Re-Evaluation of Clinical Brachytherapy Uncertainties Using Automated QA Methods

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ABSTRACT

Purpose: To revisit and systematically quantify uncertainties in clinical HDR brachytherapy source position quality assurance through the development of an automated framework that eliminates observer-dependent variability and enhance the accuracy and consistency of HDR treatment delivery.

Methods: A Python-based image-processing pipeline was developed for detection of dwell positions on films and kVs. This script utilizes the scikit-image and scipy libraries. The script was applied in two clinical quality assurance (QA) workflows: (1) ring applicator QA and (2) position verification test PermaDoc analysis. For kVs the dummy wire tip was detected. Then, a fixed offset (3.45 mm) was applied to localize the radiation center based on source geometry. For film, a region of interest was first specified, then the highest pixel value was detected to localize the radiation center of each dwell position. TPS-planned dwell positions were generated using nominal applicator geometry with 5 mm spacing. All uncertainties were characterized. The mechanical uncertainty was identified using the positional verification test (PVT) results for dummy and source cables and compared to uncertainty with added user dependency. The uncertainty calculated by using the script was compared to in-house manual workflow uncertainties as well as published clinical uncertainties in literature.

Results: Daily PVT measurements demonstrated mechanical deviations within ±0.02 cm. Estimated measurement uncertainty was 0.5–1.0 mm for kV imaging and 1–2 mm for radiochromic film. Agreement between kV-derived dwell positions and film measurements was within 1 mm across evaluated positions with the largest discrepancies observed at dwell locations in regions of maximum ring curvature. The results are consistent with the combined uncertainty range of 0.73-1.43 mm. The combined uncertainty increases to 1.14-2.25 mm when adding the uncertainty associated with manual film interpretation.

Conclusion: We demonstrate that the uncertainty budget in clinical brachytherapy QA can be reduced through automation, using a software-driven framework can systematically quantifying sources of error, eliminating observer dependence, and thus improving the reliability and reproducibility clinical patient HDR treatment delivery.

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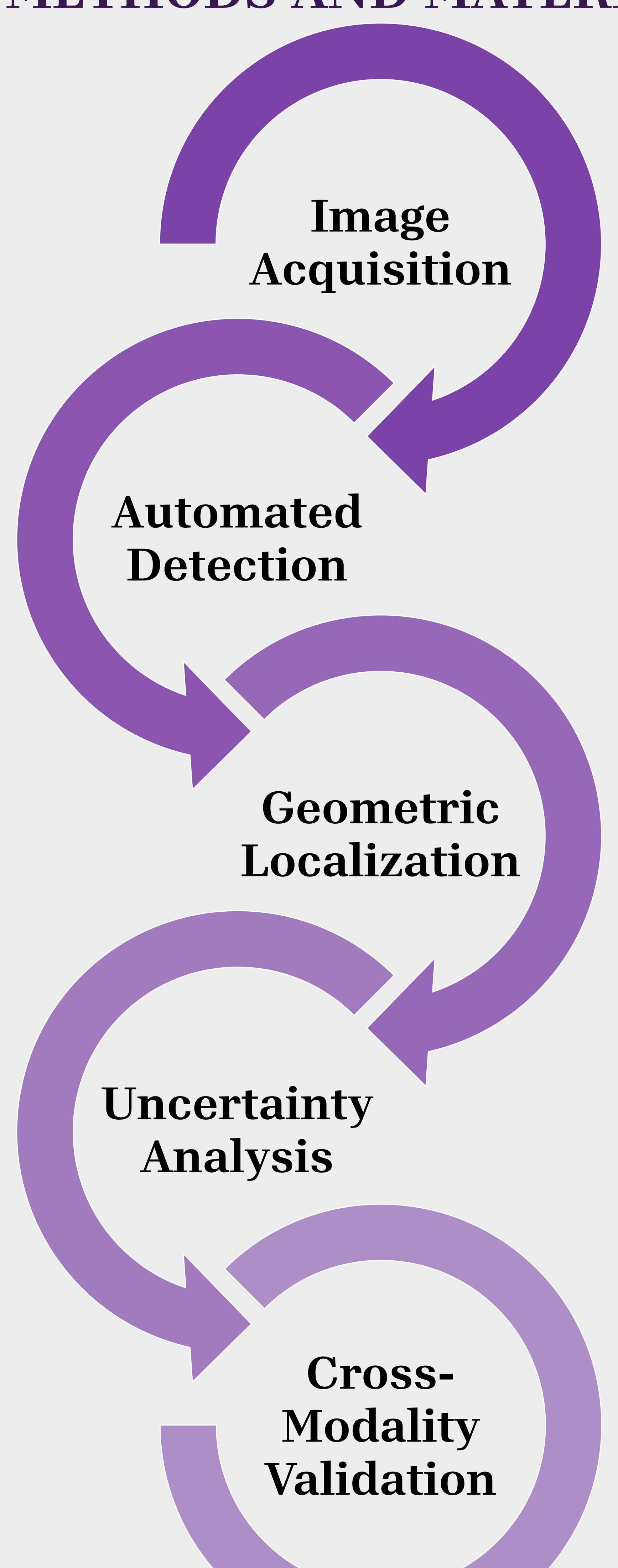
INTRODUCTION

Modern afterloaders, including the Bravos Afterloader, routinely demonstrate mechanical reproducibility on the order of 0.2 mm; however, clinical quality assurance (QA) workflows often report agreement only within 1-2 mm.

This discrepancy is not primarily driven by mechanical limitations, but by measurement uncertainty introduced during QA, including film resolution limits, geometric reconstruction assumptions, and observer-dependent interpretation of dwell positions.

As image-guided brachytherapy becomes increasingly precise, semi-qualitative QA methods risk masking true geometric effects. A transition toward automated, uncertainty-aware quantitative verification is therefore essential to distinguish measurement variability from clinically meaningful positional deviations.

METHODS AND MATERIALS



RESULTS

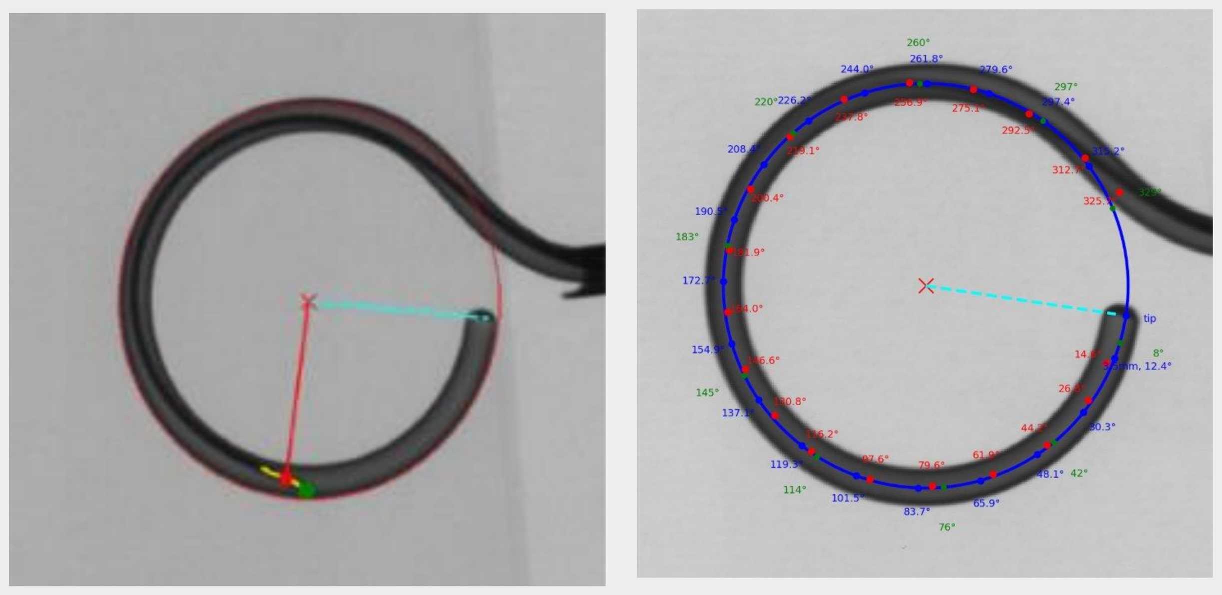
Automated kV and film-based dwell localization demonstrated strong cross-modality agreement (≤1 mm) across 30°, 45°, and 60° Varian ring applicators, confirming accurate radiation center identification without manual marking (Figure 1). Mechanical uncertainty from daily PVT measurements remained low (±0.02 cm).

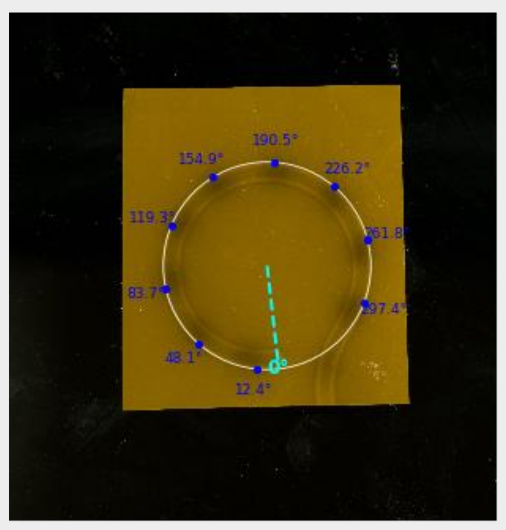
The combined root-sum-square (RSS) uncertainty for the automated workflow was 0.73–1.43 mm. Inclusion of a 1 mm observer-dependent interpretation term increased total uncertainty to 1.14–2.25 mm, representing a ~35–45% increase in overall uncertainty (Table 1).

Comparison with TPS-planned dwell positions revealed systematic, curvature-dependent deviations, most pronounced in mid-to-distal dwell positions of higher-angle rings, as previously reported. Close agreement between kV and film measurements confirmed that these discrepancies are geometry-driven rather than measurement-driven (Figure 2).

Table 1. A summary table of uncertainty contributions from mechanical positioning (PVT), kV imaging, film analysis, pixel resolution, and combined uncertainty (RSS).

Sources of Error	Uncertainty Budget (mm)	
	W/O Automation	With Automation
PVT Mechanical Uncertainty	0.2	0.2
kV Pixel Resolution Identification Error	0.5-1.0	0.5
Film Resolution Physical Error Film Flatness	0.5-1.0	0.5-1.0
User Dependence	1.0-2.0	N/A
Root-Square-Sum	**1.14-2.25**	**0.73-1.43**





	Planned_deg	Film_2mm_deg_matched_deg	Δθ_film−planned_deg	|Δθ|_deg	ArcDiff_mm
0	12.441	16.5	4.059	4.059	1.144
1	48.062	53.8	5.738	5.738	1.617
2	83.682	88.2	4.518	4.518	1.273
3	119.303	121.0	1.697	1.697	0.478
4	154.923	154.8	-0.123	0.123	-0.035
5	190.544	191.2	0.656	0.656	0.185
6	226.164	230.0	3.836	3.836	1.081
7	261.785	266.0	4.215	4.215	1.188
8	297.405	305.0	7.595	7.595	2.141

Figure 1. A series of images visualizing the procedure for automated detection and deviation calculation both on kVs and film.

DISCUSSION

This study re-evaluates clinical HDR brachytherapy QA from an uncertainty-driven perspective and demonstrates that measurement variability is the dominant contributor to dwell position discrepancies. Daily PVT data confirmed sub-millimeter mechanical reproducibility (±0.2 mm). By eliminating manual film angle and dwell identification, the automated workflow reduced the combined uncertainty budget from 1.14–2.25 mm to 0.73–1.43 mm. This ~35–45% reduction is clinically meaningful, particularly in curved applicators where geometry-driven deviations may approach 2–3 mm. Without automation, these systematic geometric effects risk being obscured by measurement noise. The strong agreement between kV-derived and automated film-based dwell positions (<1 mm) confirms accurate localization of the radiation center using the fixed 3.45 mm geometric offset. Importantly, the close cross-modality agreement allows deviations relative to TPS-planned dwell positions to be interpreted as geometry-driven rather than measurement-driven.

Application of the automated framework to PermaDoc daily QA further demonstrated the clinical utility of this approach. By establishing a tip-referenced coordinate system and quantitatively analyzing dwell centroids, daily QA was transformed from qualitative pattern recognition to objective, millimeter-scale verification. Observed deviations (<1 mm) confirm mechanical stability while enabling early detection of systematic shifts.

CONCLUSIONS

Automation reduces total HDR brachytherapy QA uncertainty by eliminating observer-dependent variability and systematically quantifying measurement contributions. This uncertainty-aware framework improves reproducibility, distinguishes geometric effects from measurement noise, and establishes a more rigorous standard for clinical commissioning and daily QA.

Collectively, these findings support a transition from semi-qualitative HDR QA toward structured, uncertainty-aware verification. Automation not only improves reproducibility but enables clinically meaningful interpretation of positional deviations in both commissioning and routine practice.

REFERENCES

Aldrovandi LG, Dessein MET, Pearson SM, Bulling SM. Position-dependent offset corrections for ring applicator reconstruction in cervical cancer brachytherapy. J Appl Clin Med Phys. 2025 Jun;26(6):e70079. doi: 10.1002/acm2.70079. Epub 2025 Mar 19. PMID: 40105150; PMCID: PMC12148795.