

Monte Carlo simulation of Co-60 gamma irradiation using P-TReCK for deep-seated soft tissue dosimetry

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ABSTRACT

Cobalt-60 (Co-60) remains a fundamental radioisotope for clinical radiotherapy, where accurate dose calculations in deep-seated soft tissues require detailed modeling of photon transport complexities. This study evaluates the Photon Transport and Response Characterization Kit (P-TReCK, version 1.0.1) for simulated 2D energy deposition mapping in a two-layer heterogeneous cylindrical phantom consisting of adipose and soft tissue. Axial and radial profiles were generated under broad disk and central pencil beam configurations and benchmarked against PHITS (v3.36) simulations. Spatial and dosimetric agreement were assessed using the Dose Uniformity Ratio (DUR), Mean Absolute Percentage Error (MAPE), and a 1D global gamma index analysis (2% dose difference, 2 mm distance-to-agreement). Under these criteria, P-TReCK achieved a 100% gamma pass rate and maintained sub-percent MAPE values across all configurations. The calculated DUR values agreed within their propagated uncertainties. These benchmark results demonstrate that P-TReCK's primary-interaction algorithm accurately reproduces depth-dose attenuation and lateral scatter in macroscopic low-Z tissues, providing a computational baseline for future extension to patient-specific geometries.

INTRODUCTION

Cobalt-60 (Co-60) is a primary radioisotope for both medical device sterilization and clinical cancer treatment (Podgorsak 2005). Its characteristic gamma emission energies (i.e., 1.173 MeV and 1.332 MeV) are fundamental to medical physics and dosimetry calculations (Khan and Gibbons 2020). In treatments involving deep-seated soft-tissue volumes, high-precision planning is critical to escalate dose to the target while adhering to strict normal-tissue constraints. Traditional population-level models often lack the

specificity essential for individual cancers, whereas mechanistic and Monte Carlo simulations enable dose distributions that account for patient-specific biological and geometric complexities (McMahon and Prise 2019). Modern computational tools are designed specifically to improve dose conformality and thereby spare larger volumes of healthy surrounding tissue from high-dose irradiation.

The Dose Uniformity Ratio (DUR), defined as the ratio of maximum to minimum absorbed dose (D_{max}/D_{min}), is a standard metric for assessing radiation field uniformity in industrial and phytosanitary processing (IAEA 2002). In clinical radiotherapy, target-volume dose uniformity is evaluated through conceptually related homogeneity indices (HIs), which evaluate the spread of doses across the target volume relative to prescription or median levels (Yan et al. 2019; George and Pradhan 2008). Conventional experimental methods relying on physical dosimeters placed within phantoms are often resource-intensive, time-consuming, and expensive. Furthermore, such measurements may lack the necessary spatial resolution in complex or small anatomical regions because the detector volume can perturb steep dose gradients, leading to measurement uncertainties.

This positions Monte Carlo (MC) simulation as a widely recognized gold standard for radiation transport modeling in radiotherapy. Unlike analytical algorithms that use simplifying approximations, MC techniques directly model individual particle interactions based on physical probability distributions, enabling high-resolution density mapping and superior accuracy in heterogeneous tissues (Goorley et al. 2012). In the energy ranges relevant to therapeutic gamma irradiation such as Co-60, incoherent (Compton) scattering is the predominant mechanism for energy deposition in low-Z materials, including human tissue. This interaction dominates dose deposition for megavoltage therapy beams across a broad energy range, making detailed modeling of these interactions critical for precise dosimetry (Podgorsak 2005).

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KEYWORDS

Cobalt-60, Monte Carlo, Dose Uniformity Ratio, Dosimetry, Gamma index, PHITS

Despite the maturity of general-purpose codes such as MCNP6 (Goorley et al. 2012) and Geant4 (Agostinelli et al. 2003), specialized tools that provide a user-friendly interface for rapid simulation and spatial dose quantification remain essential. This study utilizes the Photon Transport and Response Characterization Kit (P-TReCK) version 1.0.1 developed by Hila et al. (2025), a Monte Carlo software originally designed for gamma-ray detector dose deposition studies, and applies it to voxel-scale dose mapping in a heterogeneous phantom representing deep-seated soft-tissue irradiation. Before expanding the software to accommodate complex, patient-specific voxel anatomies, its underlying dosimetry framework requires evaluation. By modeling a Co-60 source and a simplified two-layer cylindrical phantom consisting of adipose and soft-tissue regions, radial and axial absorbed dose profiles were generated to evaluate the DUR, alongside standard clinical validation metrics including the Gamma index and Mean Absolute Percentage Error (MAPE), with results compared directly against established PHITS simulations. The study aims to benchmark P-TReCK's photon transport capabilities against PHITS, providing a baseline evaluation for future development toward patient-specific geometries.

MATERIALS AND METHODS

Computational Phantom Design

To evaluate the dosimetric mapping capabilities of P-TReCK, a simplified two-layer cylindrical phantom was designed to serve as a computational benchmark. This geometry was constructed to match P-TReCK's native two-cell architectural scoring structure, ensuring that any dosimetric discrepancies between P-TReCK and the benchmark simulations are attributable to the underlying Monte

Carlo photon transport algorithms rather than geometric structural deviations. The phantom consisted of two concentric material layers with a uniform radius of 10 cm (Figure 1). The upper 3-cm layer was modeled as adipose tissue ($\rho=0.82\text{ g/cm}^3$), representing subcutaneous tissue to assess surface photon attenuation and entrance energy deposition. Beneath this, a 15-cm deep layer was modeled as ICRU four-component soft tissue ($\rho=1.00\text{ g/cm}^3$) to evaluate photon transport and dose uniformity under deep-tissue conditions. Material elemental compositions and densities were adopted from the PNNL compendium based on standard ICRP and ICRU definitions (Detwiler et al. 2021) (Table 1).

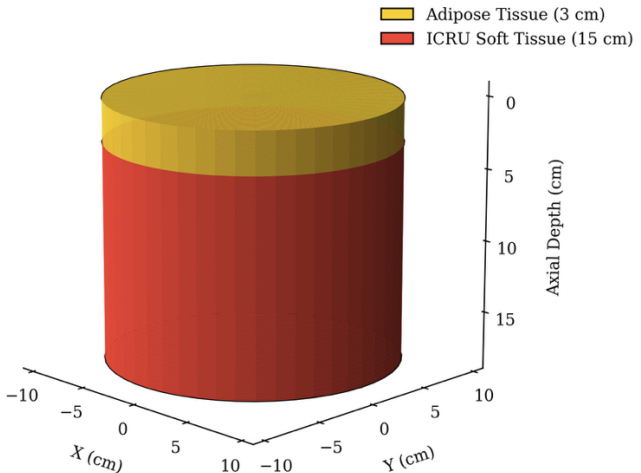


Figure 1: 3D schematic of the two-layer cylindrical phantom with a 3-cm anterior adipose tissue layer and a 15-cm ICRU soft tissue target region, both with a 10-cm radius.

Table 1: Geometric dimensions and material specifications of the two-layer cylindrical computational phantom used for Monte Carlo dosimetric benchmarking.

Parameter / Component	Specification	Purpose
Global Geometry		
Phantom Shape	Cylindrical	Mirrors P-TReCK's native two-cell architecture.
Total Radial Boundary	10 cm	Captures lateral dose spread and wide-angle scattering.
Anterior Volume (Layer 1)		
Material Composition	Adipose Tissue (ICRP)	Provides subcutaneous cross-sections.
Thickness (Z-axis)	3 cm	Captures subcutaneous photon attenuation.
Deep Target Volume (Layer 2)		
Material Composition	Soft Tissue (ICRU 4-Component)	Dosimetrically equivalent target for megavoltage transport.
Thickness (Z-axis)	15 cm	Evaluates exponential attenuation and dose homogeneity.

Source Configuration and Beam Modeling

The source was modeled as a Co-60 gamma-ray photon source, defined by its characteristic energies of 1.173 MeV and 1.332 MeV with equal emission probabilities. To evaluate spatial dose distributions under different irradiation conditions, two unidirectional beam configurations were simulated. First, a broad, monodirectional disk beam with a 10 cm radius entirely covering the phantom's anterior surface was used to simulate a broad-field macroscopic irradiation scenario (Figure 2A). This configuration

provides an extended spatial distribution of primary photon fluence, promoting lateral scatter equilibrium and enabling evaluation of dose uniformity under broad-field conditions. Second, a zero-radius pencil beam directed along the central longitudinal axis was simulated (Figure 2B). This configuration isolates photon transport from a localized source, enabling characterization of spatial dose spread arising from photon scattering and attenuation processes in the medium.

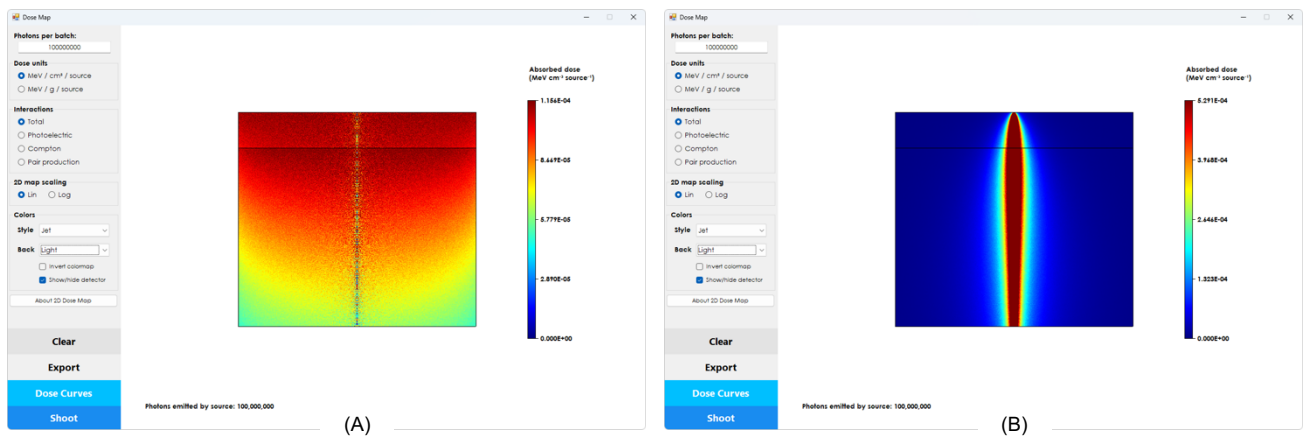


Figure 2: 2D spatial dose distributions (r-z domain) simulated in P-TReCK for the two-layer phantom under Co-60 irradiation via (A) a broad disk beam and (B) a pencil beam. Note: Figure 2 displays the global dose visualization mesh, generated simultaneously alongside the high-resolution 1D axial (Figure 3) and radial (Figure 4) profile tallies within the same simulation dataset.

Monte Carlo Transport Parameters

Simulations were executed using P-TReCK 1.0.1 and benchmarked against the Particle and Heavy Ion Transport code System (PHITS) version 3.36 (Sato et al. 2024; see Table 2). P-TReCK software (Hila et al. 2025) tracks primary photon interactions (photoelectric absorption, incoherent Compton scattering, and pair production) using photoatomic cross-section data from EPICS2025 (ENDF/B-VIII.1) (Cullen 2025). Compton angular deflections and energy transfers are evaluated from the Klein-Nishina differential cross

section assuming free stationary electrons. P-TReCK utilizes a Local Energy Deposition (LED) approximation, scoring the initial kinetic energy of liberated secondary electrons locally at the photon interaction site without charged-particle tracking. Because secondary electron transport is not tracked and radiative losses for Co-60 in low-Z media are negligible, the tallied quantity corresponds to collision kerma.

Table 2: Summary of Co-60 source configurations, Monte Carlo transport parameters, and clinical validation metrics utilized for P-TReCK and PHITS simulations.

Parameter	Specification	Purpose
Radiation Source		
Isotope Definition	Cobalt-60 (Co-60)	Modeled as discrete 1.173 MeV and 1.332 MeV energies with equal probabilities.
Config 1: Broad Beam	Monodirectional Disk (Radius = 10 cm)	Maximizes multiple-scatter events to calculate DUR.
Config 2: Pencil Beam	Monodirectional Pencil (Radius = 0 cm)	Captures the laterally integrated dose at each depth, fully accounting for wide-angle scatter contributions to evaluate total beam attenuation.
Monte Carlo Parameters		
Software Versions	P-TReCK 1.0.1; PHITS 3.36	Comparative validation of spatial dose mapping algorithms.
Primary Histories	P-TReCK: 10^8 ; PHITS: 10^7	10^8 for rapid high-res mapping; 10^7 sufficient for baseline verification.
Physics Libraries & Models	P-TReCK: EPICS2025 (ENDF/B-VIII.1); PHITS: EGS5.	Establishes the governing interaction probability frameworks for both codes.
PHITS Scoring Profiles		
Axial Depth-Dose	500 planar slices along central axis	Matches P-TReCK binning; tracks D_{max} and attenuation across the interface.
Radial Off-Axis	250 concentric cylindrical shells per layer	Doses summed and divided by volume (MeV/cm^3) to match P-TReCK bins.
Clinical Validation		
1D Gamma Index (γ)	2% Dose Difference / 2 mm DTA	Standard clinical metric evaluating spatial and dosimetric agreement simultaneously.
Evaluation Threshold	$>10\% D_{max}$ (Broad) / $>0\% D_{max}$ (Pencil)	Isolates deterministic physics from high-variance Monte Carlo statistical noise.
DUR ROI Constraint	Soft-Tissue Target (3.0 - 18.0 cm)	Excludes the entrance adipose layer to evaluate true target homogeneity.

To ensure a consistent comparison, the PHITS 3.36 benchmark was configured with the EGS5 mode (Hirayama et al. 2005) with charged-particle transport cutoffs matched to score kerma (local energy deposition tally via [t-deposit], electron cutoff set to discard secondary electrons locally), matching the physical quantity evaluated in P-TReCK. The P-TReCK software was run for 10^8 primary photon histories (yielding mean relative statistical uncertainties $<0.3\%$ in central bins), while PHITS was run with 10^7 histories (yielding mean relative uncertainties $<0.8\%$ in central bins). For both codes, photon transport was governed by the default low-energy cutoff of 1 keV native to their underlying photoatomic libraries (EPICS2025 for P-TReCK and EGS5 for PHITS), below which photon histories were terminated and deposited locally.

Spatial Dose Mapping and Code Validation

To evaluate spatial dose distributions, P-TReCK executed simultaneous cylindrical mesh tallies within a single simulation run (108 primary source histories). A 2D radial-axial (r-z) mesh was used to visualize the global spatial dose map (Figure 2). Dedicated high-resolution 1D tallies consisting of 500 axial planar slices (Figure 3) and 250 radial cylindrical shells per layer (Figure 4) were defined concurrently to extract quantitative depth-dose and lateral scatter profiles for benchmarking against PHITS.

To assess dose conformity and uniformity, the Dose Uniformity Ratio (DUR) was evaluated according to Equation (1):

$$DUR = \frac{D_{max}}{D_{min}} \quad (1)$$

where D_{max} and D_{min} represent the maximum and minimum absorbed dose within the evaluated region. To prevent artificial skewing caused by dosimetric discontinuities at the heterogeneous tissue interface, the axial DUR calculation was strictly restricted to a homogeneous Region of Interest (ROI) corresponding to the 15-cm deep soft-tissue volume (depths of 3.0 to 18.0 cm). Because the DUR is sensitive to statistical noise in the extrema, uncertainties for the DUR were computed via standard first-order error propagation in quadrature ($\pm 1\sigma$) (Chetty et al. 2007). as shown in Equation (2):

$$\sigma_{DUR} = DUR \times \sqrt{\sigma_{rel,max}^2 + \sigma_{rel,min}^2} \quad (2)$$

where $\sigma_{rel,max}$ and $\sigma_{rel,min}$ are the relative statistical uncertainties of the maximum and minimum dose voxels, respectively.

To provide robust dosimetric validation between P-TReCK and the PHITS benchmark, a 1D Global Gamma (γ) Index analysis was implemented. The Gamma index simultaneously evaluates dosimetric difference and spatial distance-to-agreement (DTA) (Low et al. 1998), calculated via Equation (3):

$$\gamma(r_e) = \min_{r_r} \sqrt{\frac{(r_r - r_e)^2}{\Delta d_{crit}^2} + \frac{(D_r(r_r) - D_e(r_e))^2}{\Delta D_{crit}^2}} \quad (3)$$

where $D_e(r_e)$ is the evaluated P-TReCK dose at position r_e , and $D_r(r_r)$ is the reference PHITS dose at position r_r . The analysis utilized standard clinical criteria setting the DTA (Δd_{crit}) to 2 mm and the global dose difference (ΔD_{crit}) to 2% of the maximum PHITS dose. To mitigate the impact of high statistical variance in low-fluence regions, a 10% low-dose threshold (relative to the maximum PHITS dose) was applied to the broad beam configurations (Miften et al. 2018). For the pencil beam configuration, the low-dose cutoff was set to 0% of maximum dose.

Because a global gamma criterion scales with D_{max} , extreme low-dose tail bins naturally exhibit low gamma values. Agreement in low-dose peripheral regions was therefore evaluated directly via point-by-point relative differences and the Mean Absolute Percentage Error (MAPE).

The MAPE was calculated within the thresholded regions according to Equation (4):

$$MAPE = \frac{1}{N} \sum_{i=1}^N \left| \frac{D_{P-TReCK,i} - D_{PHITS,i}}{D_{PHITS,i}} \right| \times 100\% \quad (4)$$

where N is the number of evaluated spatial bins above the threshold, and $D_{P-TReCK,i}$ and $D_{PHITS,i}$ represent the energy deposition tallied by each code. A complete summary of the validation metrics and thresholds is provided in Table 2.

The global 2%/2 mm gamma used elsewhere in this study is referenced to the maximum dose and is therefore insensitive to extreme low-dose tails; accordingly, the relative-difference panels and the MAPE reported here are the appropriate metrics for assessing tail behavior, and a local-gamma or dedicated relative-error analysis is recommended for future work.

To validate the spatial dose distributions calculated by P-TReCK, parallel simulations were performed using PHITS 3.36. The PHITS geometry was systematically subdivided into an identical binning configuration to match P-TReCK's native axial and radial slice-based dose scoring while preserving the two-layer cylindrical phantom geometry, consisting of a 3-cm anterior adipose layer and a 15-cm deep soft-tissue target. For the axial depth-dose distributions, the entire cylindrical geometry was segmented into 500 planar disk cells along the central longitudinal axis to track photon attenuation across the tissue interface. These planar tallies represent the volumetric energy deposition integrated over the entire phantom cross-section at each depth z . For radial distributions, each of the two tissue regions was subdivided into 250 concentric cylindrical shells. Volumetric energy deposition was tallied per shell and divided by the shell volume, yielding energy deposition density in MeV/cm³ per source photon across the composite phantom.

RESULTS AND DISCUSSION

Axial Depth-Dose Distributions

The integral axial depth-dose distributions (Figure 3) evaluated along the beam axis provide critical insight into the photon attenuation and dose build-up characteristics of the Co-60 beams as they traverse the two-cell heterogeneous phantom. For the broad disk beam configuration (Figure 3A), the depth-dose profile demonstrates the expected dosimetric behavior for MeV-range gamma irradiation under a pure photon-transport framework. By employing the Local Energy Deposition (LED) approximation, P-TReCK treats the kinetic energy of ionized electrons as being absorbed precisely at the site of photon interaction. Consequently, under the LED approximation, the code tallies collision kerma, as the radiative fraction g for Co-60 in low-Z tissue is negligible (Podgorsak 2005; Khan and Gibbons 2020). Because secondary electron transport is not explicitly modeled, no electronic build-up occurs, and the scored collision kerma serves as a surrogate for absorbed dose under conditions of transient charged-particle equilibrium beyond the entrance interface.

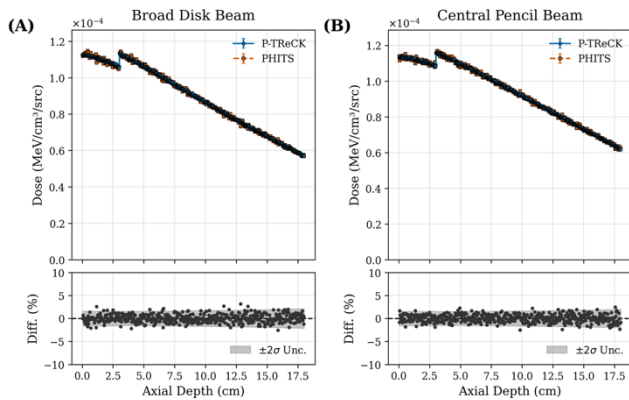


Figure 3: Axial depth-dose distributions for Co-60 irradiation. Profiles evaluate dose across the adipose/soft-tissue interface for (A) a broad disk beam and (B) a pencil beam. Top panels compare P-TReCK to the PHITS benchmark; bottom panels show the relative percentage difference alongside the $\pm 2\sigma$ combined statistical uncertainty (grey shaded region).

As a direct result of this LED approximation, the simulation accurately captures the maximum energy transfer right at the phantom entrance surface, where primary photon fluence is highest, followed by a predictable exponential decay through the deeper 15-cm soft-tissue volume. P-TReCK successfully replicated this macroscopic attenuation profile, maintaining strong agreement with the physically exhaustive PHITS benchmark. The minor relative discrepancies observed (peaking at 3.17% at a depth of $z=12.86$ cm, deep within the soft-tissue target) did not exhibit systematic deterministic bias at tissue boundaries or interfaces. Rather, they reflect expected Monte Carlo stochastic noise inherent to localized voxel scoring, especially from the PHITS code, which ran only 10^7 source photons. Because relative deviations fluctuated within or near the combined 2σ statistical uncertainty envelope throughout the entire depth profile, the two codes show consistent agreement. This indicates that P-TReCK's primary-interaction model is suitable for macroscopic depth-dose evaluations in low-Z heterogeneous media.

Under the zero-radius pencil beam configuration (Figure 3B), the axial dose profile represents the integral energy deposition across the entire 10-cm radius planar slice. The axial dose gradient for the pencil beam is shallower than that of the broad beam in both codes, with lower Dose Uniformity Ratios (e.g., P-TReCK: 1.89 vs. PHITS: 1.90 for the pencil beam; P-TReCK: 1.99 vs. PHITS: 2.02 for the broad beam). This shallower attenuation is a direct consequence of the planar tally geometry combined with the central source position. Because all primary photons in the pencil beam are injected precisely along the central axis ($r=0$), secondary scattered photons must traverse up to 10 cm of tissue laterally before escaping the radial boundary of the phantom. Consequently, a higher fraction of scattered radiation is retained and tallied within the deeper volumetric slices compared to the broad beam, where photons near the peripheral edges readily scatter out of the phantom geometry. Accurately modeling this volumetric scatter retention serves as a rigorous test of a Monte Carlo transport framework. The results demonstrate that P-TReCK's primary-interaction model captures this integral attenuation profile in close agreement with the full-physics PHITS benchmark.

Radial Dose Profiles and Lateral Scatter

Besides axial profiles which describe depth penetration, radial dose distributions (Figure 4) characterize lateral scatter and energy spread across tissue boundaries.

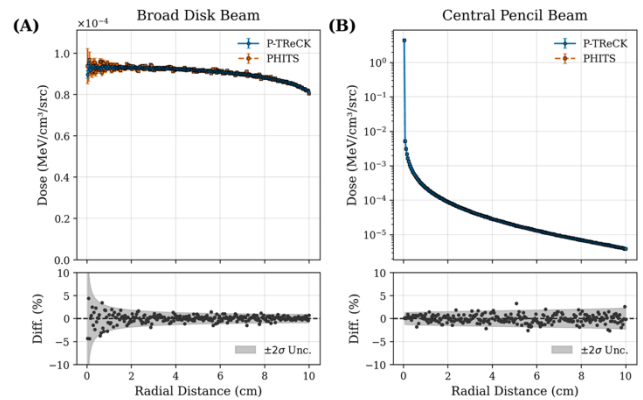


Figure 4: Radial dose distributions for Co-60 irradiation. Profiles compare P-TReCK and PHITS for (A) a broad disk beam on a linear scale, and (B) a pencil beam on a logarithmic scale to highlight low-dose lateral scatter tails. Bottom panels indicate the relative percentage difference and the $\pm 2\sigma$ combined statistical uncertainty.

For the broad disk beam (**Error! Reference source not found.A**), the radial dose profile demonstrates a high degree of lateral dose homogeneity across the central region of the 10-cm radius phantom. In this scenario, lateral scatter equilibrium is achieved because outward scattering from the central axis is compensated by inward scattering from adjacent photon tracks, eventually dropping off near the periphery due to the lack of an adjacent scatterer (the edge effect). It should be noted that for both codes, data points nearing the central axis ($r \rightarrow 0$) exhibit slightly higher Monte Carlo statistical uncertainties. This is an inherent geometric artifact of using concentric cylindrical shell tallies, wherein as the radius decreases, the cross-sectional area and volume of the tally cells diminish. Consequently, fewer source photons traverse the innermost shells, leading to reduced statistical scoring. Nonetheless, the dosimetric differences between P-TReCK and PHITS remain strictly within expected stochastic bounds, confirming P-TReCK's accuracy in modeling broad-field macroscopic equilibrium.

Conversely, the zero-radius pencil beam configuration (**Error! Reference source not found.B**, plotted on a logarithmic scale) is specifically designed to evaluate pure scatter. By ensuring no primary photons strike outside the central axis, any off-axis dose is strictly the result of lateral scattering. This creates a sensitive test for P-TReCK's Compton scatter implementation. Matching PHITS in both broad-field equilibrium and this isolated pencil configuration confirms scatter kinematics in uniform low-Z geometries.

Dose Uniformity Ratio (DUR) Analysis

The Dose Uniformity Ratio (DUR) serves as a critical quantitative metric for evaluating macroscopic dose conformity, mirroring the clinical Homogeneity Index (HI). To ensure a clinically relevant evaluation, axial DUR calculations were strictly constrained to the 15-cm deep ICRU soft-tissue target (depths of 3.0 to 18.0 cm), excluding the entrance adipose layer to evaluate attenuation strictly within the deep-seated soft-tissue target.

In the longitudinal direction, P-TReCK calculated a broad disk beam axial DUR of 1.993 ± 0.006 , demonstrating excellent agreement with the PHITS benchmark of 2.019 ± 0.026 . The axial pencil beam yielded similarly aligned results (1.886 ± 0.005 for P-TReCK vs. 1.902 ± 0.023 for PHITS). The values agree within their combined 2σ propagated uncertainties. Across all configurations, the PHITS DUR values are slightly higher than those of P-TReCK (by 0.8% to 2.0%). Because DUR depends directly on the extreme voxels (D_{max} and D_{min}), this consistent offset is primarily attributable to upward extreme-value bias arising from the higher statistical noise in the 10^7 -history PHITS baseline.

Radially, the broad beam configuration demonstrated the high spatial dose homogeneity expected under lateral scatter equilibrium, evaluating at 1.175 ± 0.013 for P-TReCK and 1.20 ± 0.05 for PHITS. The pencil beam configurations inherently lack this lateral equilibrium, resulting in very large DUR values of $(1.1308 \pm 0.0025) \times 10^6$ for P-TReCK vs. $(1.148 \pm 0.013) \times 10^6$ for PHITS. It should be emphasized that these $\sim 10^6$ -scale values do not represent a clinically interpretable measure of target homogeneity. Instead, they serve as a sensitive benchmark of the codes' dynamic range. Verifying this million-fold ratio confirms that P-TReCK accurately preserves the full dynamic range of the lateral dose spread, tracking scatter energy deposition from the unattenuated central axis down to the lowest-dose regions at the phantom's outer boundary.

Dosimetric Verification and Computational Performance

To evaluate the spatial and dosimetric agreement, a statistical comparison was performed (**Error! Reference source not found.**). The 1D Global Gamma (γ) index analysis applied standard criteria of 2% global dose difference and 2 mm distance-to-agreement (DTA). A 10% low-dose threshold (D_{max}) was used for broad beams, while pencil beams were evaluated without a threshold (0% D_{max}). Under these global criteria, P-TReCK yielded a 100.0% pass rate ($\gamma \leq 1.0$) across all evaluated profiles. Because a global 2% criterion is normalized to D_{max} , low-dose tail points in pencil beams fall far below $0.02 \times D_{max}$ and pass automatically. Therefore, agreement in the lateral scatter tails is more directly substantiated by the sub-percent MAPE values (0.63% to 0.71%) and the bounded relative-difference profiles.

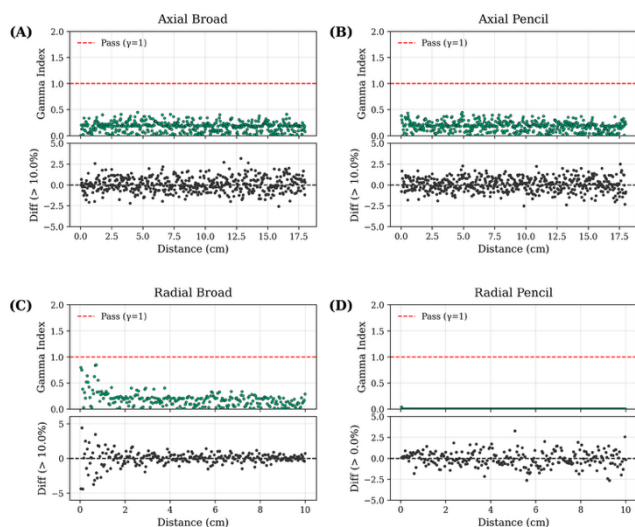


Figure 5: 1D Global Gamma (γ) index and dose difference analysis (2% / 2 mm criteria). Validation is shown for the (A) axial broad, (B) axial pencil, (C) radial broad, and (D) radial pencil beams. Broad beam configurations apply a 10% low-dose threshold, whereas pencil beams are evaluated without a low-dose threshold. Green indicates passing regions ($\gamma \leq 1.0$).

Maximum single-point dose differences peaked at 4.39% for the radial broad beam, while the pencil beams maintained maximum differences of 3.28% (radial) and 2.52% (axial). An evaluation of the spatial dose maps confirms that these isolated peak differences were not systematic or localized to physical boundaries, but were distributed randomly throughout the profiles. Because these local deviations remained strictly within the combined 2σ statistical uncertainty envelope and did not trigger Gamma index failures, they are therefore attributable to expected Monte Carlo statistical noise rather than deterministic physics errors. Overall, the sub-percent MAPE values and consistent gamma pass rates

demonstrate close agreement between the two codes for this geometry. The agreement suggests that neglecting coherent scattering and secondary X-rays does not introduce substantial error for Co-60 gamma transport in macroscopic low-Z phantoms.

Several limitations of this benchmark study should be noted. First, Co-60 gamma emissions (1.173 MeV and 1.332 MeV) in low-Z media represent a Compton-dominated regime where secondary electron ranges and secondary X-ray production are small relative to the macroscopic scoring grid. Under the present macroscopic scoring resolution and Co-60 energy regime, Local Energy Deposition agreed closely with PHITS kerma tallies. However, explicit secondary electron transport, bremsstrahlung, and atomic relaxation remain necessary for higher-energy beams or high-resolution scoring grids where voxel dimensions approach secondary particle ranges or mean free paths. Second, the simplified two-layer cylindrical phantom lacks the complex voxelized anatomies, heterogeneous tissue interfaces (e.g., bone-lung), and metallic implants that induce lateral electron disequilibrium in real patient geometries. Future P-TReCK developments will incorporate explicit electron transport and voxelized anatomical engines for advanced clinical dosimetry. While the present study establishes a computational proof-of-concept against established Monte Carlo codes, future work will incorporate physical phantom measurements (e.g., radiochromic film or micro-TLDs) to experimentally validate P-TReCK's spatial dose mapping while accounting for physical detector volume-averaging effects.

Finally, to evaluate computational performance, single-thread benchmark timing tests were conducted on an AMD Ryzen 7 7735HS CPU (3.20 GHz, 32 GB DDR5 RAM) for both codes under identical single-thread conditions. For 10^6 source histories, P-TReCK completed the simulation (including simultaneous 2D spatial, axial, and radial mesh tally generation) in 5.5 ± 0.2 s (broad beam) and 6.2 ± 0.3 s (pencil beam). In comparison, achieving matching spatial resolution in general-purpose codes such as PHITS through discrete cell segmentation (500 axial or 250 radial cells) resulted in longer execution times (1,720–3,550 s per 10^6 histories) due to boundary-crossing overhead across hundreds of explicit cell surfaces. P-TReCK's native mesh-scoring framework avoids repetitive geometric surface-crossing checks, significantly reducing runtime compared to explicitly segmented cell geometries.

CONCLUSION

This study benchmarked the Photon Transport and Response Characterization Kit (P-TReCK version 1.0.1) against PHITS (version 3.36) in a two-layer cylindrical phantom under Cobalt-60 irradiation. P-TReCK achieved high spatial and dosimetric agreement, maintaining a 100% pass rate under 1D Global Gamma index criteria (2% / 2 mm), sub-percent MAPE values ($<0.72\%$), and Dose Uniformity Ratios agreeing within 2σ propagated uncertainties across all tested configurations. These results indicate that P-TReCK's primary-interaction framework and Local Energy Deposition approximation adequately model macroscopic depth-dose attenuation and lateral Compton scatter in low-Z media. While the present work is limited to simplified geometry without secondary charged-particle transport, it provides a verified computational foundation supporting further development toward voxelized geometries and experimental validation against physical measurements.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

CONTRIBUTIONS OF INDIVIDUAL AUTHORS

Mary Margareth Bauyon-Isidro: Conceptualization; Methodology; Formal Analysis; Investigation; Writing – original draft; Writing – review and editing. Christlen Carlo L. Olivares: Methodology. Frederick C. Hila: Conceptualization; Methodology; Formal Analysis; Investigation; Writing – review and editing.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this work, the authors used Google Gemini to refine the readability of the paper. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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