Dosimetric impact of shielding in a Co-60 HDR cylindrical applicator: A Geant4 Monte Carlo and Gafchromic film study

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ABSTRACT

Objectives

High-dose-rate (HDR) vaginal brachytherapy often employs shielded applicators to enhance organ-at-risk (OAR) sparing—particularly rectal protection—in cases with asymmetric tumor distribution. While cylindrical applicators were originally designed for Ir-192 sources, they are increasingly used with Co-60, despite its higher photon energy and the potential for altered transmission. This study investigates dose calculation deviations for a Co-60 source in a specific shielded cylindrical applicator design to evaluate whether using a single transmission factor within the TG-43 formalism is sufficient in the presence of high-Z shielding, or if a more accurate method is required.

Methods

Geant4 Monte Carlo (MC) simulations were performed to model Elekta's cylindrical Flexitron applicator in both single-channel and shielded configurations with a Co-60 source. Dose distributions obtained from MC simulations were compared with those calculated by the treatment planning system (TPS). In addition, EBT3 Gafchromic film measurements were performed to provide experimental validation of the dose distributions and to quantify the shield transmission factor.

Results

For the single-channel applicator, MC, TPS, and film dosimetry were in good agreement, with 95% of points within 3%/3 mm. For the shielded applicator, MC and film showed similar agreement, while TPS calculations progressively deviated, reaching up to 10% at 5 cm from the source.

Conclusion

Dose evaluation of Co-60 HDR sources using shielded cylindrical applicators highlights TG-43 dosimetric limitations caused by material inhomogeneity. Conventional single-factor shielding corrections are inadequate, underscoring the need for Monte Carlo or model-based algorithms to achieve accurate dose calculations in the presence of high-Z materials

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INTRODUCTION

High-dose-rate (HDR) brachytherapy plays a critical role in the treatment of gynecological malignancies by delivering highly conformal radiation doses directly to the target while minimizing exposure to surrounding organs at risk (OARs), including the bladder and rectum. Vaginal cylindrical applicators are commonly used because of their simplicity, reproducibility, and effectiveness in post-hysterectomy vaginal brachytherapy. In situations involving asymmetric tumor extension or close proximity of critical structures, shielded applicators containing high-density materials have been introduced to provide directional dose reduction and improve OAR sparing. Most commercially available shielded vaginal applicators were originally designed for Iridium-192 (Ir-192) sources. However, Cobalt-60 (Co-60) HDR brachytherapy has gained popularity because of its longer half-life and lower source replacement costs. Despite these advantages, the higher photon energy of Co-60 (1.25 MeV) results in greater penetration through shielding materials, potentially altering dose distributions and reducing shielding effectiveness. Current treatment planning systems (TPS) based on the TG-43 formalism compensate for shielding using a single transmission factor and do not account for applicator heterogeneity or high-Z materials.

Therefore, this study aimed to evaluate the dosimetric impact of shielding in a Co-60 HDR cylindrical applicator using Geant4 Monte Carlo simulations and Gafchromic EBT3 film measurements, and to determine whether a single transmission factor is sufficient for accurate dose calculation.

METHODS AND MATERIALS

This study consisted of Monte Carlo (MC) simulations, treatment planning system (TPS) calculations, and Gafchromic film measurements. Geant4 version 10.1.p02 was used to model the Elekta Flexisource Co-60 source and Flexitron cylindrical vaginal applicators in both unshielded and 180° shielded configurations. The MC model was validated against published TG-43 dosimetric parameters before dose calculations were performed in a custom water-equivalent phantom containing bladder and rectum inserts.

Treatment plans were generated in Oncentra Brachy TPS v4.5.3 using TG-43 formalism. CT images of the phantom-applicator assembly were imported for contouring and dosimetric analysis. A prescription dose of 5 Gy was delivered to a reference point located 5 mm from the applicator surface.

Experimental validation was performed using EBT3 radiochromic films. Films were calibrated from 0.25–6 Gy and placed within the phantom to measure dose distributions. Gamma analysis (3%/3 mm) and relative dose comparisons were conducted between MC, TPS, and film measurements.

Fig. 1 illustrates the applicator models, phantom geometry, and OAR configurations.

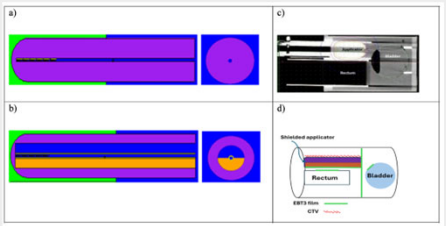

Fig. 1. (a) Single-channel cylindrical applicator, and (b) 180 ◦ shielded cylindrical applicator modeled in MC. (c) CT images of the custom water-equivalent phantom with applicator inserted, as visualized in the TPS, along with the corresponding dose distribution. (d) Schematic representation of the phantom geometry and EBT film placement

RESULTS

The validated Monte Carlo model demonstrated excellent agreement with published TG-43 data, with differences within ±2%. For the unshielded single-channel applicator, MC simulations, TPS calculations, and film measurements agreed closely, with over 97% of points passing the 3%/3 mm gamma criterion. The absolute dose at the reference point also differed by less than 2% among the three methods. Introduction of the 180° tungsten shield substantially reduced dose on the shielded side of the applicator. MC simulations and film measurements remained in strong agreement, confirming the accuracy of the shielding model. However, TPS calculations increasingly diverged from MC and film results with increasing distance from the source. At distances of approximately 6–7 cm, TPS overestimated dose by up to 10%.

Film dosimetry measured a mean shield transmission factor of 0.46, consistent with MC results. Shielding significantly lowered rectal and bladder doses, demonstrating its effectiveness for OAR sparing while highlighting inaccuracies in TG-43-based calculations when heterogeneous materials are present.

Fig. 2 illustrates the dose distributions for the single-channel and shielded cylindrical applicators in the XY plane based on MC calculations.

Table 1 presents rectal and bladder percentage doses for both applicators.

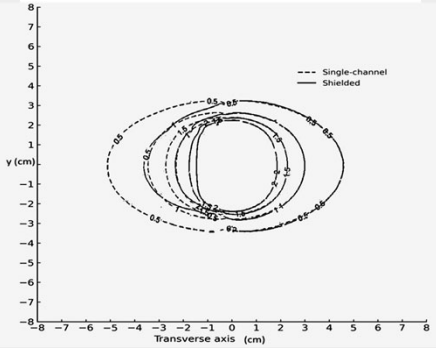

Fig. 2. Cross-sectional isodose distributions in a plane perpendicular to the applicator central axis for single-channel and shielded cylindrical applicators obtained using Monte Carlo simulations.

Table 1- Percentage dose to the OARs for both the single-channel and shielded applicators.

	Transverse axis distance (cm)	0.5	1	2	3
Rectum	Single-Channel (TPS)	65%	58.5%	33%	24%
	Shielded (TPS)	46%	38.5%	26%	18.5%
	Single-Channel (MC/Film)	64%/ 65.1%	56.5%/ 54%	31%/ 30%	21%/ 19%
	Shielded (MC/ Film)	44%/ 43%	38%/ 38.1%	24%/ 24.8%	16.1%/ 15.5%
Bladder	Single-Channel (TPS)	30%	28%	19%	15%
	Shielded (TPS)	23.5%	17.8%	14.6%	11.5%
	Single-Channel (MC/Film)	28%/ 31%	26%/ 25%	17%/ 17.5%	13.2%/ 12%
	Shielded (MC/ Film)	22%/ 21%	16.2%/ 17.1%	12.5%/ 12.1%	8.5%/ 9.7%

DISCUSSION

The findings confirm that TG-43-based dose calculations remain accurate for unshielded vaginal applicators in homogeneous water-equivalent conditions. When high-Z shielding materials are introduced, however, the TG-43 formalism becomes less reliable because it assumes an infinite homogeneous medium and cannot account for attenuation, scatter changes, and material heterogeneity. Consequently, applying a single transmission factor fails to accurately represent dose distributions throughout the treatment volume.

The observed discrepancies of up to 10% between TPS and MC calculations are clinically important, particularly in regions near OARs or at larger radial distances from the source. The higher photon energy of Co-60 increases penetration through shielding materials, further magnifying these inaccuracies. Film measurements validated the Monte Carlo predictions and confirmed the reproducibility of the measured transmission factor.

These results support previous studies recommending model-based dose calculation algorithms (MBDCAs), such as Monte Carlo and Acuros-based approaches, for shielded brachytherapy applications. Such methods can improve target coverage assessment and OAR protection in complex heterogeneous treatment scenarios.

CONCLUSIONS

This study demonstrated that the TG-43 formalism is insufficient for accurate dose calculation in shielded Co-60 HDR brachytherapy. Although shielding effectively reduces OAR dose, TPS calculations using a single transmission factor showed clinically relevant deviations. Monte Carlo–based or model-based algorithms are recommended for more accurate treatment planning in shielded applicators.

REFERENCES

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