Gaussian Process Regression of HDR Prostate Biopsy Dose for Improved Modelling of Localization-Induced Uncertainty

M. Muscat, PhD[1,2]; A. Jirasek, PhD[1]; J. Andrews, PhD[1]; J. Crook, MD[2]; N. Becker, PhD[1,2];
Affiliations: [1]UBC, [2]BC Cancer

2026 JULY 19–22 VANCOUVER, BC
JOINT AAPM | COMP MEETING

ABSTRACT

Purpose: To estimate spatially correlated HDR prostate biopsy dose profiles under localization uncertainty using Gaussian process regression (GPR).

Methods: Twenty-seven biopsy cores were propagated through a Monte Carlo localization framework. Per-voxel MC median dose was used as the GPR target, with voxel-specific MC variance included as heteroscedastic observation noise. Biopsy-specific semivariograms were fit with Matérn covariance models, and model behaviour was evaluated using kernel sensitivity, residual diagnostics, Bland–Altman analysis, and blocked cross-validation.

Results: The selected Matérn 3/2 model preserved along-core dose-profile structure while reducing posterior SD relative to independent voxelwise MC uncertainty. Across the cohort, mean posterior SD reduction was 58.2%, with blocked-CV RMSE = 1.99 Gy and MAE = 1.58 Gy.

Conclusions: GPR converts independent voxelwise MC dose summaries into covariance-informed posterior dose profiles, providing more stable biopsy-scale dosimetric context for future dose-response and assay-linked analyses.

References

1. Muscat M, Crook J, Jirasek A, Andrews J, Becker N. Probabilistic tissue classification of MR–US guided prostate biopsies under localization uncertainty. Phys Med Biol. 2025.

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, Jirasek A, Andrews J, Crook J, Becker N. Gaussian process regression of HDR prostate biopsy dose for improved modelling of localization-induced uncertainty. Med Phys. 2026. Under revision.

CONTACT

Matthew Muscat
UBC Okanagan & BC Cancer Kelowna
Incoming Resident: Johns Hopkins
matthew.muscat@mail.mcgill.ca
(514) 430 - 8022

INTRODUCTION

- HDR prostate biopsies sample tissue within steep, spatially varying dose fields.
- Monte Carlo localization propagates biopsy-position uncertainty into voxelwise dose distributions.
- Independent voxelwise summaries ignore axial spatial correlation along the biopsy core.
- GPR provides a natural framework for modelling the latent along-core dose profile as a correlated random field.

Objective: Estimate covariance-informed posterior dose uncertainty along HDR prostate biopsy cores using GPR, and test whether uncertainty reduction is stable under model diagnostics and held-out validation.

METHODS

Patient cohort and input data

- 27 HDR prostate biopsies with Monte Carlo localization trials.
- Dose sampled along voxelized biopsy cores in the prostate reference frame.
- Per-voxel MC median dose used as a robust target statistic.

Spatial correlation model

- Empirical semivariograms quantified dose dissimilarity versus axial separation.
- Matérn covariance models estimated biopsy-specific axial coherence length, partial sill, and nugget variance.
- Selected baseline: Matérn ν = 3/2.

GPR inference

- Ordinary-mean GPR was applied to centered along-core dose targets.
- Voxel-specific MC variance entered as heteroscedastic observation noise.
- Posterior mean and posterior SD were computed along each biopsy core.

Model checks

- Kernel sensitivity: exponential, Matérn 3/2, Matérn 5/2, and RBF.
- Residual diagnostics: standardized residual centering and spread.
- Blocked CV: contiguous held-out core segments tested out-of-sample prediction.

DISCUSSION

- Independent MC summaries quantify localization uncertainty but ignore spatial continuity along the biopsy core.
- GPR reframes biopsy dose as a latent spatial profile with covariance-informed posterior uncertainty.
- SD reduction is interpreted as covariance-informed uncertainty contraction, supported by kernel sensitivity, residual diagnostics, and blocked CV.
- The resulting profiles provide stable biopsy-scale dosimetry descriptors for downstream dose-response and assay-contextualization studies.

RESULTS

Key findings

- Dose uncertainty along HDR prostate biopsy cores is spatially structured, not purely voxel-independent.
- GPR reduced posterior SD by approximately 58% while preserving along-core dose-profile structure.
- Kernel sensitivity, residual diagnostics, and blocked CV supported model stability and held-out prediction.

Figure 1. Representative semivariogram-derived GPR dose profiles. Empirical semivariograms estimate biopsy-specific axial covariance, while GPR preserves along-core dose structure and reduces independent voxelwise MC uncertainty.

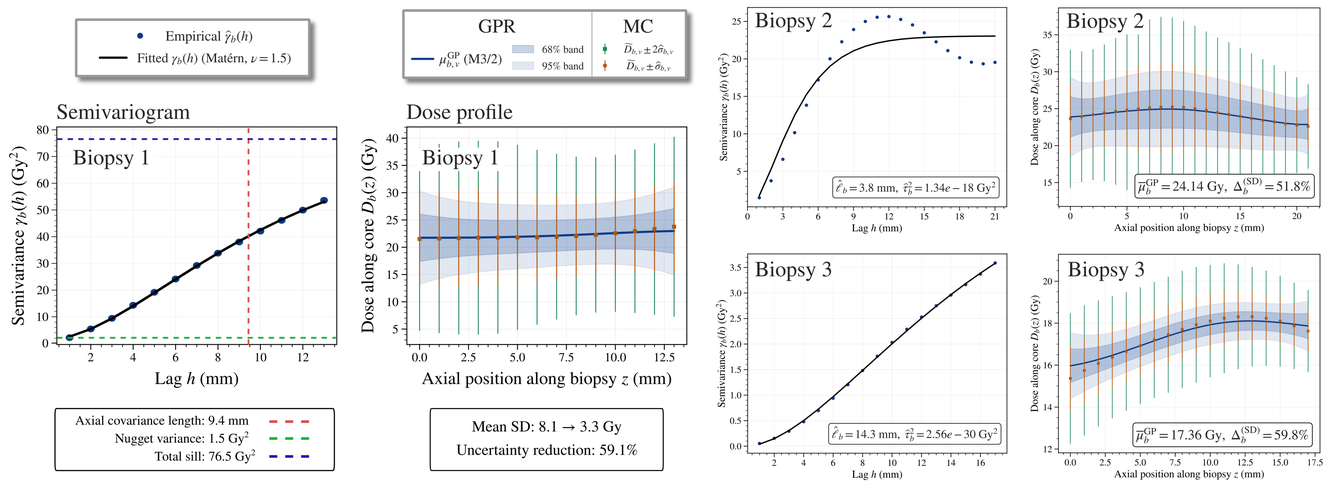
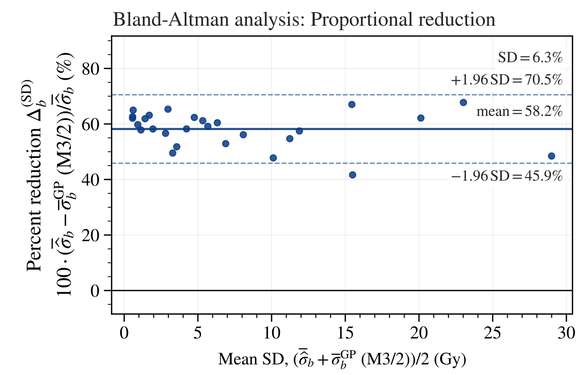


Figure 2. Cohort-level posterior SD reduction. Bland–Altman analysis summarizes proportional reduction in GPR posterior SD relative to independent voxelwise MC SD; table reports model and validation metrics.



Cohort Summary

Metric	Value
Biopsy cohort	n = 27
Baseline covariance model	Matérn nu = 3/2
Mean posterior SD reduction	58.2%
Deming slope / R^2	0.43 / 0.92
Blocked-CV RMSE / MAE	1.99 / 1.58 Gy

Posterior SD reduction compares GPR posterior uncertainty against independent voxelwise Monte Carlo uncertainty.

Figure 3. Model diagnostics. Kernel sensitivity assessed dependence on covariance choice; residual diagnostics evaluated calibration of posterior uncertainty; blocked cross-validation tested held-out prediction on contiguous biopsy-core segments.