Volumetric Modulated Arc Therapy

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Disclaimer

• Our VMAT work has been sponsored in part by Elekta.

Outline

David Shepard
• VMAT Basics and VMAT Plan Quality
• Commissioning a VMAT delivery system
• Commercial VMAT Solutions

Richard Popple
• VMAT Patient Specific Quality Assurance
• Advanced VMAT Techniques
• Starting a VMAT program
Are you using rotational IMRT in your clinic?

1. Yes 48%
2. No 52%

Rotational IMRT

Serial Tomotherapy
nomosSTAT (Best nomos)

Helical Tomotherapy
HI-Art (Tomotherapy, Inc)

Intensity Modulated Arc Therapy (IMAT)
RapidArc (Varian)
VMAT (Elekta)

If yes, what rotational IMRT approach are you using?

1. Varian RapidArc 25%
2. Eleka VMAT 25%
3. Helical Tomotherapy (Accuray) 26%
4. Serial Tomotherapy (Best NOMOS) 25%
VMAT Basics

- An arced-based approach to IMRT that can be delivered on a conventional linear accelerator with a conventional MLC.
- During each arc, the leaves of the MLC move continuously as the gantry rotates.
- The degree of intensity modulation is related to the number of beam shapes per arc and the number of arcs.
Arc Based IMRT - The First Decade

- **Serial tomotherapy**: NOMOS Peacock binary MLC and Corvus planning system served as first commercial IMRT solution.
- **Helical tomotherapy**: Tomotherapy Inc. introduced the Hi-Art system with the first patients treated in 2002 at the University of Wisconsin.
- **IMAT/VMAT**: Largely withered on the vine:
  1. Linac manufacturers did not have control systems capable of delivering IMAT.
  2. No robust inverse planning tools for IMAT.

Efforts to Revive Interest in IMAT

**University of Maryland School of Medicine**

- In 2000, we conducted a phase 1 clinical trial under an IRB protocol where IMAT plans were delivered to 50 patients.
- Key limitations were: (1) constant dose rate during rotation; and (2) no inverse planning.
Example 1 - Prostate

- Two sets of bilateral arcs.
- 1 set of arcs matches BEV of prostate.
- 1 matches BEV of prostate - rectum.
- Weights of arcs are optimized.

Example 2: Spinal Ependymoma

5 arc treatment
**IMAT - Initial Experience**

- 50 patients were treated in this trial: central nervous system (17 patients), head and neck (25 patients) and prostate (8 patients).
- Average treatment time was 7.5 minutes.
- Demonstrated IMAT can be delivered safely and accurately on a conventional linac.

**IMAT - Forward Planning**

- Dosimetrists used an iterative trial-and-error approach to determine starting and stopping angles, the beam shapes, and beam weights.
- Planning was time consuming.
- No guarantee that a plan was close to optimal.
- A robust inverse planning solution is required to take full advantage of the capabilities of IMRT.
- IMAT inverse planning, however, proved to be highly complicated due to the need to account for the interconnectedness of the beam shapes within each arc.

**Inverse Planning for IMAT**

- A robust inverse planning solution is required to take full advantage of the capabilities of IMRT.
- IMAT inverse planning, however, proved to be highly complicated due to the need to account for the interconnectedness of the beam shapes within each arc.
Interconnectedness of Beam Shapes

- Leaf motion between adjacent angles is limited by leaf travel speed and gantry rotation speed.
- For example, if the gantry speed is 10 degree/sec and the leaf travel speed is 3 cm/sec, then the maximum leaf travel distance between two adjacent angles is 3 cm.

IMAT - Inverse Planning

- We developed two IMAT inverse planning approaches:
     - Directly optimizes aperture shapes and weights throughout each arc.
     - Converts optimized fixed field IMRT plan into IMAT plan

VMAT Commercial Introduction

- In 2008, Elekta and Varian introduced control systems that are capable of delivering IMAT.
- Key innovation was that the dose rate, gantry speed, and MLC leaf positions could be changed dynamically during rotational beam delivery.
- The term VMAT was suggested by Karl Otto to differentiate single arc rotational IMRT.
New Study: VMAT vs. Tomotherapy

- Collaborative study between Swedish Cancer Institute and University of Virginia.
- 6 prostate, 6 head-and-neck, and 6 lung cases were selected for this study.
- Fixed field IMRT, VMAT, and Tomotherapy were compared in terms of plan quality, delivery time, and delivery accuracy.
Head & Neck Case #1

- Two targets with prescription levels of 5040 and 4500 cGy

Head & Neck Case #1

- Solid lines: VMAT
- Dashed lines: Tomotherapy

H&N Example #2

- Solid = VMAT
- Dashed = Tomotherapy
### Table 1: Lung cases (6 patients). Plan comparison between fixed-field IMRT, VMAT and HT

<table>
<thead>
<tr>
<th></th>
<th>IMRT</th>
<th>VMAT</th>
<th>HT</th>
<th>Wilcoxon matched-pair signed rank test P</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PTV</strong> (%)</td>
<td>96.5</td>
<td>96.5</td>
<td>98.0</td>
<td>0.575</td>
</tr>
<tr>
<td><strong>SD (Gy)</strong></td>
<td>1.4</td>
<td>1.4</td>
<td>1.5</td>
<td>0.438</td>
</tr>
<tr>
<td><strong>Mean dose (Gy)</strong></td>
<td>15.3</td>
<td>15.2</td>
<td>15.8</td>
<td>0.625</td>
</tr>
<tr>
<td><strong>Cord</strong></td>
<td>19.8</td>
<td>19.9</td>
<td>20.0</td>
<td>0.084</td>
</tr>
<tr>
<td><strong>Total body</strong></td>
<td>3.9</td>
<td>3.9</td>
<td>4.2</td>
<td>0.563</td>
</tr>
<tr>
<td><strong>MT per fraction</strong></td>
<td>559</td>
<td>574</td>
<td>564</td>
<td>-</td>
</tr>
<tr>
<td><strong>Delivery time</strong></td>
<td>31.5</td>
<td>34.2</td>
<td>33.4</td>
<td>0.004</td>
</tr>
<tr>
<td><strong>QA passing rate (%)</strong></td>
<td>99.3</td>
<td>99.0</td>
<td>99.6</td>
<td>-</td>
</tr>
</tbody>
</table>

**Abbreviations:** PTV = planning target volume; SD = volume of PTV receiving 50% of prescription; SD = standard deviation of PTV dose; Mean = volume of structures receiving >2 Gy. A 3 passing rate was obtained using gamma analysis with 3 mm/3% limit. Values expressed as mean (range). The Wilcoxon matched-pair signed rank test is listed for VMAT vs HT.

### Table 2: Prostate cases of patients. Plan comparison between fixed-field IMRT, VMAT and HT

<table>
<thead>
<tr>
<th></th>
<th>IMRT</th>
<th>VMAT</th>
<th>HT</th>
<th>Wilcoxon matched-pair signed rank test P</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PTV</strong> (%)</td>
<td>95.0</td>
<td>95.0</td>
<td>94.0</td>
<td>0.063</td>
</tr>
<tr>
<td><strong>SD (Gy)</strong></td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>0.688</td>
</tr>
<tr>
<td><strong>Rectum</strong></td>
<td>56.7</td>
<td>56.5</td>
<td>57.3</td>
<td>0.156</td>
</tr>
<tr>
<td><strong>D150 (Gy)</strong></td>
<td>25.7</td>
<td>24.3</td>
<td>24.6</td>
<td>0.098</td>
</tr>
<tr>
<td><strong>D200 (Gy)</strong></td>
<td>40.0</td>
<td>37.8</td>
<td>40.2</td>
<td>0.000</td>
</tr>
<tr>
<td><strong>Bladder</strong></td>
<td>38.0</td>
<td>37.4</td>
<td>38.6</td>
<td>0.438</td>
</tr>
<tr>
<td><strong>D100 (Gy)</strong></td>
<td>20.1</td>
<td>19.3</td>
<td>20.7</td>
<td>0.219</td>
</tr>
<tr>
<td><strong>Prostate</strong></td>
<td>25.5</td>
<td>25.1</td>
<td>25.9</td>
<td>0.000</td>
</tr>
<tr>
<td><strong>D150 (Gy)</strong></td>
<td>16.5</td>
<td>16.3</td>
<td>17.2</td>
<td>0.000</td>
</tr>
<tr>
<td><strong>D200 (Gy)</strong></td>
<td>36.5</td>
<td>37.4</td>
<td>38.6</td>
<td>0.438</td>
</tr>
<tr>
<td><strong>Total body</strong></td>
<td>5.6</td>
<td>5.3</td>
<td>5.9</td>
<td>0.333</td>
</tr>
<tr>
<td><strong>MT per fraction</strong></td>
<td>609</td>
<td>617</td>
<td>621</td>
<td>-</td>
</tr>
<tr>
<td><strong>Delivery time</strong></td>
<td>36.1</td>
<td>36.9</td>
<td>37.6</td>
<td>0.081</td>
</tr>
<tr>
<td><strong>QA passing rate (%)</strong></td>
<td>98.5</td>
<td>98.0</td>
<td>98.9</td>
<td>-</td>
</tr>
</tbody>
</table>

**Abbreviations:** (Dx = minimal dose to x% of structure, Dxy = prescription to PTV other abbreviations as in Table 1). Values expressed as mean (range). The Wilcoxon matched-pair signed rank test is listed for VMAT vs HT.

### Table 3: Brain cases (4 patients). Plan comparison between fixed-field IMRT, VMAT and HT

<table>
<thead>
<tr>
<th></th>
<th>IMRT</th>
<th>VMAT</th>
<th>HT</th>
<th>Wilcoxon matched-pair signed rank test P</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PTV</strong> (%)</td>
<td>96.8</td>
<td>96.0</td>
<td>96.9</td>
<td>0.622</td>
</tr>
<tr>
<td><strong>SD (Gy)</strong></td>
<td>1.8</td>
<td>1.4</td>
<td>1.5</td>
<td>0.641</td>
</tr>
<tr>
<td><strong>Spinal cord</strong></td>
<td>26.2</td>
<td>26.1</td>
<td>25.8</td>
<td>0.000</td>
</tr>
<tr>
<td><strong>D150 (Gy)</strong></td>
<td>13.5</td>
<td>13.2</td>
<td>13.9</td>
<td>0.037</td>
</tr>
<tr>
<td><strong>Brain</strong></td>
<td>4.8</td>
<td>4.5</td>
<td>4.9</td>
<td>0.013</td>
</tr>
<tr>
<td><strong>D150 (Gy)</strong></td>
<td>19.0</td>
<td>18.0</td>
<td>20.1</td>
<td>0.485</td>
</tr>
<tr>
<td><strong>D200 (Gy)</strong></td>
<td>9.0</td>
<td>8.0</td>
<td>10.0</td>
<td>0.001</td>
</tr>
<tr>
<td><strong>Total body</strong></td>
<td>5.8</td>
<td>5.8</td>
<td>6.0</td>
<td>0.001</td>
</tr>
<tr>
<td><strong>MT per fraction</strong></td>
<td>777</td>
<td>777</td>
<td>773</td>
<td>-</td>
</tr>
<tr>
<td><strong>Delivery time</strong></td>
<td>36.9</td>
<td>37.3</td>
<td>37.6</td>
<td>0.081</td>
</tr>
<tr>
<td><strong>QA passing rate (%)</strong></td>
<td>97.7</td>
<td>98.0</td>
<td>98.3</td>
<td>-</td>
</tr>
</tbody>
</table>

Values expressed as mean (range). The Wilcoxon matched-pair signed rank test is listed for VMAT vs HT.
Tomotherapy Developments

- With the current HiArt system, the jaw width and the couch speed are set to constant values for each plan.
- A new option with dynamic jaw motion and dynamic couch motion will be available soon that should improve the efficiency of delivery and the quality of the plans.

- DJ/DC couch plans were developed for 10 nasopharyngeal patients.
- As compared with a 2.5 cm fixed jaw setting, the mean integral dose was reduced by 6.3% and the average delivery time was reduced by 66%.

VMAT Commissioning
VMAT Commissioning

- VMAT commissioning and routine quality assurance builds upon your existing IMRT beam models and fixed-field IMRT QA program.
- During VMAT delivery, the MLC leaves are moving, the gantry is rotating, and the dose rate is changing.
- The dynamic nature of the delivery must be accounted for in the quality assurance.

VMAT Commissioning

- No AAPM guidance document has been produced and there is not a general consensus on the tests that must be performed as part of the commissioning of VMAT.
- The most commonly referenced document is a paper from Ling and colleagues from Memorial Sloan Kettering.
**Test 1: Accuracy of DMLC positioning during VMAT**

Picket fence pattern is delivered with rotating gantry. In this case a film was mounted on the blocking tray. Results compared to picket fence delivered in stationary mode.

Courtesy Richard Popple

**Test 2: Ability to vary dose rate and gantry speed during VMAT**

Each strip on the film is irradiated to the same MU using varying combinations of dose rate and gantry rotation speed.

Courtesy Richard Popple

**Test 3: Ability to accurately vary MLC speed during VMAT**

Different parts of the film were exposed to the same dose using the DMLC sliding window technique, combining different leaf speeds with different dose rates to achieve a designed dose pattern.

Courtesy Richard Popple
End-to-end test: Prostate - coronal

4.9% of pixels have $\gamma > 1$ (3%/3 mm)

Courtesy Richard Popple

Interrupted delivery

J.L. Bedford and A.P. Warrington, Commissioning of Volumetric Modulated Arc Therapy (VMAT), JROBP 73 (2) pp. 537-545 (2009)
TPS - Commissioning

- Beams that are well modelled for fixed-field may not need to be re-modelled for VMAT.
- It is critical, however, to verify the accuracy of your beam models through extensive measurements.
VMAT - Commercial TPS Solutions

- Varian → Eclipse RapidArc
- Philips → Pinnacle SmartArc
- Elekta → Monaco VMAT
- Nucletron → Oncentra MasterPlan VMAT
- Siemens/Prowess → Prowess Panther
- RaySearch → RayStation

What TPS are you using for VMAT?

1. Varian Eclipse 20%
2. Philips Pinnacle 21%
3. Elekta Monaco 19%
4. Nucletron Oncentra 20%
5. Other 20%

VMAT Planning Process

- The VMAT planning process is very similar to that for fixed-field IMRT.
- Additional VMAT-specific parameters may need to be selected. For example, in Pinnacle:
  - Number of arcs
  - Allowable delivery time per arc
  - Maximum leaf speed
1 arc vs. 2 arcs

Delivery time: 1 arc = 124 sec, 2 arcs = 181 sec

Maximum delivery time per arc

Delivery time

Thin solid: 60 sec/arc
Thick dashed: 90 sec/arc
Med. solid: 180 sec/arc
Med. dashed: 240 sec/arc
### Delivery time

<table>
<thead>
<tr>
<th>Maximum time (sec/arc)</th>
<th>Estimated time (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>140</td>
</tr>
<tr>
<td>90</td>
<td>181</td>
</tr>
<tr>
<td>180</td>
<td>325</td>
</tr>
<tr>
<td>240</td>
<td>356</td>
</tr>
</tbody>
</table>

### Leaf motion constraint

- Thin solid: 1 mm/deg
- Thin dashed: 3 mm/deg
- Med. dashed: 5 mm/deg
- Med. solid: 10 mm/deg

### Leaf motion

[Graph showing leaf motion with different thickness and speed constraints]
VMAT Planning Parameters
SmartArc Experience

• 1 arc is sufficient for simple cases such as prostate, but 2 arcs are needed for more complex cases such as H&N.
• We typically set a delivery time of 90sec/arc.
• We generally restrict the leaf motion to be 3mm/degree of gantry rotation for prostate cases and 4 or 5mm/degree for H&N cases.

Summary

• Since 2008, VMAT has become a widely adopted IMRT delivery technique.
• VMAT combines highly efficient delivery (< 2 minutes per arc) with highly conformal dose distributions.
• VMAT is a complex delivery technique requiring a thorough commissioning process.

Acknowledgments

• Daliang Cao
• Vivek Mehta
• Min Rao
• Fan Chen
• Richard Popple
• Ke Sheng
Swedish Medical Center

Picket fence test with simulated error

Gap 1.5 mm instead of 1 mm
0.5 mm offset

Courtesy Richard Popple
IMRT Delivery Techniques

- Compensators
- Step-and-shoot
- Sliding Window
- Tomotherapy
- IMAT
Why rotational delivery?

1 Beam    5 Beams    11 Beams

17 Beams    25 Beams    51 Beams

C-shaped Target Simulations

<table>
<thead>
<tr>
<th># Angles</th>
<th>Obj. Func. Value</th>
<th>Std. Dev. in target dose</th>
<th>d95</th>
<th>Mean dose to RAR</th>
<th>Total integral dose</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>0.685</td>
<td>0.124</td>
<td>0.747</td>
<td>0.488</td>
<td>2732.5</td>
</tr>
<tr>
<td>5</td>
<td>0.318</td>
<td>0.090</td>
<td>0.614</td>
<td>0.215</td>
<td>2563.3</td>
</tr>
<tr>
<td>7</td>
<td>0.242</td>
<td>0.064</td>
<td>0.667</td>
<td>0.206</td>
<td>2596.8</td>
</tr>
<tr>
<td>9</td>
<td>0.222</td>
<td>0.064</td>
<td>0.655</td>
<td>0.192</td>
<td>2508.3</td>
</tr>
<tr>
<td>11</td>
<td>0.202</td>
<td>0.058</td>
<td>0.979</td>
<td>0.186</td>
<td>2570.2</td>
</tr>
<tr>
<td>15</td>
<td>0.187</td>
<td>0.053</td>
<td>0.908</td>
<td>0.180</td>
<td>2542.9</td>
</tr>
<tr>
<td>21</td>
<td>0.176</td>
<td>0.049</td>
<td>0.912</td>
<td>0.171</td>
<td>2546.1</td>
</tr>
<tr>
<td>33</td>
<td>0.151</td>
<td>0.038</td>
<td>0.933</td>
<td>0.155</td>
<td>2543.5</td>
</tr>
</tbody>
</table>

Courtesy of Accuray Inc.