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# Geometric Asymmetry and Rotation In Proton Pencil Beam Spots: Dosimetric Sensitivity to Beam Model Parameterization

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## PURPOSE

- Proton pencil beam scanning (PBS) spot profiles are traditionally modeled using orthogonal X and Y profiles.
- In-air measurements may exhibit asymmetry and rotation.
- This study evaluates whether rotation-aware elliptical spot characterization produces meaningful dosimetric differences compared to conventional symmetric beam model parameterization.

## MATERIAL & METHODS

- In-air proton spot profiles were measured using a high-resolution 2D scintillator detector (0.2 mm) for 227.1 MeV at seven longitudinal positions relative to isocenter (± 30, ± 20, ± 10 cm, and isocenter).
- Spot boundaries were fitted to an ellipse using direct least-squares conic method via singular value decomposition, yielding major axis, minor axis, and rotation angle.
- Lateral profiles along major and minor axes were compared with conventional orthogonal X–Y profiles in the clinical beam model.
- The beam model used TPS automodeling workflow, enforcing symmetric Gaussian spot representation ($\sigma_x = \sigma_y$).
- Dosimetric impact was evaluated in a water phantom using point dose, lateral, and depth dose profiles. Square-field sensitivity was assessed using a maximum-energy layer and three spread-out Bragg peak (SOBP) fields.
- Four anthropomorphic phantom test plans (Brain, Esophagus, Prostate, and Spine) were evaluated.

## RESULTS

- Spots exhibited rotation angles from 22.3° to 29.3°. Elliptical fitting yielded major and minor spot widths differing from the symmetric σ enforced by automodeling, reflecting features not explicitly modeled.
- Dosimetric impact was minor. For square SOBP fields, point dose differences were approximately 0.3%, with close agreement in lateral and depth profiles.
- Across composite plans, target DVH and point dose differences were mostly within 1%. Localized differences up to ~3% occurred for some organ-at-risk D1 values in high-gradient regions, without systematic shifts in target coverage.

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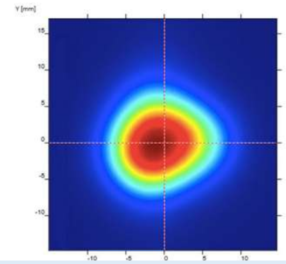


**Figure 1.** The measured spot in air at isocenter for 227.1 MeV

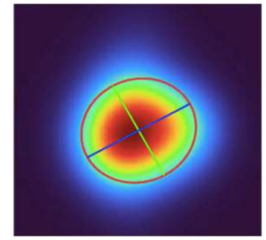

**Figure 2.** Rotation-aware elliptical fit showing the major axis, minor axis, and rotation angle of the measured proton spot.

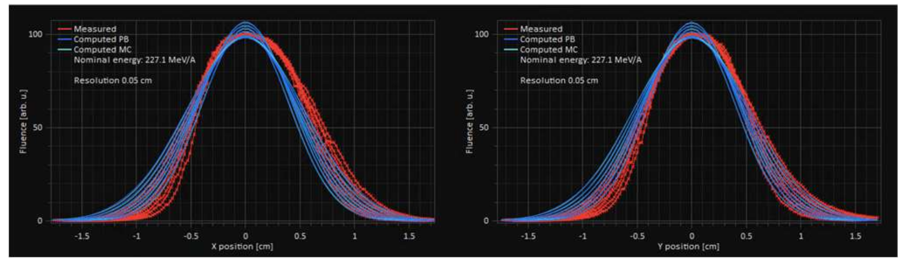


**Figure 3.** The TPS fitted spot profiles versus the rotation-aware spot major and minor profiles.

**Table 1: The calculated angular spread, divergence and spot size difference between two models after automodeling in TPS.**

| | Angular spread | Divergence (cm rad) | Spot size (cm) |
|---|---|---|---|
| Conventional orthogonal X-Y model | 0.00309 | 0.000857 | 0.47 |
| Rotation awareness model | 0.00295 | 0.000937 | 0.455 |

**Table 2: The dosimetric comparisons between the conventional orthogonal X-Y model and rotation-awareness model.**

| Category | Case | Structure/Description | Metric | Conventional orthogonal X-Y model (cGy) | Rotation-Aware (cGy) | Delta (%) |
|---|---|---|---|---|---|---|
| **Phantom** | #1 | Single layer 227.1 MeV, 10 cm x10 cm | Isocenter | 1085.57 | 1088.88 | 0.30 |
| | #2 | Range 20 cm, SOBP 10 cm, square field | Isocenter | 2089.81 | 2082.38 | -0.36 |
| | #3 | Range 18 cm, SOBP 5 cm, square field | Isocenter | 2558.46 | 2550.73 | -0.30 |
| **Patient** | Brain | Target | Mean | 3263.52 | 3294.53 | 0.95 |
| | | Target | D95 | 3207.76 | 3232.40 | 0.77 |
| | | Spinal Cord | D1 | 13.56 | 13.21 | -2.58 |
| **Patient** | Esophagus | Target | Mean | 3111.49 | 3123.91 | 0.40 |
| | | Target | D95 | 3039.20 | 3055.34 | 0.53 |
| | | Lung_R | D1 | 1657.33 | 1667.16 | 0.59 |
| **Patient** | Prostate | CTV | Mean | 3160.93 | 3198.76 | 1.20 |
| | | CTV | D95 | 3055.38 | 3082.50 | 0.89 |
| | | Bone | D1 | 1790.04 | 1850.56 | 3.38 |
| **Patient** | Spine | CTV | Mean | 3098.79 | 3106.49 | 0.25 |
| | | CTV | D95 | 3033.30 | 3041.66 | 0.28 |
| | | Lung_R | D1 | 2417.90 | 2440.17 | 0.92 |

## CONCLUSIONS

Rotation-aware spot characterization reveals substantial asymmetry suppressed by current symmetric beam models. Spot overlap, multiple Coulomb scattering, and energy-layer averaging mitigate spot-level differences, contribute to explaining PBS dose calculation robustness while highlighting commercial beam model parameterization limitations.