State-of-the-art proton therapy: The physicist’s perspective

Tony Lomax, Centre for Proton Radiotherapy, Paul Scherrer Institute, Switzerland
Overview of presentation

1. State-of-the-art proton delivery
2. Current challenges
3. New directions in proton therapy
4. Summary
State-of-the-art particle therapy:
The physicist’s perspective

Tony Lomax, PTCOG47, Jacksonville, 2008

Current delivery technology

Passive scattering

Range-shifter wheel
Scatterer
Collimator
Compensator
Target
Patient
Current delivery technology

Single passively scattered field

- Fixed extent SOBP leads to poor sparing of normal tissue proximal to target

Three passively scattered fields

- Conformation of dose can be improved through the use of multiple fields

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Current delivery technology

Spot scanning

Proton pencil beam

‘Range shifter’ plate

Magnetic scanner

Target

Patient

Current delivery technology

Selected spots

Dose calculation

Initial dose distribution

Spot weight optimisation

Dose Calculation

Optimised dose

Scheib, ETH Diss 10451, 1993

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Scheib, ETH Diss 10451, 1993

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A SFUD (single field, uniform dose) plan consists of the addition of one or more individually optimised fields. Note, each individual field is homogenous across the target volume.
Intensity Modulated Proton Therapy: The simultaneous optimisation of all Bragg peaks from all incident beams. E.g.,


State-of-the-art particle therapy: The physicist’s perspective

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Current delivery technology

The three ‘orders’ of proton therapy compared

Passive scattering
1 field
3 fields

SFUD
1 field
3 fields

IMPT
1 field
3 fields

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The advantage of protons is that they stop.

The disadvantage of protons is that we don’t always know where…

10% range error
Current challenges: range uncertainty

Tumour shrinkage

Initial Planning CT
GTV 115 cc

5 weeks later
GTV 39 cc

S. Mori, G. Chen, MGH, Boston

State-of-the-art particle therapy:
The physicist’s perspective
Current challenges: range uncertainty

Tumour shrinkage

Planning CT

CT after 5 weeks

Beam stops at distal edge

Beam overshoot

S. Mori, G. Chen, MGH, Boston
Current challenges: range uncertainty

Patient weight changes

3 field IMPT plan to an 8 year old boy

During treatment, 1.5kg weight gain was observed

Note, sparing of spinal cord in middle of PTV

Max range differences:
- SC 0.8cm
- CTV 1.5cm

Francesca Albertini and Alessandra Bolsi (PSI)

State-of-the-art particle therapy:
The physicist’s perspective
### Current challenges: range uncertainty

<table>
<thead>
<tr>
<th></th>
<th>Nominal plan</th>
<th>Recalculation on new CT</th>
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</thead>
<tbody>
<tr>
<td><strong>CTV</strong></td>
<td>Mean</td>
<td>V90</td>
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<tr>
<td>Nominal</td>
<td>96.5%</td>
<td>78%</td>
</tr>
<tr>
<td>New</td>
<td>95.0%</td>
<td>74%</td>
</tr>
<tr>
<td><strong>Spinal cord</strong></td>
<td>Mean</td>
<td>Max</td>
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Current challenges: range uncertainty

CT artefacts

Many patients referred for RT post-operatively and with metal (titanium) stabilisation.

How accurately can we calculate proton ranges in such CT data sets?
Current challenges: organ motion

What is the effect of organ motion on proton therapy?

4D-CT derived from 4D-MRI
Current challenges: organ motion

Organ motion and passive scattering

Parallel opposed photons

Single field photons

Images courtesy of Thomas Bortfeld, MGH, Boston
Current challenges: organ motion

Organ motion and passive scattering

Parallel opposed photons  |  Single field photons  |  Single field protons

Images courtesy of Thomas Bortfeld, MGH, Boston
Current challenges: organ motion

Organ motion and scanning

A scanned beam in a moving patient.

4D-CT derived from 4D-MRI

Martin von Siebenthal, Phillipe Cattin, Gabor Szekely, Tony Lomax, ETH, Zurich and PSI, Villigen
Current challenges: organ motion

Organ motion and the ‘interplay’ effect

Nominal (static) dose

Calculated with ‘real’ motion from 4D-MRI of volunteer
Current challenges: organ motion

Organ motion and the ‘interplay’ effect

Motion patient 1
Amplitude ~ 11mm

Motion patient 2
Amplitude ~ 8mm

Scanning is particularly sensitive to organ motion
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New directions in proton therapy

1. Possible improvements to passive scattering
2. Dealing with range uncertainties
3. Organ motion and scanning
Improvements to passive scattering

Field specific hardware for passive scattering

Collimator

Compensator

Can these be automated?
Improvements to passive scattering

Proton Multi-leaf collimators

Particle MLC from Chiba (Japan)

- Saves changing collimators every field
- Can be used to ‘simulate’ scanning
- Could be used to deliver IMPT?
Proton Multi-leaf collimators

Film dosimetry performed at Loma Linda using MLC and passively scattered proton beam

Shape at surface

Shape after 29cm water

Mike Moyers, LLUMC
Improvements to passive scattering

Proton Multi-leaf collimators
Simulated scanning using dynamic MLC’s

- MLC opening
- Energy 1
- Energy 2
- Energy 3
- Energy 4
- Energy 5
- Energy 6

Proximal conformation

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Proton Multi-leaf collimators

IMPT using dynamic MLC’s?

Improvements to passive scattering
New directions in proton therapy

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Dealing with range uncertainties

Imaging for range

**MV-CT**
- kV-CT
- MV-CT (Hi-Art)

**Proton radiography**
- Proton radiograph
- Proton DRR

**Activation PET**
- Measured PET activation
- Calculated PET activation

Ospedale San Raffaele, Milan
Francesca Albertini, PSI

Uwe Schneider, Zurich
Alexander Tourovsky, PSI

Katia Parodi, Thomas Bortfeld
MGH, Boston

State-of-the-art particle therapy:
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Dealing with range uncertainties

Range adapted proton therapy

Alessandra Bolsi, PSI
Dealing with range uncertainties

Range adapted proton therapy

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New directions in proton therapy

1. Possible improvements to passive scattering

2. Dealing with range uncertainties

3. Organ motion and scanning
Rescanning

Repaint scanned beam many times such that statistics dictate coverage and homogeneity of dose in target (c.f. fractionation)
Rescanning

Re-scanning in presence of $\cos^4$ motion with 1cm amplitude

- Cylindrical target volume
- Re-scanned different times to same total dose
- Scan times calculated for realistic beam intensities and dead times between spots
- Analysis carried out for different periods of motion

Not always improving homogeneity with number of re-scans!

Marco Schwarz, Sylvan Zenklusen ATREP and PSI
Rescanning
The ‘synchronicity’ effect

- Very preliminary results
- A ‘real’ effect for perfectly regular breathing?
- Could well be less of an issue when breathing is more irregular
- For regular breathing, could be avoided by selecting the rescanning period to avoid effect or varying period scan-to-scan
- Probably not a big issue in reality

See presentation from Silvan Zenklusen, Saturday
Track motion of tumour using scanning system based on some anatomical/physiological signal.
Organ motion and scanning

Tumour Tracking

Plot of dose homogeneity as function of RMS position error due to motion and ‘imperfect’ tracking

\[ \cos^4 \text{ motion with varying detection delays and tracking accuracies} \]

Steven van de Water, PSI/TUDelft

State-of-the-art particle therapy: The physicist’s perspective
Re-tracking – tracking the tumour repeatedly within one fraction

E.g. 4 times

Vedam et al 2004

\(~150\text{ms delay}\)
Main features:

- Fast upstream energy variation (~150ms for 5mm range step)
- Double magnetic scanning
- Capable of delivering 2Gy/litre in 6s!
- ‘Simulated parallel scanning’ – passive scattering with a scanning gantry
- First patients – summer 2009
The PSI Gantry 2

Organ motion and scanning

How it looks now...

... and how it will look by the end of 2008

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Organ motion and scanning

FIRST BEAM THROUGH THE NEW GANTRY 2 OF PSI


...another milestone for the PSI therapy project
(A. Lomax, M. Jermann, E. Pedroni, C. Bula, D. Meer, M. Schippers and T. Böhringer)

... the reason for the happiness

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Summary

• Although passive scattering is still the preferred choice for proton therapy, scanning and IMPT will become more widespread in the next years (c.f. MD Anderson)

• To what extent can scattering be improved through the use of automated field hardware (MLC’s etc)?

• Range uncertainty and organ motion (particularly for scanning) remain the main challenges to proton therapy and much interesting and exciting work is still to be done in organ management, range imaging and adaptive proton therapy

• The field is ripe for new input, ideas and innovations…