Alternative Strategies for Linac Beam Verification or Beam Data Collection Without Using a 3D Water Tank: Linac Beam Data Collection from 1-D to 3-D

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Disclosures

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• I receive research funding and consulting income from Varian Medical Systems
Introduction - The Problem

- **Commissioning**
  - The collection of 3D radiation beam data
  - Used to model the treatment fields we used to treat patients
  - Typically collected with a water tank that can move a detector in the 3 Cartesian directions
    - 3D water tank
Introduction - The Problem

• Commissioning
  • Mistakes here affect all patients
  • A lot of equipment required
  • Expensive (~70-100k)
  • Where do you store
  • Difficult to transport
  • Takes skill to setup and use
Introduction - The Problem

• Commissioning
  – Can this be simplified?
  – Made less expensive?
  – Could we do it with just the equipment in say checked luggage?
  – Could we utilize the linac to scan itself?

Figure 2: 3DS water tank, leveling lift platform, and reservoir. Images from SNC 3DS tank data sheet.
Introduction—Controlling the Linac—Speak the Language

- Extensible Mark Up Language (XML) used to control modern Varian linear accelerators (Halcyon, TrueBeam, VitalBeam)
- Dicom files converted internally to XML
- Developer Mode allows users to give XML directly to Linac
- This can be done in service mode as well with hardware key

Can precisely control TrueBeam
Can be used to program machine QA! (See MPC)

“Automation of Linear Accelerator Star Shot Measurement with Advanced XML Scripting and Electronic Portal Imaging Device”
- Ngoc Nguyen, Nels Knutson, Matthew Schmidt, Michael Price  AAPM 2016 Meeting

Quality control procedures for dynamic treatment delivery techniques involving couch motion

Victoria Y. Yu, Benjamin P. Fahlman, Lei Xing, and Dimitre H. Hristov
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In this study, the authors introduce and demonstrate quality control procedures for evaluating the geometric and dosimetric fidelity of dynamic treatment delivery techniques involving treatment couch motion synchronous with a multi-leaf collimator (MLC). Tests were designed to evaluate positional accuracy, velocity constancy and accuracy for dynamic couch motion under a realistic weight load. A test evaluating the geometric accuracy of the system in delivering treatments over complex dynamic trajectories was also devised. Custom XML scripts that control the Varian TrueBeamSTM STx (Serial #3) axes in Developer Mode were written to implement the delivery sequences for the tests. Delivered dose patterns were captured with radiographic films or the electronic portal imaging device. The couch translational accuracy in dynamic treatment mode was 0.01 cm, rotational accuracy was within 0.3°, with 0.04 cm displacement of the rotational axis. Dose imnortality profiles capturing the velocity constancy and accuracy for translations and rotation exhibited standard deviation and maximum deviations below 3%. For complex delivery involving MLC and couch motions, the overall translational accuracy for reproducing programmed patterns was within 0.06 cm. The authors conclude that in Developer Mode, TrueBeamSTM is capable of delivering dynamic treatment delivery techniques involving couch motion with good geometric and dosimetric fidelity. © 2014 American Association of Physics in Medicine. [http://dx.doi.org/10.1118/10.846707]
Introduction - Can We Use XML?

- Could we use automated couch motions to collect 3D (XYZ) radiotherapy data?
- My work was done in sort pieces
  - Step 1 - Section A
    - Z dimension (Depth Profiles)
    - TMR
  - Step 2 - Section B
    - X&Y dimensions (Lateral Profiles)
  - Step 3 - Section C
    - Putting it all together & Lesions learned
Section A - Measurement of 1D Data, The Direct and Continuous TMR

- Tissue Maximum Ratio (TMR)
- Fixed Source to Detector Distance (SDD) with changing amounts of buildup.
- Time consuming in practice
- Traditionally measured by
  - Adding solid water
  - Changing depth of chamber in water and manually setting table height
  - Draining water
  - Converting measured PDDs
Section A – Our Method & Workflow

- Write XML to synchronize couch motion with scanning tank motion
- Keeping the chamber at isocenter while changing the depth.

**System**
- TrueBeam
- Load XML
- Beam On and hold
- Release Beam Hold When Scan Motion Starts
- Beam Off

**Events**
- Water Tank/PCE Software
- Initiate Tank Software
- Initial scan
- Scan Ends

**Time**
Section A – Use of Imaging

Fluoroscopy during delivery to confirm setup

With some skill we found we can keep SDD within 1mm of 100 cm
Section A – Results

• Continuous TMR matches Discrete TMR
• Converted TMRs are not within 1% of measurement

<table>
<thead>
<tr>
<th>Field size [cm²]</th>
<th>Max $\Gamma$</th>
<th>Mean $\Gamma$</th>
<th>Max Abs diff in TMR</th>
<th>Mean Abs diff in TMR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 × 1</td>
<td>0.605</td>
<td>0.061</td>
<td>0.009</td>
<td>0.001</td>
</tr>
<tr>
<td>2 × 2</td>
<td>0.600</td>
<td>0.169</td>
<td>0.006</td>
<td>0.002</td>
</tr>
<tr>
<td>3 × 3</td>
<td>0.600</td>
<td>0.062</td>
<td>0.007</td>
<td>0.001</td>
</tr>
<tr>
<td>4 × 4</td>
<td>0.622</td>
<td>0.138</td>
<td>0.015</td>
<td>0.003</td>
</tr>
<tr>
<td>5 × 5</td>
<td>0.683</td>
<td>0.142</td>
<td>0.013</td>
<td>0.002</td>
</tr>
<tr>
<td>6 × 6</td>
<td>0.702</td>
<td>0.183</td>
<td>0.013</td>
<td>0.003</td>
</tr>
<tr>
<td>8 × 8</td>
<td>0.650</td>
<td>0.142</td>
<td>0.011</td>
<td>0.002</td>
</tr>
<tr>
<td>10 × 10</td>
<td>0.657</td>
<td>0.131</td>
<td>0.012</td>
<td>0.002</td>
</tr>
<tr>
<td>12 × 12</td>
<td>0.643</td>
<td>0.103</td>
<td>0.006</td>
<td>0.002</td>
</tr>
<tr>
<td>15 × 15</td>
<td>0.741</td>
<td>0.149</td>
<td>0.006</td>
<td>0.002</td>
</tr>
<tr>
<td>20 × 20</td>
<td>0.658</td>
<td>0.108</td>
<td>0.009</td>
<td>0.002</td>
</tr>
<tr>
<td>30 × 30</td>
<td>0.653</td>
<td>0.124</td>
<td>0.007</td>
<td>0.002</td>
</tr>
<tr>
<td>All field sizes</td>
<td>0.741</td>
<td>0.126</td>
<td>0.015</td>
<td>0.002</td>
</tr>
</tbody>
</table>

Section A – Conclusions

- Continuous TMR matches discrete TMR
- Converted TMRs are not within 1% of directly measured TMRs
- This method provides convenient and accurate method for direct measurement of TMRs

Technical Note: Direct measurement of continuous TMR data with a 1D tank and automated couch movements

Section B – 2D Data, Lateral Profiles

- 1D motion along Z axis worked well!
- Why not X and Y axis of the couch.
- Could we make a clinically equivalent beam model with just this equipment
Section B – Methods

• Compare dosimetry data for 6MV photons
  – Collected using a 3D water tank (3DS)
  – Collected using a 1D tank with automated couch motions (1DS)
• All data collected with IBA CC13 chambers
  – (2.5 mm/s 1.25 mm pt spacing)
• PDDs & profiles
  – 3x3, 4x4, 5x5 6x6, 10x10, 20x20, 30x30, and 40x40 cm²
• Two beams models created with the two data sets and compare the two outputs
Section B – 1DS Method-Depth Profiles

- Standard method for PDD collection.
- Scan the chamber from deep depth to surface.
- Fixed SSD.

- **Post hoc**: convert saved electrometer data to profiles using Python
- Utilized 1D gamma for all profiles.
- Depth profiles data was normalized to maximum dose.
- Lateral profiles were centered and normalized to CAX.
- For calculated comparisons a 3D gamma was used to compare calculated volumes normalized to the max dose in the TPS.

\[ \gamma(r_m) = \min\{\Gamma(r_m, r_c)\} \forall \{r_c\}, \]

where

\[ \Gamma(r_m, r_c) = \sqrt{\frac{r^2(r_m, r_c)}{\Delta d^2_M} + \frac{\delta^2(r_m, r_c)}{\Delta D^2_M}}, \]

Section B – Results - Measured PDDs

1D tank reproduces 3D tank PDDs
Not a surprise

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Table 1: 1D gamma comparison of 1D PDD data to 3D central axis depth profile data (T 1%/1 mm).

<table>
<thead>
<tr>
<th>Field size (cm²)</th>
<th>1DS vs 3DS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1% &lt; 1</td>
</tr>
<tr>
<td>3 × 3</td>
<td>100</td>
</tr>
<tr>
<td>4 × 4</td>
<td>100</td>
</tr>
<tr>
<td>6 × 6</td>
<td>100</td>
</tr>
<tr>
<td>8 × 8</td>
<td>100</td>
</tr>
<tr>
<td>10 × 10</td>
<td>100</td>
</tr>
<tr>
<td>20 × 20</td>
<td>100</td>
</tr>
<tr>
<td>30 × 30</td>
<td>99.9</td>
</tr>
<tr>
<td>40 × 40</td>
<td>100</td>
</tr>
<tr>
<td>All field sizes</td>
<td>99.9</td>
</tr>
</tbody>
</table>

Profiles generally with 2%/2mm
• All within 3%/3mm
• Within 1%/1mm for field sizes < 20x20
## Section B – Results-Beam Models

### Table 3

3D gamma comparison (1%/1 mm 5% threshold) of dose distributions calculated from the BM$_{1DS}$ and BM$_{3DS}$ beam models.

<table>
<thead>
<tr>
<th>Field size $X \times Y$ (cm$^2$)</th>
<th>(I$: 1%/1$ mm)</th>
<th># of data points</th>
<th>% points $I &lt; 1$</th>
<th>Mean $I$</th>
<th>Max $I$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2 \times 2$</td>
<td></td>
<td>$3.95 \times 10^4$</td>
<td>100.00</td>
<td>0.241</td>
<td>0.706</td>
</tr>
<tr>
<td>$3 \times 30$</td>
<td></td>
<td>$8.25 \times 10^5$</td>
<td>99.99</td>
<td>0.333</td>
<td>1.363</td>
</tr>
<tr>
<td>$4 \times 16$</td>
<td></td>
<td>$5.77 \times 10^5$</td>
<td>99.99</td>
<td>0.318</td>
<td>1.145</td>
</tr>
<tr>
<td>$5 \times 5$</td>
<td></td>
<td>$2.27 \times 10^5$</td>
<td>100.00</td>
<td>0.299</td>
<td>0.908</td>
</tr>
<tr>
<td>$5 \times 10$</td>
<td></td>
<td>$4.47 \times 10^5$</td>
<td>100.00</td>
<td>0.330</td>
<td>0.889</td>
</tr>
<tr>
<td>$7 \times 7$</td>
<td></td>
<td>$4.36 \times 10^5$</td>
<td>100.00</td>
<td>0.322</td>
<td>0.917</td>
</tr>
<tr>
<td>$10 \times 5$</td>
<td></td>
<td>$4.47 \times 10^5$</td>
<td>100.00</td>
<td>0.319</td>
<td>0.787</td>
</tr>
<tr>
<td>$10 \times 10$</td>
<td></td>
<td>$8.77 \times 10^5$</td>
<td>99.99</td>
<td>0.354</td>
<td>1.044</td>
</tr>
<tr>
<td>$15 \times 15$</td>
<td></td>
<td>$1.95 \times 10^6$</td>
<td>99.99</td>
<td>0.376</td>
<td>1.123</td>
</tr>
<tr>
<td>$16 \times 4$</td>
<td></td>
<td>$5.76 \times 10^5$</td>
<td>100.00</td>
<td>0.327</td>
<td>0.937</td>
</tr>
<tr>
<td>$25 \times 25$</td>
<td></td>
<td>$5.36 \times 10^6$</td>
<td>99.20</td>
<td>0.522</td>
<td>1.215</td>
</tr>
<tr>
<td>$30 \times 3$</td>
<td></td>
<td>$8.17 \times 10^5$</td>
<td>99.99</td>
<td>0.335</td>
<td>1.109</td>
</tr>
<tr>
<td>$35 \times 35$</td>
<td></td>
<td>$1.05 \times 10^7$</td>
<td>99.41</td>
<td>0.570</td>
<td>1.356</td>
</tr>
<tr>
<td>Dynamic chair (12 $\times$ 20)$^a$</td>
<td></td>
<td>$1.20 \times 10^6$</td>
<td>99.97</td>
<td>0.401</td>
<td>1.171</td>
</tr>
<tr>
<td>Pyramid field (12 $\times$ 25)$^a$</td>
<td></td>
<td>$6.64 \times 10^5$</td>
<td>99.66</td>
<td>0.482</td>
<td>1.254</td>
</tr>
<tr>
<td>All fields</td>
<td></td>
<td>$2.49 \times 10^7$</td>
<td>99.57</td>
<td>0.483</td>
<td>1.363</td>
</tr>
</tbody>
</table>

$^a$Dynamic MLC fields.

- Resultant calculation comparisons for numerous field sizes
- 1%/1mm gamma normalized to max dose

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Section B – Conclusions

- PDDs within 1%/1mm
- Small fields agree with 1%/1mm criterion
- Large fields generally within 2%/2mm with small percentage exceeding gamma value of 1
- Resultant beam models generally within 1%/1mm

N.C. Knutson et al., JACMP. (2018).
Section C – Lesions learned and work to do

• Sections A & B: showed a very strong proof of principal
• But still work to be done to bring all this together and optimize
  – Why were a few points > 2%/2mm?
  – Characterize the uncertainties associated with the measurement and minimize them where possible
  – Can we improve the workflow for increased efficiency and be more user friendly
  – Can we simulate the 1DS & 3DS using analytical calculation to see the expected difference between the two due to the different geometries
  – Could we calculate a correction for phantom size to allow for a more direct comparison between the two with increased accuracy
  – Can we do this on a non TrueBeam linac with no developer mode.
Section C – Halcyon Research Linac

- Varian Halcyon pre-clinical research linac:
  - Pre-clinical system installed at Wash U
  - No time for the details but the answer to the questions on the previous slide is yes (ePoster Discussion yesterday has these)
Section C – 1DS Best Practices

- Minimize cable in the beam and keep constant during scan
  - Check with Ppol at deepest depth largest Field Size
- Scan speed X electrometer rate ideally ~ 0.5 mm
- Electrometer noise can be high if collection rate < 200 ms
- Scan speed 5 mm/s is too fast due to water motion
- Accurate setup with MV imager is very helpful (Halcyon)
- Differences for large fields at deep depths can be predicted and corrected
Improved 1DS Scanning Workflow - Halcyon Example

System
- Halcyon
- Water Tank/PCE Software Python EXE

Events
- Load XML
- Initiate Electrometer Measurement, Data Logging, and Python Data Viewer
- Set initial Tank Depth
- Change Depth At Each Pause In Beam Programed in XML
- Stop Measurement and Data Logging
- Beam On XML runs with programmed pauses to change depth
- Beam Off

Department of Radiation Oncology

Water Tank/PCE Software Python EXE
Initiate Electrometer Measurement, Data Logging, and Python Data Viewer
Set initial Tank Depth
Change Depth At Each Pause In Beam Programed in XML
Stop Measurement and Data Logging
Section C – Results 3DS & TPS

• 3DS_Measured vs 3DS_Simulated all within 2%/2mm
Section C – 1DS Simulation Methods

• 1D Tank (1DS_Simulated)
  – Profile created by calculating multiple plans to simulate the tank motion and recording dose to central voxels of phantom
  – 1mm spacing in penumbra
  – 5mm spacing in-field and in umbra
Section C – Results 1DS & TPS

- 1DS_Measured vs 1DS_Simulated all within 1.5%/1.5mm
Section C – Results Cross-modality Measurements

• 1DS_Measured vs 3DS_Measured all within 3%/3mm
Section C – Results Cross-modality Measurements

• Pretty similar to our previous result.
• Is this expected? Let’s calculate and find out.
Section C – Results Cross-modality Simulation

• 1DS_Simulated vs 3DS_Simulated all within 3%/3mm
• The measured differences between 1DS and 3DS look very similar to the calculated differences!
• Can we use this ratio as a phantom size correction?
In-field $CF_{fit}(r) = \frac{D_{1DS}}{D_{3DS}} = 1 + Ar^2$ Out-of-field $CF_{fit}(r) = \frac{D_{1DS}}{D_{3DS}} = Ar + B$
Section C – Results Post Correction

- 1DS_Measured_Corrected vs 3DS_Measured all within 1.5%/1.5mm
Conclusions

- 1DS Method shows promise
- Very portable
- Potentially less than 10% of 3D tank cost
- A great validation tool for annual QA or incidental QA.
- With TPS changes could be used for commissioning
- Potential for automation!
  - Hope you saw Dr. Y Hao’s talk Monday
Acknowledgements

• Thanks to all Co Authors, Co Workers, Teachers, Mentors, & Friends