Treatment planning for scanned proton beams

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Francesca Albertini, PTCOG teaching course, 2010
Outlook

1. Planning with active scanning protons in practice
2. Single Field Uniform Dose (SFUD) plan
3. Intensity Modulated Therapy (IMPT) plan
4. Range uncertainties
5. Plan robustness
6. Summary
Planning with active scanning protons

Spot scanning

Magnetic scanner

Proton pencil beam

Energy change (e.g. ‘Range shifter’ plate)


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Planning with active scanning protons

Optimization process: in practice

Scheib, ETH Diss 10451, 1993

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Planning with active scanning protons

Spot definition

Incident field

Scheib, ETH Diss 10451, 1993

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Spot selection

Incident field

Scheib, ETH Diss 10451, 1993

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Planning with active scanning protons

- Selected spots
- Initial dose distribution
- Spot weight optimisation
- Optimised dose

Scheib, ETH Diss 10451, 1993

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Single Field, Uniform Dose (SFUD) planning

The combination of individually optimized 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)

An example SFUD plan

Note, each individual field is homogenous across the target volume.
Single Field, Uniform Dose (SFUD)

1st series (0-40CGE)
3 field SFUD plan to PTV

2nd series (40-74CGE)
3 field SFUD plan to 'TechPTV'

+ =

An example SFUD treatment

Full treatment

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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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3. **Intensity Modulated Therapy (IMPT) plan**
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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).

*Lomax PMB 1999
Intensity Modulated Proton Therapy (IMPT)

An example IMPT plan

Note, each individual field is highly in-homogenous (in dose) across the target volume (c.f. SFUD plans)
Example clinical IMPT plans delivered at PSI

Skull-base chordoma

3 field IMPT plan to an 8 year old boy

4 fields

3 fields
Spot weight degeneracy in IMPT

There’s more than one way to optimize an IMPT plan... (ex. 1)

E.g., “flat” SOBP

...or “gradient” SOBP

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Spot weight degeneracy in IMPT

There's more than one way to optimize an IMPT plan ...(ex. 1)

E.g. "flat" SOBP

...or "gradient" SOBP
Spot weight degeneracy in IMPT

There's more than one way to optimize an IMPT plan...(ex. 1)

'Gradient' SOBP

Flat SOBP

Single field dose distribution

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 used for the optimization

Albertini, Hug, Lomax 2007, IJROBP

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Planning with protons is somehow more complicated than this! …many perils (e.g. range and set-up uncertainties) are hidden along the way!
The advantage of using protons for radiotherapy is that they stop...
...the disadvantage of using protons for radiotherapy is that you don’t always know where!

Bragg-peak curve

Critical structure

dose

depth
Sources of range uncertainties

- Limitations of CT data (beam hardening, noise, resolution etc)
- Uncertainty in energy dependent RBE
- Calibration of CT to stopping power
- CT artifacts
- Variations in patient anatomy
- In-homogeneity along the beam path
- Variations in proton beam energy
- Variations in patient positioning

Range errors are generally systematic!
Range uncertainties: metal artifacts

kV-CT

Accuracy of range calculation due to reconstruction artifacts?

MV-CT (tomotherapy)

No artifacts and linear relationship CT units to proton stopping power

Ospedale San Raffaele, Milan

Ospedale San Raffaele, Milan
Range uncertainties: metal artifacts

Stopping power profiles

kV-CT artifacts

Prosthesis

Careful when planning in presence of metal artifacts

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Sources of range uncertainties

- Limitations of CT data (beam hardening, noise, resolution etc)
- Uncertainty in energy dependent RBE
- Calibration of CT to stopping power
- CT artifacts
- Variations in patient anatomy: examples
  - In-homogeneity along the beam path
  - Variations in proton beam energy
  - Variations in patient positioning
Range uncertainties: anatomy changes

Case 1: the bad of protons

“The case of the wrong underwear”
Range uncertainties: anatomy changes

Case 1: the bad of protons

CT is a snap-shot of the “density of the day”
‘Dose plan’ is only a snap-shot of the real dose distribution

Max range difference: Target    3.6 cm

“The case of the wrong underwear”

Un-expected change

Dose difference (recalc-nom)
Range uncertainties: anatomy changes

Case 2: the good of protons

„The case of the sweet cookies“

Max range differences:
- cauda + 8 mm
- target + 15 mm

What happens to the ‘dose hole’?

Note: dose hole around the cauda in the middle of target

Albertini et al Radiother. Oncol 2008

123%
90%
80%
70%
60%
50%
40%
30%

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Range uncertainties: anatomy changes

Case 2: the good of protons

"The case of the sweet cookies"

Nominal plan

Recalculation on new CT

123%
90%
80%
70%
60%
50%
40%

122%
90%
80%
70%
60%
50%
40%

'tDose plan' is a snap-shot of the real dose distribution...

...luckily IMPT plans are often more robust (i.e. less sensitive) to range errors than initially imagined!

Albertini et al Radiother. Oncol 2008

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It is potentially misleading to present a single dose distribution as "the" dose distribution characterizing a patient's treatment. At every point within the patient there is in fact a range of possible doses which may be delivered. That is to say, at each point with a conventional dose distribution there should be associated an "error bar". " (Goitein M 1986 PMB)

This is not an apple!: what you see is not what you get! (Lomax PTCOG 2009)

FUTURE: easy tool to evaluate plan robustness (for different sources of errors)
3 field SFUD plan
Nominal dose distribution

To assess plan robustness:
1. calculate n- ‘error’ dose distributions (e.g. set-up errors)
To assess plan robustness:

1. Calculate n- ‘error’ dose distributions (e.g. set-up errors)

huge amount of data to be treated

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To assess plan robustness:
1. calculate n- ‘error’ dose distributions (e.g. set-up errors)
2. reduce the data so that result can be easily understood

Max-to-Min dose distribution

ERROR BARS

Tool to assess plan robustness
Tool to assess plan robustness

3 field SFUD plan
Nominal dose distribution

Max-to-Min dose distribution
(= error bars within 95% CI)

See Albertini Saturday 22 May (12:00)
SUMMARY
Summary

- Although many similarities with conventional therapy, there are some significant differences and issues for planning active scanned proton and IMPT plans.

- 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).

- It is worth to move towards the routine use of error analysis tools to assess plan robustness.
Thanks for your attention!