Transitioning to PBS Proton Therapy
From IMRT or Passive Scattered-Based Proton Therapy

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Progression to better technology
Adoption of new methods for IMRT

Dynamic MLC

Step and Shoot

Protons are in the middle of this evolution

Intensity Modulated Proton Therapy (IMPT)

Aperture

Compensator
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Radiation Therapy is continually evolving

- Proton Vendors can now provide a delivery method that offers some dosimetric advantages over IMRT and Aperture / Compensator based delivery.
  - Intensity Modulated Proton Therapy (IMPT)

- The full potential of proton therapy can only be realized with IMPT methods.
  - Higher Quality and “Safer” plans
  - More treatment sites

- A process must be defined to develop and implement this new technology.

A Vision for the Discovery Benefit

- Defining, discovering and understanding new capabilities
  - Treatment delivery
  - Planning

- Understanding the limitations and safety concerns
  - Technology has changed
  - A need to re-evaluate all safety concerns (margins, robustness)
  - Defining the new tools needed

- Developing methods to implement these new capabilities
  - Site specific benefits

- Providing Clinical Evidence
Step 1:

Defining, discovering and understanding new capabilities of Pencil Beam Scanning

New Capabilities : What are we gaining ?

<table>
<thead>
<tr>
<th></th>
<th>3-D X-Ray</th>
<th>IMRT</th>
<th>Aperture /Comp Proton</th>
<th>IMPT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collimation : Lateral Control</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
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<tr>
<td>Intensity Control</td>
<td>✔️</td>
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</tr>
<tr>
<td>Dose Control with Depth</td>
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Pencil Beam Scanning: Intensity Modulated Proton Therapy

What benefits can we exploit when using this type of delivery method??

• Spot by spot control of Bragg Peak
  – Position (Direction perpendicular to beam direction)
  – Energy (Layer by layer control in the depth direction)
  – Intensity (Optimized using inverse planning methods)

Use of a Compensator for distal shaping
Distal conformity using a Compensator

The addition of Proximal Conformity
Intensity Control: Matching Fields

A Simple Scanning Beam Treatment Technique for CSI

Anne-Marie Gibelker, Andrew Chang, Luis Perles, Lei Dong, and Attarun S. Pai Pambidker
Affiliations of Authors: Nuppo Proton Therapy Center, San Diego, CA

Spot / Layer Patterns for a Sphere

Dose Distribution

Beam’s Eye View
How can we obtain these complex, 3-D spot patterns?

- Inverse planning techniques
  - Iterative minimizations of cost function.
    - Cover target areas
    - Minimize dose to organs at risk
  - Unlimited potential for computing and mathematical “tricks”
    - Minimizing the effects of positional errors and range errors directly into the cost function
    - Including effects of motion into the cost function
    - Multi Criteria Optimization (MCO)

- Single Field Optimized (SFO) / Multi Field Optimized (MFO)

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IMPT Optimization Methods

**Single Field Optimization (SFO)**

Uniform Dose is delivered to the entire target by each field individually

**Multi Field Optimization (MFO)**

Spot weights of all fields are optimized together. The spot weight of one field may rely on another field’s dose to create an integrated uniform target dose.
Single Field Optimized

OAR

< 100% of Dose

100% of Dose

Clinical Radiation Oncology, 3rd Addition
Multi-Field Optimized

OAR

< 100% of Dose

100% of Dose

Clinical Radiation Oncology, 3rd Addition
Step 2:

Understanding the limitations and safety concerns of Pencil Beam Scanning Methods
ICRU: Safety Methods to Avoid a Geometric Miss of the Target

With Protons: We must always consider for Range Uncertainty

<table>
<thead>
<tr>
<th>Source of range uncertainty in the patient</th>
<th>Range uncertainty without Monte Carlo</th>
<th>Range uncertainty with Monte Carlo</th>
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<tbody>
<tr>
<td>Independent of dose calculation</td>
<td>± 0.3 mm</td>
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<tr>
<td>Geometry: plans</td>
<td>± 0.2 mm</td>
<td>± 0.2 mm</td>
</tr>
<tr>
<td>Range calculation</td>
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</tr>
<tr>
<td>Total (including *)</td>
<td>± 0.1% ± 1.2 mm</td>
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Paganetti, Phys. Med Biol (57), 2012

Table 8: Estimates of uncertainties (±) in patient SFR estimation in current clinical practice.

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<thead>
<tr>
<th>Uncertainty source</th>
<th>Uncertainty in SFR estimation (±)</th>
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<tr>
<td>Uncontrollable (CT)</td>
<td>3.3 ± 0.6 ± 0.5</td>
</tr>
<tr>
<td>Uncertainties due to deviation of actual human body tissue from ICRU standard tissues</td>
<td>0.2 ± 1.6 ± 0.4</td>
</tr>
<tr>
<td>Uncertainties due to energy dependence of SFR not accounted for</td>
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Table 7: Summary of estimated uncertainties in treatment planning due to CT number and stopping power

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Moyers, Medical Dosimetry(35), 2010
Margins for Setup and Range Uncertainty with Protons

- **Perpendicular Expansion**
  - Avoid a geometric miss
  - Physical Distance (cm)

- **Parallel Expansion**
  - Avoid a range miss
  - Radiobiological Depth (Water Equiv. Thickness)
**IMPT Optimization Methods**

**Single Field Optimization (SFO)**
- Uniform Dose is delivered to the entire target by each field individually.
- Less sparing of critical structures.
- Less sensitive to Set-up/Range errors.

**Multi Field Optimization (MFO)**
- Spot weights of all fields are optimized together.
- The spot weight of one field may rely on another field’s dose to create an integrated uniform target dose.
- Better for sparing critical structures.
- More sensitive to Set-up/Range errors.

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**Understanding the limitations and safety concerns**

“Robustness”

Quantify the effects of:

- Range Uncertainty
- Intra-fraction motion
  - Respiratory motion
- Non-ideal set-up
- Inter-fraction motion
  - Anatomical consistency
Robustness for PBS Plans

• Two methods to do this:
  – Prospectively: Robustness Planning / Optimization
  – Retrospectively: Robustness Evaluation

• Adequate tools are required!!

For SFO: Beam Specific PTV : bs(PTV)

The Effect of Set-up Errors on SFO Plan

Robust Optimization

- Add penalties into the cost function for robustness
- Allow the planning system to score robustness on a spot to spot basis AND how one spot will effect the overall sensitivity to potential plan degradation.
- Spots with “poor” robustness (high sensitivity to plan degradation) will be penalized by iteratively decreasing, and potentially, eliminating their intensity

Robustness Evaluation

Quantify the differences in quality between the planned and the delivered dose in the presence of uncertainties

Robust Plan Evaluation includes:

- Calculation and Evaluation of many “Worst case” scenarios
  - Systematic offset of HU conversion
    - $(-3.5\% , +3.5\%)$
  - Systematic offset of set-up error
    - $(x=+/-3\text{mm}, y=+/-3\text{mm}, z=+/-3\text{mm})$

This concept of “Robustness” and the Quality of a “Robustness Evaluation” really has limitations

- Impossible to look at all potential scenarios

- Combinations of Random AND Systematic errors
  - Set-up errors are random
  - Range errors are systematic
    - Range errors are NOT uniformly distributed
    - Beam Hardening
    - Tissue Dependent

- Only as good as the patient model that you give it.
  - What if the patient changes??
Adaptive Planning: Naso-pharynx to $56\text{ Gy}_{(RBE)}$

Approved Plan: Naso-pharynx
Large Change in Target Region Anatomy

Calculation of Initial Plan on New Image Set

Initial Plan

On Treatment Evaluation
Step 3:

Developing methods to implement the new capabilities of Pencil Beam Scanning
Intensity Modulation: SFO with Field Matching

Intensity Modulation for Field Matching
Dose Profiles at Field Junction

A Head / Neck that requires MFO dose shaping:

- Nasopharynx target with neck nodal irradiation
  - GTV and Regional Lymphatics to $50 \text{ Gy}_{(RBE)}$
  - Boost Volume to $70 \text{ Gy}_{(RBE)}$
Optimizing IMPT strengths and robustness

Left Anterior Oblique

MFO

SFO : 50%
Right Anterior Oblique

Anterior Superior Oblique
Composite plan to 50 Gy (RBE)

New capabilities with MFO over SFO

The Problem:
Expander Filling ports
Treat around the port with MFO Methods

A real case: Medial Beam
A real case: Lateral Beam

A Real Case: Both Beams
SFO and MFO regions for robustness

Robust Optimization for OAR
Where can we exploit the benefits offered by IMPT?

Benefits of IMPT

- Minimize Integral Dose
- Advanced Dose Shaping
- Field Matching
- Treatment Efficiency
- Pediatric
- Re-treats
- Lt Sided Breast
- Head / Neck
- Esophagus
- Whole Pelvis
- Lung

A few take-a ways......

- PBS delivery methods have opened up remarkable, new capabilities for Proton Therapy
- The proton community needs to continue to work closely in an effort to find the full potential of PBS methods.
- A collection of the new “tools” is an essential part of clinical implementation of this new opportunity