Master's Thesis Engineering Technology

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Preliminary design and evaluation of a 3D-printed phantom for gynecological brachytherapy dosimetry audits

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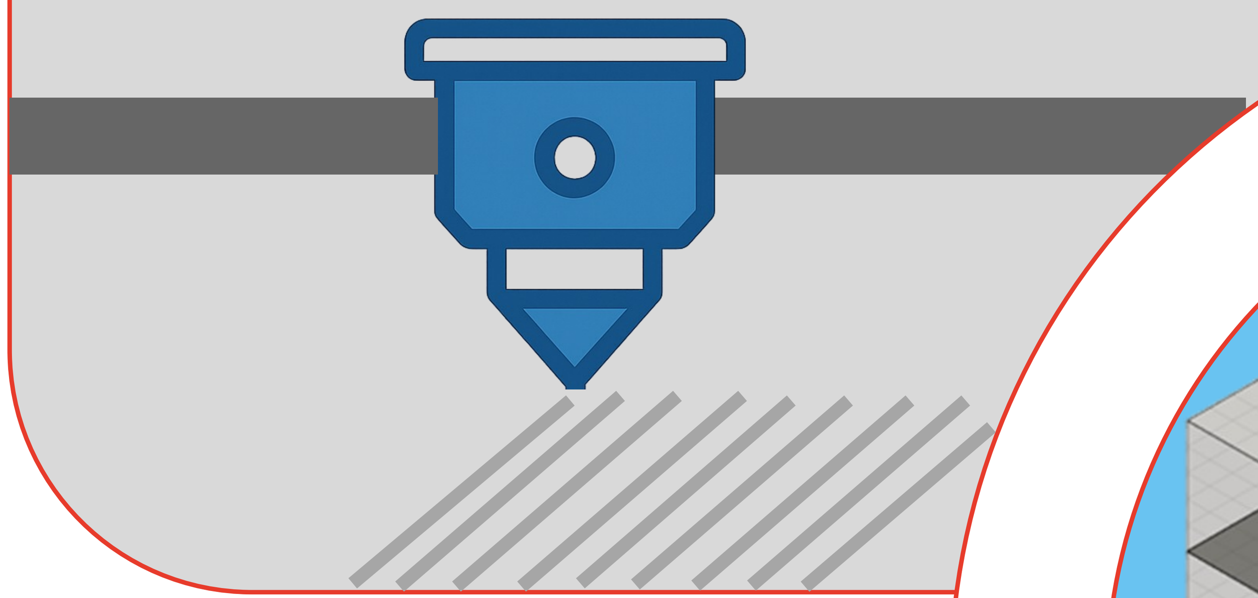
Project motivation

Cervical cancer is one of the leading causes of cancer-related mortality among women globally, with a disproportionate impact in low- and middle-income countries due to limited access to radiotherapy infrastructure and quality assurance (QA) resources [1]. High-dose-rate brachytherapy (HDR-BT) is a cornerstone of curative treatment for locally advanced cervical cancer, offering the advantage of highly localized radiation with steep dose gradients. However, this precision comes with a significant challenge: small deviations in applicator placement or source positioning can result in substantial errors in delivered dose.

Despite the critical need for accuracy, QA tools specific to gynecological brachytherapy are lacking, especially those that are both affordable and standardized. This gap has led to practice variability and reduced treatment consistency across institutions. Recent advances in 3D printing offer a promising solution, custom phantoms can be rapidly fabricated to mimic anatomical geometry, facilitate dosimetric testing, and validate treatment planning systems. The aim of this thesis is to develop a reproducible, low-cost 3D-printed QA phantom for cervical HDR-BT that can be deployed in diverse clinical and training environments, ultimately contributing to safer and more consistent care.



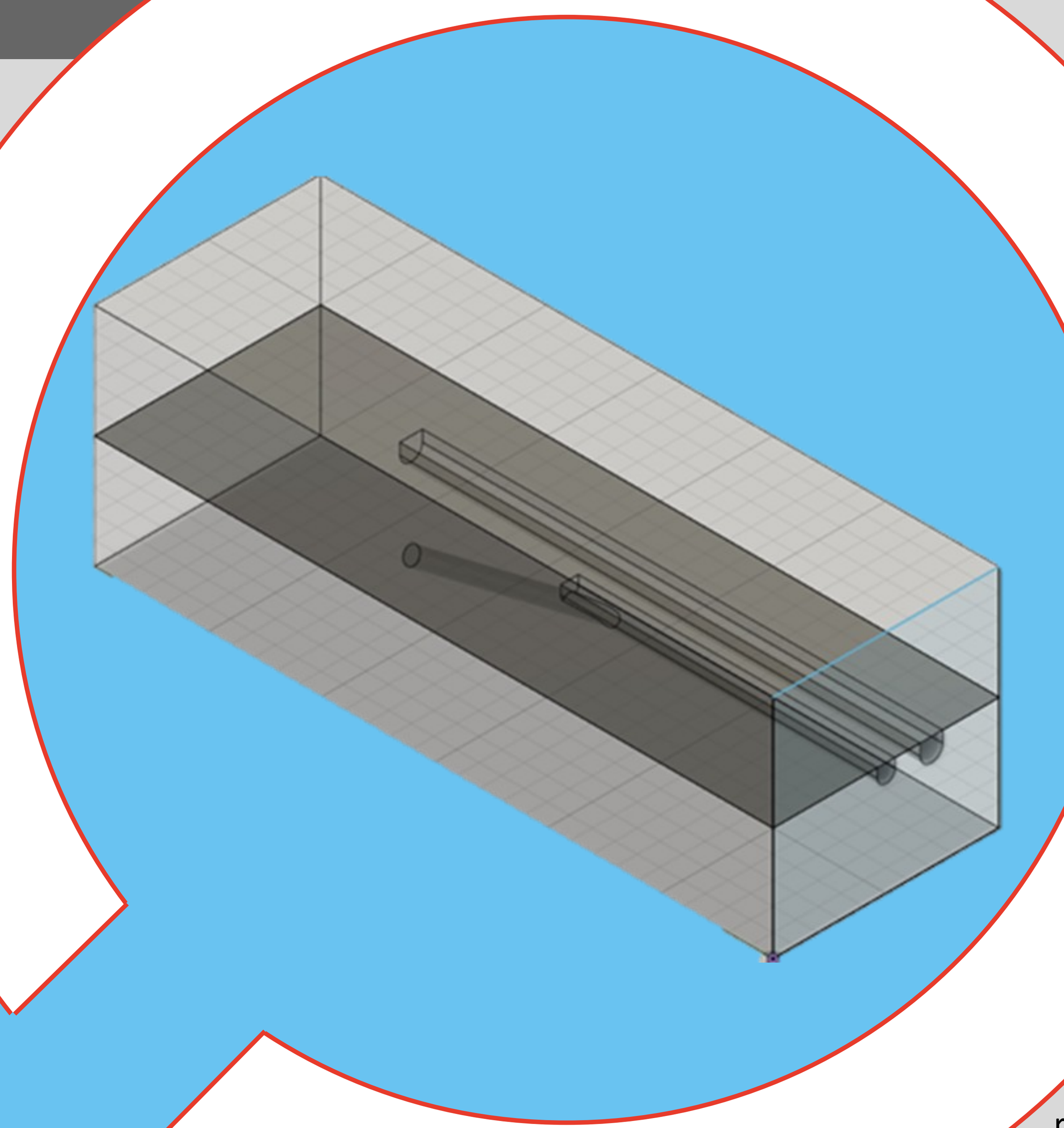
Phantom design and fabrication

Two custom phantoms were developed using 3D modeling software based on CT reconstructions of commercial HDR-BT applicators. The goal was to create test objects capable of holding both the applicator and dosimetric detectors in fixed, repeatable positions. Two materials were chosen for fabrication using fused deposition modeling (FDM): PLA, a rigid thermoplastic with good dimensional stability, and TPU, a flexible material designed to simulate soft-tissue deformation.

The PLA phantom was optimized for structural precision and ease of printability, serving as the baseline model (Figure 1). It featured a horizontally split design for easy film insertion and included two U-shaped channels: one for the applicator and another for a plastic scintillator. A separate TPU phantom was then derived from the PLA version, with slight modifications to account for material flexibility and to minimize air gaps.

Both phantoms underwent CT-based dimensional validation to ensure geometric fidelity. Measurements of channel diameter, spacing, and total phantom dimensions confirmed that deviations were within the CT scanner's resolution limits (typically under 1 mm), validating the accuracy of the printing workflow. Overall, the design and fabrication pipeline demonstrated that both rigid and flexible phantoms could be successfully manufactured using accessible 3D printing technology.

Figure 1: 3D-printed PLA phantom with applicator inside



Dosimetric testing and evaluation

To assess dose delivery accuracy, two measurement methods were employed: real-time plastic scintillator dosimetry and high-resolution Gafchromic™ EBT3 film dosimetry. The scintillator was positioned within the phantom's dedicated channel and calibrated using standard HDR-BT setups. In the PLA phantom, measured doses showed good agreement with TG-43 calculations, with deviations ranging from 1–10%, all within accepted QA thresholds (FIgure 2).

The TPU phantom, despite lower water equivalence and CT-detected structural variability (HU as low as –400), demonstrated strong mechanical conformity and consistent scintillator readings. Its flexible structure helped maintain reproducible source-detector alignment, contributing to stable measurements across varying acquisition frequencies.

Film dosimetry was used to validate spatial dose distributions in the TPU phantom. While the film captured the expected high-gradient dose patterns, measured values exceeded TG-43 calculations by up to 94%, due to the phantom's non-uniform density and TG-43's simplifying assumptions. These results confirmed the need to consider material effects when evaluating dose accuracy in flexible phantoms.

Together, these methods enabled a robust comparison of delivered and calculated doses, showcasing the utility of 3D-printed phantoms in QA and the critical role of material properties in dosimetric fidelity.

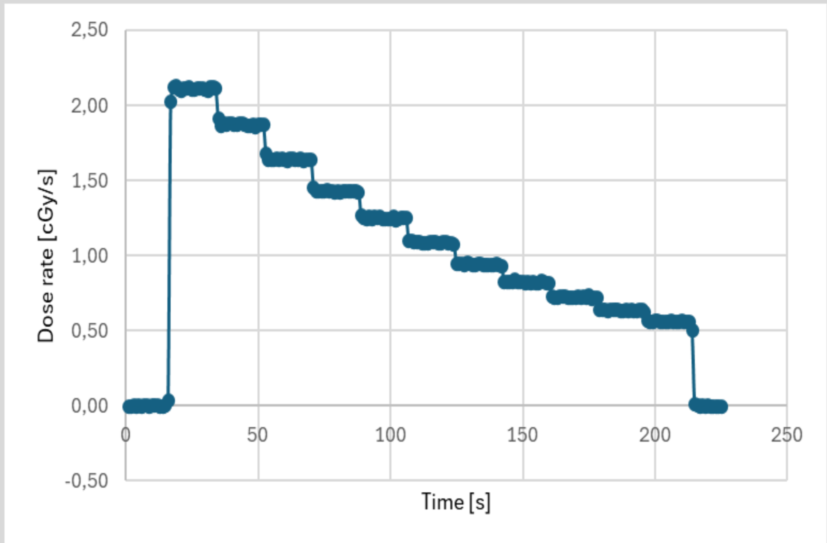


Figure 2: TPU 11-dwell scintillator graph

Conclusion and outlook

This work demonstrates that 3D-printed phantoms are a practical and cost-effective solution for QA in HDR gynecological brachytherapy. The PLA phantom showed excellent dimensional accuracy and moderate radiological equivalence, making it well-suited for QA audits where geometric precision is paramount. Its results in plastic scintillator dosimetry closely matched treatment planning predictions, indicating reliable performance under clinical conditions.

The TPU phantom offered complementary benefits, such as improved applicator conformity and setup reproducibility. However, it also highlighted the challenges of printing with flexible, non-water-equivalent materials. Despite its internal variability, the TPU phantom still produced reproducible dose readings with the plastic scintillator, although film measurements showed large deviations when compared to TG-43 calculations.

These findings suggest that while rigid materials like PLA are optimal for replicating dose distributions in line with conventional planning models, flexible phantoms such as those made with TPU can serve as useful tools for stress-testing QA processes and investigating model limitations. Future development should focus on improving the homogeneity of flexible prints, expanding validation with model-based dose algorithms (e.g., TG-186), and incorporating both phantom types into broader clinical and educational workflows. This dual-material approach holds strong potential to enhance patient safety and promote QA standardization in resource-constrained settings.

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[1] Banerjee, R., & Kamrava, M. (2014). Brachytherapy in the treatment of cervical cancer: a review. *International Journal of Women's Health*, 6, 555-564.