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MRI-Only Intracavitary Brachytherapy: Commissioning and Clinical Implementation

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ABSTRACT

Purpose:
This study reports on a comprehensive MRI-only intracavitary brachytherapy (MR-ICB) commissioning framework with quantitative isodose-based validation against CT.

Methods:
3D T2, CISS (Constructive-Interference-in-Steady-State), and TRUFI (True-Fast-Imaging-with-Steady-State-Precession) MRI sequences were optimized on a 1.5T scanner (Siemens MAGNETOM) for visualization of Elekta's MRI line markers that can be securely inserted into MR-conditional tandem and ovoid applicators (from Elekta). An in-house ultrasound gel phantom with external fiducials was constructed to validate applicator geometry and marker tip localization. Vendor-supplied applicator 3D models containing source path definitions were utilized for applicator reconstruction. Five retrospective patient cases with 15 treatment fractions were reconstructed on CT and MRI and planned using a Point-A-prescription. The CT-derived pear-shaped dose distribution served as the reference. Following manual rigid CT–MRI registration, agreement of 100%–250% isodose lines (IDLs) was quantified using 95th-percentile-Hausdorff-distance (H95), mean-distance-agreement (MDA), and Dice-coefficient (DC), enabling evaluation in dose-gradient-regions. First-dwell-position accuracy was also evaluated by loading a single dwell and comparing 100%–500% IDLs at applicator tips.

Results:
For applicator-tip verification, MDA, DC, and H95 were 1.12 ± 0.07 mm, 0.85 ± 0.012, and 1.21 ± 0.02 mm for the 500% IDL; 1.08 ± 0.03 mm, 0.91 ± 0.009, and 1.21 ± 0.02 mm for the 200% IDL; and 1.06 ± 0.03 mm, 0.94 ± 0.006, and 1.10 ± 0.21 mm for the 100% IDL. For Point-A–based-plans, H95 values ranged from 1.29–1.47 mm, with DC ≥ 0.97 and MDA ≤ 1.33mm across the 100%–250% IDLs. The maximum observed H95 (1.73mm) was within the ICRU Report 89 recommended uncertainty for applicator reconstruction of 2 mm.

Conclusion:
This work introduces an MR-ICB commissioning procedure with quantitative isodose-based validation that demonstrated millimeter-level agreement with CT-based planning thereby providing evidence for clinical adoption.

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INTRODUCTION

MRI-only intracavitary HDR brachytherapy improves workflow efficiency and leverages the superior soft-tissue visualization of MRI. However, its clinical implementation requires rigorous validation to ensure accurate applicator reconstruction and dose delivery. This framework presents a physics-based commissioning approach to:

- **Validate MRI-based applicator reconstruction and dosimetry against CT.**
- **Assess geometric and dosimetric accuracy using quantitative metrics.**
- **Demonstrate end-to-end clinical reliability.**
- **Eliminate CT dependence while maintaining treatment confidence.**
- **Provide a practical, reproducible framework for clinical adoption.**

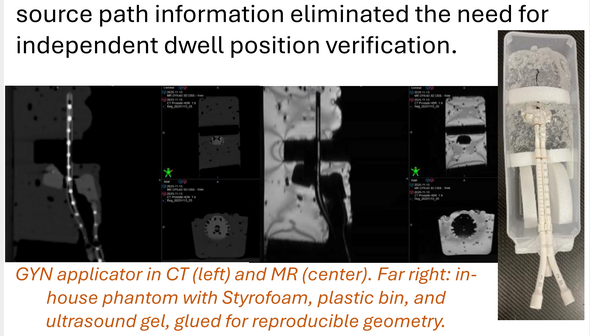
The following sections outline the commissioning methodology and validation results supporting the safe implementation of MRI-only HDR brachytherapy.

METHODS AND MATERIALS

1.MRI Sequence Optimization: 3D T2 CISS and TRUFI sequences were selected to enhance visualization of MRI line markers within IC applicators.

2.Phantom Construction: An ultrasound-gel phantom with external fiducials was used to benchmark applicator geometry and marker tip localization.

3.Applicator Reconstruction: Utilized existing vendor-supplied applicator models containing source path information eliminated the need for independent dwell position verification.

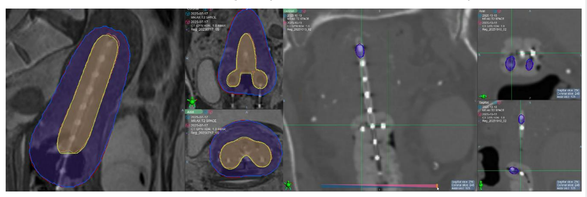


GYN applicator in CT (left) and MR (center). Far right: in-house phantom with Styrofoam, plastic bin, and ultrasound gel, glued for reproducible geometry.

4. Patient Case Validation: Fifteen retrospective cases were reconstructed on CT and MRI; dose distributions were generated using Point A prescriptions.

5. Quantitative Analysis: CT–MRI rigid registration allowed comparison of 75%–250% isodose lines using H95, MDA and DC.

6.First Dwell Verification: Single dwell loading assessed for high-dose-gradient accuracy at tandem and ovoid tips (100%–500% IDLs).



Screenshot above shows the 100% and 250% IDLs on CT and MRI superimposed on each other. Blue-100%IDL on CT; Red – 100%IDL on MRI; Orange-250%IDL on CT; Yellow-250%IDL on MRI.

Purple and blue isodoses are from CT and MR point A based plans reconstructed and normalized independent of each other. CT/MR images registered to quantify the differences in H95, DC and MDA.

RESULTS

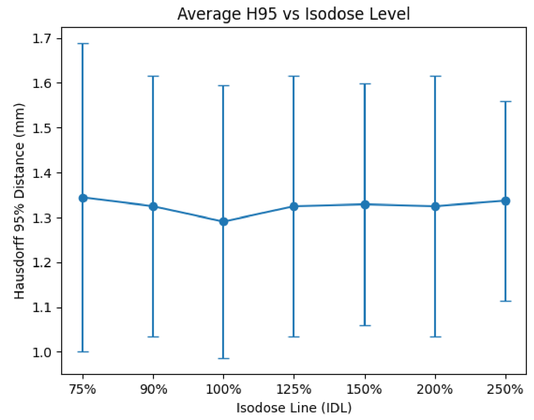


Figure 1 - *Average H95 between CT- and MRI-derived isodose surfaces across isodose levels, remaining within the 2 mm (ranged from 1.29–1.47 mm with average SD of 0.3mm) reconstruction uncertainty recommended by ICRU Report 89.*

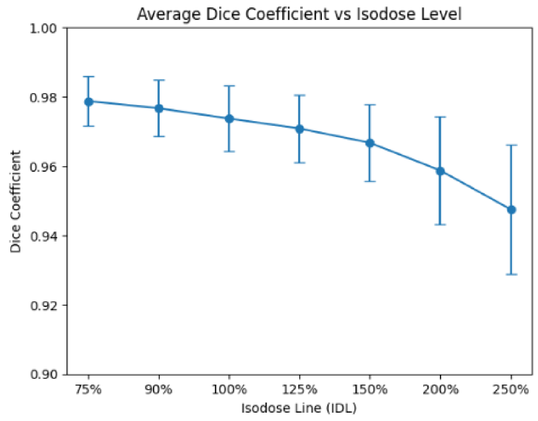


Figure 2 - *Average DC (≥0.97 ±0.009) between CT- and MRI-derived isodose surfaces as a function of isodose level (75%–250%), demonstrating high spatial agreement across moderate- and high-dose-gradient regions.*

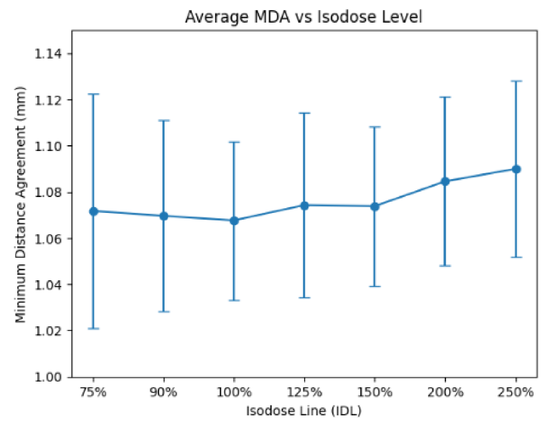
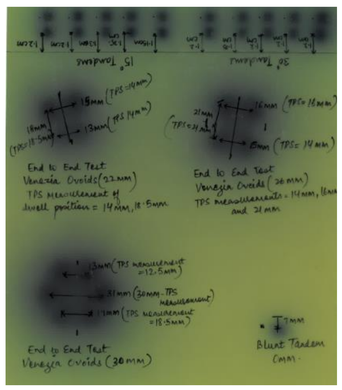


Figure 3 - *Average MDA (≤1.1 mm with Av. SD of 0.035mm) between CT- and MRI-derived isodose surfaces as a function of isodose level (75%–250%). MDA remains approximately 1 mm across all dose levels, indicating consistent geometric agreement in both moderate- and high-dose-gradient regions.*

An end-to-end test of applicator modeling was performed prior to clinical implementation to verify the reliability of CT- and MR-based reconstruction and accurate dose delivery to the intended dwell positions. The film-based method of applicator commissioning has used to perform this QA.



DISCUSSION

Physics-based MRI-only commissioning framework: Unlike prior studies focused primarily on feasibility, this work provides a comprehensive commissioning and validation strategy with quantitative comparison to CT.

Geometric and dosimetric equivalence to CT: MRI-only planning achieved accuracy comparable to conventional CT-based workflows, supporting safe clinical implementation.

Robust validation in high-dose-gradient regions: Applicator reconstruction and source localization remained within clinically acceptable tolerances, even in regions most sensitive to geometric uncertainties.

Objective quantitative evaluation: Dose and reconstruction accuracy were assessed using Dice Coefficient (DC), H95 (95th percentile Hausdorff distance), and Mean Distance Agreement (MDA), providing rigorous validation across clinically relevant isodose levels.

Compliance with established standards: Maximum geometric deviations remained below the 2 mm reconstruction uncertainty recommended by ICRU Report 89.

Clinical workflow advantages: Eliminating CT verification reduces imaging requirements, patient transfers, and overall workflow complexity while maintaining treatment confidence.

Generalizability and adoption: This commissioning methodology is reproducible, practical, and readily transferable to other institutions implementing MRI-only HDR brachytherapy.

CONCLUSIONS

- **MRI-only intracavitary HDR brachytherapy can be safely implemented** using a robust commissioning and validation approach.
- **Excellent agreement was demonstrated between MRI-only and CT-based planning** was demonstrated, with geometric and dosimetric accuracy maintained within clinical tolerances.
- **Eliminating CT verification** streamlines workflow while preserving confidence in applicator reconstruction and dose delivery.
- **The commissioning methodology is practical, reproducible, and transferable** providing a framework for institutions adopting MRI-only brachytherapy.

REFERENCES

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2. TG-59: HDR Brachytherapy Quality Assurance.AAPM TG-229: MRI in Brachytherapy.AAPM
3. TG-303: Image-Guided Brachytherapy Quality Management.
4. ICRU Report 89.GEC-ESTRO Recommendations for Image-Guided Cervical Brachytherapy.American Brachytherapy Society consensus guidelines.