Needs for Treatment Planning and Quality Assurance in Proton Spot Scanning Therapy

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PTV Doesn’t Work for Protons

- Single volume doesn’t describe necessary dose coverage for all beams
- Need to prescribe dose to CTV, with defined positional and range uncertainties
  - Evaluate CTV and OAR including uncertainties
- Optimization algorithm needs to consider these uncertainties when determining spot weights
  - Range uncertainties
  - Setup variations
  - Intra-fractional motion
Back to the PTV

Beam Direction 1

GTV

Positional Uncertainty
Back to the PTV

Beam Direction 1

GTV

Positional Uncertainty

Range Uncertainty
Back to the PTV

Positional Uncertainty

Range Uncertainty

GTV

Beam Direction 2
Proton PTVs Different for Each Beam
Evaluate DVH “band”, not just curve

Fig. 1. Comparison of the robust IMPT optimization method and the OTV-based method: DVHs of CTV and hypothalamus in a pediatric brain case. The DVHs for the nominal scenario and eight uncertainty scenarios are plotted in each panel. The result of the robust optimization is on the left, and the result of the OTV-based IMPT optimization is on the right.
Standard Optimization

Jan Unkelbach¹, Timothy C Y Chan² and Thomas Bortfeld¹
Range Uncertainty Optimization

(a) nominal range
(b) shorter range
(c) larger range
(d) beam at 45 degree
(e) beam at 0 degree
(f) standard deviation

Jan Unkelbach¹, Timothy C Y Chan² and Thomas Bortfeld¹
Dose Calculation

• It has been well published that current pencil beam calculation algorithms have notable limitations

• It has been recommended to use Monte Carlo calculations
Figure 5. Above are the dose colorwash of the TPS generated distribution (left) and the Monte Carlo generated dose distribution (right) for a central brain tumor with a CTV (red) that is approximately 2cm in diameter. The graph in the center displays the dose profile through the center of the CTV. Note that the MC dose distribution is 2.2% lower than that from the TPS. This difference is attributed to the small target size and the complex heterogeneous surroundings. This plan would be suitable for renormalization.
TPS on Left                          MC on Right
Robust Optimization

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Biological Considerations

- It has been well published that the Relative Biological effectiveness of Proton therapy is larger than 1.1 near the Bragg Peak.

- Notable side effects, such as Brainstem necrosis in pediatric cases have been reported.
Linear Energy Transfer

(a) Cell and Cell nucleus with Tracks

(b) Local Dose [Gy] vs. High LET Proton

(c) Local Dose [Gy] vs. Photons

(d) Local Dose [Gy] with x10000 increase
Fig. 1. Experimental proton RBE values (relative to $^{60}$Co) as a function of dose/fraction for $<100$-MeV beams and triangles for $>100$-MeV beams. Closed symbols show measurements using Chinese Hamster cells in the center of a SOBP. Circles represent data for other cell lines.

Fig. 2. Experimental proton RBE values (relative to $^{60}$Co) as a function of dose/fraction measured in vivo in the center of a SOBP. Closed symbols show RBE values for jejunal crypt cells, open symbols stand for RBEs for all other tissues. Circles represent RBEs for $<100$-MeV beams and triangles for $>100$-MeV beams.
Figure 6. RBE for cell survival as a function of \( LET_d \) at a proton dose of 2 Gy (from left to right: (\( \alpha/\beta \))\(_X \) between 0 Gy and 3 Gy, between 3 Gy and 6 Gy, between 6 Gy and 9 Gy, and above 9 Gy). The upper row shows all data points included in the analysis. The lower row includes only data with \( LET_d \) values \( \leq 15 \text{ keV \mu m}^{-1} \), the area most clinically relevant. \( LET_d \) values are given relative to the reference photon radiation. The solid lines are fits through the data included in each plot considering the published uncertainties. The dashed lines show the fit results without considering individual uncertainties.

**Beltran equation**

Dose/fraction = 2Gy

$\alpha/\beta = 3$

Dose/fraction = 2Gy

$\alpha/\beta = 6$
H&N $\alpha/\beta=2$ Biodose

MKM
Carabe
Wedenberg
McNamara
Beltran
LETd
H&N $\alpha/\beta=10$ Biodose

For large $a/b$ and large dose/fraction, maybe biological = physical dose
Modify the Treatment Plan based on biological considerations

Figure 6. Above are the dose colorwash for the LETd weighted biological dose calculation, (top) initial plan and (bottom) after mitigation for high biological dose. In the region of the biological hot spots, the physical dose of the initial plan is 2% higher than the modified plan, but the biological dose is ~10% different. Small modifications of margin and gantry angle resulted in an improved biologic dose profile in critical location such as the brainstem and spinal cord.
Biological based Treatment Planning
Quality Assurance

• For future Clinical trials involving spot scanning proton therapy,
  • Monte Carlo calculations are needed
  • Robust evaluation of the plans are needed
    • Ideally robust optimization
  • Biological considerations are needed

• For routine clinical QA
  • True Failure Mode Analysis is needed
  • There is not time to measure everything
  • May give a false sense of “quality”
Patient Specific QA with time consuming “flat water phantom” measurements
Moved to more efficient and meaningful Patient Specific QA

G30T0

Number of spots = 14356

1.2.246.352.71.5.412950970433.1842648.20151231145540_SI.dcm

Absolute Max Deviation = 0.0013 MU

X Deviations: Systematic Aborts = 0, Random Aborts = 0

Y Deviations: Systematic Aborts = 0, Random Aborts = 0
Thank you for your time

• QUESTIONS