A Supplemental Technique for Analysis of Pre-Treatment PSQA

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Abstract

Purpose: PSQA measurement analysis depends on generating metrics representative of calculation and measurement agreement. The per-spot modulation capability of spot-scanning proton delivery is enhanced relative to modulated x-rays. This work introduces a dose-plane comparison algorithm, based on a cylindrical search shape (as opposed to the ellipse-based γ-test), with search limits empirically determined from machine QA, potentially more suited for the per-spot modulation capabilities of modern particle therapy. Dose-plane agreement is reported per pixel as the dose difference minimum (DDM) within an empirically-established search radius: $\Delta D_{min}(r)$.

Methods: DDM analysis was performed for 300 scanning-beam proton-patient fields. Search-distance criteria of 1.0 mm was based on a frequency-weighted 99.5% confidence level of beamlet radial position accuracy, based on 6 months sampling over the full deliverable field dimension. Tracked image registration restricted spatial error to beamlet deviation. Pass rate was the percentage of pixels within the fixed search radius with <3% dose difference.

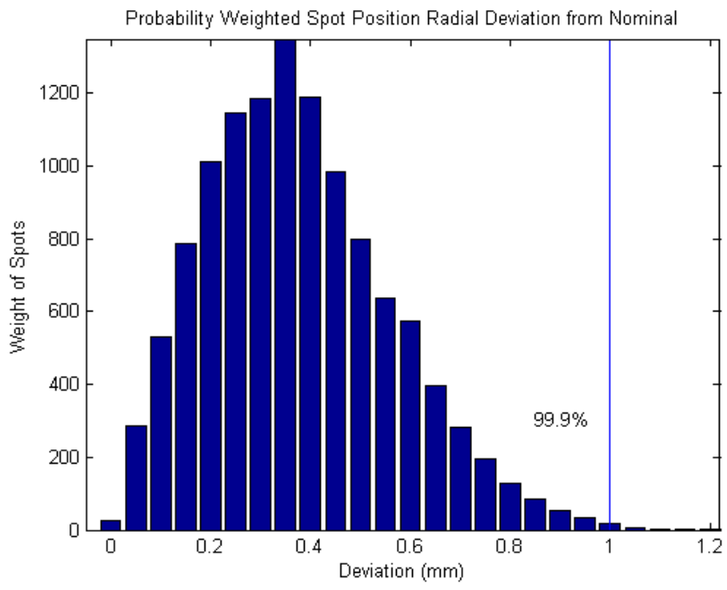
Results: >99.5% of proton beamlet radial deviations were less than 1.0mm. The proton field pass rate saw no change between a 3%/2mm γ-test (97.7 +/- 3.2%) and a 3%/1mm $\Delta D_{min}(r)$ (97.6 +/- 3.6%).

Conclusions: Extensive QA and delivery logs established a spot-delivery spatial accuracy well below 1mm. However, the 1mm elliptical shape of the γ-test is too exclusive, effectively enforcing a dose agreement closer to 2.5% for a 3% setting; further, expanding the γ-test tolerances to increase the effective dose agreement requires a search distance well beyond machine performance tolerances, enabling potential false positives. The cylindrical search shape of the new DDM algorithm, proposed herein as more relevant to plan quality, accepts all pixels with <3% agreement inside the search area. DDM also provides additional diagnostic information by reporting dose deviation magnitude per pixel, beyond the limited Boolean metrics reported from the γ-test.

References

1. Low, D.A., et al., *A technique for the quantitative evaluation of dose distributions.* Med Phys, 1998. **25**(5): p. 656-61.
2. Jiang, S.B., et al., *On dose distribution comparison.* Phys Med Biol, 2006. **51**(4): p. 759-76.

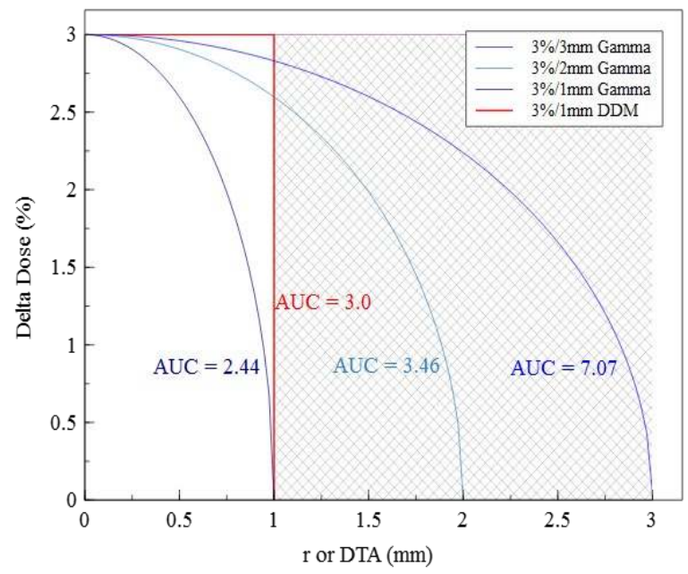
Spot Position Accuracy



Probability-weighted radial distance deviations from nominal position of scanning pencil beam. Data was measured over 30x40cm^2 field size grid in four gantries over six months, probability density function of spot delivery was determined from 93 random proton plans. 99.9% of delivered spots probabilistically deviate from nominal position by <1.0mm.

Considering the <1mm measured accuracy, it is suspected that a 2mm or 3mm DTA is permitting false positive results from γ-Analysis, yet a 1mm DTA is too exclusive in dose for reliability.

Area Under the Curve

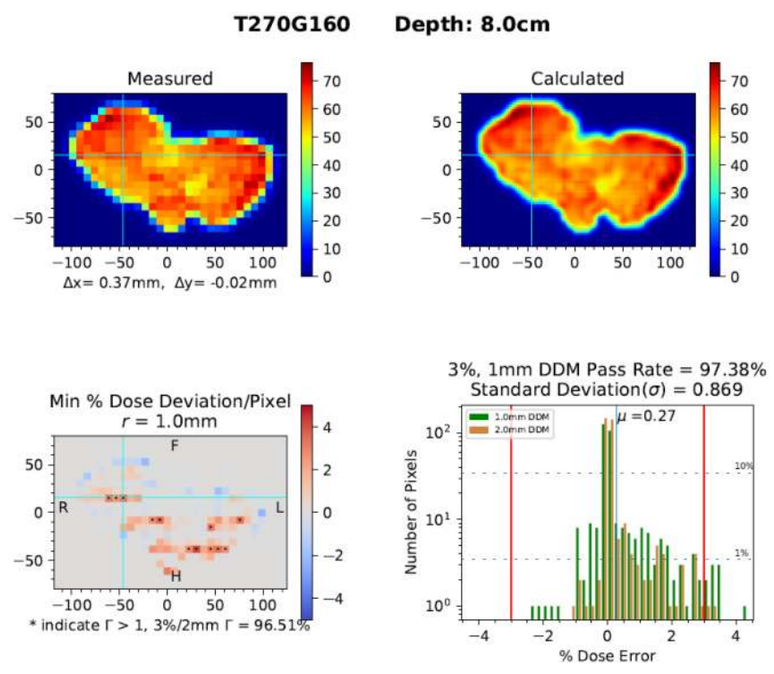


Area Under the Curve (AUC) displaying relative sensitivity of DTA and Percent Dose Difference for three sets of γ-index criteria (3%/3mm AUC = 7.07; 3%/2mm AUC = 3.46; 3%/1mm AUC = 2.44) and fixed Search Radius and passing dose limit for DDM (3%/1mm AUC = 3.0). Hash marks designate area outside of 99.5% confidence interval for beamlet accuracy.

Utilizing an empirically determined search distance, instead of DTA, can eliminate false positives and permit a continuum of dose errors to be more intuitively analyzed.

With these findings, it was determined appropriate to report the best dose agreement between a measured point and an array of calculated points within a statistically probable radius.

Output

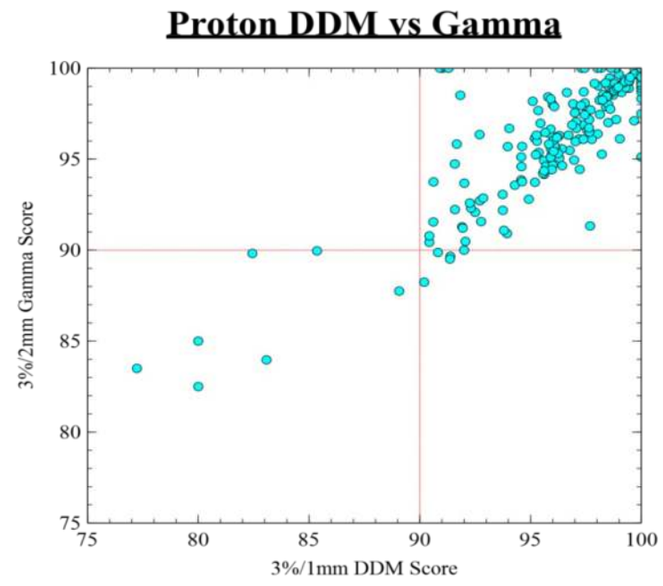


[Top row] Single plane dose measurement (left) and corresponding plane from calculated dose volume (right), image registration is reported with Δx and Δy to negate setup error, rendering beamlet positional accuracy the dominant source of spatial error. Registration is tracked to verify that laser and couch tolerances are maintained.

[Bottom row] DDM heatmap (left) showing relative dose deviation of each voxel (Measured – Calculated) and histogram (right) reporting magnitude and frequency of per-voxel deviations along with DDM score, Standard Deviation (σ), and Average Dose Offset (μ). Failing voxels of a 3%/2mm γ-Analysis are represented by asterisks overlaying the heatmap, a γ-score is provided below the heatmap.

The direct reporting of statistically-relevant dose deviations permits easier analysis while the histogram allows for more reliable metrics to be produced and trends to be observed.

Sensitivity and Specificity



Comparison of passing rates between DDM technique and γ-test for 300 dose planes.

Specificity is similar to the γ-test based on pass rates, sensitivity is concluded to be improved based on a lower AUC for the DDM algorithm.