $T_1$, $T_2$, and STIR).
- Requires additional acquisition time.
- May reduce SNR unless acquisition time is increased.
- Image contrast may differ from conventional images.

<table>
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<th>Material</th>
<th>Magnetic Susceptibility (ppm) (\chi)</th>
<th>Electrical Conductivity (S/m)</th>
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<tr>
<td>Gold</td>
<td>-34</td>
<td>44.2E6</td>
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<tr>
<td>Silver</td>
<td>-23.1</td>
<td>62.1E6</td>
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<td>Iodine</td>
<td>-22.2</td>
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<td>Soft Tissue or Distilled Water</td>
<td>-9.05</td>
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<td>Stainless Steel</td>
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<tr>
<td>Iron</td>
<td>2E5 - 2E11</td>
<td>10E6</td>
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</table>
O-MAR Proton Density

Nominal
2 Avgs, 2.5 mm thick, TE: 5 ms
TA: 336 s (with resp. gating)
rBW: 449 Hz/pixel

SEMAC (Medium)
1 Avg, 2.5 mm thick, TE: 30 ms
TA: 463 s (no gating), rBW: 943 Hz/pixel

Rao Y. et al.
Physics Med Biol,
Brain O-MAR in Cochlear Implant (Magnet Removed)

- 2D T1W TSE postGd (TE/TR: 15/732 ms)
- 3D FLAIR T2W (TE/TR: 0.33/4.8 s)
- 3D T1W MPRAGE (TE/TR: 4/8 ms)
- 2D T2W Medium O-MAR (TE/TR: 0.1/5.5 s)
Proton Density MRIs of Fiducials
Goal: Conspicuous with minimal susceptibility

Visicoil Au Coil (1x10 mm)
Civco Ti-Au Coil (1x10 mm)
Bard CapSure Stainless Steel Tack (3x3x4 mm)
Medtronic Ti ProTack (3x3x4 mm)
Stainless Steel Surgical Staple (4x8 mm)

Troubleshooting
MR RT-Facts
Aliasing (1.5 T)

3D TSE: TE/TR: 10/500 ms
1x1x1.2 mm, 819 Hz/Pixel, 2 Avgs

SENSE Factor 1.8 in both phase and slice directions

SENSE Factor 1.8 in phase dir. and off in slice direction
Moire Fringe Artifacts
(1.5 T Siemens Espree)

FL3D: TE/TR: 7.7/38 ms
BW: 90 Hz/pixel
Moire Fringe Artifacts
(1.5 T Philips Ingenia)

3D T2W Drive
TE/TR: 75/1400 ms

Strong Image
Filter

FID Reduction
(Stronger crusher gradients)
RF Spikes – Searching for the needle in the haystack

- Manifests as white pixels, corduroy (herringbone) artifacts, or increased noise.
- Cause: metal-metal contact or RF source inside Faraday cage.

Examples:
- Loose cables or broken conductors/components
- Improper lighting or electrical sources
- Failed line filters or Faraday cage seals
- (Gradient) resonant excitation of components

RF Coil Troubleshooting
ViewRay (0.35 T)

Expected Result

Bad Coil Element
ViewRay Receive Coils

Torso (6 elements/coil)

Head/Neck (5 elements/coil)

Coils are thin and flexible to minimize photon attenuation.
Phased Array Coil Test Phantom Holder

Bottles filled with NiCl\(\cdot\)6H\(_2\)O doped water

Add Load (e.g., Saline)

Coil Under Test
VR RF Phased Array Coil QA (6 Element Coil)

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<tr>
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<th>VAS1</th>
<th>VAS2</th>
<th>VAS3</th>
<th>VAP1</th>
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<td><img src="image1" alt="Coil 1 Image" /></td>
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<td><img src="image3" alt="Coil 1 Image" /></td>
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<td><img src="image17" alt="Coil 3 Image" /></td>
<td><img src="image18" alt="Coil 3 Image" /></td>
</tr>
</tbody>
</table>

Coil 1: Bad Coil Element
Coil 2: Bad Coil Element
Coil 3: Bad Coil Element

For more details see ePOSTER: MO-RPM-GePD-IT-5
Oops!

Anterior coil has weak signal but passed phased array coil QA.

Solution: Add signal intensity uniformity test
Phased Array Coil Test Findings

- VR coils fail frequently (e.g., every 1-2 months).

- The phased array coil QA test detects failed elements with coils laying flat.

- However, coils often fail only when flexed.

- Better troubleshooting solutions are needed.
Philips Ingenia 1.5 T MRI

Torso coil is more rigid and robust.
Stability Tests

- Assess the stability of RF and gradient components (drivers and coils).
- Acquire longitudinal data during repeated scans.
- Stress the system and components, similar to actual operations.
- Can detect loose fittings and components (e.g., metal-to-metal contact) that can produce spike noise.
- Can detect issues that may not show up in a standard QA test (e.g., ACR).
- Spec will be based on manufacturer specs and baseline measurements.

3T EPI Stability Tests
(Siemens 3 T Trio)

Arbitrary (%) BAD GOOD

EPI stability spec typically: +/- 0.25-0.5%
ViewRay (0.35 T) Stability

TrueFISP 3 Slices TE/TR: 1/2 ms

Pass  Fail

Herringbone pattern typical of RF spike noise

EPI 9 Slices TE/TR: 22/367 ms

Pass  Fail

White pixels

Normalized Mean

Normalized Mean
Summary

● MRI-based and MRI-guided RT is growing. More MRI-Sim and MRIgRT systems will be sited.

Optimization
● RT priorities may differ from diagnostic radiology priorities.
● MRI physicists are needed to help optimize protocols to meet the needs of RT.

Troubleshooting:
● RT demands high MRI performance for treatment accuracy.
● Lessons learned from diagnostic and research MRI should be applied to MRI in RT.
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Questions?
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Josef Dadok

Aksel