Feasibility of Collapsed Cone Convolution Dose Calculation Algorithm for Nanoparticle-Enhanced Radiotherapy: A Comparison with GEANT4 Monte Carlo Simulations

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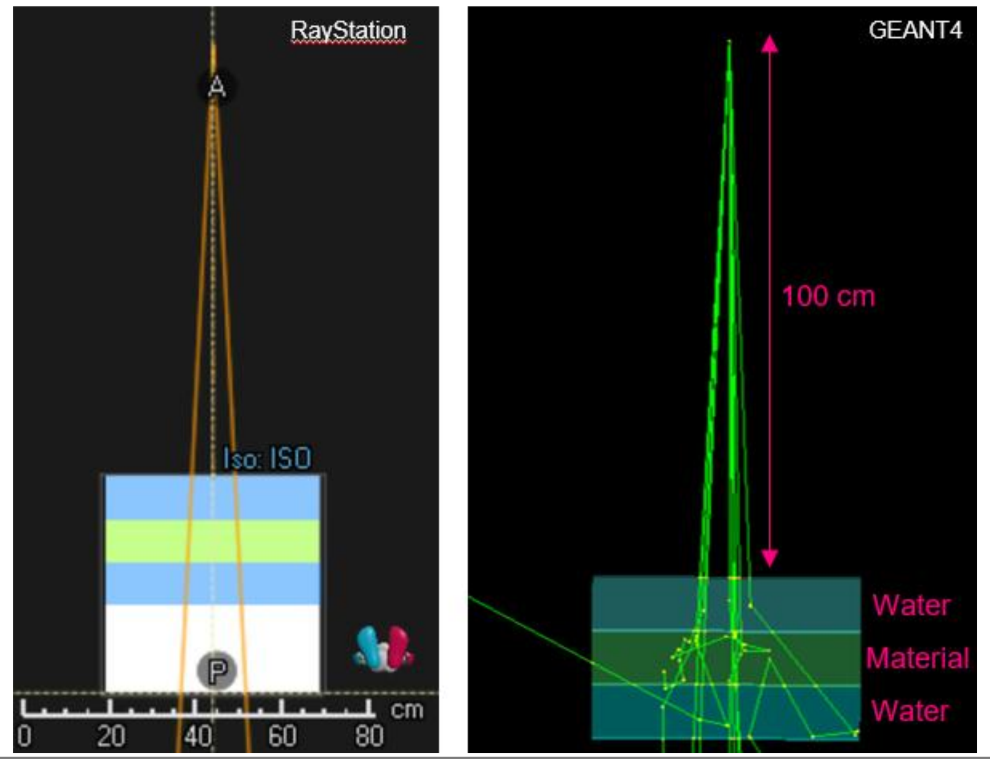
INTRODUCTION

- This study investigates the limitations of Collapsed Cone Convolution (CCC) dose calculation algorithm in modeling dose perturbations in nanoparticle-enhanced radiotherapy for lung tumors.
- CCC is compared with a Monte Carlo (MC) simulation platform using GEANT4, which provides an accurate representation of radiation transport and particle interactions in heterogeneous tissues.

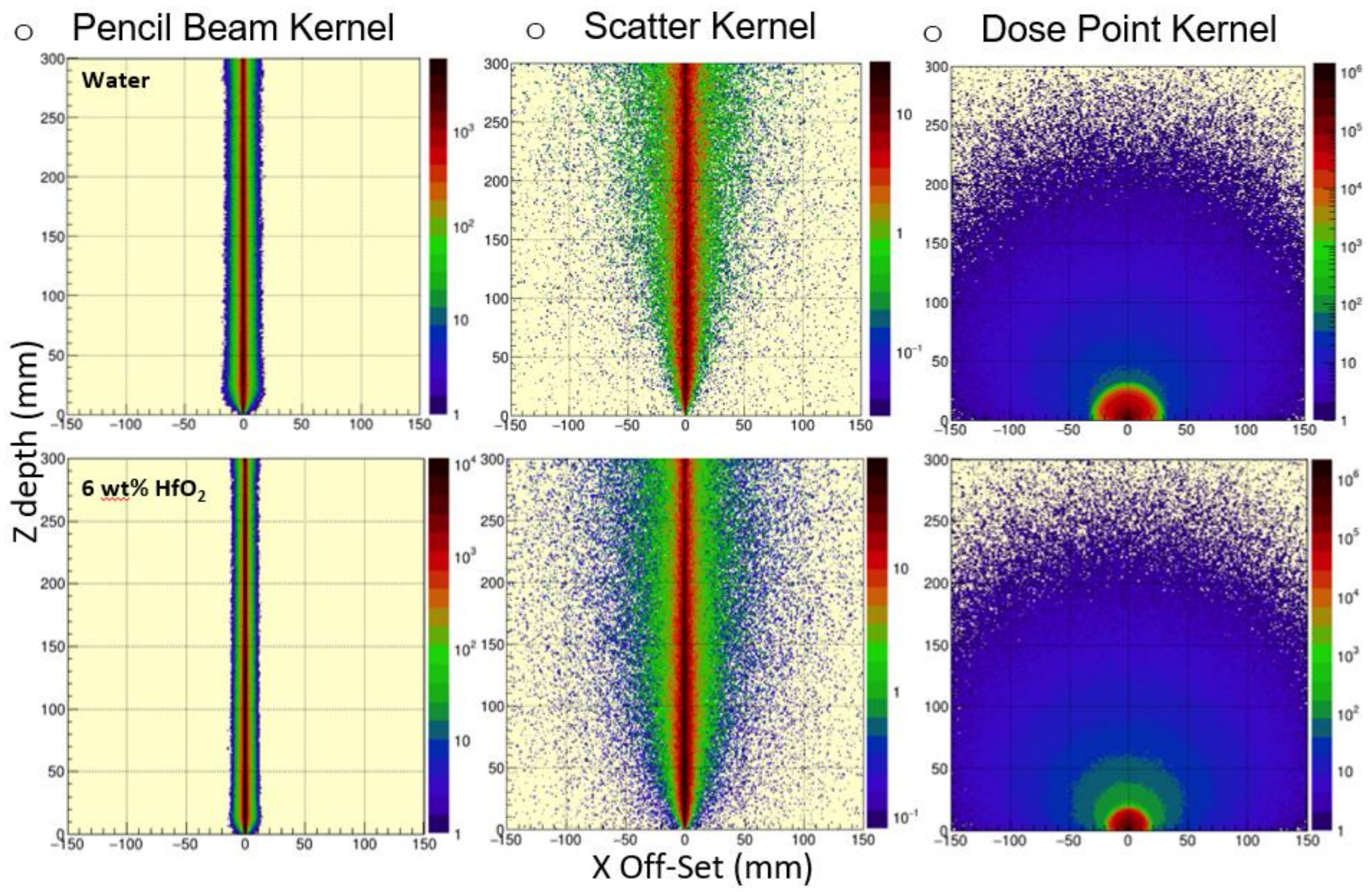
METHODS

- The RayStation™-CCC algorithm was initially evaluated at the dose point kernel (DPK) level for lung tumors treated with HfO_2 nanoparticles.
- This analysis assessed CCC's ability to account for complex tissue heterogeneities and high-Z nanoparticle–radiation interactions that influence local dose deposition.
- An in-house MC simulation framework using GEANT4 was then used to model photon, electron, and secondary particle transport in HfO_2-loaded tissue geometries.
- Dose distributions derived from GEANT4 simulations were compared with CCC calculations to quantify discrepancies and assess the clinical feasibility of CCC for nanoparticle-enhanced radiotherapy.

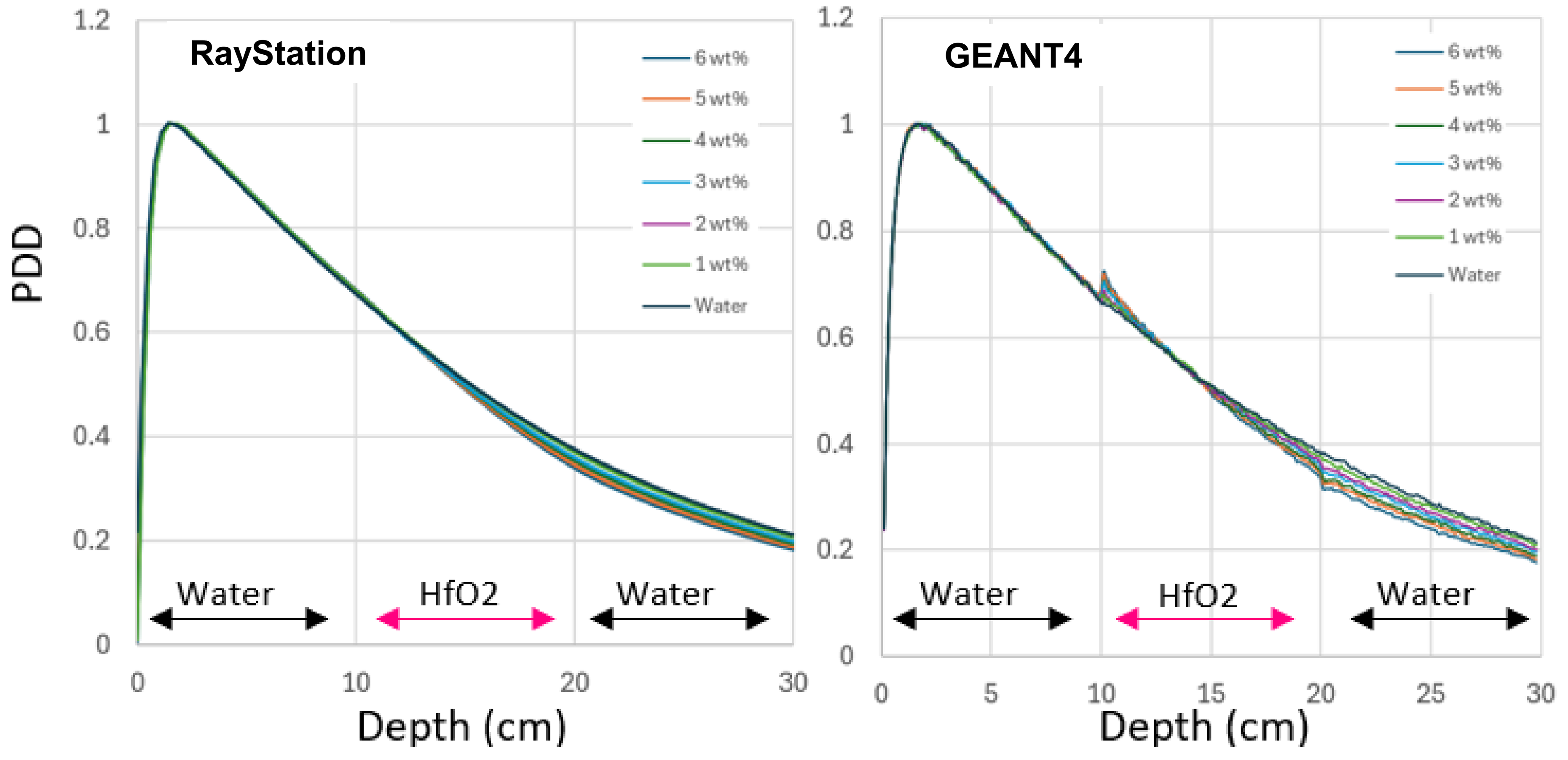


- Comparison of the RayStation linac model with a GEANT4 linac head highlights the advantages of realistic Monte Carlo modeling.
- GEANT4 simulate complex physics of Full Field Flattening Filter beams, which exhibit distinct dose profiles
- Unlike RayStation, which relies on pre-calculated dose kernels assuming idealized beam–tissue interactions, GEANT4 tracks individual photon and electron transport, capturing the effects of material interfaces in real time, enabling more accurate dose quantification for high-Z nanoparticles such as HfO_2.

RESULTS



GEANT4-derived pencil beam kernels, scatter kernels, and DPKs for both homogeneous water and 6 wt% HfO_2 solutions show significant differences. In standard treatment planning systems, DPKs derived from water are typically scaled using physical properties like inverse density and stopping power ratios to estimate dose distributions. However, for high-concentration HfO_2 media, these scaling methods fail to provide accurate dose predictions, highlighting their limited applicability in clinical practice.



PDD in water–HfO_2–water medium in RayStation CCC method and GEANT4 highlights significant differences. RayStation approach, scales dose kernels assuming homogeneous media, shows up to ~20% systematic discrepancies at 6 wt% HfO_2 due to limited modeling of photoelectric interactions and interface attenuation. In contrast, GEANT4 Monte Carlo simulations explicitly account for detailed photon interactions, showing more accurate results and interface effects.

CONCLUSIONS

- This study demonstrates the dose calculation limitations of DPK-based algorithms for nanoparticle-enhanced radiotherapy.
- Preliminary results indicate that GEANT4 MC simulations offer a precise representation of dose enhancement, at high nanoparticle concentrations.
- Evaluating CCC against GEANT4 highlights the feasibility and limitations of CCC for clinical treatment planning in high-Z nanoparticle therapies.

INNOVATION

This study innovatively integrates high-resolution Monte Carlo simulations with experimental phantom validation to capture photon, electron, and secondary particle interactions in nanoparticle-enhanced radiotherapy. By comparing the feasibility of CCC against GEANT4, it bridges the gap between preclinical models and clinical treatment planning, advancing personalized and precise radiotherapy strategies.

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