MR-guided Radiotherapy: from Cobalt-60 to linear accelerator

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Disclosures

• 2018 honoraria from ViewRay, Varian, WePassed, and Sun Nuclear
Learning objectives

1. Gain familiarity behind the principles of MRI-guided radiotherapy (MRgRT)
2. Understand the advantages and limitations of MRI-guided radiotherapy systems
Principles behind MRgRT
Lorentz Force

\[ F = q \mathbf{v} \times \mathbf{B} \]

- Dependence on:
  1. Distortion increases with B strength in homogeneous media
  2. Density of medium
  3. Charged particle energy spectrum


**Figure 2.** Monte Carlo calculated pointspread kernels for secondary electrons, depending on the magnetic field strength $B$. Logarithmic grey value scaling is used. Primary photons are simulated with a realistic 6 MV linear accelerator energy spectrum.

**Table 1.** In-vacuum electron trajectory radius (in mm), depending on the electron energy and magnetic field strength.

<table>
<thead>
<tr>
<th>Electron energy (MeV)</th>
<th>Magnetic field strength</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.2 T</td>
</tr>
<tr>
<td>0.5</td>
<td>14.5</td>
</tr>
<tr>
<td>1.0</td>
<td>23.7</td>
</tr>
<tr>
<td>1.5</td>
<td>32.4</td>
</tr>
<tr>
<td>2.0</td>
<td>41.0</td>
</tr>
</tbody>
</table>
Undesired Lorentz force on...

Anywhere with charged particles, including:

- Magnetron/Klystron
- Electron gun
- Linac
- Current carrying cables
- Detectors (particularly large air volume—farmer type chamber)
- Patient (lung, esophagus, gastric)
Overcome Lorentz force on linac and patient

• Cobalt-60
• Putting as many linac components >distance from isocenter
• “Shielding” linac and its subcomponents
• Using Monte Carlo to account for in patients

Courtesy of ViewRay Inc.
MRIdian by ViewRay

From Co-60 to 6 MV FFF Linac System

- Cobalt $^{60}$ X 3
- DU Heads X 3
- MLC’s X 2
- Heavy Gantry X 1
- Install & Other
- Linac Sub-system*

*Technology in development. Descriptions and performance subject to change. Not available for sale or clinical use in the United States or for clinical use elsewhere.
MRIdian by ViewRay
Undesired effects on magnetic field

- Radiofrequency generated from linac, klystron/magnetron, pulse transformer, gun driver, etc.
- Potentially some degree of ferrous material in non-static elements
- Non-static components including gantry and MLC
Overcome disturbance on magnetic field

- Move linac components away from isocenter
- Shield RF components
- Add “shimming” systems to negate non-static elements (gantry and MLC)
- Imaging only @ static gantry and MLC.....

Currently MR-guided systems are limited to step-and-shoot IMRT for this reason

Courtesy of ViewRay Inc.
Magnetic susceptibility effects

Relationship between spatial distortion and effect of magnetic inhomogeneity, magnetic field strength, and gradient linearity:

\[ \Delta x = \text{ppm} \cdot \frac{B_0}{G_E} \]

ViewRay $B_0 = 0.345\, \text{T}$, $G_E = 12\, \text{mT/m}$ for 25 ppm $\Rightarrow 0.718\, \text{mm}$

where $G_E = \text{strength of encoding gradient}$

Mutic, WUSTL

Magnetic field strength considerations

Low magnetic field strength may provide benefit in MR-guided radiotherapy in considerations of:

- Spatial Integrity
- Magnetic Susceptibility Artifacts
- Dose Distribution-Electron Return Effects
- High-field Heats the Patient - SAR

...at the potential decrease of SNR
Cobalt to linac: Vault modifications
Additional shielding Co-60 to 6 MV
RF shielding survey

- 15 MHz and 100.5 MHz planewave
Vault considerations: MRI

- Ferrous material removal within the 5 Gauss line (~10’ radius isocenter for 0.35 T)
- Hand magnet to test materials
- All ferrous room components in place prior to shim

Vault considerations: MRI

- Rebar in floor “hides” shields when a shield is located in pit (i.e., gantry 180)
- Other gantry angles may have no shield within pit; therefore no hiding of shields
- Difficult to match shimming at all gantry angles
Cobalt to linac: Imaging
Cobalt to linac gantry modification

- Six 450 lbs steal ferrous steal shield located every 60 degrees on gantry to reduce Lorentz force on linac components.
- Shields located 87 cm from isocenter.
- No ferrous material on cobalt gantry.
Shimming out ferrous material

- Static passive shim
- Rotational passive shim (linac only)
- Cryoshim or superconducting shims
Magnetic homogeneity: linac vs. cobalt

18.38 ± 0.76 ppm (cobalt) vs. 14.85 ± 0.80 ppm (linac); p<0.0001

IEC-Y non-linear harmonics in MR-linac

Mittauer, Yadav, McMain, Paliwal, Bayouth “Characterization of ferromagnetic influence of a MR-guided radiotherapy (MRgRT) system and vault: cobalt to linac” AAPM Annual Meeting 2018
A marginal increase in coronal distortion was observed (1.04±0.25mm linac vs. 0.85±0.33mm cobalt), likely due to variability of non-linear Y-harmonics during rotational interplay of MR-linac ferrous-shields and floor-rebar.
RF artifacts in MR-linac

Hill P and Mittauer K, MR-guidance in radiation therapy, AAPM Summer School, 2018
Cobalt to linac: Source and collimation
• No jaws
• SAD: 90 cm
• ISO to distal side of MLC: 50.5 cm
• Double stacked, double focused
• Minimum field size 0.2 cm x 0.415 cm and max field size of 24.1 cm x 27.4 cm
Output factors: MC-corrections for SNC edge diode

Output Factors

Square Field Size (cm²)

Output Factor

%Difference

25.64 cm² field,
MC CF=0.986

0.415 cm² field
MC CF=0.970

\[
k_{f_{\text{clin}}, f_{\text{msr}}}^{Q_{\text{clin}}, Q_{\text{msr}}} = \frac{D_{w, Q_{\text{clin}}}}{D_{w, Q_{\text{msr}}}} \times \frac{D_{d, Q_{\text{clin}}}}{D_{d, Q_{\text{msr}}}}
\]
Change in source size

<table>
<thead>
<tr>
<th>Field Size</th>
<th>Beam Center</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.38 cm (A)</td>
<td>0.01 cm</td>
</tr>
<tr>
<td>Light Rad Coinc. (20)</td>
<td>10.44 cm (A)</td>
</tr>
<tr>
<td>Field Size Mismatch</td>
<td>Light Rad Coinc. (18.9)</td>
</tr>
<tr>
<td>Tolerance</td>
<td>0.5 cm</td>
</tr>
<tr>
<td>Flatness-hm(80)</td>
<td>Flatness-hm(80)</td>
</tr>
<tr>
<td>5.8% Variance</td>
<td>0.2% Variance</td>
</tr>
<tr>
<td>Symmetry-hm(80)</td>
<td>Symmetry-hm(80)</td>
</tr>
<tr>
<td>-0.5% Area</td>
<td>0.5% Area</td>
</tr>
</tbody>
</table>

Linac 2 cm diameter
Cobalt 0.9 mm spot size

![Graph showing differences in source size](image-url)
LINAC: TPS MC vs Measured

0.4 cm x 0.415 cm X-Positive

Relative Dose vs X (cm)
LINAC large fields: MC vs Measured

Large fields data collections with ICP

Y profile d=10cm; 19.92x19.92cm
Plan quality: Cobalt-60 vs Linac
SBRT Liver (40 Gy/5 fxn): Cobalt-60 vs Linac
MRgRT clinical considerations and indications
236 patients: 09/10/2014 - 07/19/2017

UW-Madison cobalt-60

SBRT: Liver, Breast, Pancreas, Lung, GEJ, Gastric

Gastric: 22%
Liver: 21%
Breast: 11%
Pancreas: 11%
Lung: 11%
GEJ: 4%
Stomach: 3%
Kidney: 3%
Breast: 2%
Pancreas: 5%
Lung: 3%
Bladder: 2%
GE Junction: 1%
Bile Duct: 1%
Gall Bladder: 1%
Esophagus: 1%
Sacrum/Si Joint/Lspine: 0%
Iliac (pelvic bone): 0%
Head and Neck: 0%
Rectosigmoid: 0%
Abdomen: 0%
MR imaging in MRgRT

- Clinical Applications & Technical Challenges
  - Motion Management
  - Response Assessment
  - Online-Adaptation
  - Same-day-treatment
Contraindications for MR-guided radiotherapy

- Non-MR compatible implant
- Pacemaker
- Claustrophobic
- Patient size and target location
- Patient compliance
Motion Management

- Latency ~350 msec (cobalt) to 250 msec (linac)
- Shutter dose (cobalt)
- Deformation
- Surrogacy
- Slice thickness
- Frame rate
- Spatial distortion
- Shimming
- SAR (heating up patient)
- Coil reproducibility- soft tissue deformations
- Patient compliance
- Eddy current

Real-time tracking cine sagittal view

Superior

Heart
Liver
Stomach
Pancreatic Tumor
Radiation Target
Bowel Loops

Inferior

Anterior
Posterior
Use of immobilization in MRgRT

- Effect of coil position
- Maybe of limited use for thoracic and abdominal patients
- Arguably not necessary due to online adaptive and real-time tracking
- Most patients wingboard with towels may suffice
Contrast agents

Eovist™ MRI shows Metastasis the Best
Adaptive radiotherapy (ART)

ART is driven by interfractional (random or systematic) anatomical changes

**Random changes -> online**
1. Target and/or OAR deformation
2. Target and/or OAR positional variation

**Systematic changes -> offline**
1. Weight change
2. Tumor response
ART to avoid missing target coverage

ART due to organ at risk changes

ART for tumor response

- MRI promising biomarker for predictor of tumor response
- Early evidence shows GI tumor response at early treatment
- May suggest role of adaptive radiotherapy mid-treatment

UW on-table adaptive clinical workflow

THERAPIST:
Image and registration of scan of the day to initial simulation scan

Positioning
Deformation
Contouring
Plan re-optimization

Plan quality evaluation

Treatment

PHYSICIAN:
Verify localization for SBRT

PHYSICIAN:
Edit deformed contours

PHYSICIST:
Evaluate deformed electron density; edit deformed contours; apply contour Boolean operations and margin expansion

Plan generation; Compare adaptive plan to initial plan recalculated on anatomy of the day

Plan QA through secondary dose calculation

PHYSICIAN:
Plan quality review

THERAPIST:
Treatment delivery

Has the bowel moved during planning?
How to adapt efficiently?

Utilize rings with partial contours

Potential sources of error in online ART

1. Electron density
2. Segmentation
3. IMRT plan fidelity (non-measured based IMRT QA)
4. Cumulative dose from summed ART fractions

K Mittauer, P Hill, J Bayouth, “Validation Phantom of Dosimetric and Deformable Accuracy for Purposes of Commissioning An MR-Guided Online Adaptive Radiotherapy (ART) Program” Medical Physics, AAPM Annual Meeting 2017
ART commissioning procedures

1. Workflow and adaptive planning technique validation
   • Benchmark plans
2. Contour operations (Boolean operations, margin expansions etc)
   • Phantom evaluation
3. Deformable auto-segmentation evaluation
   • Phantom evaluation (deformable phantom)
4. Dosimetric end-to-end (electron density)
   • Phantom evaluation (deformable phantom with TLD)
5. Cumulative dose
   • Phantom evaluation (deformable phantom with TLD)
6. ART IMRT QA plan fidelity
   • Phantom (ArcCHECK)
7. Calculation-based IMRT QA
   • Phantom (ArcCHECK)

Commissioning: deformation & dosimetric accuracy

End-to-end test assessment of:

(1) Auto-segmentation
(2) Deformed electron density
(3) Dosimetric accuracy
(4) Cumulative dose using MIM software*

*currently, MRIdian does not offer cumulative summed dose

“MEAT” Larry
Auto-segmentation results

- Mean dice similarity coefficient was 0.9±0.0 (n=6, MRIdian CT-MR deformation), 0.8±0.2 (n=27, MRIdian MR-MR deformation)
### Dosimetric results: Dose to TLD

<table>
<thead>
<tr>
<th>TLD group</th>
<th>Target or OAR</th>
<th>Applied deformation Mean ± stdev (max) for 5 fractions (cm)</th>
<th>TLD measured Mean dose to TLD group (Gy)</th>
<th>MRIdian calculated Mean dose summed over 5 fractions (Gy) % difference to TLD measured</th>
<th>MIM calculated Mean dose accumulation (Gy) % difference to TLD measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Banana</td>
<td>Target</td>
<td>0.6±0.1 (0.8)</td>
<td>4.98</td>
<td>5.23</td>
<td>5.0%</td>
</tr>
<tr>
<td>Tangerine</td>
<td>Target</td>
<td>3.0±1.0 (4.3)</td>
<td>4.94</td>
<td>5.27</td>
<td>6.7%</td>
</tr>
<tr>
<td>Small bowel</td>
<td>OAR</td>
<td>2.1±0.8 (2.7)</td>
<td>2.16</td>
<td>2.29</td>
<td>5.8%</td>
</tr>
<tr>
<td>Lemon</td>
<td>OAR</td>
<td>3.7±1.1 (4.4)</td>
<td>2.15</td>
<td>2.52</td>
<td>17.0%</td>
</tr>
<tr>
<td>Left rib (bone)</td>
<td>NA</td>
<td>3.0±1.0 (4.4)</td>
<td>1.26</td>
<td>1.38</td>
<td>9.2%</td>
</tr>
<tr>
<td>Right rib (muscle)</td>
<td>NA</td>
<td>2.7±1.0 (3.9)</td>
<td>1.20</td>
<td>1.11</td>
<td>-7.6%</td>
</tr>
<tr>
<td>Right rib (bone)</td>
<td>NA</td>
<td>2.4±1.3 (3.8)</td>
<td>1.11</td>
<td>1.18</td>
<td>6.0%</td>
</tr>
<tr>
<td>Large orange</td>
<td>OAR</td>
<td>2.0±0.6 (2.4)</td>
<td>1.09</td>
<td>1.08</td>
<td>-0.7%</td>
</tr>
</tbody>
</table>

- Agreement for targets (i.e., low gradient regions) with a heterogenous deformable phantom remained within clinical trial limits (calculated dose within ±7% measured TLD)
Weekly QA for ART

**IC-Profiler:**
- To supplement calculation-based IMRT QA for ART cases
- **MLC positional accuracy** at four cardinal gantry angles
- **Energy check** through profile

*In addition to TG 142 Daily QA and Monthly QA*
Clinical example: LAPC

Fraction 1 of 15 – Bowel has moved away from PTV
Clinical example: LAPC
Clinical example: LAPC

Median f/u for survivors is 17.5 months
Conclusion

MR-guided radiotherapy

• Unique considerations of vault, TPS model, and patient workflow
• Reduced gating latency and treatment time with improved plan quality and magnetic homogeneity has been observed for MR-linac compared to MR-cobalt
• Provides a powerful tool for simulation, daily positioning, adaptive re-planning, real-time monitoring
• Early clinical evidence (i.e., hypofractionated MR-guided online adaptive radiotherapy in pancreas) supports potential survival benefit over conventional radiotherapy
THANK YOU.