Toward Fully Automated Prostate HDR Brachytherapy Planning Using Deep Learning–Based Dose Prediction

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ABSTRACT

Purpose: To develop and evaluate a fully automated prostate HDR brachytherapy planning framework using deep learning–based dose prediction, reducing planner dependence and planning time.
Methods: A 3D-UNet model was trained on 219 retrospective prostate HDR brachytherapy cases to predict patient-specific dose distributions from anatomical structure masks, dwell position information, and spatial distance maps. Predicted dose was converted into deliverable plans by optimizing dwell times using a non-negative least squares (NNLS) solver and a precomputed dose-rate matrix. The pipeline was evaluated on an independent cohort of 28 patients by comparing dosimetric metrics, prescription-dose isodose Dice similarity coefficients, and voxel-wise mean absolute dose differences between automated and clinical plans.
Results: Predicted dose distributions showed strong agreement with clinical plans across target and organs at risk. Dosimetric differences between automated and clinical plans were within clinically acceptable ranges.
Conclusions: The proposed framework demonstrates feasibility of fully automated prostate HDR brachytherapy planning with minimal human intervention, providing a foundation for more efficient clinical workflows..

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INTRODUCTION

Prostate HDR brachytherapy is an effective treatment for localized and locally advanced prostate cancer.[1] Treatment planning must be completed within a single anesthetic session (1-2 hours), creating a time-critical, labor-intensive workflow vulnerable to planner variability.[2]
Deep learning-based dose prediction has shown promise for automated planning,[3] but a critical gap remains: predicted dose distributions must be converted into physically deliverable dwell times. This conversion has not previously been demonstrated for prostate HDR brachytherapy.[4]
Purpose : To develop and validate an end-to-end automated HDR prostate brachytherapy planning framework that integrates 3D U-Net dose prediction with a reverse optimization approach to generate physically deliverable treatment plans in under 30 seconds.

METHODS AND MATERIALS

- 219 retrospective prostate HDR brachytherapy plans (13.5 Gy/fraction, 2016-2023) from a single institution
- 191 cases used for training; 28 independent cases reserved for evaluation
- 3D U-Net trained on anatomy masks, dwell position arrays, and PTV distance maps to predict 3D dose distributions (64×64×64, PyTorch, 150 epochs, MAE loss)
- Predicted dose converted to deliverable dwell times by solving a non-negative least squares (NNLS) constrained optimization: $\min\|At - D_{target}\|^2$ subject to $t \geq 0$, using a kernel-based TG-43 dose-rate matrix A
- Evaluated using DVH metrics (PTV D95, urethra D0.1cc, bladder D2cc, rectum D2cc), Dice similarity coefficient (DSC), and voxel-wise mean absolute dose difference (MAD)
- Plans assessed against institutional criteria and RTOG-0924 guidelines

RESULTS

- The 3D U-Net model produced dose distributions in strong agreement with clinical plans.
- Mean DVH differences below 1% of the prescription dose (13.5 Gy) and a mean DSC of 0.91 ± 0.03 for the prescription isodose volume.
- The NNLS reverse optimization framework closely reproduced clinical dose when using clinical dose as target (DSC: 0.96 ± 0.01), validating the conversion pipeline.
- Automated plans generated from predicted dose achieved comparable dosimetric quality (DSC: 0.90 ± 0.02), with the full pipeline completing in 20-25 seconds per patient.
- Against RTOG-0924 criteria, automated plans met all OAR goals in 100% of cases and PTV coverage in 78.6% of cases.

	Predicted dose	Validation plans	Automated plans
PTV D95 (Gy)	0.08±0.61	0.24±0.22	−0.34±0.67
UrethraD0.1cc (Gy)	0.14±0.58	−0.01±0.22	0.16±0.52
BladderD2cc (Gy)	−0.09±0.57	0.10±0.16	0.02±0.55
RectumD2cc (Gy)	−0.02±0.84	−0.17±0.21	0.07±0.67

Table 1. Dosimetric comparison with clinical.

	PTV	Urethra	Rectum	Bladder
Institutional				
Clinical	89.3%	96.4%	46.4%	71.4%
Automated	64.3%	92.9%	50.0%	75.0%
RTOG 0924				
Clinical	92.9%	96.4%	82.1%	100%
Automated	78.6%	100%	100%	100%

Table 2. Percentage of plans satisfying the clinical goals for institutional and RTOG-0924 criteria.

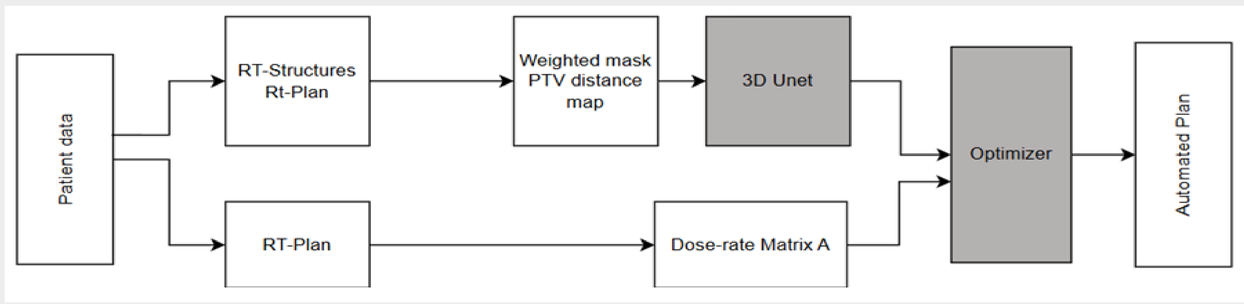

Figure 1. Schematic of the workflow for generating automated brachytherapy plans

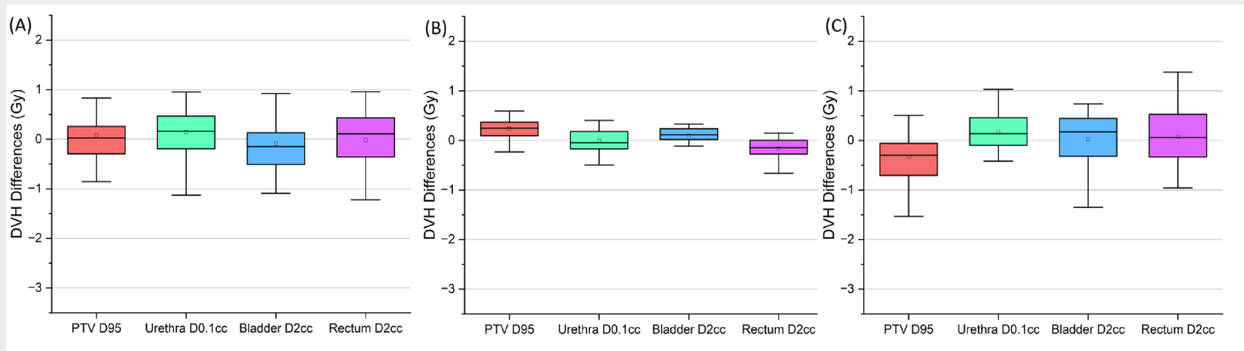

Figure 2. Box-and-Whisker plot of DVH metrics comparison with clinical dose for (A) dose prediction, (B) validation plans, and (C) automated plans.

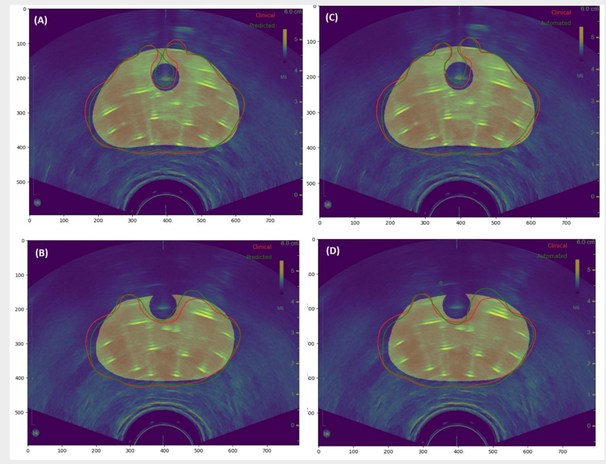

Figure 3. Isodose line comparisons for predicted dose, automated dose, and clinical dose overlayed on images along with PTV structure. (A,B) Clinical dose vs predicted dose (C,D) clinal dose vs automated plan dose.

DISCUSSION

- U-Net dose prediction accuracy is comparable to prior HDR deep learning studies,[3] with mean DVH differences <1% of prescription dose
- NNLS reverse optimization successfully converted both clinical and predicted dose distributions to deliverable plans for all 28 test patients
- Automated plans met all RTOG-0924 OAR goals in 100% of cases; PTV coverage met in 78.6% vs. 92.9% for clinical plans
- Larger dwell time deviations in automated vs. validation plans attributed to prediction uncertainty and subtle dose gradient differences propagated through optimization
- Complete pipeline (prediction + optimization + dose calculation) runs in 20-25 seconds — well within the single-anesthesia time window

CONCLUSIONS

This study demonstrates a fully automated prostate HDR brachytherapy planning framework integrating 3D U-Net dose prediction with NNLS-based reverse optimization. The framework generates clinically deliverable plans in 20–25 seconds, with the majority meeting RTOG-0924 criteria. This approach has strong potential to streamline the time-critical HDR workflow, reduce planner dependence, and serve as a starting point for clinical refinement or quality assurance.

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