Chapter 9
Field Shaping: Scanning Beam

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June 14-18, 2015

AAPM - Summer School 2015, Colorado Spring
Acknowledgement

- Falk Poenisch, PhD
- Heng Li, PhD
- Xiaodong Zhang, PhD
- Narayan Sahoo, PhD
- Michael Gillin, PhD
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Spot Scanning of Proton Beam Delivery

Scanning Nozzle

Schematic of the Hitazchi scanning nozzle at the MD Anderson Cancer Center. Upper panel: major components (adapted from Fig.1 of ref. 27 with permission. Bottom panel: 3D rendering (from Fig. 4 of ref. 22 with permission)
Scanning Nozzle

- Elements unique to scanning nozzle:
  - Scanning magnets – scanning speed 5 to 20 m/s
  - Spot position monitor – monitoring the spot position and profile
Spot Scanning

- Discrete step & shot
- Beam stops at a planned position and delivers specific amount of dose
- The beam is then turned off and move to the next position
- Advantages:
  - Modulation achieved by varying the monitor units
  - No modulation in beam intensity and speed scanning is required
  - Safety of delivering process – verified each spot

- Disadvantages:
  - Less efficient due to the “dead time” between spots
Spot Scanning

- A target is divided into many layers
- A layer is divided into many spots
- Spots are irradiated one by one

Range modulation

Proton Beam

Scanning Magnets
Spot position checked after each spot. Maximum MUs per spot is 0.04 MUs.

Smith et al. Med Phys 2009
Delivery Timing Chart

- **Beam Energy Synchrotron**
  - Irradiating Beam Intensity
  - Layer
  - Time
  - Irradiation Time: 4.4 s max.
  - Spill Change: 2.1 s
  - Proton Charge: 3-5 nC/spill

- **Scanning Magnet Current**
  - Cumulated charge
  - Trigger
  - Preset
  - Time

- **Beam**
  - OFF
  - Spot 1
  - Spot 2
  - Time

- Proton Charge: typically 1-10 pC/spot
- Irradiation Time: typically 1-10 ms/spot
- Spot Interval: typically 3 ms/spot
Raster Scanning

- Similar to spot scanning except the beam is not switched off when moving to the next spot:

Fig. 2. Schematic of trajectories for three scanning methods. (a) Spot scanning, (b) raster scanning and (c) continuous raster scanning.

Furukawa et al, Med Phys 2007
Continuous Scanning

- The beam is continuously scanned and is only off when the energy is changed:
  - Scanning speed and beam intensity are modulated to create arbitrary complex fluence

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Fig. 2. Schematic of trajectories for three scanning methods. (a) Spot scanning, (b) raster scanning and (c) continuous raster scanning.

Furukawa et al, Med Phys 2007
Energy

- Proton energies: typically 70 to 240 MeV
- Range in water: 4 to 36 cm
- The selection of energies is determined by the ability to create a uniform SOBP using scanning beam
- For example - Hitachi system at MD Anderson: 94 energies – 72.5 to 221.8 MeV (range in water 4.0 to 30.6 cm):
  - 4.0 – 7.1 g/cm² (72.5 – 98.0 MeV): 0.1 g/cm² 31
  - 7.1 – 11.2 g/cm² (98.0 – 125.6 MeV): 0.2 g/cm² 20
  - 11.2 – 15.2 g/cm² (125.6 – 148.8 MeV): 0.3 g/cm² 13
  - 15.2 – 17.6 g/cm² (148.8 – 161.6 MeV): 0.4 g/cm² 6
  - 17.6 – 23.5 g/cm² (161.6 – 190.5 MeV): 0.5 g/cm² 12
  - 23.5 – 30.6 g/cm² (190.5 – 221.8 MeV): 0.6 g/cm² 12
- Range adjustment: = 0.1 g/cm²
  - Range shifter
**Energy - Example**

- Integrated depth dose for 94 energies
- Range resolution: 0.1 to 0.6 cm

(a) Integral depth doses for 94 energies in units of Gy mm²/MU generated using Monte Carlo simulation and (b) full-width-half-maximum (FWHM) of Bragg peak as a function of energy. (From Figure 2 of reference [27] with permission.)
Energy – Ridge Filter

- Many low energies make the delivery less efficient
- Mini Ridge filter (MRF):

Energy - Optimization

- Many low energies make the delivery less efficient
- Optimization - Mixed-integer programming (MIP)

Cao et al. PMB 2014
Energy - Optimization

- Many low energies make the delivery less efficient
- Optimization - Mixed-integer programming (MIP)

**Table 2.** Comparison of number of energies obtained from the conventional approach (all available) and the PER approach (reduced) for six IMPT plans.

<table>
<thead>
<tr>
<th>Plan</th>
<th>All (Conventional)</th>
<th>Reduced (PER)</th>
<th>Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prostate 1: two-field</td>
<td>19 + 19 = 38</td>
<td>14 + 19 = 32</td>
<td>15.9%</td>
</tr>
<tr>
<td>Prostate 2: two-field</td>
<td>19 + 18 = 37</td>
<td>12 + 18 = 30</td>
<td>18.9%</td>
</tr>
<tr>
<td>Prostate 3: two-field</td>
<td>20 + 19 = 39</td>
<td>13 + 19 = 32</td>
<td>17.9%</td>
</tr>
<tr>
<td>Prostate 4: two-field</td>
<td>24 + 25 = 49</td>
<td>23 + 19 = 42</td>
<td>14.3%</td>
</tr>
<tr>
<td>Lung: three-field</td>
<td>38 + 36 + 26 = 100</td>
<td>35 + 31 + 23 = 89</td>
<td>11.0%</td>
</tr>
<tr>
<td>Mesothelioma: three-field</td>
<td>63 + 59 + 59 + 57 = 238</td>
<td>40 + 47 + 51 + 37 = 175</td>
<td>26.5%</td>
</tr>
</tbody>
</table>

Cao et al. PMB 2014
Energy – Other Considerations

• For cyclotron based systems:
  – any energy (resolution ~ 0.1 MeV) could be selected by the treatment planning system (TPS)
  – Only selected number energies are used in each field

• Almost all systems use ~70 MeV as the lowest energy (~ 4 g/cm²):
  – Effectively transported from accelerator/energy selection system to the delivery nozzle
  – But too deep for shallow target volumes (e.g., head & neck)

• Range shifter:
  – 4 to 7 g/cm² at the end of the nozzle
Energy – Range Shifter

• Example: 6.7 g/cm$^2$ range shifter

- Smaller air-gap whenever possible
- Dosimetric dependence on air-gap
Energy – Range Shifter

- Different thickness of range shifter with air-gap 5 cm:
  - Lateral spot sizes
  - Longitudinal spot size

Titt et al, PMB 2010
Spot Spacing & Lateral Margins

- Current TPS limits to:
  - Rect-linear spot positions
  - Lateral spot spacing, $s$ is constant for each beam
  - Spot spacing in depth direction, depending on available proton beam energies ($\Delta d = 0.1 \sim 0.6$ cm for MDACC)

- Lateral spot margins:
  - Allow one spot outside the planning target volume, $s' = s$.
  - For better penumbra, $s'$ can be slightly < $s$.
  - $s'$ is equivalent to block margin
Spot spacing

- Spot spacing
  \[ s = \alpha \times FWHM_{air} \]
- What \( \alpha \) should be?

\[ \alpha = 0.8 \]
\[ \alpha = 0.65 \]
Spot spacing and penumbra

1. Evenly spaced/weighted spots to achieve uniform field

2. Optimum spacing/weighting to achieve sharper penumbra
Spot position uncertainty

Figure 9–8 (a) Uniform dose created by evenly spaced spots in a plane and (b) 1 mm spot position error for the spots at Y = 0 mm, resulting in dose deviation about ±7%
Spot position uncertainty

**Figure 9–7** Example of planned, measured, and recorded (in the treatment log file) spot positions for a proton beam with energy of 173.7 MeV. (a) A pattern with spots at (0,0), (−50 mm, 0), (50 mm, 0), (0, −50 mm), (0, 50 mm), (−100 mm, 100 mm), (100 mm, 100 mm), (100 mm, −100 mm), and (−100 mm, −100 mm). (b) A close-up view of the spot position planned at (100.0 mm, 100.0 mm), the measured position using film (100.2 mm, 100.8 mm), and the mean recorded position (100.4 mm, 100.6 mm).
Spot position Uncertainty

- Peterson et al. (PMB 2009) attributed spot position errors due to uncertainties in scanning magnets.
- Yu et al. (Med Phys 2014) reported that smaller spot spacing would result in the dose distribution less sensitive to the spot position error.
Maximum MU/spot

- MaxMU/spot:
  - Necessary for safety consideration – stop wrong position/dose before too much dose is delivered
  - Important to achieve precise measurements of spot position and size – spot position monitor might have limited dynamic range
  - Set the up limit of MU per spot – re-scanning if the spot MU exceeds the up limit
  - Lower the MaxMU/spot to force more re-scanning (isolayer)
Minimum MU/spot

- miniMU/spot:
  - Imposed on by the delayed charge – small amount charge that leaks because of the finite time required to stop the delivery.
  - Typically miniMU/spot is set to be ~ 2 x delayed charge
Potential Impact of mini MU/spot

• If the miniMU/spot is not considered by the optimization algorithm in the TPS, there are rounding errors introduced by the post-processing.

• Significant distortions from ideally optimized dose distribution could be introduced by the rounding process. For example,
  – Spots with MUs < 0.5minMU/spot → “0”
  – Spots 0.5minMU/spot < MUs < minMU/spot → “miniMU”
  – Zhu et al. (Med Phys 2010) studied the dependence of this effect on dose/field, SOBP width, spot spacing and beam range.
  – “MU starvation” – not enough MUs to be shared to keep spots > miniMU/spot.
Effect of miniMU Constraint

- Dose/field dependence
- SOBP dependence
Effect of miniMU Constraint

- Range dependence
- Spots suffer from rounding error vs spot spacing – average 4 prostate patients
Effect of miniMU Constraint

- Range dependence
- Spots suffer from rounding error vs spot spacing – average 4 prostate patients
Example - Prostate case
Different spot spacing (SS)

- (a) Without miniMU constraint
- (b) With miniMU constraint

Solid lines: SS = 0.7 cm
Dashed line: SS = 0.4 cm
Dynamic Collimator System

- Reduce the normal tissue dose

Hyer et al, Med Phys, 2014
Hyer et al, PMB 2014
Scanning beam for moving targets

• Interplay effect – between the motion of the scanning beam and respiratory motion
• It will be discussed in Chapter 24 in details
• We only discuss:
  – How to perform motion analysis
  – How to assess the dosimetric impact

Yupeng Li, MS
IMPT Treatment Planning For Lung Cancer

New Patients with 4DCT

Motion <=5 mm

N → Additional Analysis Required / Not Recommended for IMPT

Y →

SFO/Eclipse

Robust MFO

Robust Evaluation

Physicist and Physician Review & Approval

Monitor inter-fractional anatomic change with verification plan on repeat 4DCT

“Optimal plan” for patient treatment

Chang et al IJROBP 2014
How to quantify the motion?

• Along the beam direction:
  – Motion in this direction has little dosimetric effect
  – WET changes – selecting gantry angles with smallest $\Delta$WET

• Perpendicular to the proton beam direction:
  – In the axial plane – depending on gantry angle
  – Superior/inferior direction – independent gantry angle
Tumor motion analysis

- Using ray tracing method to determine WET changes between T0 & T50 along the beam direction
- Deformation vector between T0 & T50 - for motion analysis
  - 3 components:
    - Parallel to the proton beam
    - Perpendicular to the proton beam – in the axial plane
    - Perpendicular to the proton beam – superior/inferior
Tumor motion analysis – Example

- Adenocarcinoma of the left lower lobe lung cancer

Proton Beam

Gantry angles with smaller effect of motion
Tumor motion analysis – Example

- Adenocarcinoma of the esophageal cancer

**Proton Beam**

- $\parallel$ beam
- $\perp$ beam – axial
- $\perp$ beam – S/I

**Gantry angles with smaller effect of motion**
How to assess the dosimetric effect due to motion interplay?

• Measurements
  – Relatively simple dose distributions in simple phantoms

• Simulations:
  – 4D composite dose (4DCD)– equally weighted average dose among the respiratory phases of 4DCT.
  – 4D dynamic dose (4DDD)– estimation of the delivered dose under the influence of the interplay effect
  – 1FX dynamic dose (1FXDD)– one fraction 4D dynamic dose (Kardar et al PRO 2014)
4D Dynamic Dose - Simulation

Scanning beam treatment plan

4D Interplay Dose Simulator

Li Y et al Med Phys 2014
Kardar et al. PRO, 2014

Dose Distribution

Breathing Pattern
Simulation results - Examples

Magnitude of motion is NOT the only variable
- Smaller volume has larger relative effect

Li Y et al Med Phys 2014
Kardar et al. PRO, 2014
Reduce the max MU for each spot

4D Composite

MU = 0.04

MU = 0.01

Isodoses (cGy)
7000.0
4500.0
1000.0

MU = 0.005

Isolayer re-scanning

Kardar et al PRO 2014
Dynamic Dose based workflow

4DCD and 1FXDD
\[ d = [CTV(V_{p\text{composite}}(\%))- V_{p\text{dynamic}}(\%))] \]

≤3% \[ Y \rightarrow \text{IMPT} \]

No IMPT \[ N \]

Adapted from Kardar et al. PRO 2014
Other factors to consider

• Optimized delivery sequence – interplay effect would be reduced if one could effective reduce the dose rate:
  – Li H et al, Med Phys 2011
  – Li H et al, IJOBP (under review)

• Fraction re-scanning - The motion interplay effect on the accumulated dynamic dose will be averaged out over a normal course of the fractionated treatment delivery:
  – Li Y et al. Med Phys 2014
  – Grassberger et al. IJOBP 2013
Moving targets

• Motion analysis
  – Gantry angles with minimum effects of motion
  – Select scanning direction

• 4D Dynamic dose simulation to determine,
  – If the patient can be treated with IMPT
  – If not, use motion mitigation methods:
    • Isolayer re-scanning
    • Optimized delivery sequence
    • 4D robust optimization
    • Breath hold, Gating and others (future developments)
  – Also consider fractional re-scanning

• Recommendation: Each institutions should perform its own analysis & simulation to determine if a moving target can be treated with IMPT.
Summary

• Scanning beam technology has created a new era of radiation therapy
• Field shaping with scanning beam is achieved through scanning magnets
• The positions and weights of beam are determined through a optimization process
• Motion interplay effect remains a challenge for scanning beam delivery
• 3D collimation may useful for low energy beams
• Delivery efficiency is important to consider for any busy clinic
Thank you!