PROTON TREATMENT PLANNING

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Today's objectives

- Discuss the general planning concepts used in proton planning
- Review the unique handling of CTV / ITV / PTV when treating with protons
- Pencil Beam distributions and PBS optimization
Planning Strategies 101–Protons

- Cover the target with appropriate margins
- Spare the critical structures
- Plan with fields that deliver the most “robust” plan
Tools to do our job

- Protons
  - Range: The depth of the Bragg peak (D90%)
  - Modulation: The spread of the Bragg peak
  - Compensators: Distal Shaping
  - Patch Fields: Distal Edge to Lateral Edge Matching
  - IMPT: Inverse planning method
The Physics of Protons

Spread Out Bragg Peak (SOBP)

Relative Dose

Depth in Tissue (cm)

Healthy Tissue

Tumor

Healthy Tissue
Spreading the beam across the field
Patient Specific Devices

Aperture
Penumbra at Various Air Gaps
Penumbra at Various Ranges, mid-SOPB (4cm)
No Compensator

Proton Beam

Aperture

Inhomogeneity (Air Pocket)

Target Area
Design of the compensator
Design of the compensator
With Discrete Compensator

Compensator

Aperture

Inhomogeneity (Air Pocket)

Target Area
With Discrete Compensator

Compensator

Target Area

Inhomogeneity (Air Pocket)

Aperture
With Discrete Compensator

Compensator

Target Area

Inhomogeneity (Air Pocket)

Aperture
Sacrificing distal conformity to ensure you have enough range (and Modulation) to cover the target.

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

Can easily be built into compensator design.

Not directly accounted for in PBS.
The concept of smearing is used in compensator based proton therapy to account for:

a) Possible compensator thickness errors generated by the milling process

b) Inaccurate stopping power data of compensator materials

c) Daily patient set-up uncertainties and possible movement of anatomical inhomogeneities during treatment

d) All of the above
Patch Field Technique

- Patch Field
- Patch Line
- Through Beam
- Tumor
- OAR
Patch Field Technique
Match-line Change

Through Beam

Tumor

OAR

Patch Field
Match Technique

Through Beam

Match Field

Tumor

Match Line

OAR
ICRU Definitions

CTV

GTV

ITV

PTV = ITV + SM

Patient
ICRU Definitions

Patient

ITV

PTV = ITV + SM
ICRU Definitions

PTV = ITV + SM
Protons need no distal Setup margin?

But.... What about Range Uncertainties
Figure 12. Dotted lines: typically applied range uncertainty margins in proton therapy treatment planning as currently typically applied at the MGH (3.5% + 1 mm), the MD Anderson Proton Therapy Center in Houston (3.5% + 3 mm), the Loma Linda University Medical Center (3.5% + 3 mm), the Roberts Proton Therapy Center at the University of Pennsylvania (3.5% + 3 mm) and the University of Florida Proton Therapy Institute (2.5% + 1.5 mm). Note that these centers may apply bigger margins in specific treatment scenarios. Dashed line: estimated uncertainty without the use of Monte Carlo dose calculation. Solid line: estimated uncertainty for complex geometries without the use of Monte Carlo dose calculation. Dashed-dotted line: estimated uncertainty with the use of Monte Carlo dose calculation.
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</td>
<td>±0.3% day-to-day</td>
<td>Patient-specific scaling</td>
<td>±0.0%</td>
<td>±0.0%</td>
</tr>
<tr>
<td>kVp, filter, and FOV selection</td>
<td>±2.0% PMMA, FC</td>
<td>Use only calibrated conditions</td>
<td>±0.0%</td>
<td>±0.0%</td>
</tr>
<tr>
<td>&gt; ± 2.0% bone</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Volume and configuration scanned</td>
<td>±2.5%</td>
<td>Patient-specific scaling</td>
<td>±0.0%</td>
<td>±0.0%</td>
</tr>
<tr>
<td>Position in scan</td>
<td>±1.5% water</td>
<td></td>
<td>±1.5% water*</td>
<td>±0.5% water&lt;sub&gt;DE&lt;/sub&gt;*</td>
</tr>
<tr>
<td></td>
<td>±2.5% tissue</td>
<td></td>
<td>±2.5% tissue</td>
<td>±0.8% tissue&lt;sub&gt;DE&lt;/sub&gt;</td>
</tr>
<tr>
<td></td>
<td>&gt; ± 3.0% bone</td>
<td></td>
<td>&gt; ± 3.0% bone*</td>
<td>&gt; ± 1.0% bone&lt;sub&gt;DE&lt;/sub&gt;*</td>
</tr>
<tr>
<td>Metal implants</td>
<td>100%</td>
<td>z ≤ 22 – MVXCT</td>
<td>±5.0% metal*</td>
<td>±5.0% metal*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>z &gt; 22 - substitution</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stopping power of water</td>
<td>±1.0%</td>
<td></td>
<td>±1.0%</td>
<td>±0.5%</td>
</tr>
<tr>
<td>RLS of tissues and devices</td>
<td>±0.0 to 3.0%</td>
<td>Contour and substitute</td>
<td>±1.0%</td>
<td>±1.0%</td>
</tr>
<tr>
<td>WEQ w.r. RLS (soft tissues only)</td>
<td>±1.6%</td>
<td></td>
<td>±1.6</td>
<td>±1.6</td>
</tr>
<tr>
<td>Energy dependence of RLS for low Z</td>
<td>±1.2%</td>
<td></td>
<td>±1.2</td>
<td>±0.5&lt;sub&gt;MC&lt;/sub&gt;</td>
</tr>
<tr>
<td>Total (soft tissues only)</td>
<td></td>
<td></td>
<td>±3.5</td>
<td>±2.2</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>

**Table 9.** Median, 90th percentile and 95th percentile of composite range uncertainties and the corresponding percentile when the range uncertainty is 3.5% at different clinical sites.

<table>
<thead>
<tr>
<th>Tumor site</th>
<th>Composite range uncertainty (%)</th>
<th>Percentile when range uncertainty = 3.5%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Median</td>
<td>90th percentile</td>
</tr>
<tr>
<td>Prostate</td>
<td>1.3</td>
<td>2.5</td>
</tr>
<tr>
<td>Lung</td>
<td>1.5</td>
<td>2.9</td>
</tr>
<tr>
<td>Head and neck</td>
<td>1.3</td>
<td>2.6</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><strong>Independent of dose calculation</strong></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><strong>Dose calculation</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Biology (always positive) ^</td>
<td>+ approximately 0.8%</td>
<td>+ approximately 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%^e</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>*<em>Total (excluding <em>, ^)</em></em></td>
<td>2.7% + 1.2 mm</td>
<td>2.4% + 1.2 mm</td>
</tr>
<tr>
<td><strong>Total (excluding ^)</strong></td>
<td>4.6% + 1.2 mm</td>
<td>2.4% + 1.2 mm</td>
</tr>
</tbody>
</table>
Adding the Uncertainty with Protons

- Physical Distance (cm)
- Radiobiological Depth (WET)
Graphics Measure

Point Location 1:
X(cm): -7.56
Y(cm): -15.90
Z(cm): -0.52
CT: -531 Relative Electron Density: 0.447

Point Location 2:
X(cm): -8.02
Y(cm): -15.90
Z(cm): -0.71
CT: -740 Relative Electron Density: 0.229

Distance Between Points(cm): 0.50
Radiological Distance (cm): 0.12

Mouse buttons in SPV's
LEFT : Place point 1
MIDDLE : Place point 2
CANCEL
Graphics Measure
Point Location 1:
X(cm): -1.73
Y(cm): -15.90
Z(cm): -0.42
CT: 266  Relative Electron Density: 1.140

Point Location 2:
X(cm): -1.38
Y(cm): -15.90
Z(cm): -0.78
CT: 189  Relative Electron Density: 1.104

Distance Between Points(cm): 0.50
Radiological Distance (cm): 0.57

Mouse buttons in SPV's
LEFT : Place point 1
MIDDLE : Place point 2
Why is the standard PTV concept NOT fully applicable to proton therapy?

a) Targets treated with protons tend to have no setup and intra-fraction changes in the target volume.

b) The use of smearing negates the need for lateral margins in proton therapy.

c) For protons, distal and proximal margins around the target are required to account for range uncertainties which are not accurately achieved using a standard PTV.

d) None of the above.
HU Unit conversions

- 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
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?

- MVCT
- Proton activation (PET/SPECT) Tomography
- Prompt Gamma verification
- Proton Tomography / radiography
The More I Think
The More Confused I Get
Norm:Dose(1000.0 cGy = 100%)

Isovalues(%)  
100.0  
95.0  
90.0  
70.0  
50.0
Advantage of a Compensator

No Compensator

With Compensator
Advantage of PBS

PBS

With Compensator
Single Field Uniform Dose

OAR

< 100% of Dose

100% of Dose
Multi-Field Optimized

OAR

< 100% of Dose

100% of Dose
SFUD with range error

< 100% of Dose

OAR

100% of Dose
Multi Field Optimized with a range error

OAR

< 100% of Dose

100% of Dose
So how can we quantify this?

Robustness analysis

- Move individual fields and recalculate
  - Mimic Set-up errors

- Re-assign shifted HU conversion curves and recalculate
  - Mimic HU conversion errors

- Move Target structures and recalculate
  - Mimic smearing
The true benefit of proton is in the difference in integral dose. Make the best of this!!
Where is the community putting efforts to improve proton planning??

- Faster layer switching
- Smaller and variable Spot Size
- Better understanding of Range Uncertainties
- Robustness tools for evaluations, probability DVH
- Robustness penalties included in optimization
- Robustness optimizations using in 4-D evaluations
- Streamlined Verification CT/plans
- Motivation to build strong proton protocols
Thanks You for listening!