Radiation Therapy in Patients with Implanted Hip Prostheses: Phantom Study Results

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Disclosure

• Speaker has received travel funding from Varian Medical Systems.

• A portion of this project was funded by the Cancer Care Manitoba Foundation.
Acknowledgments

Medical Physics:
- Dave Sasaki
- Marlon Evan

Radiation Therapy:
- John Ioculano

Machine Shop:
- Todd Boyer
- Chad Harris
- Roy Norton

Cancer Care Manitoba Foundation
• Overview of hip prostheses
• Problems delivering RT:
  – Image Quality
  – Dose Uncertainty
• Case Study: SCC Vagina, Prostate Bed
• Phantom Creation
• Research Results
• Conclusions
• First modern hip replacement done in 1960
• In 10 years, hip replacement surgery has increased 63% in Canada
Diagnosis Causing Primary Hip Replacements

N = 14,184 hip replacements.

Canadian Joint Replacement Registry (CJRR) Hip and Knee Replacements in Canada
—2011 Annual Statistics
Increased number of young patients with long life expectancy receiving hip replacements:

- Increased risk of needing bilateral surgery (up to 1/3 of patients)
- Increased chance of developing a pelvic malignancy while prostheses in place.
Hip and Knee Replacements by BMI Category

Underweight—BMI <18.5
Overweight—BMI 25 to 29.9
Obese II—BMI 35 to 39.9
Normal—BMI 18.5 to 24.9;
Obese I—BMI 30 to 34.9
Obese III—BMI 40+

7.7% of Canadians
15.4% of replacements

N = 10,883 hip replacements.
N = 16,454 knee replacements.
Total Hip Replacement

Most often done for **Osteoarthritis**

1. Compartment opened
2. Femur neck is cut off
3. Acetabulum reamed, cup placed

*Mirza et al., The Open Orthopedics Journal, 4:169-80, 2010.*
Total Hip Replacement

Most often done for Osteoarthritis

1. Compartment opened
2. Femur neck is cut off
3. Acetabulum reamed, cup placed
4. Rasp used to clean out femoral canal
5. Stem placed in canal
6. New head inserted into cup

Hip Prostheses Components

- **Shell** that is fixed to the hip socket.
- **Liner** fits between the shell and the head.
- **Head** or ball which articulates with the liner.
- **Stem** that fixes into the Femur

*Mirza et al., The Open Orthopedics Journal, 4:169-80, 2010.*
Hard on Soft
- Femur head is metal (cobalt chrome) or ceramic
- Liner is polyethylene

Hard on Hard

- Femur head and articulation surface is ceramic. (Ceramic on Ceramic)

**Hard on Hard**

- Metal femur head and articulation surface. (METAL on METAL)

*Mirza et al., The Open Orthopedics Journal, 4:169-80, 2010.*
Bearing Surfaces for Hip Replacements

In our radiotherapy dept:
15 Patients/year with prostheses, usually 3-4 bilateral
Problems
# Physical Makeup

<table>
<thead>
<tr>
<th>Material</th>
<th>Density g/cm³</th>
<th>Atomic #</th>
<th>Electron density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stainless</td>
<td>8.1</td>
<td>26.7</td>
<td>6.8</td>
</tr>
<tr>
<td>Co–Crome</td>
<td>7.9</td>
<td>27.6</td>
<td>6.7</td>
</tr>
<tr>
<td>Titanium</td>
<td>4.3</td>
<td>21.4</td>
<td>3.6</td>
</tr>
<tr>
<td>Ceramic (Al2O3)</td>
<td>3.97</td>
<td>≈16</td>
<td>3.5</td>
</tr>
<tr>
<td>HD xLink Poly</td>
<td>≈ 0.950</td>
<td>Varies</td>
<td>Varies</td>
</tr>
<tr>
<td>Muscle</td>
<td>≈ 1.0</td>
<td>≈ 7.4</td>
<td>3.3</td>
</tr>
<tr>
<td>Bone</td>
<td>≈ 1.6</td>
<td>≈ 12.5</td>
<td>3.0</td>
</tr>
</tbody>
</table>

Hendee, W et al. Medical Imaging Physics, 4th ed. 2002
Densities must be manually assigned beyond this point.

Artifacts generated beyond this point.
Problem: Image Artifact

• Artifact due to large attenuation coefficient in the diagnostic X-ray range
• Target and OAR difficult to contour with artifacts present.
• Hard to treat what you can’t see
Problem: Image Artifact

• Image artifact reduction using an automatic algorithm
• Tested on a patient with prostate cancer and bilateral hip replacement.
• Target was not visible without enhancements.

“Without this enhancement, physicians would have drawn bigger margins to be sure to include the target and, at the same time, could have prescribed a lower dose to keep the same level of normal tissue toxicity.”

Problem: Image Artifact

(a) raw projection data; (b) initial reconstructed image; (c) metal object segmentation; (f) missing projections in raw projection data

Problem: Image Artifact
• MV CBCT images were imported into the treatment planning system and registered with the original planning CT.
• Provide sufficient soft-tissue contrast to help delineate the prostate, bladder and rectum.
“Prostate volumes contoured with the help of MV CBCT were generally smaller ...may prevent over dosage of the rectum”
Problem: Image Artifact

MRI can help...
Problem: Dose Uncertainty

Problem: Dose Uncertainty

Dosimetric considerations for patients with HIP prostheses undergoing pelvic irradiation. Report of the AAPM Radiation Therapy Committee Task Group 63

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Published in 2003, most cited document regarding RT and hip prosthesis

Problem: Dose Uncertainty

Dose measured through a 3cm cobalt-chromium-molybdenum bar:

**6Mv**
- High dose at surface of bar, +20% (back scatter)
- Low dose at distal end of bar, -15%
- For large beam, lines start to come back together 4cm beyond metal (scatter for un-obstructed beam)

**18Mv**
- High dose on bar surface, +15%
- High dose at distal end, +20% (>10MV pair production, Neutrons)

Problem: Dose Uncertainty

Attenuation factors for 6 and 18 MV photon beams 15x15 field size, at a depth of 10 cm for a selection of prostheses. The prostheses were set at 5 cm depth

- Ti #1 18Mv = 17% attenuation
- Co-Cr#5 6Mv=50% attenuation
Treatment Planning Computer Dose Calculation

- Calculation models attempt to calculate attenuation of high Z materials.
- Some systems allow for a density max of 3 g/cm³. Density of prostheses can be as high as 8 g/cm³. Others set max of 2500 – 4000 HU.

AAPM Recommendations:

How does your treatment planning system handle high density?

1. Radiation oncologist should inform the physicist (before sim).

2. Beam arrangements that avoid the prosthesis should be done first.

The following are recommended:
   i. Use standard immobilization
   ii. Ensure prostheses does not shadow part of the target volume. For CT planning you can edit out the streak artifacts
   iii. Take port/EPID to verify prosthesis does not shadow target volume

One Side or Two

- \(\approx 330^\circ\) to bring in beams
- \(\approx 300^\circ\) to bring in beams
- Dose spreads Ant-Post
What about IMRT / VMAT?
• 2001, IMRT (9 fields) and avoid unilateral prosthesis

“Each of the 9-field IMRT plans spared the bladder and rectum better than the corresponding 3DCRT plan. One negative feature of the IMRT plans was the homogeneity across the target, which ranged from 95% to 115.”
For our patient with bilateral prostheses, treatment with conventional conformal techniques provided unacceptable plans. The current investigation reports in general, the ability of IMRT to permit offering external beam to a patient who otherwise would not have been able to be treated.
- Low risk prostate cancer, 79.2 Gy/44 Tx
- Fused with MRI to delineate organs,
- Override artifact (HU 0)
- Used avoidance sectors so arc did not enter through prostheses (angles not stated)
- 2, 3 & 4 arcs tested.
- 4 arcs best for sparing rectum and bladder
Case Study
Case Study SCC Vagina

- 85 Year Old Female, SCC Vagina
- Patient would normally be a candidate for HDR brachytherapy, unfortunately she could not lift her legs.
Case Study SCC Vagina

Target Volumes:
PTV 45 Gy
PTV 54Gy
Case Study SCC Vagina

- AP/PA fields to 45Gy volume, 3 field oblique for boost
3DCRT - Sm Bowel, Rectum over tolerance. Bladder getting 100% dose.
• Using custom shaped IMRT fields to avoid beam entry through prostheses

• “Fixed” jaw plans were more conformal and better able to spare OARs when compared to plans which limited beam angles
IMRT

- Manually adjust field size to shield *entrance* through prosthesis, *but allow exit* through contra lateral.
Case Study SCC Vagina

- Manually adjust field size to shield entrance through prosthesis, but allow exit through contra lateral.
Case Study SCC Vagina

- Choose “Fixed Jaws”
Case Study SCC Vagina

IMRT – 7 field

IMRT – 11 field
Normal Tissue

PTV 45Gy

5 fld • 7 fld • 11 fld Δ

PTV 54Gy
<table>
<thead>
<tr>
<th>Plan</th>
<th>Conformality Index 45Gy</th>
<th>Conformality Index 54Gy</th>
<th>Plan Dmax (%)</th>
<th>Normal Tissue Mean (cGy)</th>
<th>Rectum V50 (%)</th>
<th>Bladder V50 (%)</th>
<th>Bowel V50 (%)</th>
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</thead>
<tbody>
<tr>
<td>3DCRT</td>
<td>4.0</td>
<td>4.9</td>
<td>109</td>
<td>822</td>
<td>99</td>
<td>100</td>
<td>25</td>
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<tr>
<td>5FLD IMRT</td>
<td>1.6</td>
<td>1.5</td>
<td>118</td>
<td>797</td>
<td>47</td>
<td>50</td>
<td>1.5</td>
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<tr>
<td>7FLD IMRT</td>
<td>1.4</td>
<td>1.2</td>
<td>115</td>
<td>757</td>
<td>47</td>
<td>40</td>
<td>0.1</td>
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<tr>
<td>11FLD IMRT</td>
<td>1.4</td>
<td>1.2</td>
<td>109</td>
<td>768</td>
<td>47</td>
<td>42</td>
<td>0.4</td>
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<tr>
<td>Non-Coplan</td>
<td>1.5</td>
<td>1.3</td>
<td>112</td>
<td>873</td>
<td>51</td>
<td>45</td>
<td>3.7</td>
</tr>
</tbody>
</table>
VMAT

1. Hips as Avoidance
2. Separate avoidance structures
3. Avoidance sectors
VMAT – Avoidance Sectors

- Tell the optimizer to turn off beam for beam angles that would pass through the hip.

80° 40°
<table>
<thead>
<tr>
<th>Plan</th>
<th>CI 45Gy</th>
<th>CI 54Gy</th>
<th>Plan Dmax (%)</th>
<th>Normal Tissue Mean (cGy)</th>
<th>Rectum V50 (%)</th>
<th>Bladder V50 (%)</th>
<th>Bowel V50 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11FLD IMRT</td>
<td>1.4</td>
<td>1.2</td>
<td>109</td>
<td>767</td>
<td>47</td>
<td>42</td>
<td>0.4</td>
</tr>
<tr>
<td>80° Avoid Sectors</td>
<td>1.9</td>
<td>2.1</td>
<td>119</td>
<td>754</td>
<td>86</td>
<td>74</td>
<td>1.0</td>
</tr>
<tr>
<td>40° Avoid Sectors</td>
<td>1.5</td>
<td>1.6</td>
<td>112</td>
<td>793</td>
<td>53</td>
<td>54</td>
<td>2.0</td>
</tr>
</tbody>
</table>
Prostate Bed
Case Study Prostate Bed

Volumes:
PTV 66Gy  Bladder  Rectum
Case Study Prostate Bed

9FId IMRT

Rapid Arc: 60 degree Avoid Sector
## Case Study: Prostate Bed

<table>
<thead>
<tr>
<th></th>
<th>CI 66Gy</th>
<th>Plan Dmax (%)</th>
<th>Normal Tissue Mean (cGy)</th>
<th>Rectum V50 (%)</th>
<th>Rectum V66 (%)</th>
<th>Bladder V50 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 Fld</td>
<td>1.42</td>
<td>136</td>
<td>412</td>
<td>67</td>
<td>33</td>
<td>47</td>
</tr>
<tr>
<td>7 Fld</td>
<td>1.19</td>
<td>130</td>
<td>382</td>
<td>64</td>
<td>7</td>
<td>48</td>
</tr>
<tr>
<td>9 Fld</td>
<td>1.07</td>
<td>114</td>
<td>373</td>
<td>61</td>
<td>9</td>
<td>43</td>
</tr>
<tr>
<td>RA 60° Avoid</td>
<td>2.04</td>
<td>125</td>
<td>402</td>
<td>73</td>
<td>63</td>
<td>59</td>
</tr>
</tbody>
</table>
However...

Is the Plan Deliverable?
Cancer Care Manitoba Research
Research Project

• Little research existed about IMRT/VMAT treatment delivery in patients with hip prostheses.
• We submitted proposal to for support of the creation of a phantom (human analog) with implanted hip prostheses.
• Phantom would have the ability to measure dose using Film, TLD’s, MOSFET detectors, and ion chambers.
• **CCMB Machine Shop** and Mould Room to build phantom.
• **Concordia Joint Replacement Group** to obtain hip prostheses
Phantom Design
Building the Phantom

• Material:
  – that could be poured
  – easy to machine
  – density $\approx 1.0\text{g/cc}$

• Tested dozens of materials

• Settled on liquid urethane Crystal Clear® 206.
  – Density close to water (60 HU)
  – Stable for pours $> 6''$ thick, 5 day cure time
  – Easily machined with conventional tools
Building the Phantom

- Uvex vacuum formed “Bust” of volunteer
- Filled with liquid urathane
Building the Phantom

- Pockets cut out for hip prostheses and dose measuring equipment
- Prostheses imbedded in tissue equivalent material.
- Prostheses are removable so phantom can be used for other purposes.
Building the Phantom

Separation:
AP = 22 cm
Lat = 40 cm
Building the Phantom

- Fasteners
- Films
- Threaded rod
- Acrylic slabs

Not shown:
- Pins
- Ion chamber
Experiments

• Phantom scanned on a CT Simulator
• Various VMAT plans attempted in Eclipse (V.10, AAA algorithm)
• Various tissue overrides attempted
• Deliverability of plans verified with ion chamber and film in the phantom
Prostate patient of similar size and shape fused with phantom to obtain Target and OAR positions.
Challenges
Gafchromatic EBT2 Film

10cm x 5.5 cm
Gafchromic EBT2 Film
# Gafchormic EBT2 Film

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>100.1</td>
<td>99.6</td>
<td>100.4</td>
<td></td>
</tr>
</tbody>
</table>

![Graph showing the distribution of values](image_url)
Film Scanner
Method

Results from each test include:

- Ion chamber measurement
- Gamma analysis of film (3% / 3mm)
- 20% and 70% dose level

<table>
<thead>
<tr>
<th></th>
<th>Ion Chamber</th>
<th>Film Gamma (3%/3mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PASS</td>
<td>&lt;2%</td>
<td>&lt;5%</td>
</tr>
<tr>
<td>Physics</td>
<td>2-3%</td>
<td>5-10%</td>
</tr>
<tr>
<td>Review</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FAIL</td>
<td>&gt;3%</td>
<td>&gt;10%</td>
</tr>
</tbody>
</table>
Results
Base Line: No Prostheses & Full Arcs

Ion Chamber vs Eclipse plan = Avg -2.0% (1.8%-2.1%)
Gamma (Film vs Eclipse plan) = Avg 4% (1.8-5.7%)
### 4 Field Box – 23MV

<table>
<thead>
<tr>
<th>Ion chamber</th>
<th>Film Gamma</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 Field Box</td>
<td>-9.40%</td>
</tr>
</tbody>
</table>
Density Override?

No Override

Low Density Override
(-1000 to -150 HU)

Low and High Override
(150 to 3000 HU)
Density Override?

<table>
<thead>
<tr>
<th>Ion Chamber</th>
<th>Film Gamma (6 films analyzed)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
</tr>
<tr>
<td>No Density Override</td>
<td>-2.20%</td>
</tr>
<tr>
<td>Low Density only</td>
<td>-0.99%</td>
</tr>
<tr>
<td>Low and High Density Override</td>
<td>0.29%</td>
</tr>
</tbody>
</table>
VMAT Avoidance

No Avoidance

30 Degree Avoidance

60 Degree Avoidance
• More Arc (less avoidance) means better plan
• Lower OAR dose & lower hot spots
Ion Chamber Results

Ion Chamber Dose vs Eclipse Dose

-5.0% -4.0% -3.0% -2.0% -1.0% 0.0% 1.0%

Run #

% Difference

-5.0% -4.0% -3.0% -2.0% -1.0% 0.0% 1.0%

No avoidance
30 deg avoid
60 deg avoid
Film Gamma Results

Film Gamma Analysis @ 20% dose

% of points outside 3%/3mm

Run #

No avoidance
30 deg avoid
60 deg avoid
Film Gamma Results

Dose Thresholded at 20%

% of points outside 3%/3mm

Vertical Profile

Reference Image
Target Image
Dose Difference

- Reference Image: L:\RRIC Study\...\No_avoid_filmD.dcm
- Target Image: L:\RRIC Study ID\...\noavoid_d.\...\dric
- Profile Position: 2.15cm
- Maximum Difference: 24.19% at 6.80cm
- Minimum Difference: -8.74% at 0.50cm
- Mean Difference: -0.56%
- Std. Deviation: 6.07%
- Profile Pixels: 86
- Total Pixels outside 3%/3mm: 35 (51.47%)
Film Gamma Results

Film Gamma Results at 70% dose

- % of points outside 3%/3mm

Run #

No avoidance
- 30 deg avoid
- 60 deg avoid
Summary

• All of our plans independently passed our COMPASS QA, however 60 degree avoidance sectors were closed to failing.
  – More modulation = less deliverable plans?
• Our preliminary data shows that large avoidance sectors in VMAT planning do not necessarily = more deliverable plan.
• Even though our results using the phantom are inconsistent, plans either pass or are close to passing our film QA criteria.
• Future:
  – Try breaking the arcs up…3 partial arcs instead on avoidance
  – Try EBT3 film
  – Try MOSFET detectors
So what’s going on?

• Are the avoidance sectors degrading plan quality? (<control points? more modulation?)
• 3 partial arcs (181-240, 300-60, 120-179)
60 Avoid – 6 Partial Arcs

**Ion Chamber Results**

- **No avoidance**
- **30 deg avoid**
- **60 deg avoid**
- **6 part arc**
60 Avoid – 6 Partial Arcs

Film Gamma Analysis @ 20% dose

% of points outside 3%/3mm

Run #
Conclusions

- Hip prostheses are becoming more common in patients with pelvic cancers.
- Traditionally treatment through hip prosthesis is not advised due to inability to accurately calculate dose.
- Treatment with IMRT or VMAT is technically possible, and yields plans of reasonable quality.
- Our phantom research shows that avoidance sectors that do not completely avoid the prostheses seem as deliverable as plans with 30 degree and 60 degree avoidance sectors.
- Small or no avoidance = <OAR dose
- More research is required to conclude what technique best balances deliverability and OAR sparing.
Questions?