New Developments in Proton Treatment Planning Systems

Daniel Yeung
Statement of Disclosure

Funded Research & Development:

Philips Medical Systems

IBA
# Proton Planning Systems

<table>
<thead>
<tr>
<th></th>
<th>Commercial Systems</th>
<th>Academic Systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analytical/Semi-Analytical</td>
<td>CMS - Xio</td>
<td>MGH, HCL</td>
</tr>
<tr>
<td>Varian – Eclipse Proton</td>
<td></td>
<td>PSI</td>
</tr>
<tr>
<td>Varian – EyePlan</td>
<td></td>
<td>Clatterbridge</td>
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<tr>
<td>Optivus - Odyssey</td>
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<td>Loma Linda</td>
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<tr>
<td>Dosigray</td>
<td></td>
<td>Orsay</td>
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<tr>
<td>Others…</td>
<td></td>
<td>Others…</td>
</tr>
<tr>
<td>* Under Development</td>
<td>Philips – Pinnacle*</td>
<td>UF*</td>
</tr>
<tr>
<td>Monte Carlo</td>
<td>CMS*, Varian*,…</td>
<td>MGH, DKFZ,…</td>
</tr>
</tbody>
</table>
Proton Pencil Beam Algorithms

Hong et al, MGH 1996

A pencil beam algorithm for proton dose calculations

Linda Hong†‡, Michael Goitein†, Marta Bucciolini§, Robert Comiskey†, Bernard Gottschalk∥, Skip Rosenthal†, Chris Serago† and Marcia Urie†
† Department of Radiation Oncology, Massachusetts General Hospital, Boston, MA, USA
‡ Department of Radiation Oncology, Mt Sinai Medical Center, New York, NY, USA
§ Department of Radiation Oncology, Institute of Oncology, Milan, Italy
∥ Department of Radiation Oncology, Stanford University School of Medicine, Stanford, CA, USA

Szymanowski et al, Institut Curie 2001

Experimental determination and verification of the parameters used in a proton pencil beam algorithm

H. Szymanowski(§)
Service de Physique Médicale, Institut Curie, 26 rue d’Ulm, 75005 Paris, France

A. Mazal
Service de Physique Médicale, Institut Curie, 26 rue d’Ulm, 75005 Paris, France
and Centre de Protonthérapie d’Orsay (C.P.O.), B.P. 65, 91402 Orsay, France

Beam Model

- dosimetry in water
- inhomogeneity correction
  - water equivalent thickness (wet)
  - HU stopping power
Proton Pencil Beam Algorithm

Beam Model

CAX Depth Dose (DD)
- broad beam
- pristine peak sobp

Radial Spread (RS)
- multi coloumb scatter
  - beamline: degrader, nozzle elements (wet only)
  - compensator: material dependent scattering power
  - patient: wet only
- gaussian kernel
  \[ \sigma^2_{\text{total}} = \sigma^2_{\text{line}} + \sigma^2_{\text{comp}} + \sigma^2_{\text{patient}} \]
Proton Pencil Beam Algorithm

Dose Calculation
- Dose from a pencil beam

\[
D_{PB}(x, y, z) = C(z_{eq}, x_0, y_0) \times \frac{1}{2\pi \sigma^2_{tot}(z_{eq})} \times \exp\left(-\frac{(x-x_0)^2 + (y-y_0)^2}{2\sigma^2_{tot}(z_{eq})}\right),
\]

- Convolve DD with RS for each pencil
- Sum dose from all pencils
**Bortfeld Model of Pristine Peak**

**An analytical approximation of the Bragg curve for therapeutic proton beams**

Thomas Bortfeld\(^a\)

*Deutsches Krebsforschungszentrum (DKFZ), Abteilung Medizinische Physik and Universität Heidelberg, Fakultät für Physik und Astronomie, Heidelberg, Germany*

(Received 28 October 1996; accepted for publication 17 September 1997)

\[
D(z) = \Phi_0 \frac{e^{-\xi^2/4} \sigma^{1/p} \Gamma(1/p)}{\sqrt{2 \pi \rho \alpha^{1/p} (1 + \beta R_0)}} \left[ \frac{1}{\sigma} \mathcal{D}_{-1/p}(-\xi) \right.
\]

\[
+ \left( \frac{\beta}{p} + \gamma \beta + \frac{\epsilon}{R_0} \right) \mathcal{D}_{-1/p-1}(-\xi) \right].
\]

Analytical model of proton BP (up to ~ 200 MeV)
- accounts for energy spread
- empirical model of nuclear fragmentation (data fitting)
- numeric depth dose calculation of fitted BP
- assumption – range straggling ‘constant’ with depth
Pristine Peak - Analytical Model

For $R > 15 \text{ g/cm}^2$, Range straggling $\uparrow$ depth
Error in Bortfeld model

Eclipse Model
Bortfeld Model

$R = 21.86 \text{ g/cm}^2$

$R = 5.86 \text{ g/cm}^2$

$R = 9.0 \text{ g/cm}^2$

$R = 19.8 \text{ g/cm}^2$
Pristine Peak – Bortfeld Model

R = 19.8 g/cm²

Bortfeld Model

R = 28.4 g/cm²

Bortfeld - Enhanced
SOBP
Calc vs Measurement

R=13.00, M=10.00

R=13.50, M=9.00

D_{Eclipse} - D_{measured} [%]

Depth [g/cm²]

Courtesy R. Slopsema
Beam Profile

Calc vs Measurement

R = 15.1, M = 10.4

d = 5 mm

d = 10 cm

d = 15 cm

Option B5 - R = 15.1 g/cm², M = 10.4 g/cm², Air gap = 11.7 cm, SSD = 220.1 cm, aperture: 15 cm x 15 cm

Eclipse convolved - @ 9.9 cm
Measurement (av) - @ 9.9 cm
Eclipse convolved - @ 0.5 cm
Measurement (av) - @ 0.5 cm
Eclipse convolved - @ 14.1 cm
Measurement (av) - @ 14.1 cm

20%-80% Lateral Penumbra (cm)

Air Gap (cm)

Courtesy R. Slopsema
Proton Dose Calc in water is generally accurate!
…ok, what about Clinical Issues?
Match & Patch Fields

- used to avoid OARs adjacent to target
- partition target into segments (sub-targets)
  - sub-targets treated with ‘sub-beams’
  - angle sub-beams to avoid OARs
- combined with other fields for dose uniformity
Match Fields

- match fields abutting each other
- penumbra matching penumbra
Patch Fields

- thru beam txt partial target
- residual txt with patch
- lateral penumbra (t-beam) ‘matched’ with distal falloff (p-beam)
- LPO beam (inferior) patched with SPO (superior)
Lacrimal Gland Carcinoma
PTV 50.4

partition into sup + inf targets

<table>
<thead>
<tr>
<th>PTV50.4: 5 fields with match &amp; patch</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Target</strong></td>
</tr>
<tr>
<td>PTV</td>
</tr>
<tr>
<td>PTV(Inf)</td>
</tr>
<tr>
<td>PTV(Sup)</td>
</tr>
</tbody>
</table>

SPO-patch

LPO-Inf (spare optics & BS)

brainstem
Lacrimal Gland Carcinoma
PTV50.4 – 5 Fields

Inf - LPO  Sup – LAO match  Sup – SPO patch

LPO  LAO
Patch Field Selection

Patch Field Angle Selection
- optimal geometric coverage ($G = 230$)
- avoid inhomogeneity along path ($G = 205$)
Patch Field – Beam Angle Selection

Gantry 230°

Gantry 205°

G = 230°

G = 205°
Distal Blocking

- selective pullback of range to spare OARs
- pullback achieved with added compensator
- potential pitfalls
  - setup error or motion may nullify sparing
  - ‘simple’ distal blocking may compromise target coverage
- assess robustness of approach
Distal Blocking

- Target
- Added compensator
- Distal block
- Range pullback
Distal Blocking

Whole BS

Partial BS

RPO Field
Clinical Tools

Integrate Clinical workflow
- clinical database
- web-based applications
  - mu model
  - physics qa
  - plan evaluation
- quality assurance
- clinical efficiency & efficacy
Plan/Dvh Evaluation

Dvh statistics for CTV, PTV, OARs are extracted manually from plots

Courtesy R. Malyapa, C. McKenzie, Z. Li
Electronic Q/A Process:
Upon export of tx plan to RT-PACS, clinical Q/A forms are generated. Active forms are sent via email to the personnel on the list. Contents of active forms is stored in a Clinical Information Database.

Courtesy V. Frouhar
Upon completion of treatment plan to RT-PACS, appropriate clinical Q/A forms are generated. Active forms are sent via email to the personnel on the list. Contents of active forms is stored in a Clinical Information Database.
# H & N Treatment Dosimetry Automated Report Sheet

<table>
<thead>
<tr>
<th>Patient Name:</th>
<th>UFPTI Patient</th>
<th>ID:</th>
<th>12345</th>
<th>Age:</th>
<th>32</th>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Physicist:</th>
<th>Physicist A</th>
<th>Dosimetrist:</th>
<th>Dosimetrist C</th>
<th>Physician:</th>
<th>Physician B</th>
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</thead>
</table>

<table>
<thead>
<tr>
<th>Disease Site:</th>
<th>Nasal</th>
<th>Tx. Room:</th>
<th>P2</th>
<th>Final Plan Name:</th>
<th>PNS</th>
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</table>

<table>
<thead>
<tr>
<th>Scan Date:</th>
<th>2/2/2009</th>
<th>Start Date:</th>
<th>2/14/2009</th>
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</table>

<table>
<thead>
<tr>
<th>Site Protocol</th>
<th></th>
<th></th>
<th></th>
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</tr>
</thead>
</table>

- **Initial Dose**
  - Standard risk
    - 45.5 Gy @ 1.5 Gy/frac. QO
  - Intermittent high risk
    - 64 Gy @ 1.8 Gy/frac. QO MRT

<table>
<thead>
<tr>
<th>Boost Dose</th>
<th>High Risk:</th>
<th>None (low neck photons)</th>
<th>None (low neck photons)</th>
</tr>
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</table>

<table>
<thead>
<tr>
<th>4D CT/Image Fusion</th>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td>Physician: Select</td>
<td>Date:</td>
<td>Physicist: Select</td>
</tr>
<tr>
<td>CT without contrast</td>
<td>CT with contrast</td>
<td>MR:</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Contours</th>
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<tbody>
<tr>
<td>Physician: Physician B</td>
<td>Date:</td>
<td>2/10/2009</td>
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</table>

<table>
<thead>
<tr>
<th>Dosimetrist:</th>
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</thead>
<tbody>
<tr>
<td>Malignant</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brainstem+3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brain</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L/RT O.N.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other:</td>
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</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Physician:</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>L/RT SMLG</td>
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<tr>
<td>Brainstem</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chest</td>
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<tr>
<td>Other:</td>
<td></td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Targets:</th>
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</thead>
<tbody>
<tr>
<td>GTV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CTVs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PTVs</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### DVH Analysis

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>PTV D95 = 100%</td>
<td>95%</td>
</tr>
<tr>
<td>PTV Hotspot V110% ≤ 20%</td>
<td>6%</td>
</tr>
<tr>
<td>PTV D99 &lt; 93%</td>
<td></td>
</tr>
<tr>
<td>Brainstem Surface ≤ 64 CGE</td>
<td></td>
</tr>
<tr>
<td>Brainstem Middle ≤ 55 CGE</td>
<td></td>
</tr>
<tr>
<td>Brainstem Post ≤ 50 CGE</td>
<td></td>
</tr>
<tr>
<td>Cord D0.1 cc ≤ 50 Gy</td>
<td>2</td>
</tr>
<tr>
<td>Cavern 0.1 cc = 31</td>
<td>≤ 55 CGE</td>
</tr>
<tr>
<td>LT O N. 0.1 cc = 37</td>
<td>≤ 55 CGE</td>
</tr>
<tr>
<td>Contralateral portal mean dose ≤ 26 Gy</td>
<td></td>
</tr>
<tr>
<td>Petoe (posterior globe) D0.1 cc ≤ 50 Gy</td>
<td></td>
</tr>
<tr>
<td>RT Roda = 41</td>
<td></td>
</tr>
<tr>
<td>LT Roda = 41</td>
<td></td>
</tr>
<tr>
<td>RT O N. 0.1 cc = 32</td>
<td>≤ 55 CGE</td>
</tr>
</tbody>
</table>

### Chart

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dose: Initial</td>
<td>74.4 CGE</td>
</tr>
<tr>
<td>Dose: Boost</td>
<td>0 CGE</td>
</tr>
<tr>
<td># Pred. dose/day</td>
<td>3</td>
</tr>
<tr>
<td>Prescription updated</td>
<td></td>
</tr>
</tbody>
</table>
Integration of Clinical Workflow

- **Patient Information**
- **HIS**
- **External Connectivity**
- **R&V**
- **IGRT Linac**
- **TPS**
- **CT Sim**
- **PET/MR**
- **Quality Assurance**
- **Clinical Data Management & Workflow**
- **Machine Data**
- **Delivery Setup**
- **Physics Calc.**
- **RX**
- **Physician**
- **Physicist**
- **Dosimetrist**
- **Therapist**
Golden Beam Data

- TPS commissioning time consuming
- Share beam data among gantries (institutions)?
  - Golden beam data set
  - Accuracy requirements on modeling parameters
    - Pristine depth dose & SOBP
    - Effective source size
    - Virtual SAD
    - Effective SAD
max error in penumbra of ±0.5mm in air, at isocenter

Courtesy R. Slopsema
Golden Beam Data

Range = 15.10 g/cm² - Mod = 10.40 g/cm²

Range = 25.00 g/cm² - Mod = 12.00 g/cm²
Analytical Proton Algorithms provide accurate dose model

Proton specific clinical planning issues requires vigilance

Dose plan is a snap shot of dose distribution

Dose delivered depends on
- uncertainties in range, setup, organ motion, etc.

Select beams and parameters to minimize uncertainties

Tools to integrate clinical workflow are essential

Golden beam data looks feasible
Thanks!