The Radiation Planning Assistant (RPA) – algorithms and workflow

Laurence Court PhD
University of Texas
MD Anderson Cancer Center

- Automated treatment planning (Radiation Planning Assistant)
- Automated treatment planning for cervical cancer
- Automated treatment planning for head/neck cancer patients
- Quality Assurance
Conflicts of Interest

• Funded by NCI UH2 CA202665
• Equipment and technical support provided by:
  – Varian Medical Systems
  – Mobius Medical Systems
• Other, not related projects funded by NCI, CPRIT, Varian, Elekta
MD Anderson Cancer Center, Houston
- Laurence Court, PhD - PI
- Beth Beadle, MD/PhD - PI
- Joy Zhang, PhD – algorithms and integration
- Rachel McCarroll – H&N algorithms
- Kelly Kisling, MS – GYN, breast algorithms
- Jinzhong Yang, PhD - atlas segmentation
- Peter Balter, PhD – radiation physics
- Ryan Williamson, MS – software tools
- Ann Klopp, MD/PhD – GYN planning
- Anuja Jhingram, MD – GYN planning
- David Followill, PhD – audits/deployment
- James Kanke and dosimetry team

Primary Global Partners
- Stellenbosch University, Cape Town
  - Hannah Simonds, MD
  - Monique Du Toit – physics
  - Chris Trauernicht - physics
  - Vikash Sewram, PhD
- Santo Tomas University, Manila
  - Michael Mejia, MD
  - Maureen Bojador, MS (physics)
  - Teresa Sy Ortin, MD

Global testing sites
- University of Cape Town
  - Hester Berger, PhD
  - Jeannette Parkes, MD
- University of the Free State
  - William Rae, PhD
  - William Shaw, PhD
  - Alicia Sherriff, MD

Commercial Partners
- Varian Medical Systems (providing 10 Eclipse boxes for UH2 phase + API technical support)
- Mobius Medical Systems (providing 10 Mobius boxes for UH2 phase)

- Additional centers TBD
Workflow (user’s perspective)

1. Physician’s Plan Order
2. CT simulation
3. Autoplanner
   - 30 min
4. Radiotherapy treatment plan
5. Documentation
MD treatment planning order

CT or 2D simulation

Primary Planning
- CT Table Removal
- Body Contour Definition
- Marked Isocenter Detection
- Atlas-Based Contouring
- Create fields
- Optimize dose
- Calculate dose

Secondary Planning
- CT Table Removal
- Body Contour Definition
- Marked Isocenter Detection
- Atlas-Based Contouring
- Create fields
- Optimize dose
- Calculate dose

Do primary and secondary methods agree?

Plan Documentation

Transfer Plan to Record and Verify

Manual planning

MD approves plan?

Key
- Radiation oncologist
- Medical physicist
- Technologist

Primary dose: Eclipse
Secondary dose: Mobius
Option 1: MDACC Cluster Computing
- RPA Engine
- Eclipse Boxes
- Mobius Boxes

Option 2: Local Computing
- RPA Engine
- Eclipse Box
- Mobius Box

Version 3 Architecture
PRE-PROCESSING
CT Table Removal

Method 1: *Peak Detection*
By finding peaks slice by slice at sum projection signal along lateral direction.

Method 2: *Line Detection*
By detecting Hough lines at maximum intensity projection image.

- Average difference between two approaches: $2.6 \pm 1.6\text{mm}$ (max: $4.9\text{mm}$)
Body Contour

**Method 1: Active Contour**
By contracting initial active contour to the body edge.

**Method 2: Intensity Thresholding**
By thresholding CT image into binary mask.

- Average agreement = 0.6mm, Average max: 7.6mm
Auto Body Contour Check

Instructions
Two independent methods were used to detect body contour. The difference between them are compared to decide the result of primary method is passed or failed.

Result
<table>
<thead>
<tr>
<th>Primary Method</th>
<th>Secondary Method</th>
<th>Pass</th>
</tr>
</thead>
<tbody>
<tr>
<td>By Threshold</td>
<td>By ActiveContour</td>
<td>✓</td>
</tr>
</tbody>
</table>

Metrics
<table>
<thead>
<tr>
<th>Metric</th>
<th>Value</th>
<th>Criteria</th>
<th>Pass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Distance Difference</td>
<td>0.28 cm</td>
<td>Pass: &lt;= 0.5 cm. Fail: &gt; 0.5 cm.</td>
<td>✓</td>
</tr>
<tr>
<td>Average Distance Difference</td>
<td>0.046 cm</td>
<td>Pass: &lt;= 0.5 cm. Fail: &gt; 0.5 cm.</td>
<td>✓</td>
</tr>
<tr>
<td>Dice Index</td>
<td>1</td>
<td>Pass: &gt;= 0.97. Fail: &lt; 0.97.</td>
<td>✓</td>
</tr>
</tbody>
</table>

Images

Primary Body Contour

Secondary Body Contour
Marked Isocenter Detection

Method 1: Body Ring Method
By searching BB candidates in the body ring domain.

Method 2: BB Topology Method
By searching BBs that constitute the triangle topology.

• Average difference between two approaches: 0.4 ± 0.8mm (max: 3.0mm)
CERVICAL CANCER 4-FIELD BOX
For cervical cancer treatment: Determine the jaws and blocks

1st Algorithm
“3D Method”

Input: Patient CT
And Isocenter

2nd Algorithm
“2D Method”

Output: treatment fields

Inter-compare

Output: treatment fields
Create Treatment Beams (3D method)

INPUT: Patient CT and Isocenter

OUTPUT: 4 treatment fields
Retrospective Testing

- Total 500+ patients
- Reviewed by physicians from MD Anderson (USA) and Stellenbosch University (South Africa)
- Most recent version
  - n = 150
  - 89% Approval Rate
  - #1 cause of rejection: superior border
  - Otherwise, 99% of plans are acceptable
Clinical Version Deployed at MD Anderson

Auto-planned fields After physician edits

Anterior

Right Lateral

20 patients so far
~10 minutes per patient
Beam weight optimization

• Goal: minimize dose heterogeneity in the treatment volume
• Results:
  – Average hotspot reduction of 1.7%
  – No loss in coverage
Optimized vs. equal weighting

Large reduction in max dose for patients with high max doses (≥107%)
  - 3.5% on average

# of patients with dose ≥110% was reduced from 16 to 1
Use of secondary algorithm for QA

**“3D Method” algorithm**
- Segment bony anatomy using multi-atlas deformable registration
- Project these 3D segmentations into the 2D plane of the BEV
- On the projections, identify landmarks (e.g. inferior edge of the obturator foramen)
- Define the treatment field borders based on these landmarks
- **Output**: 4-field box treatment fields

**“2D Method” algorithm**
- Create DRRs at each beam angle from the patient CT
- Deform an atlas of DRRs to the patient DRRs. The atlas DRRs have corresponding treatment fields.
- Apply deformations to the treatment fields to obtain deformed blocks
- Define the treatment field borders by least-squares fitting to the set of deformed blocks
- **Output**: 4-field box treatment fields
Comparison of primary and verification algorithms (39 patients)

<table>
<thead>
<tr>
<th>Physician Rating</th>
<th>3D Method</th>
<th>2D Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Per Protocol</td>
<td>62%</td>
<td>17%</td>
</tr>
<tr>
<td>Acceptable Variation</td>
<td>34%</td>
<td>62%</td>
</tr>
<tr>
<td>Unacceptable Deviation</td>
<td>4%</td>
<td>21%</td>
</tr>
</tbody>
</table>

a.) 3D Method algorithm

b.) 2D Method algorithm

Anterior Right lateral
Status of cervical cancer autoplanning

- 3D algorithm deployed to MDACC clinical use
- Workflow designed and integrated
- Secondary (verification) algorithms developed
- Still working on superior border issue
- Next: Further testing using local data at Stellenbosch, Santo Tomas, and others
- Beth Beadle to present some sample plans for feedback.......
HEAD/NECK VMAT
Head and neck treatments

- Range of complexities in treatments
  - VMAT or IMRT
  - Opposed laterals / off-cord cone-downs
  - Complex conformal plans
- Starting with VMAT (IMRT)
  - Auto-contouring normal tissue
  - Auto-contouring low-risk CTV
  - Manual contouring of GTV
  - RapidPlan (Eclipse)
Workflow overview (user’s perspective)

1. Add GTV
2. Review / edit contours

Physician’s Plan Order

CT

Autoplanner

Radiotherapy treatment plan

QA report
The search for a good contouring algorithm

Eight Contouring algorithms options evaluated:

1. Eclipse Smart Detection (Heuristic)
2. Eclipse Smart Segmentation (DIR)
   a) Single Atlas
   b) Fused Atlas
3. Varian Deeds (DIR)
   a) Varian Atlas
   Two fusion techniques:
   – Majority voting
   – STAPLE fusion
   b) MDACC Atlas
4. In-house multi-atlas technique - MACS (DIR) [STAPLE fusion]
   a) MDACC Atlas
   b) Original Varian Atlas
Validation - MACS

- MACS – developed in-house
- Normal tissues
- Scored by MDACC radiation oncologist

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>Physician Rating</th>
<th>Dice</th>
<th>MSD (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brain</td>
<td>128</td>
<td>4.04 ± 0.48</td>
<td>0.98 ± 0.01</td>
<td>1.03 ± 0.31</td>
</tr>
<tr>
<td>Brainstem</td>
<td>128</td>
<td>4.14 ± 0.48</td>
<td>0.81 ± 0.12</td>
<td>2.31 ± 1.5</td>
</tr>
<tr>
<td>Cochlea</td>
<td>256</td>
<td>3.91 ± 0.81</td>
<td>0.47 ± 0.16</td>
<td>1.75 ± 0.71</td>
</tr>
<tr>
<td>Eye</td>
<td>256</td>
<td>4.13 ± 0.58</td>
<td>0.85 ± 0.06</td>
<td>1.33 ± 0.45</td>
</tr>
<tr>
<td>Lung</td>
<td>123</td>
<td>3.95 ± 0.49</td>
<td>0.48 ± 0.12</td>
<td>21.88 ± 10.65</td>
</tr>
<tr>
<td>Mandible</td>
<td>128</td>
<td>4.27 ± 0.54</td>
<td>0.84 ± 0.07</td>
<td>1.89 ± 1.55</td>
</tr>
<tr>
<td>Parotid</td>
<td>255</td>
<td>4.33 ± 0.66</td>
<td>0.78 ± 0.07</td>
<td>2.39 ± 0.8</td>
</tr>
<tr>
<td>SpinalCord</td>
<td>128</td>
<td>4.94 ± 0.24</td>
<td>0.71 ± 0.13</td>
<td>4.77 ± 6.13</td>
</tr>
<tr>
<td>Lung Modified</td>
<td>128</td>
<td></td>
<td>0.93 ± 0.04</td>
<td>2.05 ± 1.24</td>
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<tr>
<td>Spinal Cord Modified</td>
<td>128</td>
<td></td>
<td>0.81 ± 0.06</td>
<td>1.16 ± 0.4</td>
</tr>
</tbody>
</table>
## Validation - MACS

- MACS – developed in-house
- 1 MDACC radiation oncologist
- 5 outside (international) physicians
- Evaluated 10 patients

<table>
<thead>
<tr>
<th></th>
<th>Physician 1</th>
<th>Physicians 2-6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brain</td>
<td>4.7 ± 0.48</td>
<td>3.51 ± 0.23</td>
</tr>
<tr>
<td>Brainstem</td>
<td>3.4 ± 0.52</td>
<td>3.08 ± 0.25</td>
</tr>
<tr>
<td>Cochlea</td>
<td>3.45 ± 0.60</td>
<td>4.03 ± 0.16</td>
</tr>
<tr>
<td>Eye</td>
<td>3.7 ± 0.66</td>
<td>3.48 ± 0.47</td>
</tr>
<tr>
<td>Lung</td>
<td>4.1 ± 0.32</td>
<td>3.74 ± 0.31</td>
</tr>
<tr>
<td>Mandible</td>
<td>4.5 ± 0.53</td>
<td>3.8 ± 0.21</td>
</tr>
<tr>
<td>Parotid</td>
<td>3.85 ± 0.67</td>
<td>3.76 ± 0.24</td>
</tr>
<tr>
<td>SpinalCord</td>
<td>4.8 ± 0.42</td>
<td>3.52 ± 0.19</td>
</tr>
</tbody>
</table>
Deployed to clinical use at MDA
- 200+ patients since May 2016

Compare auto-contour pre- and post-edits

<table>
<thead>
<tr>
<th>Tissue</th>
<th>n</th>
<th>DSC</th>
<th>MDA (cm)</th>
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</thead>
<tbody>
<tr>
<td>Brain</td>
<td>10</td>
<td>0.98</td>
<td>0.07</td>
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<tr>
<td>Brainstem</td>
<td>10</td>
<td>0.88</td>
<td>0.14</td>
</tr>
<tr>
<td>Cochlea</td>
<td>18</td>
<td>0.65</td>
<td>0.09</td>
</tr>
<tr>
<td>Esophagus</td>
<td>10</td>
<td>0.62</td>
<td>0.30</td>
</tr>
<tr>
<td>Eye</td>
<td>20</td>
<td>0.87</td>
<td>0.11</td>
</tr>
<tr>
<td>Lung</td>
<td>10</td>
<td>0.92</td>
<td>0.25</td>
</tr>
<tr>
<td>Mandible</td>
<td>10</td>
<td>0.90</td>
<td>0.08</td>
</tr>
<tr>
<td>Parotid</td>
<td>19</td>
<td>0.84</td>
<td>0.18</td>
</tr>
<tr>
<td>Spinal Cord</td>
<td>10</td>
<td>0.81</td>
<td>0.14</td>
</tr>
</tbody>
</table>

DSC: Dice similarity coefficient

\[
DSC = 2 \frac{D \cap T}{|D| + |T|}
\]

>0.7 is considered acceptable
Auto-contouring of targets

- GTV – this will have to be done manually (for now......)
- Lymph nodes (left / right):
  - Levels II-IV
  - Levels IB-V
  - Levels IA-V
  - Retropharyngeal lymph node

<table>
<thead>
<tr>
<th>Node</th>
<th>N</th>
<th>Mean</th>
<th>Stdev</th>
</tr>
</thead>
<tbody>
<tr>
<td>Node_Rp, L</td>
<td>105</td>
<td>3.9</td>
<td>0.5</td>
</tr>
<tr>
<td>Node_Rp, R</td>
<td>105</td>
<td>3.9</td>
<td>0.5</td>
</tr>
<tr>
<td>Node_Ii-Iv, L</td>
<td>105</td>
<td>3.9</td>
<td>0.4</td>
</tr>
<tr>
<td>Node_Ii-Iv, R</td>
<td>105</td>
<td>3.9</td>
<td>0.4</td>
</tr>
<tr>
<td>Node_Ib-V, L</td>
<td>105</td>
<td>3.7</td>
<td>0.6</td>
</tr>
<tr>
<td>Node_Ib-V, R</td>
<td>105</td>
<td>3.8</td>
<td>0.5</td>
</tr>
<tr>
<td>Node_Ia-V, L</td>
<td>105</td>
<td>3.5</td>
<td>0.6</td>
</tr>
<tr>
<td>Node_Ia-V, R</td>
<td>105</td>
<td>3.6</td>
<td>0.5</td>
</tr>
</tbody>
</table>
Use Eclipse RapidPlan to predict DVHs

- mandible
- Right parotid
- Left parotid
- cord
- brain
And optimization constraints
Then optimize the plan

- (RapidPlan model required fine-tuning)
- Our current process is to simultaneously optimize 4 plans
  - Standard RPA constraints vs. additional weights for parotid, cord, brainstem
  - 2 vs. 4 arcs
- Final plan chosen automatically based on homogeneity etc. (TBD)
- (most vendors are working on multi-criteria optimization which will help...)
- Beth Beadle to present some sample plans for feedback......
Quality Assurance

- Basic QA of input data
  - Does the site match?
    - H/N vs. pelvis
  - Is the orientation correct?
  - CT scan length sufficient?
- Comparison of primary and secondary algorithms
  - Dose calculation: Eclipse vs. Mobius
  - Other independent algorithms for all other functions
    - Couch removal
    - Contours
    - Beam apertures

Simple image registration
Quality Assurance

• Comparison with population values
  – MU
  – Jaw positions
  – ........

• Data transfer checks (automatic)

• Manual plan checks
  – Physics
  – Radiation oncology

Total MU – population statistics

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>average</td>
<td>208</td>
</tr>
<tr>
<td>St. dev.</td>
<td>9</td>
</tr>
<tr>
<td>min</td>
<td>200</td>
</tr>
<tr>
<td>max</td>
<td>220</td>
</tr>
</tbody>
</table>

Jaw positions – population statistics

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td>average</td>
<td>16.8</td>
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<tr>
<td>St. dev.</td>
<td>0.9</td>
</tr>
<tr>
<td>min</td>
<td>15.7</td>
</tr>
<tr>
<td>max</td>
<td>18.2</td>
</tr>
</tbody>
</table>
How long does it take?

• Cervical cancer 4-field box: 21 minutes
• Head/neck VMAT (current, AAA dose calculation):
  – 2-arc plan: 46 minutes
  – 4-arc plan: 54 minutes
• Head/neck VMAT (future – distributed MACS and Acuros dose calculation):
  – 2-arc plan: 32 minutes
  – 4-arc plan: 36 minutes
Automation of treatment planning: Summary

• Automatic treatment planning may help reduce the planning burden, reducing staff shortages
• Fully automated cervical cancer 4-field box treatments –
  – Field aperture task already deployed at MDA
• Fully automated H/N IMRT/VMAT treatment planning – almost ready
  – Normal tissue contouring task already deployed at MDA
  – Fine-tuning plan quality
• Breast / chest wall – next
• (and also work on 2D plans, not mentioned today......)

Contact: lecourt@mdanderson.org