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

UniGeoDose: A universal real-time dose verification model for all beam energies and treatment units via beam characteristics embedded geometry encoding

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ABSTRACT

Purpose: Timely dose verification is essential for quality assurance (QA) in modern radiotherapy (RT), particularly in online adaptive RT, where measurement-based QA is often impractical. Current approaches are limited by machine/energy-specific designs, hindering scalability in real-world clinical applications. To address this, we propose UniGeoDose, a universal framework that supports real-time dose verification for all treatment machines and beam energies using a single model, providing a deploy-once, use-everywhere solution for all clinical settings.

Methods: To generalize across diverse clinical settings, UniGeoDose incorporates machine/beam characteristics as model input via a designated encoding block. Specifically, line profiles and percentage depth dose curves are integrated to represent both spatial and depth-dose characteristics of each beam energy on each LINAC. An autoencoder was trained to extract key features and concatenated with dosimetric leaf gap and leaf transmission factor for a comprehensive representation of beam characteristics. This representation conditions a geometry-encoded U-Net, a novel architecture that resolves the exact treatment delivery geometry by directly embedding control points from treatment plans into CT volumes, to specify the machine/energy under evaluation. To build the UniGeoDose model, a cohort of 995 prostate cancer cases were collected, and randomly split into 850 cases for training, 74 cases for validation, and 71 cases for independent testing with stratified sampling by machine and energy.

Results: Compared to dose calculated with the treatment planning system, UniGeoDose achieved an average γ-passing rate (3%/2mm, 10% threshold) of 99.8% ± 0.35% for all machines and energies available in our clinic with mean computation time <40ms per case, demonstrating superior performance comparing against the same model established without beam information encoded.

Conclusion: By introducing a novel beam-aware design, this study established a highly scalable approach to achieve real-time 3D dose verification, providing a universal solution for any beam energies, LINACs, and clinical settings.

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INTRODUCTION

Traditional measurement-based approach requires machine availability and entails substantial time and efforts, which is ill-suited for rigorous and timely QA in busy clinics especially in the transformative paradigm of adaptive RT. Recently, deep learning (DL)-based verification tools have been developed to address the computational efficiency issue. However, most of them rely on machine- or energy-specific designs, limiting their feasibility and scalability in deployment, especially for clinics with diverse treatment platforms. To address this scalability issue, this study proposes UniGeoDose, **a universal framework that supports real-time 3D dose verification for all treatment machines and beam energies** using a single model, providing a deploy-once solution for all clinical settings.

METHODS AND MATERIALS

To generalize across diverse clinical settings, the proposed UniGeoDose framework embeds machine/beam characteristics via a designated beam-information extraction block (Fig. 1).

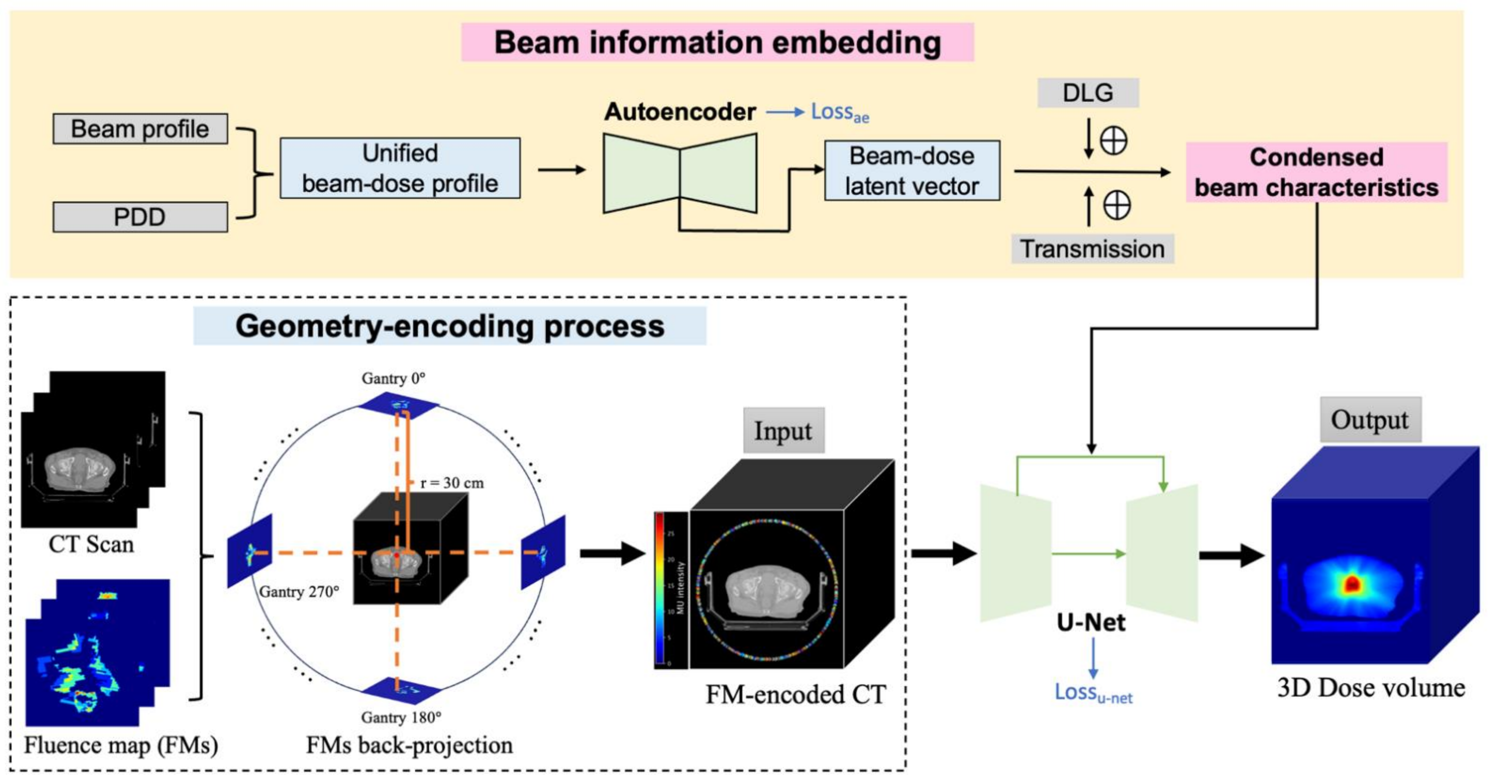

Figure 1. Proposed secondary dose verification UniGeoDose workflow.

Specifically, an integrated beam-dose profile tensor was constructed using beam profile and percentage depth dose for every single beam energy on each LINAC to represent the spatial and depth dose characteristics. A dedicated autoencoder was trained to *extract key features from the unified beam-dose tensor, which were subsequently concatenated with dosimetric leaf gap (DLG) and leaf transmission factor (LTF)* to account for multi-leaf collimator transmission effect. The condensed beam-characteristics tensor then conditions the U-Net at the bottleneck layer to specify the machine/energy under evaluation. To realize real-time 3D dose verification, *a geometry-encoded DL framework innovatively transforms FMs into patient image domain,* serving as a single input to a carefully designed 3D U-Net for dose estimation.

Specifically, each FM was projected onto a plane 30cm away from the isocenter with respect to the beam angle and linear accelerator (LINAC) geometry to preserve treatment delivery geometry while avoiding any overlap with patient body and motion management device. In this study, we collected a cohort of 995 prostate cancer cases across multiple machine and beam energies (Table 1).

Table 1. Distribution of collected plans

Machine	Beam energy	Train	Validation	Test	Total
TrueBeam VitalBeam	6X	88	8	7	103
	6FFF	50	4	4	58
	10X	151	13	13	177
	10FFF	89	8	7	104
	15	138	12	12	162
Versa	6X	25	2	2	29
	6FFF	95	8	8	111
	10X	38	3	3	44
	10FFF	176	16	15	207
Sum	-	850	74	71	995

CONCLUSIONS

By introducing a novel beam-aware design, this study established a **highly scalable** approach to achieve **real-time 3D dose verification**, providing a **universal solution** for any beam energies, LINACs, and clinical settings. Future work will focus on expanding the proposed framework to other disease sites and integrating with routine RT workflows for broader clinical applicability.

REFERENCES

[1] Yan, S., et al., *Quality assurance for online adaptive radiotherapy: a secondary dose verification model with geometry-encoded U-Net.* Mach Learn Sci Technol, 2024. **5**(4): p. 045013.
[2] Yan, S., et al., *Geometry-encoded deep learning (GeoDL) framework for real-time 3D dose verification for online adaptive radiotherapy.* Machine Learning: Health, 2025. **1**(1): p. 015004.

RESULTS

The average computational time of end-to-end 3D dose verification with UniGeoDose framework is ~**36.9ms** for each patient, with 8.1ms for geometry encoding process and 28.8ms for model inference. Overall speaking, a good agreement was observed between the TPS-calculated dose and the estimated dose from UniGeoDose framework. Using the 3%/2 mm criteria with a 10% low-dose threshold, the proposed framework achieved an average 3D γ passing rate of $99.80\% \pm 0.35\%$. Under the stricter 2%/2 mm criteria, the average γ passing rate was $98.60\% \pm 1.61\%$. The average of absolute dose differences for both Dmax and Dmean across target volumes and organs-at-risks (rectum, bladder, and femoral heads) were all within 1Gy. Fig. 2 depicted dose comparison results for a representative testing case.

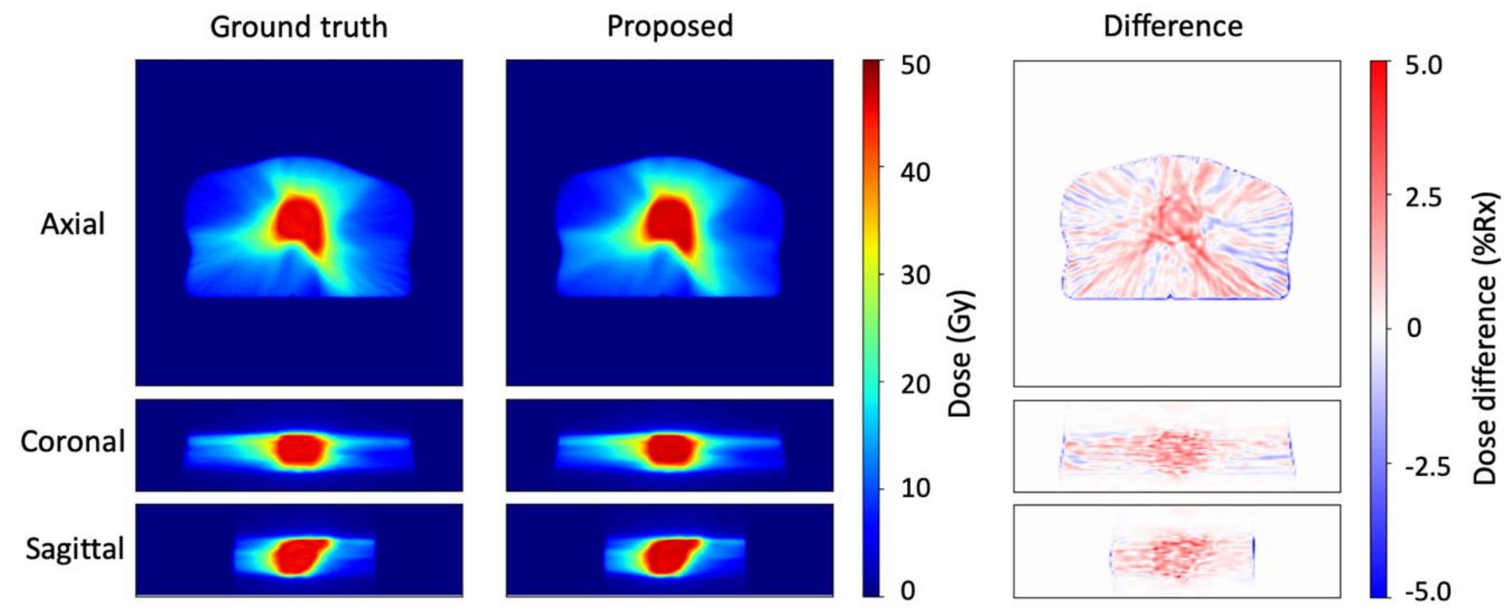

Figure 2. Dose comparison for a representative TBVB-15MV testing case.

To assess the generalizability of the proposed GeoDose framework across heterogeneous treatment platforms, group-wise γ passing rates under the 3%/2 mm and 2%/2 mm criteria with 10% threshold is presented in Fig. 3. Under the 3%/2 mm criterion, GeoDose achieved consistently high agreement with the TPS-calculated dose across all nine configurations, with median passing rates above 99% and all groups exceeding 98%. Under the more stringent 2%/2 mm criterion, passing rates remained high overall, with most configurations maintaining median passing rates above 95%.

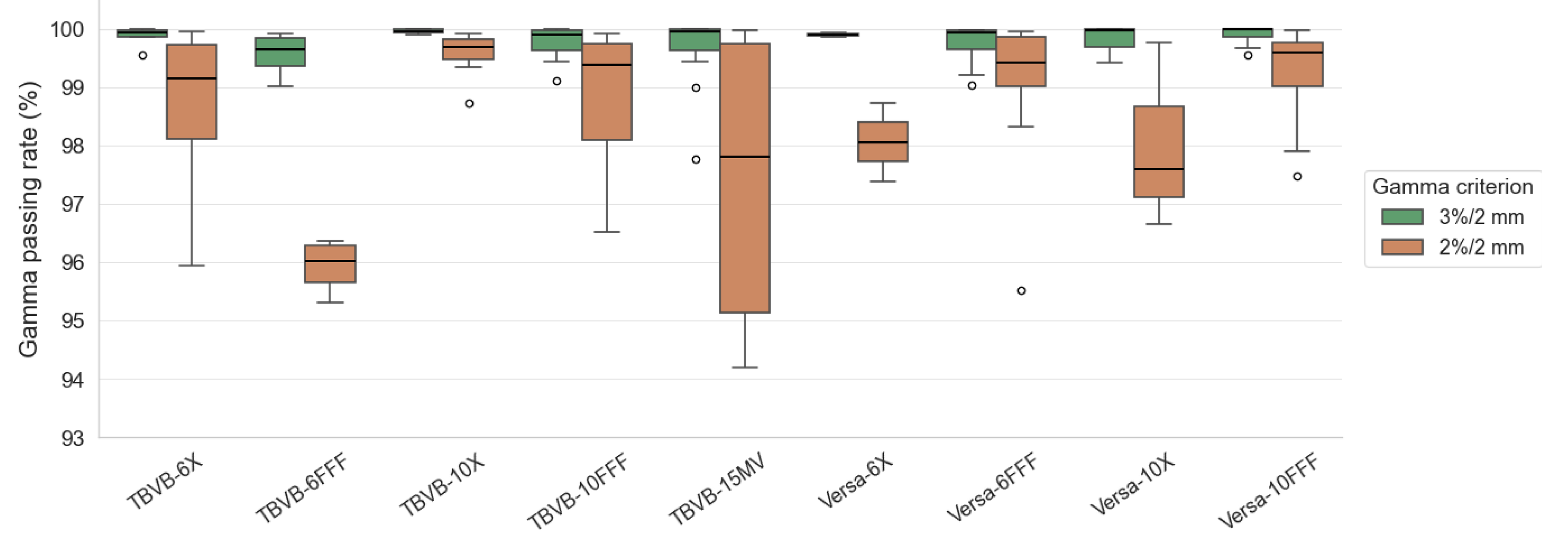

Figure 3. γ passing rate under the 3%/2mm criteria and 2%/2mm criteria across beam/machine categories.

To validate the contribution of beam-information embedding, we compare against a baseline model of same U-Net architecture without beam encoding. The baseline yielded an average γ-passing rate (3%/2mm, 10% threshold) of $91.16\% \pm 6.62\%$, confirming the improved dose estimation accuracy and enhanced generalizability of the proposed framework. To evaluate whether a single universal model can maintain machine–energy-specific accuracy, UniGeoDose was then compared with a model trained exclusively on the same TBVB-10X cases. Under the 3%/2 mm criterion, UniGeoDose achieved a γ passing rate of $99.95\% \pm 0.04\%$ compared with $99.93\% \pm 0.07\%$ for the TBVB-10X-specific model.

To further demonstrate the generalization capability of the proposed beam-aware dose calculation framework, two robustness studies were conducted. In the first study, cross-vendor generalization was investigated by training the model using all beam energies from the Varian TBVB systems and testing on the Elekta VersaHD, representing a previously unseen machine design. The proposed model achieved an overall γ passing rate (3%/2 mm, 10% threshold) of $99.39\% \pm 0.57\%$, demonstrating strong robustness across different LINAC vendors. In the second study, cross-energy generalization was evaluated by training the model using 6X, 6FFF, and 10X beams from both vendors while withholding 10FFF and 15 beam energies for testing. Even on these unseen beam qualities, the model maintained an overall γ passing rate of $98.90\% \pm 0.86\%$, indicating that the proposed model is capable of generalizing beyond the beam energies observed during training. These results demonstrate that UniGeoDose achieves accurate and robust dose estimation across heterogeneous treatment settings while preserving real-time computational efficiency.