Measurement Considerations in an MR-guided Radiation Therapy Environment

John Bayouth, PhD
Chief of Physics and Bhudatt Paliwal Professor
Department of Human Oncology
University of Wisconsin - Madison
Disclosures

• Member of ViewRay Scientific Advisory Board
System Specifications - Imaging

- Superconducting split-bore magnet
- 28 cm central gap - 0.35 T
- Geometric Accuracy: 1 mm < 20 cm / 2 mm < 35 cm diameter sphere
- 3D volumetric acquisitions (35x35x35 cm) with an SNR > 30 (23 sec)
- Cine planar acquisitions every 250
Can we really see anything at 0.35T?

iPhone. Jobs, et al.
Image Quality

3D Volumetric images of patient: bladder cancer
MR Guidance for Treatment of Soft Tissue Disease
MR Guidance for Treatment of Soft Tissue Motion
Specifications – Mechanical

3 Gantry Heads: 120 degrees of separation

Gantry Rotation: ± 60 degrees from its zero position for treatment mode, ± 120 degrees for physics mode.

Gantry Bore: 70 cm
System Specifications - MLC

MLC Geometry

60 leaves, two opposing banks of 30 leaves
27.3 cm x 27.3 cm field sizes
1.05 cm leaf resolution at the nominal isocenter distance of 105 cm
doubly divergent design
leakage: < 0.375%
Welcome Back Co-60

Dose Rate
600 cGy / minute, ~ 200 cGy/min/15,000 Ci source at 105 cm

Penumbra
9 mm - distance between the 20% and 80% isodose lines for a 10 cm x 10 cm field measured at a depth of 10 cm with a 105 cm TSD
Treatment by Disease Site (%):

- Liver: 23%
- Pancreas: 17%
- Lung: 14%
- Breast: 14%
- Stomach: 9%
- Esophagus: 5%
- Kidney: 3%
- Bladder: 3%
- Bile Duct: 3%
- Sacrum/SI joint/Lspine: 3%
- GE Junction: 3%
- Gall Bladder: 3%
- Iliac (pelvic bone): 3%
- Head and Neck: 1%
- Rectosigmoid: 1%
- Abdomen: 1%
- Rib: 1%
Over 500 patients treated across first 4 customers
- WUSTL
- UW-Madison
- UCLA
- Seoul National
RT challenges in presence of magnetic field

MRI image formation assumes linear field gradients
  - nonlinearities can distort images
  - Field strength independent
  - QA is needed to check this during clinical use.

The patient’s tissues can locally change the magnetic field leading to “magnetic susceptibility artifacts”
  - Tissues have paramagnetic or diamagnetic nature
  - Increases with magnetic field strength

The chemical environment can change the precession frequency leading to “chemical shift artifacts”
  - C-H and O-H Hydrogen has different chemical environment and different precession rates
  - Increases with magnetic field strength
How is Dose Influenced by Magnetic Fields?

Photon transport is unperturbed by magnetic field

- polarization of spins could influence interaction cross sections (Zeeman effect)
- polarization is in competition with thermal excitations
- the energy difference between the spin states due to the Zeeman effect is very small in comparison with the average thermal energy of about 0.04 eV at 300K temperature
- Radiation source is much hotter by 100’s of K
- At 1 Tesla, the fraction of nuclei polarized are ~ 4 ppm
- Practically, the atomic level physics is unperturbed by external

Electron transport experiences drift due to magnetic field (Lorentz force)
Distortion of Radiation Dose from the Lorentz force


The radius of gyration for 1 MeV electron

- 1.5 T 0.2 cm
- 0.35 T 1.0 cm

1. Radial confinement

While in vacuum in the presence of uniform magnetic fields, electrons are known to spiral about magnetic field lines in a helical orbit with a gyration radius, $r_g$, given by

$$r_g = \frac{p_\perp}{3.00B}, \quad (1)$$

where $r_g$ is measured in cm, $p_\perp$, the momentum of the electron perpendicular to the direction of the magnetic field, measured in MeV/c, $c$ is the speed of light, and $B$ is the magnetic field strength measured in Tesla (T).
Competition: large angle scattering
MFP vs. radius of gyration

0.0 T

0.35 T

1.5 T

Scrolling from 0.0 T to 7.0 T
Diode Measurements of Radiation Dose in Magnetic Field

![Graph showing ArcCHECK Deviation from ViewRay TPS (cGy)]
Diode Measurements of Radiation Dose in Magnetic Field

Figure 3.8 Bar graph depicting differences between ion chamber measurement and ViewRay TPS calculation (black) and ArcCHECK measurement (red). Error bars are representative of total k=1 measurement uncertainty, derived using the uncertainty budget in Appendix B.
@ 0.35 T Dose Perturbations are negligible but accounted for by Monte Carlo
Clinical Workflow: Automatically Identify & Locate Tissue
Predict Dose
Optimize New Plan
MRTC Workflow

1. Acquire Daily 3D Image
2. Treatment Plan Image
3. Register
4. Copy/deform/edit contours
5. Select tracking plane
6. Review/Modify Target Contour
7. Preview Cine
8. Position Adjustment Required?
   - Yes
     9. Is 2D adjustment adequate?
        - Yes
          10. Apply Shift and Adjust MRTC Criteria
        - No
          11. Treatment Delivery
   - No
     12. Treatment Delivery
Lung Cancer Motion and Targeting with MRI Guidance

- MRI allows us to continuously ensure the treated area is within the treatment area.
- Radiation is only on when the target is within the radiation field.
- Deep breath expands lung so less normal lung treated.
Lung Cancer Motion and Targeting with MRI Guidance

- MRI allows us to continuously ensure treated area is within the treatment area.

- Radiation is only on when the target is within the radiation field.

- Deep breath expands lung so less normal lung treated.
Pancreas IMRT with breath hold gating

Superior

Heart
Liver
Stomach
Pancreatic Tumor
Radiation Target
Bowel Loops

Anterior
Inferior
posterior
Pancreas IMRT with breath hold gating

Superior

Heart

Liver

Stomach

Pancreatic Tumor

Radiation Target

Bowel Loops

Inferior

Anterior

posterior
Pancreas IMRT with breath hold gating

Superior

Anterior

Inferior

posterior
**Stereotactic Ablative Liver Metastasis Radiation**

50Gy in 5 Fx

Patient driven repeated breath-hold technique with a high duty cycle

Radiation beam is only on when tumor is in proper position

Contrast used to highlight the tumor and allow daily tracking

Unique to be able to see and track actual tumor (not a surrogate) in realtime

---

**MRI Tracking During Treatment**

Superior

Anterior

Lung

Liver

Radiation

Tumor

Inferior

posterior
Quality Assurance
Report of IMRT Head and Neck Phantom Irradiation

Date of Report: September 28, 2014
Institution: University of Wisconsin
Physician: Mark Geurts
Radiation Machine: ViewRay, ViewRay (101) – 6 MV
Intensity Modulation Device: Multileaf Collimator
IMRT Technique: Segmented (step and shoot) MLC
Treatment Planning System: ViewRay McPlan (IMRT) – Monte Carlo
Date of Irradiation: September 4, 2014

Description of Procedure

An anthropomorphic head phantom incorporating a rectangular dosimetry insert was imaged and irradiated to approximately 6.6 Gy using an IMRT technique. The dosimetry insert consisted of one primary PTV containing four TLD capsules, a secondary PTV and an organ at risk (OAR), each containing two TLD capsules. The TLD capsule provided dose information. Three sheets of GAFChromic™ Dosimetry Media provided dose profiles through the center of primary PTV.

The dosimetric precision of the TLD is ±1%, and the spatial precision of the film and dosimeter system is ±1 mm.

Summary of TLD and film results:

<table>
<thead>
<tr>
<th>Location</th>
<th>IROC vs. Inst.</th>
<th>Criteria</th>
<th>Acceptable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary PTV sup. ant.</td>
<td>0.95</td>
<td>0.02 – 1.10</td>
<td>Yes</td>
</tr>
<tr>
<td>Primary PTV inf. ant.</td>
<td>0.98</td>
<td>0.02 – 1.10</td>
<td>Yes</td>
</tr>
<tr>
<td>Primary PTV sup. post.</td>
<td>0.96</td>
<td>0.02 – 1.07</td>
<td>Yes</td>
</tr>
<tr>
<td>Primary PTV inf. post.</td>
<td>0.95</td>
<td>0.02 – 1.07</td>
<td>Yes</td>
</tr>
<tr>
<td>Secondary PTV sup.</td>
<td>0.98</td>
<td>0.02 – 1.07</td>
<td>Yes</td>
</tr>
<tr>
<td>Secondary PTV inf.</td>
<td>0.98</td>
<td>0.02 – 1.07</td>
<td>Yes</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Film Plane</th>
<th>Gamma Index*</th>
<th>Criteria</th>
<th>Acceptable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axial</td>
<td></td>
<td>≥85%</td>
<td>Yes</td>
</tr>
<tr>
<td>Sagittal</td>
<td></td>
<td>≥85%</td>
<td>Yes</td>
</tr>
</tbody>
</table>

*Percentage of points meeting gamma-index criteria of ≥7% and 4 mm.

The phantom irradiation results listed in the table above do meet the criteria established by IROC Houston in collaboration with the cooperative study groups. Therefore, your institution has satisfied the phantom irradiation component of the credentialing process to enter patients into certain protocols that allow the use of IMRT.

TLD and Film Analysis by: Nadia Hernandez and Andrea Moineu, M.S.

Report Checked by: David S. Fowlow, Ph.D.
Director, IROC Houston QA Center

OSLD was evaluated using the AAPM TG-51 Dosimetry Calibration Protocol.

OSLD read on: 12-Sep-2014
OSLD read by: Travell Hollingsworth
Checked by: Stephen Kry, Ph.D.

David S. Fowlow
Director

IROC Quality Assurance Center Locations
Houston | Ohio | Philadelphia | Rhode Island | St Louis
Sponsored by the National Cancer Institute

MD Anderson Cancer Center
Making Cancer History®
Quality Assurance - MLC
Quality Assurance - MLC
Quality Assurance

Radiation Isocenter(s)
**Quality Assurance**

System Latency

Trigger beam hold within 500 msec of target moving outside predefined boundary

---

**Dosimetric Consistency with RealTargeting –**

<table>
<thead>
<tr>
<th>Measured value</th>
<th>Disposition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured dose without motion.</td>
<td>Stationary Chamber (nC)</td>
</tr>
<tr>
<td>Target Chamber (nC)</td>
<td>7.03</td>
</tr>
<tr>
<td>Measured dose with measurement</td>
<td>Stationary Chamber (nC)</td>
</tr>
<tr>
<td>Target Chamber (nC)</td>
<td>7.12</td>
</tr>
<tr>
<td>Dose difference between with and without target motion ≤ 3%</td>
<td>Stationary Chamber (% diff)</td>
</tr>
<tr>
<td>Target Chamber (% diff)</td>
<td>1.3%</td>
</tr>
</tbody>
</table>

Describe:

Quality Assurance System Latency

Trigger beam hold within 500 msec of target moving outside predefined boundary
Quality Assurance
Verification of Dose during MRTC
Phantom Motion
2 cm motion at 6 second periods (10 bpm)
(~ 10 mm/sec speed)
## Verification of Dose during MRTC

### Dosimetric Consistency with RealTargeting – Conformal Plan

<table>
<thead>
<tr>
<th>Test Item</th>
<th>Measured values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured dose without motion</td>
<td>Target Chamber (nC) 7.03</td>
</tr>
<tr>
<td>Measured dose with motion</td>
<td>Target Chamber (nC) 7.12</td>
</tr>
<tr>
<td></td>
<td>Target Chamber (% diff) 1.3%</td>
</tr>
</tbody>
</table>

![Image of radiation therapy planning system]
Spatial Distortion

CT

MRI

Calaboration with CIRS
Red = 0–19 mm, Yellow = 19–38 mm, Green = 38–57 mm, Cyan = 57–76 mm, Black = 76–95 mm, 5 mm Axial Resolution, Blue line represents pixel spacing

ViewRay 3-D Spatial Distortion

Average value of distortion = 1.2354
Standard deviation of average = 0.55207

Collaboration with Antolak & Jackson
Conclusions

• Our clinic finds the ViewRay MRIdian to be highly accurate clinical tool
• MRTC allows visualization of targets and OARs during entire treatment
• Robust QA of MRTC possible
Acknowledgements

Physicists
Mark Geurts, Adam Bayliss, Zac Labby, Patrick Hill, Bhudatt Paliwal, Alexander Antolak, Edward Jackson, Wes Culberson, Larry DeWerd

Physicians
Paul Harari, Mike Bassetti, Kristen Bradley, Bethany Anderson, Andrew Baschnagel

RTTs

ViewRay & CIRS
Recently Announced 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.