IMPT Delivery Systems and Current Limitations

Lei Dong, PhD
Scripps Proton Therapy Center
San Diego, California

AAPM Symposium
July, 2014

Disclosure

• Varian’s ProBeam user

Goals

• To learn about typical components of IMPT delivery system
• To understand various potential limitations in treatment delivery and treatment planning
Scripps Proton Therapy Center Layout

Five Treatment Rooms
3 – Isocentric Gantry Rooms
2 – Fixed beam rooms

Cyclotron

Alternating Radio Frequency (RF) voltage accelerates protons when they go across the gap in each turn.
Current Modulation

Vertical Deflector Transmission curve
What is the maximum number of beam spots deliverable within one gating window for synchrotron based scanning proton beam therapy of lung cancer?

Yoshikazu Tsunashima¹, Sastry Vedam², Lei Dong², Masumi Umezawa³, Xiaodong Zhang², Peter Balter² and Radhe Mohan²

1. Graduate School of Biomedical Sciences, University of Texas at Houston
2. Department of Radiation Physics, MD Anderson Cancer Center
3. Hitachi Ltd., Energy and Environmental Systems Laboratory

Key Result

Number of spots (average) delivered within one expiration phase from simulation results vs. Number of spots from treatment plan

Maximum number of spots/layer whose plot within $\sigma$ from the line

- 85 spots 30 %DC threshold
- 83 spots 20 %DC threshold
- 77 spots 10 %DC threshold

Cyclotron vs. Synchrotron

- Energy:
  - Degrader
  - 70 – 250 MeV
- Energy resolution:
  - ~ 0.1 MeV
- Beam current
  - 300 – 800 nA
- Intensity Modulation
  - Vertical deflector
  - Cycle time
    - Continuous (50 MHz)
- Energy:
  - On-demand acceleration
  - 70 – 250 MeV
- Energy resolution:
  - ~ 0.1 MeV (94 energies)
- Beam current
  - 300 – 800 nA
- Intensity Modulation
  - Modulated @ 1000 Hz, duty cycle 0.2%
- Cycle time
  - ~ 2 seconds
Beam Steering by Magnetic Fields

- Dipoles: for bending the beam
- Quadrupoles: focusing the beam
- Vacuum pumps to keep beamline under very high level of vacuum (think about outer space)
- Beam profile monitors to measure beam along the central tube

Beamline

Changing Field Strength and Managing Residual Magnetic Field

Magnetic Hysteresis

Compensation:
- Degaussing → Switching dipoles (MFCS)
- Initial Saturation → Quads & remaining Dipoles
Beam Delivery System

- Nozzle
- Lateral scanning system
- Position monitoring system
- Dose monitoring system
- Accessory holders (range shifter and aperture)
- Imaging (optional)

Scanning System Challenges

- Power requirements
  - Faster scans and large fields require high power (>1000A)
  - Raster vs. Spot Scanning
- High precision is required for magnetic field
- Gantry dependence
- Position monitoring at low dose rate
- Preferred fast scan direction to minimize breathing motion

Variations in proton scanned beam dose delivery due to uncertainties in magnetic beam steering

Stephen Peterson and Jerimy Polf et al.

Med. Phys. 36 (8), 2009
Variations in magnetic field strength leads to fluctuations in the steering of the pencil beams to their intended final position.

Analytical formula between magnet strength and lateral spot position

Magnetic steering beam position relationship: physics

Find the function mapping magnet strength to beam position:

Lorentz and centripetal force:

Relativity effect:

Results

Dose-spot displacement vs. absolute spot positions at fixed $\Delta B/B$
Position Monitor

- Multi Strip Ionization Chamber (MSIC) or two-dimensional multi-wire system is used to monitor spot position and spot shape

Minimum MU per Spot

- To accurately measure spot position and shape
- Delayed charge – delay of the beam termination
- Beamline activation at high energy
- (MDACC) Upper limit: Safety consideration – limit the maximum dose per spot

Impact of Scan Direction

Experiment: Tsunashima et al.

**Beam delivery**
- Field: 10cm x 10cm field
- Spot spacing: 8mm (x and y direction)
- Number of spot: 13 x 13 = 169 spots (one painting)
- Spot duration time: 7ms/spot (4ms delivery + 3ms moving)
- One layer time: 169 x 7ms = 1.2 s (one painting)
- Scan directions: Orthogonal and Parallel to Motion
**Results**

Orthogonal scan

Phantom motion
Reference:
- 10x10 cm² field
- Spot spacing 8mm
- 169 spots
- 1.18 s for delivery
- No repainting

Tsunashima et al.

Parallel scan

Phantom motion
Reference:
- 10x10 cm² field
- Spot spacing 8mm
- 169 spots
- 1.18 s for delivery
- No repainting

Tsunashima et al.

**Spot Size Issue**

In-air Spot Size (TR4)
Photons vs. Future Protons

IMRT

IMPT

Target

Spinal Cord


Impact of Spot Size to Planning Quality


H&N PTV 66 Gy

PTV1 (66 Gy) with sigma=5mm and several grids

- grid 2.8x2.8mm
- grid 3x3mm
- grid 3.5x3.5mm
- grid 4x4mm
- grid 5x5mm
- grid 5.5x5.5mm
- grid 6x6mm
- grid 7x7mm
- grid 8x8mm

Volume [%]

98% PD

Dose [Gy]

64.7 66.7 68.7 70.7 72.7 74.7
Conclusions

We determined the dependence of the maximum σ that obtains comparable target coverage and sparing of OARs to advanced photon techniques for three clinical cases: σ must be ≤4 mm for the head and neck cancer, ≤3 mm for the prostate cancer and ≤6 mm for the malignant pleural mesothelioma. Furthermore, the spot spacing was optimized for

Summary: Why is PBS Possible Today?

- Better power supply for magnets (dipole; quadruple; fast scanning coils)
- More advanced accelerator technology
  - More efficient accelerator
  - Better beam optics (smaller spots)
  - Fast energy change and current modulation
  - Automatic beam tuning and control system
  - Better and faster electronic circuits