Basics of Proton Therapy

Proton Treatment Planning and Beam Optimization

SAM Educational Session, WE-D-BRB-2

Mark Pankuch, PhD
Northwestern Medicine Chicago Proton Center
Today’s objectives

– Review the concepts of CTV / ITV / PTV when treating with protons

– Discuss the general planning parameters used in proton planning

– Present Aperture / Compensator, forward based, treatment planning methods

– Discuss the methods and clinical benefits of Intensity Modulated Proton Therapy (IMPT)
PTV = ITV + SM
ICRU Definitions

Patient

ITV

PTV = ITV + SM
ICRU Definitions

Patient

PTV = ITV + SM

Northwestern Medicine
Chicago Proton Center
So....
Distal margins of Protons fields need to consider potential path length differences (Smearing and Robustness)

But are there other considerations for the distal edge margins??

What about Proton Range Uncertainties??
Where do range uncertainties come from and how big are they??

• It depends on who you ask......
### Table 7. Summary of estimated uncertainties in treatment planning due to CT numbers and stopping powers

<table>
<thead>
<tr>
<th>Cause</th>
<th>Uncertainty Before Mitigation</th>
<th>Mitigation</th>
<th>Uncertainty After Mitigation</th>
<th>Possible Future Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scanner calibration for standard conditions KVP, filter, and FOV selection</td>
<td>±0.3% day-to-day, ±2.0% FMMA, FC, &gt; ±2.0% bone, ±2.5%</td>
<td>Patient-specific scaling, Use only calibrated conditions</td>
<td>±0.0%, ±0.0%</td>
<td>±0.0%, ±0.0%</td>
</tr>
<tr>
<td>Volume and configuration scanned</td>
<td>±1.5% water, ±2.5% tissue, &gt; ±3.0% bone, 100%</td>
<td>Patient-specific scaling</td>
<td>±0.0%, ±1.5% water*, ±2.5% tissue, &gt; ±3.0% bone*, ±5.0% metal*</td>
<td>±0.0%, ±0.5% water, ±0.8% tissue, &gt; ±1.0% bone, ±5.0% metal*</td>
</tr>
<tr>
<td>Position in scan</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Metal implants</td>
<td>±1.0%, ±0.0 to 3.0%</td>
<td></td>
<td>±1.0%</td>
<td>±0.5%</td>
</tr>
<tr>
<td>Stopping power of water</td>
<td>±1.6%</td>
<td></td>
<td>±1.0%</td>
<td>±1.0%</td>
</tr>
<tr>
<td>RLSF of tissues and devices</td>
<td>±1.2%</td>
<td></td>
<td>±1.6, ±1.2</td>
<td>±1.6, ±0.5</td>
</tr>
<tr>
<td>WEQ vs. RLSF (soft tissues only)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy dependence of RLSF for low Z</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total (soft tissues only)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Abbreviations: DE, dual-energy CT; MC, Monte Carlo calculations.
*Not considered in total.
Yang: Comprehensive analysis of proton range uncertainties related to patient stopping power ratio estimation using the stoichiometric calibration

Table 8. Estimates of uncertainties (1σ) in patient SPR estimation in current clinical practice.

<table>
<thead>
<tr>
<th>Uncertainty source</th>
<th>Uncertainties in SPR estimation (1σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lung (%)</td>
</tr>
<tr>
<td>Uncertainties in patient CT imaging</td>
<td>3.3</td>
</tr>
<tr>
<td>Uncertainties in the parameterized stoichiometric formula to calculate theoretical CT numbers</td>
<td>3.8</td>
</tr>
<tr>
<td>Uncertainties due to deviation of actual human body tissue from ICRU standard tissue</td>
<td>0.2</td>
</tr>
<tr>
<td>Uncertainties in mean excitation energies</td>
<td>0.2</td>
</tr>
<tr>
<td>Uncertainties due to energy dependence of SPR not accounted by dose algorithm</td>
<td>0.2</td>
</tr>
<tr>
<td>Total (root-sum-square)</td>
<td>5.0</td>
</tr>
</tbody>
</table>
Paganetti: Range uncertainties in proton therapy and the role of Monte Carlo simulations

<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>
</tr>
</thead>
<tbody>
<tr>
<td>Independent of dose calculation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measurement uncertainty in water for commissioning</td>
<td>± 0.3 mm</td>
<td>± 0.3 mm</td>
</tr>
<tr>
<td>Compensator design</td>
<td>± 0.2 mm</td>
<td>± 0.2 mm</td>
</tr>
<tr>
<td>Beam reproducibility</td>
<td>± 0.2 mm</td>
<td>± 0.2 mm</td>
</tr>
<tr>
<td>Patient setup</td>
<td>± 0.7 mm</td>
<td>± 0.7 mm</td>
</tr>
<tr>
<td>Dose calculation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Biology (always positive) *</td>
<td>+~0.8%</td>
<td>+~0.8%</td>
</tr>
<tr>
<td>CT imaging and calibration</td>
<td>± 0.5%(^a)</td>
<td>± 0.5%(^a)</td>
</tr>
<tr>
<td>CT conversion to tissue (excluding I-values)</td>
<td>± 0.5%(^b)</td>
<td>± 0.2%(^g)</td>
</tr>
<tr>
<td>CT grid size</td>
<td>± 0.3%(^c)</td>
<td>± 0.3%(^c)</td>
</tr>
<tr>
<td>Mean excitation energy (I-values) in tissues</td>
<td>± 1.5%(^d)</td>
<td>± 1.5%(^d)</td>
</tr>
<tr>
<td>Range degradation; complex inhomogeneities</td>
<td>−0.7%(^c)</td>
<td>± 0.1%</td>
</tr>
<tr>
<td>Range degradation; local lateral inhomogeneities *</td>
<td>± 2.5%(^f)</td>
<td>± 0.1%</td>
</tr>
<tr>
<td>Total (excluding *, *)</td>
<td>2.7% + 1.2 mm</td>
<td>2.4% + 1.2 mm</td>
</tr>
<tr>
<td>Total (excluding *)</td>
<td>4.6% + 1.2 mm</td>
<td>2.4% + 1.2 mm</td>
</tr>
</tbody>
</table>
Setup and Range Uncertainty with Protons: Field Specific Margins

Perpendicular Expansion
Avoid a geometric miss
Physical Distance (cm)

Parallel Expansion
Avoid a range miss
Radiobiological Depth (Water Equiv. Thickness)
CT is the Patient “Map” : Areas of Specific Concern for Protons

• Conversion from HU to RSP has inherent problems
  – Noise
  – Beam hardening

• Trying to make our CT scanner a spectrometer
  – Two tissues can have same HU but different RSP

• Anything not natural can have large errors.
  – Contrast
  – Fillings
  – Implants
Chestwall Expander
Breast Prosthesis

Fig. 3: Treatment plan for patient with silicone breast prosthesis. (a) Planned dose distribution without RLSP reassignment. (b) Delivered dose distribution if planned without proper pRLSP assignment.
Is there any hope for improvements?

• Dual Energy CT (kV / MVCT)

• Proton activation (PET/SPECT) Tomography

• Prompt Gamma verification

• Proton Radiography

• Proton Tomography
Treatment Planning Methods depend on Proton Delivery Methods

Double-Scatter (DS)
Uniform Scanning (US)
Pencil Beam Scanning (PBS)
Intensity Modulated Proton Therapy (IMPT)

Aperture / Compensator Based Planning
Inversed planned proton spot intensity optimization
Aperture / Compensator based Planning Strategies

• Cover the target with appropriate margins

• Spare the critical structures

• Plan with fields that deliver the most “robust” plan
Tools to do our job

– Range: The depth of the Bragg peak (Distal 90%)

– Modulation: The spread of the Bragg peak

– Apertures: Shaping the beam perpendicular to the path

– Compensators: Distal Shaping
The Physics of Protons

Spread Out Bragg Peak (SOBP)

Depth in Tissue (cm)

Relative Dose

Healthy Tissue

Tumor

Healthy Tissue
Range and Modulation
Spreading the beam across the field
Patient Specific Devices

Aperture
Aperture Design

95% Penumbra

- Air Gap 5
- Air Gap 10
- Air Gap 15
- Air Gap 20
- Air Gap 25
- Air Gap 30

Penumbra (cm)

Range (cm)
Brass Aperture mounted in Treatment Snout
Penumbra at Various Air Gaps
Penumbra as Mid SOBP at various ranges

Penumbra at Various Ranges, mid-SOPB (4cm)

- Range 10cm
- Range 20cm
- Range 30cm
For treatments, the snout is extended to be close to the patient.
Reduced Air Gap = smaller penumbra.
Compensators for Distal Shaping
No Compensator

Target Area

Inhomogeneity (Air Pocket)

Proton Beam

Aperture
With Compensator

Compensator

Aperture

Target Area

Inhomogeneity (Air Pocket)
Design of the compensator
Design of the compensator
With Discrete Compensator

Compensator

Aperture

Target Area

Inhomogeneity (Air Pocket)
With Discrete Compensator

Compensator

Aperture

Target Area

Inhomogeneity (Air Pocket)
Smearing

• Sacrificing distal conformity to ensure you have enough range (and modulation) to cover the target in the case of anticipated misalignments

• Accounts for the fact that treatment path lengths may be different than planned path lengths due to set-up errors and internal motion.

• Can easily be built into compensator design

• Is not directly “mechanically” accounted for in IMPT (No compensator)
Intensity Modulated Proton Therapy (IMPT)

- Layers of spot patterns delivered over the target volume
- Variable Intensity Control
  - Dose uniformity
  - Simultaneous Intergrated Boost
- Distal AND Proximal conformity
- The ability to perform Single Field or Multi-Field Optimizations

Movie clip from Varian ProBeam: https://www.youtube.com/watch?v=AQTE7Uqbj0Y
Spot Intensity for SFUD plan

BEV of the spot intensity patterns
Spot Positions and Intensity

- Impossible to manually define spot positions and intensities and hope they relate to each other.
- Inverse planning is required
- Objective function is defined
- An iterative process is used to minimize the objective function
Use of a Compensator for distal shaping
Distal conformity using a Compensator

No Compensator

With Compensator
Advantage of PBS: The addition of Proximal Conformity
**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 will 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
Single Field Optimized: (SFO)
Multi-Field Optimized: (MFO)

- OAR
- < 100% of Dose
- 100% of Dose
Single Field Optimized with a systematic range error

OAR

< 100% of Dose

100% of Dose
Multi Field Optimized with a systematic range error

< 100% of Dose

100% of Dose

OAR
A need to Quantify and account for the effects of:

“Robustness”

- Non-ideal set-up
- Range uncertainty
- Intra-fraction motion
  - Respiratory motion
- Inter-fraction motion
  - Anatomical consistency
Quantify and account for the effects of:

“Robustness”

• Two methods to do this:

  – Prospectively: Robustness Optimization
  – Retrospectively: Robustness Evaluation
PBS 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

Process of evaluating several potential scenarios to understand potential “worse case” results

• Translate and/or rotate individual fields and recalculate
  – Mimic Set-up errors

• Re-assign systematically shifted HU conversion curves and recalculate
  – Mimic HU conversion errors

• Move Target structures and recalculate
  – Mimic Internal Motion and Anatomical Variances
Robust Evaluations
In Conclusion ..... 

• Because the protons stop, the standard planning methods used in photon planning may not be directly applicable.

• Treatment Planning with proton requires several addition consideration.

• The proper application of proton planning techniques can generate some very wonderful treatment plans.
Thanks You for listening!