Modeling Expert Clinical Knowledge In Treatment Planning

Jackie Wu, PhD

Duke University Medical Center
Department of Radiation Oncology
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Motivation

- Extract human expert’s knowledge in treatment planning
- Model past planning experience
- Improve, or even automate the planning process

Hypothesis

- Past knowledge and experience has always be applied to new patient case
- Mathematical extraction and modeling such application of knowledge and experience enables systematic knowledge modeling

- Ultimately, to improve treatment planning efficiency, consistency and quality.
Treatment Planning Knowledge Modeling

- RT Knowledge System
- Target and OAR delineation
- Dose prescription
- Treatment plan/parameter generation
- Treatment plan evaluation/selection
- Treatment plan DVH and toxicity
Modeling Treatment Planning Knowledge

- Dose Based

Dose based knowledge planning:
1. Deformable registration -> CTref and CTnew anatomy registration
2. Wrap CTref dose to CTnew anatomy -> “goal” dose distribution
3. Solve fluence map -> known optimization parameter settings

Wu et al, PMB 2008.
Fluence map based knowledge planning:

1. Deform anatomy in BEV
2. Warp fluence map
3. Refine the fluence map (planning)

Modeling Treatment Planning Knowledge

DVH based knowledge planning:

1. Learning OAR DVH from past plans
2. Associate DVH property with patient-specific anatomy feature
3. Estimate OAR DVH of new patient
4. Solve treatment plan with OAR DVH goals

Wu et al. Med Phys 2009
Modeling Treatment Planning Knowledge

- DVH Based

Appenzoller et al, Med Phys 2012
Treatment Planning Modeling – Our Strategy

Database of Tx Cases, published guidelines

- Distance-Based
- Volume-Based
- Dose-Based

Feature Extraction

- High Order
- Institutional
Treatment Planning Modeling – Our Strategy

- DVH Based
- Distance-to-target Histogram (DTH)
  - Signed Distance-to-target histogram (DTH)
  - (overlap: negative distance)
  - Relative geometrical relationships betw

\[ V(d) = \bigcup \{ v_i | v_i \in V_{OAR} \text{ and } r(v_i, PTV) \leq d \} \bigcup \{ v_i | v_i \in V_{OAR} \} \]

Zhu et al. Med Phys 2011
Treatment Planning Modeling – Our Strategy

- Distance to target histogram (DTH): PCS
- Distance to OAR (DOH): PCS
- OAR volumes
- PTV volume
- Fraction of OAR volume overlapping with PTV (overlap volume)
- Fraction of OAR volume outside the treatment fields (out-of-field volume)
- Tightness of the geometric enclosure of PTV surrounding OAR
- Curvature of specific OAR

Yuan et al, Med Phys 2012
Treatment Planning Modeling – Our Strategy

- Principal Component Analysis (PCA): Data Dimension Reduction
  - Distance to target histogram (DTH): PCS
  - Distance to OAR (DOH): PCS

Example: Parotid DVH PCA
Treatment Planning Modeling – Our Strategy

Database of Tx Cases, published guidelines

Feature Extraction

Model Training

Multi-regression
Support Vector Regression

Predictive Model

Neural Network
Treatment Planning Modeling – Our Strategy

Database of Tx Cases, published guidelines

Feature Extraction

Model Training

Predictive Model

Prospective New Pt Case Planning Reference

A planning quality evaluation tool for prostate adaptive IMRT based on machine learning
Medical Physics 38, 719, 2011

Quantitative analysis of the factors which affect the interpatient organ-at-risk dose sparing variation in IMRT plans.
Medical Physics 39, 6868, 2012

Retrospective Plan Databases Quality Analysis
## Model Prediction Validation

<table>
<thead>
<tr>
<th></th>
<th>Bladder DVH PCS1 (Median Dose)</th>
<th>Rectum DVH PCS1 (Median Dose)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Significant Factors</strong></td>
<td><strong>R²</strong></td>
<td><strong>R²</strong></td>
</tr>
<tr>
<td>Bladder DTH PCS1 (Median Distance)</td>
<td>0.81</td>
<td>Rectum DTH PCS1 (Median Distance)</td>
</tr>
<tr>
<td>2\textsuperscript{nd} Order of Bladder DTH PCS1</td>
<td>0.22</td>
<td>Volume of Rectum</td>
</tr>
<tr>
<td><strong>Combined</strong></td>
<td>0.88</td>
<td>Overlap Volume</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Combined</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Bladder DVH PCS2 (DVH Slope)</th>
<th>Rectum DVH PCS2 (DVH Slope)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Significant Factors</strong></td>
<td><strong>R²</strong></td>
<td><strong>R²</strong></td>
</tr>
<tr>
<td>Out-of-field Volume</td>
<td>0.50</td>
<td>Rectum DTH PCS2 (gradient)</td>
</tr>
<tr>
<td>Overlap Volume</td>
<td>0.33</td>
<td>Out-of-field Volume</td>
</tr>
<tr>
<td>Bladder DTH PCS2 (gradient)</td>
<td>0.30</td>
<td>Overlap Volume</td>
</tr>
<tr>
<td><strong>Combined</strong></td>
<td>0.85</td>
<td>Rectum DTH PCS3</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Combined</strong></td>
</tr>
</tbody>
</table>
## Cross-Institution Validation

- **LUNG IMRT Pilot Study By RTOG**
- **71 Cases**
- **3 Institutions**

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>Median</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prescriptions (Gy)</td>
<td>67</td>
<td>64</td>
<td>40</td>
<td>74</td>
</tr>
<tr>
<td></td>
<td>Institution 1</td>
<td>Institution 2</td>
<td>Institution 3</td>
<td></td>
</tr>
<tr>
<td>Volume (cm$^3$)</td>
<td>mean 421</td>
<td>595</td>
<td>512</td>
<td></td>
</tr>
<tr>
<td></td>
<td>median 343</td>
<td>519</td>
<td>379</td>
<td></td>
</tr>
<tr>
<td></td>
<td>min, max 62, 1132</td>
<td>76, 1132</td>
<td>175, 1161</td>
<td></td>
</tr>
<tr>
<td>Location (side)</td>
<td>Total 45</td>
<td>10</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Left/Left-Medial 18</td>
<td>4</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Right/Right-Medial 21</td>
<td>6</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Medial 6</td>
<td>0</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>
Cross-Institution Validation

Circle: Training Plan
Cross: Validation Plan

Not contributing to model
Cross-Institution Validation

Institution 2  Not contributing to model

Photon
Contralateral Lung

Prediction
Plan

Institution 3  Contributing to model
Cross-Institution Validation

Institution 2  Not contributing to model

Photon
Ipsilateral Lung

The high agreement between model and plan:

1. Modeling accuracy of representing anatomical influence on dose sparing
2. High consistency of planning quality among institutions
**Cross-modality, Cross-Institution Validation**

<table>
<thead>
<tr>
<th>Institution A</th>
<th>Institution B</th>
</tr>
</thead>
<tbody>
<tr>
<td>7-8 min delivery time</td>
<td>7-8 min delivery time</td>
</tr>
<tr>
<td><strong>Delivery system:</strong> Varian IMRT</td>
<td><strong>Delivery system:</strong> Tomotherapy</td>
</tr>
<tr>
<td><strong>Planning system:</strong> Eclipse</td>
<td><strong>Planning system:</strong> Tomotherapy</td>
</tr>
<tr>
<td>Multiple PTVs</td>
<td>Multiple PTVs</td>
</tr>
<tr>
<td>Sequential Boost</td>
<td>SIB</td>
</tr>
<tr>
<td>- Multiple plans (one plan for 1 PTV)</td>
<td>- 1 plan (one plan cover all PTVs with diff. daily doses)</td>
</tr>
<tr>
<td>- 40-50 Gy and 60-70 Gy</td>
<td>- 54.25 Gy and 70 Gy</td>
</tr>
<tr>
<td>~60 head-and-neck cases</td>
<td>~60 head-and-neck cases</td>
</tr>
</tbody>
</table>
Cross-modality, Cross-Institution Validation

Parotid

Tomotherapy Model vs. IMRT Model vs. Actual Plan DVH
The high agreement between model and plan:

1. IMRT and Tomotherapy Can Share One Dosimetry Model
Model-based Plan Validation (IMRT)
Model-based Plan Validation (VMAT)
Model-based Plan Validation

- Time Savings
  - Prostate:
    - 30-60 min vs. 3-5 min (IMRT)
  - HN:
    - 60min-hrs vs. 5-8 min (IMRT) vs. 20-30 min (VMAT)

- From no trial-and-error adjustments – fast planning time
## Model-based Plan Validation (VMAT)

<table>
<thead>
<tr>
<th>OAR/PTV</th>
<th>Dosimetric Parameters</th>
<th>IMRT Mean (S.D.) (Gy)</th>
<th>VMAT Mean (S.D.) (Gy)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parotids</td>
<td>Median</td>
<td>25.7 (12.8)</td>
<td>25.8 (8.6)</td>
<td>0.23</td>
</tr>
<tr>
<td>Oral Cavity</td>
<td>Median</td>
<td>31.6 (9.5)</td>
<td>33.2 (8.5)</td>
<td>0.61</td>
</tr>
<tr>
<td>Larynx</td>
<td>Median</td>
<td>26.3 (14.5)</td>
<td>27.6 (13.3)</td>
<td>0.64</td>
</tr>
<tr>
<td>Pharynx</td>
<td>Median</td>
<td>58.4 (9.4)</td>
<td>54.8 (10.3)</td>
<td>0.24</td>
</tr>
<tr>
<td>Spinal Cord</td>
<td>D2%</td>
<td>36.2 (4.5)</td>
<td>34.9 (2.2)</td>
<td>0.48</td>
</tr>
<tr>
<td>Brainstem</td>
<td>D2%</td>
<td>20.7 (5.9)</td>
<td>18.9 (5.9)</td>
<td>0.40</td>
</tr>
<tr>
<td>Mandible</td>
<td>D2%</td>
<td>68.0 (7.7)</td>
<td>64.3 (10.4)</td>
<td>0.32</td>
</tr>
<tr>
<td>PTV54</td>
<td>D95%</td>
<td>54.8 (1.5)</td>
<td>54.3 (0.8)</td>
<td>0.26</td>
</tr>
<tr>
<td>PTV70</td>
<td>HI†</td>
<td>7.1 (1.8)</td>
<td>5.2 (0.9)</td>
<td>0.0006</td>
</tr>
</tbody>
</table>

† homogeneity index (D2%-D99%)

- OAR Dosimetric parameters in the VMAT and IMRT plans not significant different by Wilcoxon ranksum test
- Dose homogeneity index of the boost PTV better in the VMAT plans, but may not carry clinical significance
Summary: What Knowledge Modeling May Help

Physician Contouring, Prescription

IMRT/VMAT Planning

Physician Plan Evaluation

Plan Approved For Treatment

Planned vs. Modeled
Summary Treatment Planning Knowledge Modeling

- Treatment Planning Knowledge System
- Target and OAR delineation
- Dose prescription
- Treatment plan/parameter generation
- Treatment plan evaluation/selection
- Treatment plan DVH and toxicity model prediction

Model Prediction

QUANTEC Guidelines

![Graph showing model prediction and QUANTEC guidelines](image)

- Wachter 66 Gy: 14%
- Cozzarini 66.2 Gy: 11%
- Jackson 75.6 Gy: 19%
- Akimoto 69 Gy: 25% 3 Gy/3
- Jackson 70.2 Gy: 6%
- Zapatero 70-75.6 Gy: 7%
- Kopey 66 Gy: 33%
- Fiorino 70-76 Gy: 9%
- Hartford 75.6 Gy: 34% Grade 1
- Huang 74-78 Gy: 23%
Thank You!
Model-based Plan Validation

- Head-and-Neck
- Modeling Base
  - 61 prior clinical plans
  - IMRT with sequential boost (40-50 Gy and 60-70 Gy)
- Validation
  - 18 HN cases
  - IMRT with sequential boost (40-50 Gy and 60-70 Gy)
  - VMAT with SIB (54.25 Gy and 70 Gy)
- Quality of the model-based plans evaluated by compare the dosimetric parameters with those in the clinical plans
Summary: Current Treatment Planning

Physician Contouring, Prescription

IMRT/VMAT Planning

Plan Finished

Physician Plan Evaluation

Plan Approved For Treatment

Not Approved

Iterative Planning

Adj. OAR objective dose-volume indices

Adj. OAR objective weighting

Adj. PTV coverage weighting

Dose Calculation