Treatment planning for scanned proton beams and IMPT

Tony Lomax, Centre for Proton Radiotherapy, Paul Scherrer Institute, Switzerland
Treatment planning for scanning

1. Single Field, Uniform Dose (SFUD)
2. Intensity Modulated Proton Therapy (IMPT)
3. Field selection in proton therapy
4. Dealing with uncertainties
4. Summary
Spot scanning with protons

Spot scanning – the principle

Proton pencil beam

‘Range shifter’ plate

Magnetic scanner

Target

Patient

Single field, uniform dose (SFUD) planning

The combination of individually optimised fields, each of which deliver a (more or less) homogenous dose across the target volume

SFUD is the spot scanning equivalent of treating with ‘open’ fields.
Single Field, Uniform Dose (SFUD)

Selected spots

Spot weight optimisation

Initial dose distribution

Dose calculation

Optimised dose

Dose Calculation

Dose calculation

protons useful in planning in practice

Tony Lomax, PTCOG teaching course, 2008

Treatment planning for scanned proton beams and IMPT
A SFUD plan consists of the addition of one or more individually optimised fields. Note, each individual field is homogenous across the target volume.
Single Field, Uniform Dose (SFUD)

1st series (0-40CGE)
3 field ‘hand’ plan to PTV

+ =

2nd series (40-74CGE)
3 field ‘hand’ plan to ‘TechPTV’

An example SFUD treatment

Full treatment

Treatment planning for scanned proton beams and IMPT

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The TechPTV or ‘Virtual 3d block’

In order to carve-out dose to neighbouring critical structures, need to be able to ‘block’ out dose

Modified target volume used to define ‘Virtual 3d blocks’

Currently, such volumes are defined manually on a slice-by-slice basis
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Intensity Modulated Proton Therapy (IMPT)

The simultaneous optimisation of all Bragg peaks from all fields (with or without additional dose constraints to neighbouring critical structures)

IMPT is the spot scanning equivalent of IMRT (and field patching for passive scattering proton therapy).
The simultaneous optimisation of all Bragg peaks from all incident beams. E.g..

Lomax 1999, PMB 44: 185-205
Intensity Modulated Proton Therapy (IMPT)

Example clinical IMPT plans delivered at PSI

Skull-base chordoma

3 field IMPT plan to an 8 year old boy

4 fields

3 fields

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There's more than one way to optimise an IMPT plan...

E.g...

- 'flat SOBP'
  - Individual Bragg peaks

...Or

- 'gradient SOBP'
  - Individual Bragg peaks

Albertini and Lomax 2007, IJROBP

Tony Lomax, PTCOG teaching course, 2008
Spot weight degeneracy in IMPT.

There’s more than one way to optimise an IMPT plan...

E.g...

‘flat SOBP’

...Or

‘gradient SOBP’

Albertini and Lomax 2007, IJROBP
Spot weight degeneracy in IMPT.

There's more than one way to optimise an IMPT plan...

‘Gradient’ vs ‘Flat’

Very similar PTV coverage but with significantly higher dose in entrance region for ‘Gradient’ SOBP.

This can be an ‘invisible’ consequence of the starting conditions for optimisation.

Albertini and Lomax 2007, IJROBP

Treatment planning for scanned proton beams and IMPT

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Spot weight degeneracy in IMPT.

Two, 5 field IMPT dose distributions

Corresponding spot weight distributions from field 2
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Geometric avoidance of organs at risk.

The selection of beam incidences which avoid critical structures leads…

…‘automatically’ to reduced doses to the critical structures
For same mean dose to target, 15MV photons deliver an integral dose of.. 16%…

…and 19%

The corresponding values for two proton fields are.. 7%…

…and 13%
Avoidance of coarse density heterogeneities.

- Accuracy of dose calculations
- Effects on dose homogeneity and conformity
- Sensitivity of a plan to spatial delivery uncertainties.
Field selection for proton therapy.

A ‘homogenous’ field direction

Analytical  |  MC

Difference histogram

Vol = 86%
Vol = 99%

An ‘inhomogenous’ field direction

Analytical  |  MC

Difference histogram

Vol = 64%
Vol = 89%

Treatment planning for scanned proton beams and IMPT

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Field selection for proton therapy.

Effects on (single field) dose conformity

Example field through relatively homogenous anatomy

Example field through very inhomogenous anatomy
Nominal 3 field spot scanned proton plan

Dose differences after recalculation in repeated CT (residual error ~1mm!)

Alessandra Bolsi, PSI

Field selection for proton therapy.
Can the order of density heterogeneity in a field be quantified?

The Heterogeneity index – a measure of the local integral density gradient for points that lie on the proximal surface of the target (after B Schaffner et al 1999).
Can the order of density heterogeneity in a field be quantified?

<table>
<thead>
<tr>
<th>Field</th>
<th>Applied plan</th>
<th>‘Standard’ plan</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Gantry angle</td>
<td>Table angle</td>
</tr>
<tr>
<td>1</td>
<td>-45</td>
<td>-90</td>
</tr>
<tr>
<td>2</td>
<td>-10</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>-120</td>
<td>-120</td>
</tr>
</tbody>
</table>
Can the order of density heterogeneity in a field be quantified?

Analysis of differences (gamma analysis) between doses calculated on nominal and spatially shifted CT’s ($\sigma=2\text{mm}$) for 42 fields of varying heterogeneity index.

<table>
<thead>
<tr>
<th>Field Selection</th>
<th>With internal heterogeneities</th>
<th>Homogenous CT</th>
</tr>
</thead>
<tbody>
<tr>
<td>HI V ($\text{gamma}&gt;1$) [%]</td>
<td>[Graphs showing differences in heterogeneity]</td>
<td>[Graphs showing differences in heterogeneity]</td>
</tr>
</tbody>
</table>

Cezarina Negreanu, PSI (supported by Siemens)
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To PTV or not to PTV? – that is the question

- Definition of a PTV is conventional way of dealing with potential delivery errors
- For passive scattering protons, PTV often not used with uncertainties dealt with through expansion of apertures and smoothing and shaving of compensator
- No collimators or compensators for scanning, therefore current method is to define PTV
- Is this necessarily the best approach?
Do we need field specific PTV’s?

E.g. could be necessary if $\sigma_{pos} <> \sigma_{range}$

..or when passing along strong density interfaces (c.f. smearing of compensators)
Dealing with uncertainties – To PTV or not to PTV

PTV’s in the presence of areas of low density

‘Normal’ situation. More or less regular grid of spots covering whole PTV

Situation in lung. No Bragg peaks can be placed in PTV due to low density.

Situation for superficial CTV’s. No Bragg peaks can be placed in part of PTV that extends into air.
Dealing with uncertainties – To PTV or not to PTV

Example of hot-spots on surface due to ‘missing spots’ in PTV

Planned to actual PTV

Planned to ‘TechPTV’, pulled 5mm away from surface
The advantage of protons is that they stop.

The disadvantage of protons is that we don’t always know where…
Dealing with uncertainties – range uncertainties.

Sources of range uncertainties

- Limitations of CT data (beam hardening, noise, resolution etc) \[\Sigma \sim 1\%\]
- Uncertainty in energy dependent RBE \[\Sigma \sim 2\%\]
- Calibration of CT to stopping power \[\Sigma \sim 1-2\%\]
- CT artifacts \[\Sigma\]
- Variations in patient anatomy \[\Sigma, \sigma\]
- Variations in proton beam energy \[\sigma\]
- Variations in patient positioning \[\sigma\]

Range errors are generally systematic!
Dealing with uncertainties – range uncertainties.

Consider 5 field 3D-IMPT and DET plans for a prostate case simulated in a homogenous phantom.

3D IMPT

DET
Dealing with uncertainties – range uncertainties.

Now recalculate assuming a 3% over- or undershoot of all Bragg peaks…

3D IMPT

3% undershoot

3% undershoot

3% overshot

3% overshoot

DET

3% undershoot

3% undershoot

3% overshoot

3% overshoot

DET appears to be VERY sensitive to even modest range uncertainties!

Note: DET is just one ‘flavour’ of IMPT
Dealing with uncertainties – range uncertainties.

Range uncertainty for SFUD and IMPT plans


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Dealing with uncertainties – range uncertainties.

Range uncertainty for SFUD and IMPT plans

+5% CT  
-5% CT

Dealing with uncertainties – range uncertainties.

Range uncertainty for SFUD and IMPT plans

Dealing with range uncertainties - robust IMPT planning?


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Dealing with range uncertainties – robust IMPT planning?


Treatment planning for scanned proton beams and IMPT

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Summary

- Although many similarities with conventional therapy, there are some significant differences and issues for planning active scanned proton and IMPT plans.
- Is the conventional PTV criteria still valid? Are field specific PTV’s required?
- Active scanned plans (fields) have a large degeneracy – many distributions of pencil beam intensities give very similar dose distributions.
- In general, spot scanned plans are more sensitive to errors than conventional photon plans and IMPT plans more sensitive to simple spot scanned plans.

Don’t abandon ‘simple’ planning techniques (e.g. SFUD)!