Clinical Implementation of a Proton Therapy System

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Acknowledgements

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Stella Flampouri, PhD
Darren Kahler, PhD
Wen Hsi, PhD
George Zhao, PhD
Liyong Lin, PhD

Outline

• Overview of the University of Florida Proton Therapy Institute (UFPTI)
• Overview of clinical operations and workflow at UFPTI
• Review of a strategic and operational optimization model of Patient Scheduling
• Personal Observations

The University of Florida Proton Therapy Institute (UFPTI)

Contract Signed: Feb 04
Start Install: March 05
Gantry Install: May 05
Building Complete: Jan 06
1st Patient Tx: Aug 14, 2006
UFPTI Proton Area

- Integrated Facility Management
- Treatment Planning
- Patient Scheduling
- Treatment Control & Delivery

UFPTI Conventional and Simulation Area

- PET/CT
- Large-bore CT
- Image Guided RT
- Tomotherapy

UFPTI Equipment

- IBA Proteus 235 Proton Therapy System
  - 3 Gantry Treatment Rooms, 1 Eye Treatment Room
- Conventional Therapy Equipment
  - 2 Elekta Synergy LINACs with Camera Systems
- Simulation
  - Philips Big Bore CT, PET-CT, and 0.23 T open MR Scanners
- Treatment Planning
  - Varian Eclipse and Philips Pinnacle system for proton and conventional treatment planning respectively
- Facility Management System
  - IMPAC MOSAiQ

Proton Gantry and PPS

- Nozzle installed on gantry Snout installed in nozzle
- PPS: 6 degree-of-freedom isocentric motion
  - 50X50X50 cm³ treatable volume
  - +/- 3° ranges of pitch and roll corrections
Clinical Operations and Workflow

Carlos Vargas, Robert Malypa, and Nancy Mendenhall: Physicians
Zuofeng Li, Wen Hsi, and Daniel Yeung: Physicists
Gary Barlow, Trevor Fleming Ernie St John: Therapists
Debbie Louis and Craig McKenzie: Dosimetrist
Stuart Klein: Administrator

Average Daily Treatments at UFPTI
(August, 2006 - August 2008)

Hours of Operation: 6:00AM-10:00PM

Clinical Workflow

Conventional Therapy
- Patient Referral
- New Patient Consultation
- Patient Diagnostic Workup
- Simulation

Proton Therapy
- Patient Referral
- New Patient Consultation
- Patient Diagnostic Workup
- Simulation

Completion of Treatment Course
- Treatment Planning
- Treatment Delivery

Need for Optimized Workflow in Proton Therapy

- Dose calculation and delivery of proton therapy is highly sensitive to various sources of uncertainties
  - CT HU – stopping power conversion
  - Increased RBE at distal falloff region of SOBP
  - Dose calculation uncertainties
  - Physiological changes
  - High-Z metal implant artifacts
  - Organ motion
  - Tumor regression or progression
Proton Therapy Workflow

- Patient selection for proton therapy performed in Proton Therapy Patient Disposition Conference for new disease sites or patients that may require special considerations in simulation, planning, and delivery techniques.
Prostate Motion Monitoring

- A PTV margin was calculated to allow CTV coverage in 95% of treatments for 90% of patients (van Herk, IJROBP, 2000)
  - Assuming setup error bounded within +/- 2 mm with daily orthogonal imaging and VisiCoil fiducial markers
  - Assuming prostate intra-fraction motion of 2 mm in 5 min
  - PTV margin = 4 mm axial and 6 mm cranial-caudal
  - How to identify the 10% patients with larger intra-fraction prostate motion magnitude?

Prostate Motion Monitoring

- Treatment Delivery Workflow Tasks:
  - Confirmation of appropriateness of PTV margin for a specific patient during treatment delivery
  - Selection of actions to take for a specific patient when intra-fraction motion magnitude is larger than assumption

Results of Prostate Motion Monitoring

- For week of May 12, 2008 – May 16, 2008:
  - 181 Post-treatment DIPS image pairs taken
  - 10 of 181 with DIPS-calculated correction vectors larger than 4 mm axial or 6 mm cranial-caudal
  - 5.5% of image pairs out of tolerance ➔ 9% expected
  - Prostate motion monitoring working as expected

Curtesy Zuofeng Li DSc
**Prostate Motion Monitoring and Control**

- Actions to improve control and reduce dosimetric effect of prostate intra-fraction motion
  - Patient diet control
  - Additional saline in rectum
  - Use of rectal balloon
  - Increase aperture margin

**Thoracic/Abdomen Organ Motion Evaluation**

1. Perform 4D CT scan
2. If patient is candidate for use of ABC device, perform 3 ABC scans
3. Compare maximum target excursion between 4D CT scans and ABC scans to select technique to use
4. Calculate PTV margin and patient setup imaging tolerances

**Treatment Planning for Thoracic and Abdomen Tumors**

1. Use average 4D CT or ABC scans for ITV delineation
2. Override IGTV with tissue HU for thoracic tumor (Kang et al., IJROBP 2007)
3. Minimize weightings of beams with larger range uncertainties due to physiological changes
4. Use distal blocking for beams stopping near critical organs to reduce impact of range uncertainties and increased RBE
5. For patients receiving proton therapy as boost treatment following photon irradiation, constrain proton beam paths to within previous photon beam paths when possible

**Thoracic and Abdomen Organ Motion Monitoring**

1. For initial 3 days of treatments, perform DIPS imaging for each treatment field and calculate correction vectors
2. Inform physics if any field-specific correction value is larger than 5 mm (1 out of 3 expected)
   - Correction must be calculated from a suitable surrogate of target
3. If no correction vectors larger than 5 mm in first 3 days of treatment, perform no more field-specific DIPS imaging

**Completion of Treatment**

- Tumor regression dosage evaluation
- Organ motion?
- Tumor regression? Yes
- Room scheduling
- No
- Thorax/Abdomen Treatment Delivery
- In-Room Patient Setup
- Yes
- Organ motion?
Results of Thoracic and Abdomen Organ Motion Monitoring

- Between April 30, 2008 and May 15, 2008:
  - 36 field-specific DIPS images obtained
  - 1 image showed larger than 5 mm correction
  - 2.8% of images out of tolerance
  - More data needed for validation of hypothesis
  - Potential to reduce target margin

Thoracic and Abdomen Tumor Regression Monitoring

- Patient receives, in alternate weeks, PET-CT activation study scans, or 4D CT/ABC scans as patient is treated
- 4D CT/ABC scans reviewed for tumor regression
  - Tumor regression models under development at UF
  - Verification plan performed on new CT scans if significant dosimetric changes suspected

Patient Simulation Protocols

- Step-by-step protocols developed for all treated sites

Dosimetry Check List

Hypofractionated Prostate

- [ ] [ ] [ ]
## Outcome tracking protocol for Prostate

### Base of Skull Chordoma, Chondrosarcoma, and Cervical Spine

<table>
<thead>
<tr>
<th>Protocol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outcome tracking</td>
<td>Track the outcome according to the specified protocol.</td>
</tr>
</tbody>
</table>

### Head and Neck

**Dosimetry Check List**

<table>
<thead>
<tr>
<th>Protocol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outcome tracking</td>
<td>Track the outcome according to the specified protocol.</td>
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</tbody>
</table>

### Intracranial Tumor

**Dosimetry Check List**

<table>
<thead>
<tr>
<th>Protocol</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>Outcome tracking</td>
<td>Track the outcome according to the specified protocol.</td>
</tr>
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</table>
**Dosimetry Check List**

Unresectable Pancreatic Cancer

<table>
<thead>
<tr>
<th>Patient Name</th>
<th>Date</th>
<th>Problem</th>
<th>Model</th>
<th>Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patient 1</td>
<td>01/01/2022</td>
<td>Problem 1</td>
<td>Model A</td>
<td>Test 1</td>
</tr>
<tr>
<td>Patient 2</td>
<td>02/02/2022</td>
<td>Problem 2</td>
<td>Model B</td>
<td>Test 2</td>
</tr>
</tbody>
</table>

**Patient-Specific QA**

- Verification of aperture and compensator geometries
  - Dosimetric properties verified as part of commissioning with regularly-shaped apertures and compensators
  - 1 mm tolerance
- Output model (Kooy, 2003 & 2005) commissioned for limited proton beam range and modulation combinations
  - Output measured for range and modulations outside commissioned model
  - Range verifier readings obtained for commissioned range and modulation combinations
  - Output measured for small field sizes
- Depth dose and profiles measured per physicist recommendations
  - Depth doses measured for first 5 uses of a sub-option
  - Dose profiles measured for each new disease site for first 5 patients

**Strategic and Operational Optimization Model of Patient Scheduling for a Multi-Room Proton Therapy Facility**

Edwin Romeijn and Ehsan Saliari: Industrial Engineers
Nancy Mendenhall: Physician
Jatinder Palta and Zuofeng Li: Physicists
Gary Barlow: Therapists
Stuart Klein: Administrator

**Project goals**

- Analyzing the capacity of the center in treatment delivery
- Studying the effect of different scenarios on the capacity
- Investigating the potential capacity improvements
- Developing an operational algorithm to schedule individual patients for treatment
UFPTI specifications

- Number of gantry rooms: 3 gantries
- Capacity of each gantry: 15 hours/day
- New patients’ treatment starting day: Monday–Wednesday
- New patient’s treatment starting time: 7 am – 4 pm
- Minimum time between fractions for B.I.D patients: 6 hours
- Snout changing time: 15 minutes
- Anesthesia team availability: 4 hours/day on a single gantry
- Gantry switches are not allowed during the treatment.
- Gantry 3 is specialized to 1-field prostate patients.

Patient Categories and Patient Mix

<table>
<thead>
<tr>
<th>Category</th>
<th>Anesthesia (Y/N)</th>
<th>Time/Fraction (min)</th>
<th># Fractions</th>
<th># Fractions/day</th>
<th>Add 1st Fraction (min)</th>
<th>Snout Size</th>
<th>Option 1 (Y/N)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>N</td>
<td>18</td>
<td>40</td>
<td>1</td>
<td>15</td>
<td>18</td>
<td>65</td>
<td>1-Field Prostate</td>
</tr>
<tr>
<td>2</td>
<td>N</td>
<td>30</td>
<td>40</td>
<td>1</td>
<td>15</td>
<td>18</td>
<td>15</td>
<td>2-Field Prostate</td>
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<tr>
<td>3</td>
<td>N</td>
<td>25</td>
<td>62</td>
<td>2</td>
<td>20</td>
<td>18</td>
<td>7</td>
<td>H&amp;N/BOS</td>
</tr>
<tr>
<td>4</td>
<td>N</td>
<td>45</td>
<td>62</td>
<td>2</td>
<td>25</td>
<td>25</td>
<td>3</td>
<td>Transaxial chordomas</td>
</tr>
<tr>
<td>5</td>
<td>N</td>
<td>35</td>
<td>30</td>
<td>1</td>
<td>20</td>
<td>10</td>
<td>3</td>
<td>Simple Face</td>
</tr>
<tr>
<td>6</td>
<td>Y</td>
<td>55</td>
<td>30</td>
<td>1</td>
<td>20</td>
<td>18</td>
<td>2</td>
<td>Face Brian with Anesthesia</td>
</tr>
<tr>
<td>7</td>
<td>N</td>
<td>60</td>
<td>30</td>
<td>1</td>
<td>45</td>
<td>25</td>
<td>1</td>
<td>C&amp;S with Anesthesia</td>
</tr>
<tr>
<td>8</td>
<td>Y</td>
<td>90</td>
<td>30</td>
<td>1</td>
<td>45</td>
<td>25</td>
<td>1</td>
<td>C&amp;S with Anesthesia, Lung/Nasopharynx, Etc.</td>
</tr>
<tr>
<td>9</td>
<td>N</td>
<td>50</td>
<td>42</td>
<td>1</td>
<td>30</td>
<td>18</td>
<td>2</td>
<td>Concomitant Boost Patients</td>
</tr>
<tr>
<td>10</td>
<td>N</td>
<td>35</td>
<td>12</td>
<td>1</td>
<td>20</td>
<td>18</td>
<td>1</td>
<td>Concomitant Boost Patients</td>
</tr>
</tbody>
</table>

Strategic-level model

Objective function:
- Maximizing number of fractions delivered per day
- Minimizing deviation from the desired patient mix
- Maximizing number of pediatrics patients treated

Constraints:
- Patients’ treatment continuity
- Gantry capacity
- Constraints on
  - Starting day for new patients
  - Starting time for new patients during a day
  - Anesthesia team availability
  - Minimum time between fractions for B.I.D patients
- Gantry specialization
- Gantry switching (allowed/not allowed)

Other Considerations
- Treatment time/fraction reduction
  - Category1: 3min; Category2: 2min; Category6: 15 min
  - Category7: 15 min; Category8: 30 min
- Saturday start for prostate cases (categories1 and 2)
- No gantry specification/no gantry switching
- Gantry capacity variability: reducing gantry availability on Thu-Fri while extending the availability on Mon-Wed
- Vary patient mix
Modeling and Solution Approach

- **Modeling approach:**
  - A Mixed-Integer-Programming model has been developed based on these objective functions and constraints.
  - This model is a cyclic one assuming the system is in steady state.
- **Solution approach:**
  - The model is implemented in Cplex and solved close to optimality using Branch & Bound techniques.

Sensitivity analysis

- Studying the effect of:
  - Allowing gantry switches during treatment
  - Reducing snout changing time
  - Specializing a gantry for a certain category
  - Reducing the treatment time/fraction for some categories
  - Changing the desired patient mix
  - Extending the anesthesia team's availability
  - Extending gantries' working hours
  - Saturday start for prostate patients
  - Increasing the average number of fractions delivered per day

- On:
  - Average daily number of fractions delivered
  - Performance measures (resource utilization and set-up time)
  - Treated patient mix

---

Results

### Patient mix scenarios

<table>
<thead>
<tr>
<th>Scenario</th>
<th>C1</th>
<th>C2</th>
<th>C3</th>
<th>C4</th>
<th>C5</th>
<th>C6</th>
<th>C7</th>
<th>C8</th>
<th>C9</th>
<th>C10</th>
<th>Desired mix</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ideal</td>
<td>40</td>
<td>11</td>
<td>16</td>
<td>6</td>
<td>8</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>2</td>
<td>TBD</td>
</tr>
<tr>
<td>Basic</td>
<td>36</td>
<td>15</td>
<td>16</td>
<td>6</td>
<td>8</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>2</td>
<td>TBD</td>
</tr>
</tbody>
</table>

### Daily capacity and utilization

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Average frac/day</th>
<th>Gantry 1 utilization</th>
<th>Gantry 2 utilization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ideal</td>
<td>62</td>
<td>96</td>
<td>87</td>
</tr>
<tr>
<td>Basic</td>
<td>100</td>
<td>96</td>
<td>95</td>
</tr>
</tbody>
</table>

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### Studying the effect of extending the anesthesia team availability (an example)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>C1 %</th>
<th>C2 %</th>
<th>C3 %</th>
<th>C4 %</th>
<th>C5 %</th>
<th>Desired patient mix</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>66.5</td>
<td>16.4</td>
<td>5.7</td>
<td>1.7</td>
<td>2.3</td>
<td>0.6</td>
</tr>
<tr>
<td>C2</td>
<td>65.3</td>
<td>15.9</td>
<td>5.1</td>
<td>2.8</td>
<td>1.2</td>
<td>2.8</td>
</tr>
<tr>
<td>C3</td>
<td>64.1</td>
<td>11.6</td>
<td>6.1</td>
<td>0</td>
<td>2.2</td>
<td>6.6</td>
</tr>
</tbody>
</table>

- Performance measures
  - Desired patient mix vs. the solution patient mix

<table>
<thead>
<tr>
<th>Performance measures</th>
<th>C1 %</th>
<th>C2 %</th>
<th>C3 %</th>
<th>C4 %</th>
<th>C5 %</th>
<th>Average # patients/day</th>
<th>Average # frac/day</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 x 4</td>
<td>91</td>
<td>90</td>
<td>93</td>
<td>3.7</td>
<td>110.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 x 5</td>
<td>95</td>
<td>92</td>
<td>93</td>
<td>4.6</td>
<td>110.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 x 6</td>
<td>95</td>
<td>97</td>
<td>96</td>
<td>11</td>
<td>110.1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Performance measures for different scenarios
Strategic Model Conclusions

- With the treatment time/fraction reduction of:
  - Category 1: 3min; Category 2: 2min; Category 6: 15 min; Category 7: 15 min; Category 8: 30 min
  - Can treat up to 15 pediatric patients per day
  - Treat up to a maximum of 135 fractions per day (30,000 fractions per year)
- Concerns:
  - The optimal patient mix with respect to pediatric patients consists largely of Category 6 cases
  - The optimal patient mix with respect to other patients consists largely of single-field prostate cases

Summary and Personal Observations

- Proton therapy differs significantly from conventional radiotherapy in its higher sensitivity to various sources of uncertainties
  - What you see is not what you get
- Disease-site-specific clinical workflow must be designed to address the dosimetric effects of these uncertainties
  - Even then some patients may have to be treated with modalities other than protons
- These workflow modifications may require increased efforts compared to their conventional therapy counterparts, but are necessary to optimize proton therapy treatments
  - It is highly unlikely that we will realize greater efficiency in clinical operation of PTS compared to conventional radiation therapy