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Benchmarking Heterogeneity-Aware ^{131}Cs Intracranial Brachytherapy using Monte Carlo Simulation and Patient-Specific Voxelized Lattice

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ABSTRACT

Brachytherapy dose calculations are commonly based on the AAPM TG-43 formalism, which assumes a homogeneous water medium. Although widely used for high-dose-rate and Low-dose-rate brachytherapy, this assumption inadequately represents dose distributions in heterogeneous tissues, particularly for low-energy photon emitters. This study was to design and validate a clinically derived, patient-specific voxelized lattice for benchmarking heterogeneity-aware brachytherapy dose calculation algorithms.

A glioblastoma patient treated with GammaTile ^{131}Cs brachytherapy was modeled in MCNP6 using a voxelized lattice derived from CT images. Benchmark simulations were performed with all voxels assigned as water and compared with treatment planning system (TPS) calculations. Tissue heterogeneity was then incorporated using HU-based segmentation of air, skin, brain, and bone, and Monte Carlo dose-to-material calculations were compared with TPS results.

Water-only simulations agreed within 1% for High-Risk Clinical Target Volume (HR-CTV) V_{60} and V_{100}. With heterogeneous tissues, TPS overestimated V_{60} and V_{100} by 13.4% and 14.0%, respectively.

The validated patient-specific phantom enables robust Monte Carlo benchmarking of heterogeneity-aware brachytherapy dose calculations and supports implementation of AAPM TG-186 recommendations.

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INTRODUCTION

The AAPM TG-43[1] formalism remains the clinical standard for brachytherapy dose calculations but assumes a homogeneous water medium, neglecting patient-specific tissue heterogeneities. While this approximation is generally acceptable for high-energy sources such as ^{192}Ir, 382 keV, it can introduce clinically significant dose errors for low-energy radionuclides such as ^{131}Cs, 30.4 keV, used in GammaTile brachytherapy[3]. AAPM TG-186[2] recommends model-based dose calculation algorithms that account for tissue composition and density; however, clinically realistic benchmark datasets for their validation remain limited. This study presents a patient-specific voxelized Monte Carlo phantom derived from clinical CT images to benchmark heterogeneity-aware brachytherapy dose calculations and quantify dosimetric differences relative to TG-43-based treatment planning.

METHODS AND MATERIALS

A patient with glioblastoma multiforme treated with GammaTile ^{131}Cs brachytherapy was selected. Patient geometry was converted into a voxelized lattice model in MCNP6, and a ^{131}Cs source model was placed at each implanted seed position. Dose calculations were performed using an energy-deposition mesh tally with 10^8 histories. For benchmarking, all voxels were initially assigned as water and resulting dose distributions were compared with those from the treatment planning system and Monte Carlo calculations for a single source. Subsequently, tissues were assigned using Hounsfield Unit (HU)-based thresholding to classify air, skin, brain, and bone as distinct material universes. Simulations including all implanted seeds were then performed, and dose distributions from the treatment planning system and Monte Carlo were compared within the HR-CTV brain parenchyma. Dose to material was used as the comparison metric.

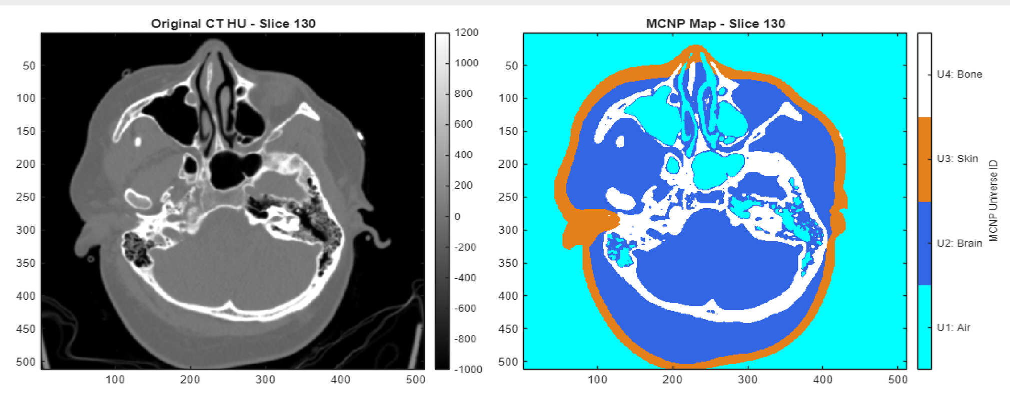

Figure 1. Verification of material map with original CT image. Left: original CT image, Right: material mapped image.

Table 1. Material Hounsfield number assignment in this phantom construction study

Material	Hounsfield Number (HU)	Material Universe	Density gm/cm^3
Air	< - 900	1	0.001205
Brain Tissue	>-900 < 60	2	1.04
Skin	>61<120	3	1.09
Bone	>120	4	1.92

Table 2. Dose–volume metrics (in cc) for the single seed and all the seeds for HR-CTV Volume (brain parenchyma).

Media	Number of Seeds	HRCTV	TPS	MC	Ratio (TPS/MC)
Water only	1	V60	0.355	0.357	0.994
		V100	0.171	0.169	1.012
Air, Brain, Skin, Bone	20	V60	16.374	12.235	1.336
		V100	8.392	5.990	1.401

RESULTS

Material segmentation was successfully achieved for all tissue classes and demonstrated strong spatial agreement with the original CT images. In the water-only benchmark, dose to water agreed within 1% between the treatment planning system and Monte Carlo for both V_{60} and V_{100}. When tissue-specific densities and materials were applied, the treatment planning system overestimated HR-CTV V_{60} and V_{100} by 13.4% and 14.0%, respectively, relative to Monte Carlo results.

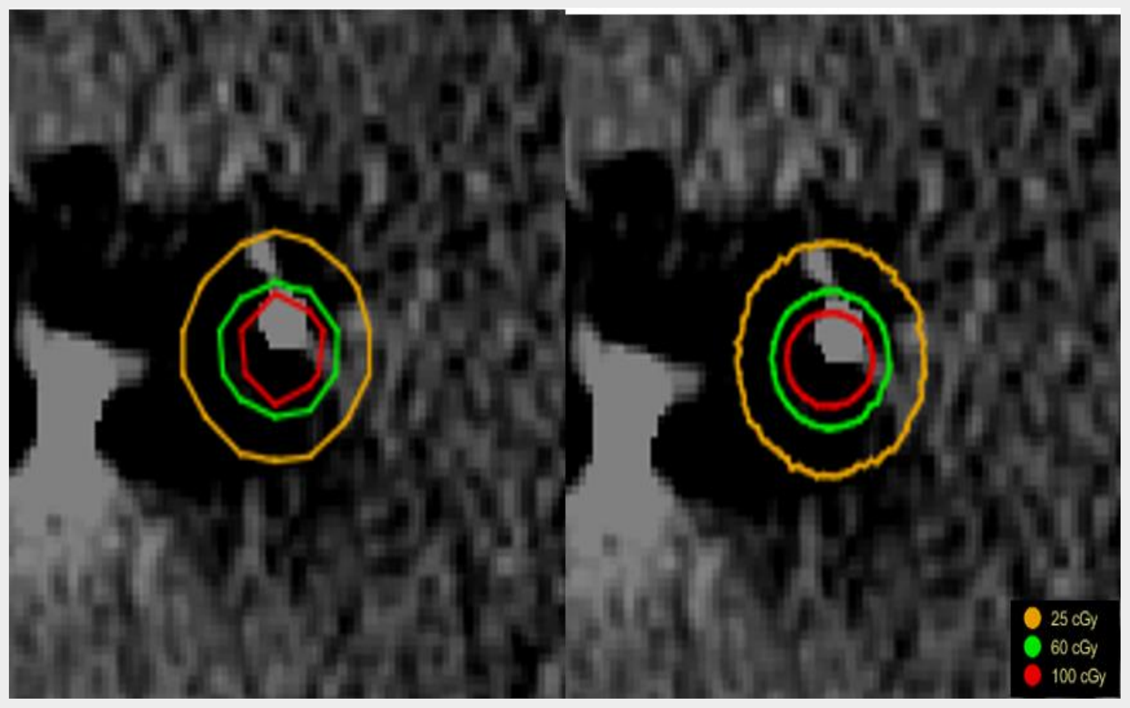

Figure 2. Iso-dose comparison with TPS and MC using water medium. Left: TPS, Right: Monte Carlo

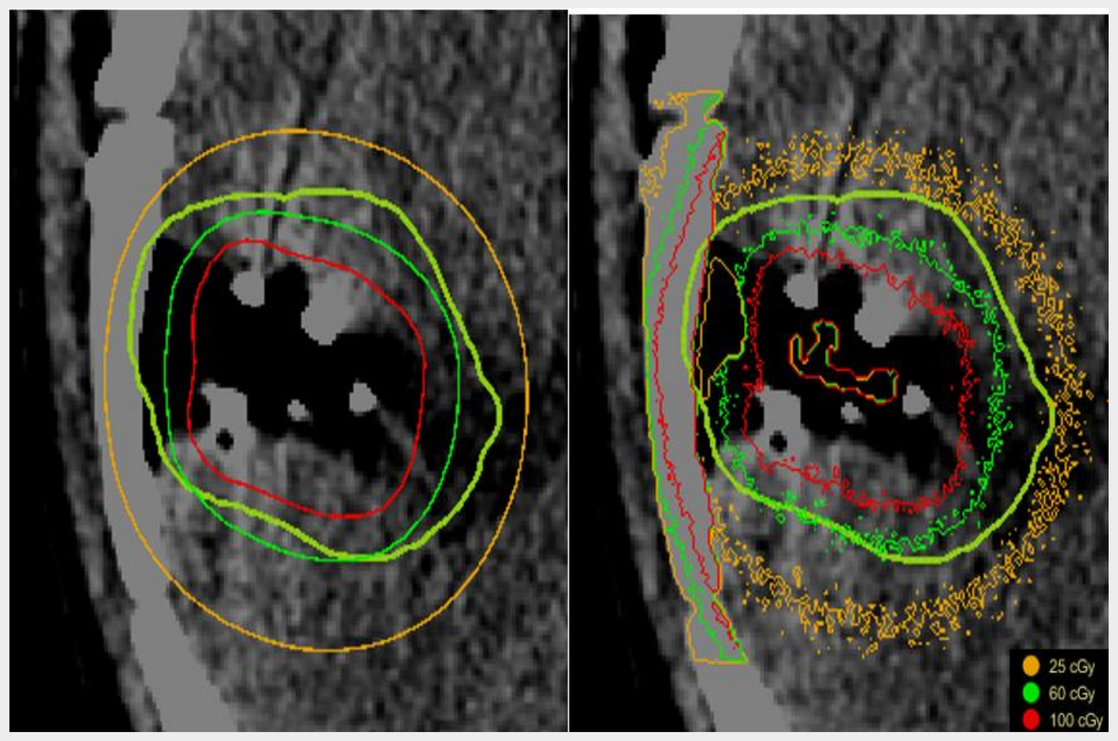

Figure 3. Iso-dose comparison with TPS and MC using air, brain, skin, and bone medium with HR-CTV contouring (thick green). Left: TPS, Right: Monte Carlo

DISCUSSION

This study demonstrates that patient-specific tissue heterogeneity has a measurable impact on dose distributions for low-energy ^{131}Cs brachytherapy. Under homogeneous water conditions, Monte Carlo and the TG-43-based treatment planning system showed excellent agreement, confirming the validity of the developed voxelized model. However, incorporating tissue-specific materials and densities resulted in clinically relevant reductions in HR-CTV dose metrics, highlighting the limitations of the TG-43 water-equivalent assumption. A limitation of this work is that materials were assigned using tissue-specific classifications rather than voxel-by-voxel compositions. Tissue segmentation was performed using HU thresholding, which simplifies the continuous variation in tissue density and composition and may introduce uncertainties near tissue interfaces, potentially affecting local dosimetric accuracy. Nevertheless, this approach reflects a practical workflow for clinical implementation while preserving computational efficiency. Future work will focus on voxel-level material assignment using continuous HU-to-density and elemental composition calibration, as well as validation across additional anatomical sites and brachytherapy isotopes to further improve heterogeneity-aware dose calculation accuracy.

CONCLUSIONS

A clinically realistic, patient-specific voxelized three-dimensional lattice phantom incorporating tissue heterogeneity was developed and validated, enabling Monte Carlo benchmarking of heterogeneity-aware brachytherapy dose calculation algorithms and supporting implementation of AAPM TG-186 recommendations beyond TG-43.

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