Probabilistic Quality Assurance of Biopsy DVH Thresholds In HDR Prostate Brachytherapy Using Monte Carlo Localization Uncertainty

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ABSTRACT

Purpose: To evaluate biopsy-scale DVH threshold robustness in HDR prostate brachytherapy under Monte Carlo localization uncertainty.

Methods: Twenty-seven MR-US guided biopsy cores from 15 HDR monotherapy patients were reconstructed as 1 mm voxelized cores and propagated through 10,000 localization trials per biopsy. Trialwise DVH metrics were evaluated for D2%, D50%, D98%, and V150%, and Monte Carlo pass probability was defined as the fraction of trials satisfying each threshold.

Results: Borderline classifications were common across DVH rules: 73% for D2% ≥ 32 Gy, 63% for D50% ≥ 27 Gy, and 44% for both D98% ≥ 20 Gy and V150% ≥ 50%. Nominal DVH margin was the dominant predictor of pass probability.

Conclusions: Monte Carlo pass probability provides an uncertainty-sensitive QA metric for biopsy-scale dosimetry. Reported 95% margins should be interpreted as robustness buffers under the stated uncertainty model, not clinical dose prescriptions.

References

1. Muscat M, Crook J, Jirasek A, Andrews J, Becker N. Millimetre-scale dosimetry along MR-US guided prostate core-needle biopsies in HDR brachytherapy with explicit modelling of localization uncertainty. Phys Med Biol. 2026. Under revision.

2. Muscat M, Crook J, Jirasek A, Andrews J, Becker N. Probabilistic quality assurance of biopsy DVH thresholds in HDR prostate brachytherapy under localization uncertainty. J Appl Clin Med Phys. 2026. In press.

3. Muscat M, Crook J, Jirasek A, Andrews J, Becker N. A probabilistic tissue classification metric for MR-US guided prostate core-needle biopsies with explicit modelling of localization uncertainty. Phys Med Biol. 2026.

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INTRODUCTION

- MR-US guided prostate biopsies link localized tissue sampling with spatially resolved HDR dose.
- Steep HDR dose gradients make biopsy dose assignment sensitive to millimetre-scale localization uncertainty.
- A single nominal biopsy DVH value does not describe the probability that a threshold is robustly satisfied.

Objective: Quantify biopsy DVH threshold robustness under localization uncertainty and determine whether nominal DVH margin predicts Monte Carlo pass probability.

METHODS

Clinical cohort and biopsy reconstruction

- 27 MR-US guided biopsy cores from 15 HDR monotherapy patients.
- Biopsies reconstructed as 1 mm voxelized cores in the prostate planning frame.
- Clinical HDR dose and dose-gradient magnitude sampled on the biopsy voxels.

Monte Carlo localization model

- 10,000 localization trials per biopsy.
- Rigid 3D Gaussian translations with σ = 1.25 mm plus axial tissue-deficit offset.
- Dose and dose-gradient magnitude re-sampled for each perturbed core.

DVH threshold QA

- Trialwise biopsy DVH metrics computed for D2%, D50%, D98%, and V150%.
- Rules evaluated: D2% ≥ 32 Gy, D50% ≥ 27 Gy, D98% ≥ 20 Gy, and V150% ≥ 50%.
- Monte Carlo pass probability = fraction of trials satisfying each rule.

Robustness and supporting analyses

- Pass probabilities classified as confident pass, borderline, or confident fail.
- Logistic models related pass probability to nominal distance from threshold; secondary predictors tested for added value.
- Nominal − MC dose deltas and voxel-pair differences assessed dose misrepresentation and along-core decorrelation.

DISCUSSION

- Nominal biopsy DVH values are computed from the observed reconstructed biopsy geometry, but do not capture localization uncertainty in sampled dose.
- Monte Carlo pass probability converts nominal threshold labels into robustness classes; reported 95% margins are uncertainty-model-specific buffers, not clinical dose prescriptions.
- Nominal DVH margin dominated robustness prediction; secondary predictors added limited improvement.
- Dose misrepresentation and ~1–1.5 cm along-core decorrelation support spatially explicit biopsy-dose reporting for QA and dose-biology studies.

RESULTS

Key findings

- Biopsy DVH metrics are uncertainty-sensitive under millimetre-scale localization perturbations.
- Monte Carlo pass probability classifies biopsy-rule pairs as confident pass, borderline, or confident fail.
- Nominal DVH margin dominates robustness; dose decorrelates along the core over ~1–1.5 cm.

Figure 1. Biopsy-scale dose context motivating probabilistic DVH QA. Biopsy cores sample steep and heterogeneous HDR dose fields; Monte Carlo localization exposes per-trial dose perturbations, nominal − MC summary bias, and uncertainty bands along the core.

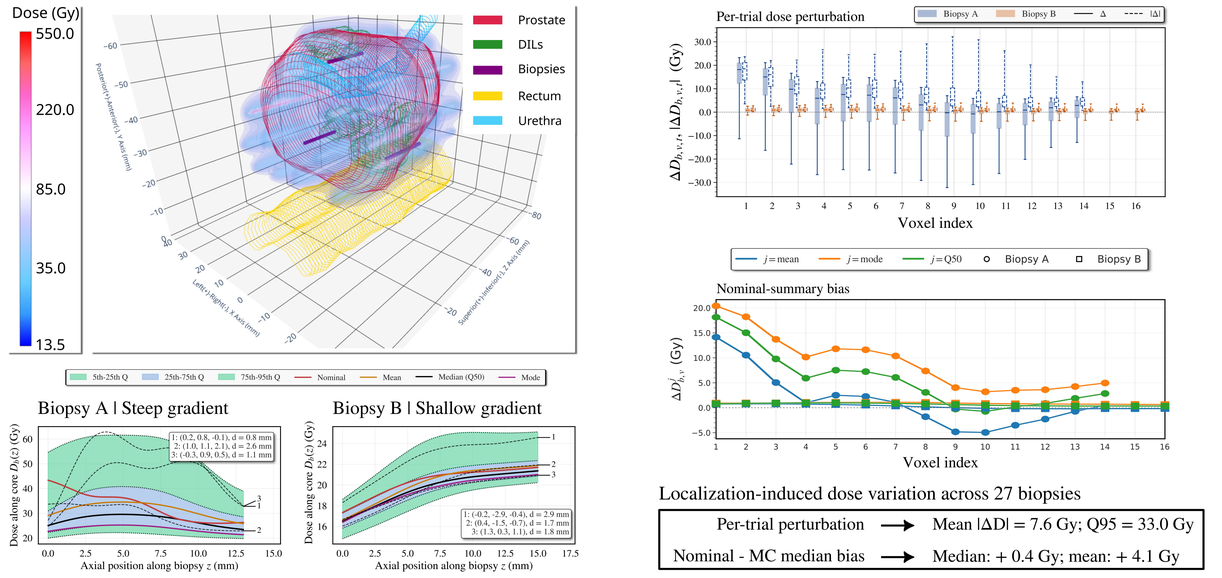

Figure 2. Probabilistic DVH threshold classification and robustness modelling. Monte Carlo pass probabilities classify biopsy-rule pairs as confident pass, borderline, or confident fail; logistic modelling relates pass probability to nominal DVH margin and estimates the nominal buffer required for 95% robustness.

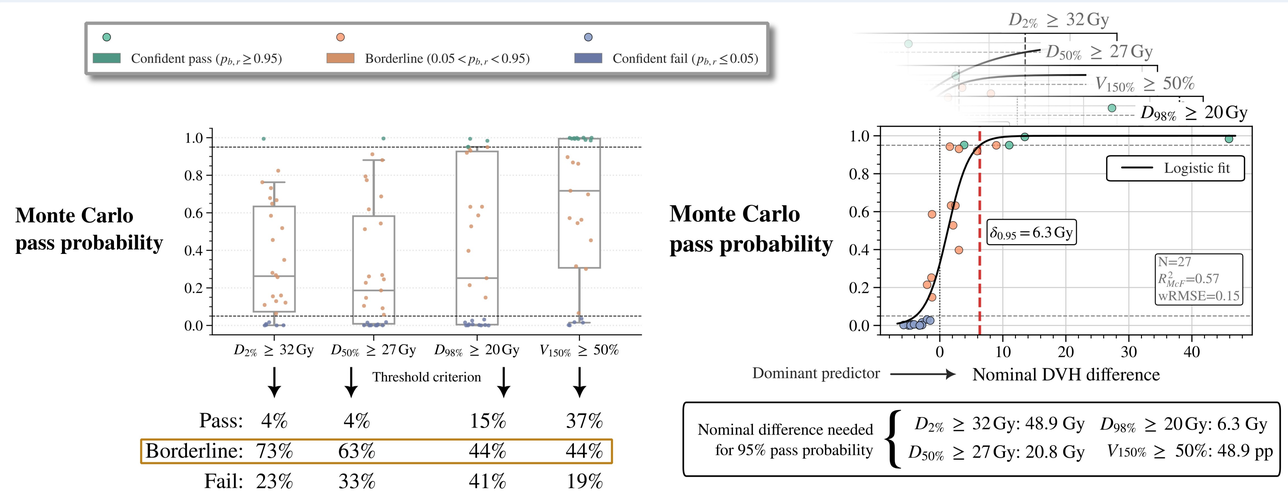

Figure 3. Nominal-dose bias and spatial heterogeneity. Voxel-level absolute dose deltas increased most strongly with nominal dose and nominal dose-gradient magnitude, while geometric and radiomics-style predictors were weaker. Along-core voxel-pair analysis showed dose decorrelation over approximately 1–1.5 cm, supporting spatially explicit biopsy dosimetry.