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Impact of Inorganic Scintillators on Dose Response: A Gate Modeling Study

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ABSTRACT

Purpose: Inorganic scintillating detectors offer high-precision and high spatiotemporal resolution dosimetry for small-field radiotherapy applications such as SRS, SBRT, and SFRT. This study examines the impact of detector materials and volume on dose distributions to ensure accurate dose measurement and clinical calibration.
Methods: Comprehensive clinical dose measurement modeling was performed using Monte Carlo simulations in GATE based on GEANT4. The detection channel was modeled according to the sensitive volume geometry and scintillator material composition to evaluate dose quantification and perturbation analysis. A realistic clinical setup was implemented using treatment room geometry, clinical phantoms, and an Elekta LINAC source. A 6 MV photon beam with field sizes of 0.5 × 0.5 cm^2, 3 × 3 cm^2, and 10 × 10 cm^2 was simulated using TPS data. Two inorganic scintillating detectors with sensitive volumes of 2 × 10^{-5} mm^3 and 5 × 10^{-3} mm^3 were evaluated, including the addition of thin material layers to assess material-dependent effects on absorbed dose measurements.
Results: The detector with the smallest sensitive volume(2 × 10^{-5} mm^3) showed no measurable impact on dose distributions. In contrast, a tenfold increase in scintillating volume using the same material produced average dose deviations of approximately 2 % for the smallest field (0.5 × 0.5 cm^2) and about 1% for larger fields (3 × 3 cm^2 and 10 × 10 cm^2). The addition of an external amplification layer (~ 200 µm aluminum coating) introduced a negligible dose perturbation (<0.1%) for all fields in both cases. Overall, simulation results show improved accuracy in dose distributions for the smaller-volume detector relative to the larger-volume design.
Conclusion: The study shows that scintillator volumes above a critical threshold value can perturb dose distributions and measurements. These results highlight the importance of designing geometry-controlled sensitive volume detectors for accurate small-field dosimetry and have the potential for multi-modality applications.

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INTRODUCTION

Conventional radiotherapy detectors have limited dosimetric accuracy in small-field radiation therapy due to their relatively large sensitive volumes and the associated volume-averaging and perturbation effects [1-2]. These limitations reduce lateral spatial resolution and necessitate multiple detector-specific correction factors to achieve accurate absorbed-dose measurements, particularly in small radiation fields. Inorganic scintillating detectors offer high-precision and high spatiotemporal resolution dosimetry for small-field radiotherapy applications such as SRS, SBRT, and SFRT [3]. This study examines the impact of detector materials and volume on dose distributions and the relevant dose perturbation to ensure accurate dose measurement and clinical calibration.

METHODS AND MATERIALS

A Comprehensive clinical dose measurement modeling was performed for scintillating detectors using Monte Carlo simulations in GATE based on GEANT4 electromagnetic tools. The detection channel was modeled according to the sensitive volume geometry and scintillator material composition to evaluate dose quantification and perturbation analysis. A realistic clinical setup was implemented using treatment room geometry, clinical phantoms, and an Elekta LINAC source. A 6 MV photon beam with field sizes of 0.5 × 0.5 cm^2, 3 × 3 cm^2, and 10 × 10 cm^2 was simulated using TPS data. Two inorganic scintillating detectors with sensitive volumes of 2 × 10^{-5} mm^3 and 5 × 10^{-3} mm^3 were evaluated, including the addition of thin material layers (200 um of aluminum) on top of the scintillating volume to assess material-dependent effects on absorbed dose measurements within the phantom system.

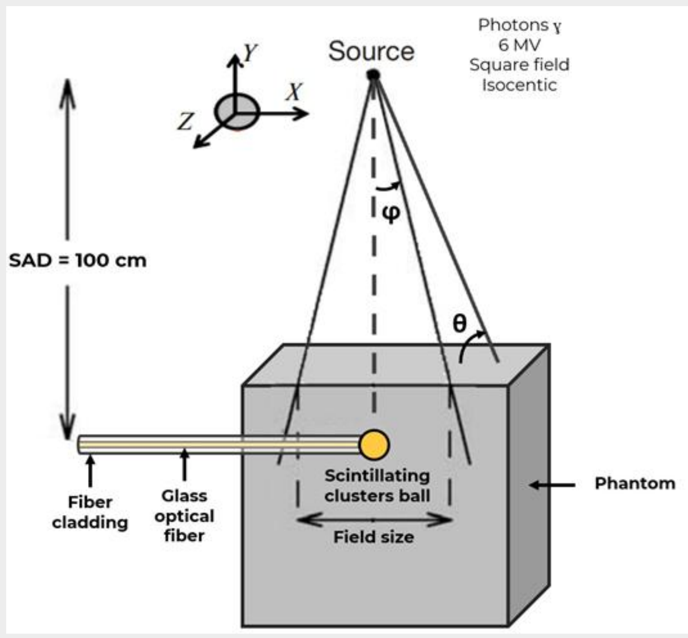

Fig.1. Schematic View of Dosimetry setup

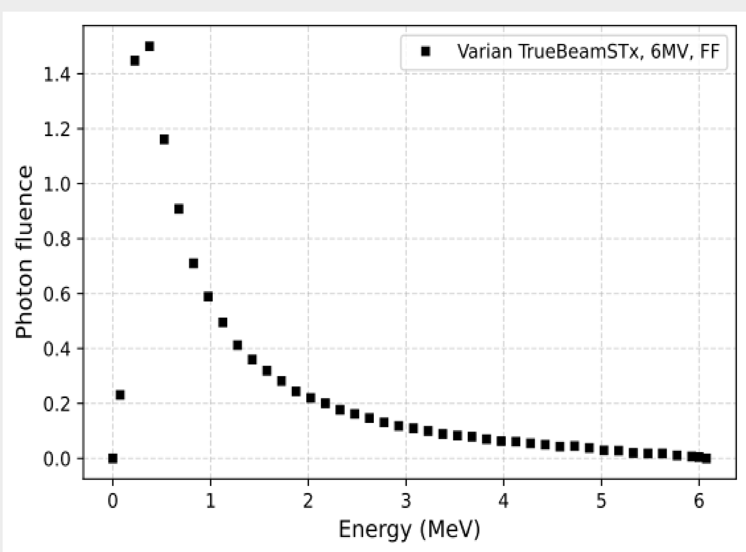

Fig.2. Energy spectra of 6 MV FF Beam

RESULTS

The detector with the smallest sensitive volume (2 × 10^{-5} mm^3) showed almost no measurable impact on dose distributions with or without metallization layer (<0.1%). In contrast, a tenfold increase in scintillating volume using the same material produced average dose deviations of approximately 2% for the smallest field (0.5 × 0.5 cm^2) and about 1% for larger fields (3 × 3 cm^2 and 10 × 10 cm^2). The addition of an external amplification layer (~200 µm aluminum coating) introduced a negligible dose perturbation (<0.1%) for all fields in both cases. Overall, monte-carlo simulation results show improved accuracy in dose distributions for the smaller-volume detector relative to the larger-volume detector investigated in this study.

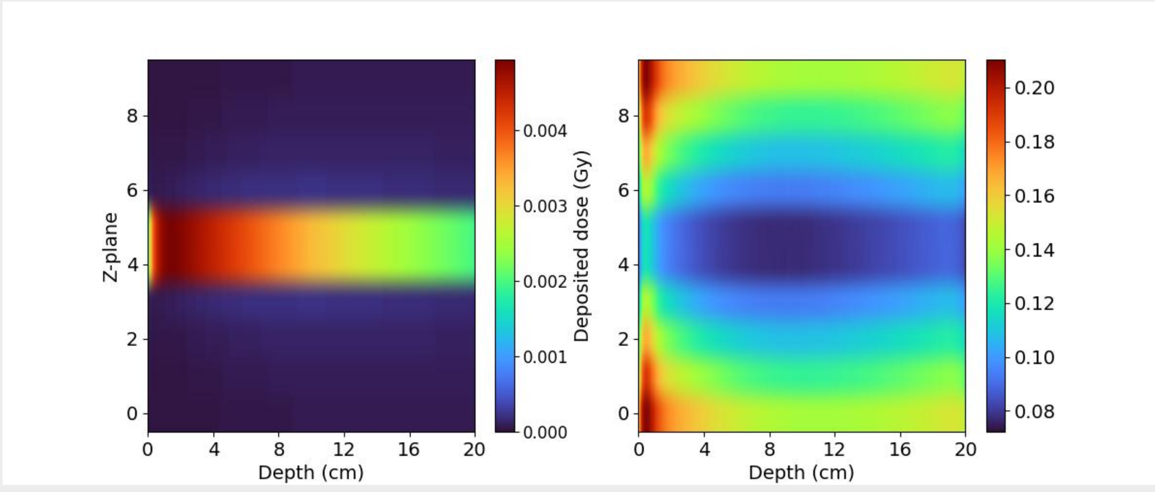

Fig.3. Spatial dose distribution (left) and statistical uncertainty map (right) for ISD with 2 × 10^{-5} mm^3 volume and field size of 0.5 x 0.5 cm^2

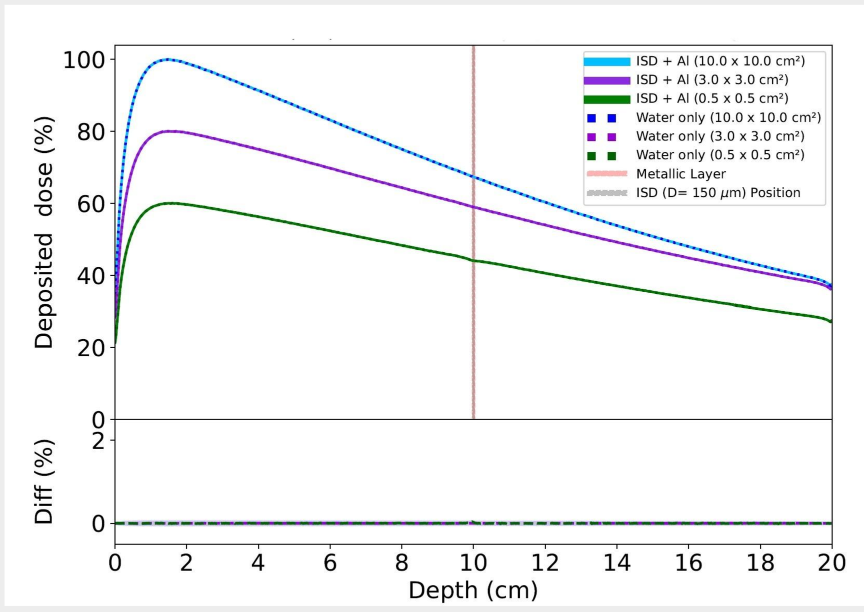

Fig.4. Dose perturbation for 2 × 10^{-5} mm^3 volume detector + Al(200 um)

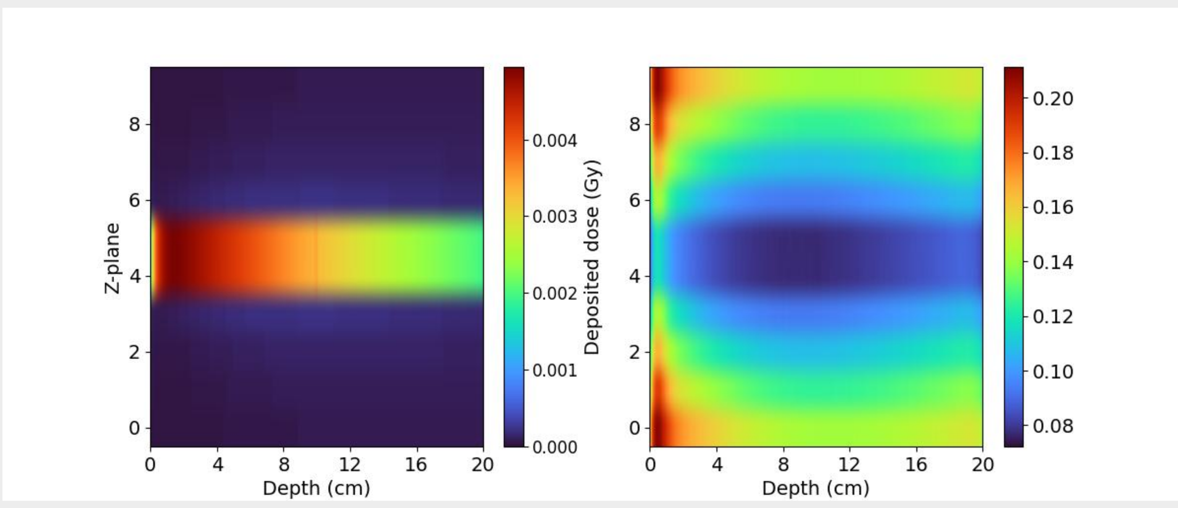

Fig.5. Spatial dose distribution (left) and statistical uncertainty map (right) for ISD with 5 × 10^{-3} mm^3 volume and field size of 0.5 x 0.5 cm^2

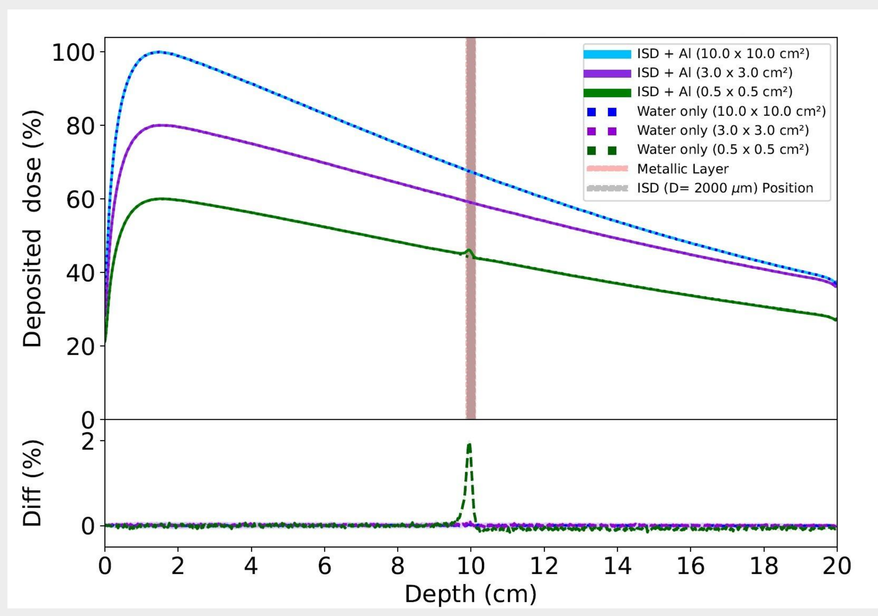

Fig.6. Dose perturbation for 5 × 10^{-3} mm^3 volume detector + Al (200um)

DISCUSSION

The study presents a comprehensive Monte Carlo (MC) investigation that is validated against experimental measurements, to quantify the dose perturbation response of ISDs for small-field dosimetry. The validated MC model reproduced the measured percentage depth-dose (PDD) distributions with good agreement across all investigated field sizes and enabled detailed characterization of detector-induced perturbations that cannot be directly resolved experimentally

The results demonstrate that detector sensitive volume is the dominant factor governing local dose perturbation, with the 2 × 10^{-5} volume detector exhibiting negligible perturbation (<0.1%) across all field sizes, whereas a larger volume of 5 × 10^{-3} mm^3 detector produced localized perturbations of up to 2% under ultra-small field irradiations.

The simulations demonstrate that the ultra-miniaturized detector preserves the surrounding dose distribution, behaving as a near point-like detector despite the non-water-equivalent composition of the scintillator. In contrast, increasing the sensitive volume produces measurable local perturbations under the smallest irradiation fields. 3D dose maps revealed a distinct discontinuity at the detector location, while the projected depth-dose profiles showed localized perturbation peaks . These perturbations progressively disappeared with increasing field size, indicating restoration of lateral electronic equilibrium. The negligible perturbation observed for the smallest detector indicates that reducing the scintillating sensitive volume effectively minimizes detector-induced disturbance of the charged-particle fluence.

CONCLUSIONS

The study shows that scintillator volumes above a critical threshold value can perturb dose distributions and measurements at small-fields. These results highlight the importance of designing geometry-controlled sensitive volume detectors for accurate small-field dosimetry. Hence, a miniaturized scintillating volume enables near-perturbation-free point-dose measurements while preserving high spatial resolution, making it well suited for high-precision dosimetry in SRS, SBRT, SFRT, and other small-field radiotherapy applications.

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