Study of Secondary Neutron Ambient Dose Equivalent Distribution During Proton Radiotherapy

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Abstract

Proton radiotherapy (RT) exhibits superior dosimetry benefits compared to conventional photon RT, primarily due to its capability to concentrate the therapeutic dose within a defined depth of the tumor volume. The production of secondary charged particles during proton irradiation results in a limited distribution close to the target volume. However, secondary neutrons exhibit a notable penetration capacity and higher relative biological effectiveness, accompanied by an increased risk of secondary tumors, particularly in pediatric patients. Monte Carlo toolkit, such as TOPAS, was widely used for dose evaluation. However, the lack of nuclear data for neutrons with kinematic energies exceeding 20 MeV, secondary particles resulting from the interaction of high-energy protons with tissues, necessitates improvements in simulation accuracy. Present study investigated the secondary neutron distribution during proton RT through a combination of TOPAS simulations and experimental measurements. The experiment was performed based on the IBA proton Proteus PLUS system with a gantry. A liquid scintillation detector (EJ301) with a diameter of 12.70 cm was utilized to measure secondary fast neutrons. Additionally, a wide-energy range neutron dosimeter was employed to measure the ambient dose equivalent of secondary neutrons, validating the simulation accuracy with favorable agreement. The Maximum Likelihood Expectation-Maximization (MLEM) inversion algorithm was used within TOPAS, the secondary neutron energy spectra were obtained with a distance of 50 cm from the isocenter and scattering angles of 0° and 135°. Present study indicated that the simulated fast neutron spectra agree with the measurement-derived distribution. It' s shown that the neutron ambient dose equivalent with a distance of 50 cm from the isocenter ranges from 0.19 to 18.6 mSv/Gy.

Full Text

Preamble

Study of secondary neutron ambient dose equivalent distribution during proton radiotherapy∗

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Proton radiotherapy (RT) exhibits superior dosimetric benefits compared to conventional photon RT, primarily due to its capability to concentrate the therapeutic dose within a defined depth of the tumor volume. While secondary charged particles produced during proton irradiation exhibit limited distributions close to the target volume, secondary neutrons possess notable penetration capacity and higher relative biological effectiveness, accompanied by an increased risk of secondary tumors, particularly in pediatric patients. Monte Carlo toolkits such as TOPAS are widely used for dose evaluation; however, the lack of nuclear data for neutrons with kinetic energies exceeding 20 MeV−secondary particles resulting from interactions of high-energy protons with tissues−necessitates improvements in simulation accuracy. The present study investigated secondary neutron distribution during proton RT through a combination of TOPAS simulations and experimental measurements conducted on an IBA Proteus PLUS system with a gantry.

A liquid scintillation detector (EJ301) with a diameter of 12.70 cm was utilized to measure secondary fast neutrons, while a wide-energy range neutron dosimeter was employed to measure the ambient dose equivalent of secondary neutrons, validating the simulation accuracy with favorable agreement. The Maximum Likelihood Expectation-Maximization (MLEM) inversion algorithm was implemented within TOPAS to obtain secondary neutron energy spectra at a distance of 50 cm from the isocenter and scattering angles of 0° and 135°. The present study indicated that the simulated fast neutron spectra agree with the measurement-derived distribution, showing that the neutron ambient dose equivalent at 50 cm from the isocenter ranges from 0.19 to 18.6 mSv/Gy.

Keywords: Proton radiotherapy; Secondary neutron; TOPAS; Liquid scintillation; Pulse shape discrimination.

Introduction

Proton radiotherapy (RT) has been widely adopted for treating pediatric brain tumors due to its significant advantages in radiation physics and radiobiology [**?**, **?**, **?**]. Current research efforts in proton therapy have primarily concentrated on proton beam dynamics and auxiliary equipment [**?**, **?**, **?**, **?**]. Although the dose contributions from secondary particles generated by proton beams have garnered considerable attention, relatively insufficient experimental investigations have been conducted to elucidate their underlying mechanisms and clinical implications [**?**, **?**]. Beyond energy deposition, secondary particles—including neutrons, deuterons, and ^{4}He—are produced during interactions between high-energy protons (70–260 MeV) and tissues. While secondary charged particles exhibit limited distributions close to the target volume, secondary neutrons possess high penetration capabilities, potentially delivering unintended radiation doses to normal tissues, which is crucial for assessing the risk of secondary tumors [**?**, **?**, **?**]. Secondary neutrons in proton RT arise predominantly from nuclear interactions between high-energy proton beams and components of the treatment system (e.g., collimators, beamline apertures) or patient tissues, primarily through spallation and (p,n) reactions. These neutrons exhibit a broad energy spectrum spanning thermal to relativistic ranges, enabling deep tissue penetration and dose deposition in organs distant from the target volume, such as the thyroid and bone marrow.

Indirect biological damage is mediated via secondary recoil nuclei generated during neutron scattering, which induce clustered DNA lesions—including complex double-strand breaks—with elevated relative biological effectiveness, a critical determinant of their carcinogenic potential. Clinically, this stochastic exposure contributes to lifelong secondary malignancy risks, particularly in pediatric populations where proton RT is estimated to confer a substantial lifetime risk of secondary cancers. Challenges in risk quantification persist due to facility-specific variations in neutron production (e.g., passive scattering vs. pencil-beam scanning systems) and limitations in radiation weighting factors, which inadequately address the energy-dependent biological effects of high-energy neutrons. Current mitigation strategies focus on technological advancements, such as the adoption of pencil-beam scanning to reduce neutron yields, coupled with boron-doped shielding materials to attenuate thermal neutrons. Parallel efforts emphasize standardized dosimetry protocols using advanced detectors and refinement of RBE models through energy-dependent DNA damage analysis and long-term epidemiological data.

The spatial distribution of secondary neutron doses in proton radiotherapy is influenced by both treatment system design (e.g., scattering material thickness, beam modulation methods) and patient anatomy (e.g., tissue density, target depth). For example, in passive scattering systems, neutron flux peaks at the edges of the radiation field and near the patient' s surface due to interactions between the proton beam and beamline components such as scattering foils and collimators. In contrast, pencil-beam scanning (PBS) systems reduce neutron generation in proximal regions by minimizing beam interactions with hardware, thereby concentrating neutron doses primarily in the distal region of the Bragg peak. Quantifying these distribution characteristics is critical for accurately assessing cumulative doses to radiosensitive organs (e.g., lens, thyroid, and gonads), especially in pediatric patients whose lifetime radiation risk is closely tied to the spatiotemporal patterns of low-dose exposure. Additionally, dose distribution data are essential for optimizing shielding designs, such as selecting materials and configurations to attenuate neutron penetration effectively [?, ?]. In clinical proton RT studies, the Rem-meter is commonly used for detecting secondary neutron fluence; however, wide-energy neutron dosimeters such as WENDI-II underestimate ambient dose equivalents by approximately 40% for neutrons above 14.8 MeV [?, ?]. The tissue equivalent proportional counter (TEPC) has also been employed to assess neutron dose equivalents during RT, showing reduced sensitivity to particle energies but facing challenges distinguishing contributions from different particle types [?]. Howell et al. utilized the extended Bonner Sphere Spectrometer (EBSS) to investigate a passive scattering proton therapy facility, measuring the secondary neutron energy spectrum produced by a 250 MeV passively scattered proton beam at 100 cm laterally from the isocenter. Ambient dose equivalent $H^*(10)$ was derived using measured neutron fluence combined with energy-specific fluence-to-$H^*(10)$ conversion coefficients. The spectrum displayed four characteristic components: a high-energy direct neutron peak, an evaporation peak, a thermal neutron peak, and an intermediate-energy continuum between thermal and evaporation regions. The evaporation peak dominated $H^*(10)$ contributions due to both its high neutron fluence and elevated conversion coefficients in this energy range, yielding an ambient neutron dose equivalent of 1.5 mSv/Gy surrounding the target volume, with high-energy neutrons above 20 MeV contributing approximately 35% to dose equivalent [?]. However, the EBSS spectrometer is complex to operate experimentally and requires extended measurement times. Clarke et al. used an EJ309 liquid scintillator detector to study secondary neutron dose from an uncollimated proton beam with incident energies of 155 and 200 MeV at the Loma Linda University Cancer Treatment Center, developing a simulation model using the MCNPX-PoliMi code to replicate secondary neutron fields. The simulation results exhibited strong consistency with experimental measurements, demonstrating that experimental validation prior to utilizing the verified simulation framework for expanded studies serves as a robust methodology for systematic radiation field analysis [?]. The EJ309 detector demonstrated sensitivity to neutrons above 0.5 MeV and effective pulse shape discrimination [?, ?]. Additional organic scintillator detectors have also been used for secondary neutron measurements in proton RT [?].

Monte Carlo simulation is a widely adopted method for dosimetry studies, providing detailed neutron distribution data throughout the treatment room essential for treatment planning systems (TPS) [?, ?, ?, ?]. This approach significantly improves dose calculation accuracy, mitigating issues like underestimating doses to organs at risk (OAR) [?, ?]. The accuracy of Monte Carlo simulations relies on experimental data and physical interaction models [?, ?], though neutron data above 20 MeV remain scarce [?]. In a related study at the ProCure proton center in Oklahoma, USA, Islam et al. utilized the FLUKA toolkit to investigate secondary neutron ambient dose equivalents generated by IBA pencil beam scanning (PBS), demonstrating that ambient neutron dose equivalents were closely related to incident proton energies and measurement locations. For instance, a proton beam with incident energy of 78 MeV yielded an ambient dose equivalent of approximately 2.71 mSv/Gy at 7.5 cm from the phantom center, decreasing to 1.22 mSv/Gy at 35 cm, while a 226 MeV beam increased the ambient dose equivalent to 50 mSv/Gy at the same distance [?].

Perl et al. introduced TOPAS (Tool for Particle Simulation) in 2012, a specialized Monte Carlo simulation tool derived from an established general Monte Carlo code for proton RT [?]. By abstracting low-level C++ programming complexities, it integrates predefined modules tailored for radiotherapy, medical imaging, and radiation protection, including clinical-grade anatomical models (e.g., ICRP voxel phantoms), simulations of intensity-modulated radiation therapy (IMRT) and proton/heavy-ion beamlines, and LET-based dose calculation algorithms. The platform employs a script-driven interface (YAML/text-based) for fully parameterized simulation setups, coupled with multithreaded CPU parallelism and GPU acceleration (via CUDA/OpenCL) to enhance computational efficiency for large-scale scenarios, while intelligent particle-tracking termination criteria optimize resource utilization. Released under the open-source BSD license, TOPAS enables customization of physics processes, geometry definitions, and scoring metrics through its modular architecture, with community-driven updates incorporating cutting-edge clinical advancements such as FLASH ultra-high-dose-rate radiotherapy and MR-linac integration [?]. Supported by standardized validation benchmarks, comprehensive documentation, and an active developer community, TOPAS adheres to the FAIR (Findable, Accessible, Interoperable, Reusable) principles in computational research, making it a pivotal tool for validating treatment planning systems, prototyping novel medical devices, and investigating radiation-tissue interactions, thereby bridging methodological rigor with computational performance in contemporary medical physics studies [?]. Yu et al. employed TOPAS to calculate ambient dose equivalents and annual effective doses generated by secondary neutron fields in proton therapy, demonstrating significant advantages in shielding design and safety assessment applications [?]. Yang et al. compared dose distributions between TOPAS and RayStation, revealing that TOPAS demonstrated superior performance in beam splitting optimization for intensity-modulated proton therapy (IMPT) [?].

Fast neutrons can be detected efficiently by liquid scintillation detectors, which show good discrimination between neutrons and gamma rays, playing a crucial role in accurately measuring secondary neutrons during proton RT and providing essential data for Monte Carlo simulation corrections. The comprehensive assessment of secondary neutron dose distributions in clinical proton RT remains technically challenging due to three principal constraints: the intricate geometry of treatment devices, patient-specific anatomical heterogeneities, and the time-limited nature of therapeutic irradiation procedures. These limitations necessitate Monte Carlo simulation techniques as a critical tool for characterizing neutron dose distributions. Through development of high-fidelity models that precisely replicate clinical configurations—including radiation delivery systems, proton beam parameters, and patient-specific anatomical geometries—this computational approach enables per-treatment quantification of secondary neutron fields, providing essential foundations for precise evaluation of secondary malignancy risks associated with neutron exposure. To ensure clinical relevance of simulation outcomes, a rigorous validation protocol was executed involving experimental measurements of neutron dose equivalents and energy spectra at strategically defined positions during proton irradiation of tissue-equivalent phantoms. Subsequent comparative analysis between empirical measurements and simulation predictions under matched irradiation conditions confirmed the model' s predictive accuracy.

This study was performed at Yizhou Cancer Hospital in Hebei, China, to evaluate the IBA Protons PLUS system under various beam conditions. Spatial and energy distributions were obtained by irradiating the RW3 Slab Phantom with mono-energetic proton beams using the TOPAS toolkit. Simulation parameters were calibrated using TPS data. The EJ301 liquid scintillation detector was employed to capture neutron energy spectra at different positions, providing better pulse shape discrimination (PSD) characteristics than EJ-309, while the WENDI-II wide energy neutron dosimeter measured ambient dose equivalents under identical conditions. The experimental results were compared with TOPAS simulations.

This paper is organized as follows: the theoretical framework and methods are introduced in Sec. II, Sec. III presents the results and discussion of simulations and measurements, and finally, the conclusions and future prospects are presented in Sec. IV.

Materials and Methods

A. TOPAS simulations

A comprehensive calibration protocol involving multiple experimental datasets was implemented to systematically refine the geometric and dosimetric fidelity of the computational model. The proton pencil beam configuration within the TOPAS Monte Carlo platform utilized a dual-axis "Bi-Gaussian" intensity distribution model, mathematically expressed as a composite function of orthogonal Gaussian profiles in the spatial x-y coordinate system. This approach ensured accurate replication of the experimental beam' s transverse fluence characteristics, maintaining clinical relevance through rigorous adherence to measured beam parameters.

The calibration process specifically incorporated two critical experimental benchmarks: (1) integral depth dose (IDD) curves quantifying longitudinal energy deposition, and (2) lateral spot intensity profiles acquired under air-scan conditions. These datasets enabled iterative optimization of the Bi-Gaussian model parameters—including spatial spread and angular divergence—through comparative analysis between simulated and measured dose distributions. The calibrated beam model' s clinical validity received further confirmation via independent monitor unit (MU) verification in the RayStation TPS. Following this calibration, a high-precision simulation framework was executed to characterize secondary neutron production from a vertically incident mono-energetic proton beam interacting with an RW3 Slab Phantom.

A water phantom was constructed based on measured IDD data with dimensions of 30 cm × 30 cm × 30 cm in the simulation geometry. The proton source was positioned 43 cm away from the phantom isocenter. The IDD curve for the proton beam in the water phantom was generated using TOPAS. Simulations encompassed 14 monoenergetic beams ranging from 70 MeV to 220 MeV, comprising 1×10^7 simulated particles for each energy. By tuning the "Beam Energy Spread," the simulated values were made consistent with measured values. The proton beam diffusion in air adhered to the particle transport theory of Courant-Snyder and the methodology outlined by Huang et al. [**?**]. For the incident beam, the correlation between beam spot size and depth can be described as:

$$r^2(z) = r^2(0) - 2c(0)r(0)\theta(0)z + \theta^2(z)z^2$$

where z denotes the depth in air, with the isocenter position typically set as the origin ($z = 0$); $r(z)$ is the standard deviation of the beam spot size; $\theta(z)$ represents the angular divergence of the proton beam; and $c(0)$ stands for a correlation parameter between beam spot size and angular divergence. In the TOPAS program, the "Bi-Gaussian" model simulates the shape of the proton pencil beam by adjusting parameters such as "Sigma," "Sigma prime," and "Correlation" [**?**]. Gaussian fitting was performed on the experimentally measured beam spot intensity distribution using the least squares method to determine the standard deviation $r(z)$ at five depths. The "Bi-Gaussian" model parameters were then adjusted using Eq. (1) to match the simulated beam spot shape in TOPAS with experimental measurements. For both the X-direction and Y-direction, "Sigma" was set to 2.0 mm, "Sigma prime" was set to 0.0032, and "Correlation" was set to -0.8. The MU value was calculated based on the incident proton particles and dose, then compared with the MU value provided by the TPS to validate the simulation model.

The TOPAS toolkit simulated the spatial distribution of secondary neutrons produced by the RW3 Slab Phantom. This study investigated secondary neutrons generated by nuclear reactions between protons and the solid-water phantom, excluding building materials and counter-weights in the Nozzle and treatment room. The proton beam energies were set at 75, 100, 150, and 200 MeV with event numbers of 5×10^8, 2×10^8, 1×10^8, and 1×10^8, respectively. The proton source was positioned 43 cm from the center of the solid water phantom, with mono-energetic proton beams vertically incident on the phantom surface. During simulation, the TOPAS "Phase Space" scorer plane was employed, defining a circular recording surface to record neutron flux with a radius of 50 cm, height of 12.7 cm, and thickness of 1 mm. The center of the surface coincides with the phantom center, covering an angular range from 0° to 170° relative to the proton incidence direction at 0°. The RW3 Slab Phantom, developed by IBA Dosimetry GmbH, consists of hydrogen (7.6%), carbon (90.4%), oxygen (0.8%), and titanium (1.2%) by mass, with dimensions of 30 cm × 30 cm × 30 cm.

To compare the ambient neutron flux generated by incident proton beams with varying energies, the neutron ambient dose equivalent was normalized using the absorbed dose in the Bragg peak region (mSv/Gy), representing the ambient neutron dose equivalent per Gy of proton dose, calculated as:

$$H^*(10) = \sum_i \left(\frac{H^*(10)}{\Phi} \right)_i \Phi_i$$

where D_p represents the absorbed dose (Gy) at the Bragg peak within a 0.5 mm mesh, $(H^*(10)/\Phi)_i$ represents the conversion coefficient of neutron fluence to ambient equivalent dose for the corresponding energy, and Φ_i stands for the neutron flux simulated by TOPAS.

B. Experimental setup

The experiment utilized detectors comprising a cylindrical EJ301 liquid scintillator coupled to a H7195 photomultiplier tube (HAMAMATSU), a DT5730 digitizer (CAEN), and a WENDI-II wide-energy neutron dosimeter (Thermo Fisher) to measure secondary neutrons produced by mono-energetic proton beams impacting the RW3 Slab Phantom within the IBA Proteus PLUS system gantry. The EJ301 liquid scintillator detector from ElJen Technologies featured dimensions of 12.7 cm in both diameter and height. Signal pulses from the EJ301 detector were recorded and preprocessed by the CAEN DT5730 digitizer. The WENDI-II wide-energy neutron dosimeter from Thermo Fisher was used to measure ambient dose equivalent values of neutrons in the treatment room. This cylindrical device measured 32 cm in height and 23 cm in diameter, including a tungsten powder layer 1.5 cm thick to enhance response to high-energy neutrons within a detection energy range spanning thermal neutrons to 5 GeV, while simultaneously demonstrating effective gamma ray suppression.

[Figure 1: see original paper]

As shown in Fig. 1(a), the centers of the Nozzle, RW3 solid water phantom, and detector system were horizontally aligned, with the phantom center located 43 cm downstream from the Nozzle. Four EJ301 liquid scintillator detectors were positioned 50 cm away from the phantom center at angles of 0°, 45°, 90°, and 135° relative to the beam direction, while the WENDI-II dosimeter was placed at the same location for comparative purposes. A proton beam was irradiated for 2 minutes as programmed on the TPS.

C. Neutron Energy Spectrum measurement

The light output is directly proportional to the deposited energy of neutrons. To analyze neutron energy spectra, the light output was studied by processing pulse waveforms to obtain light output distributions of recoil protons generated by incident neutrons in the liquid scintillator detector. The neutron response function of the detector was used to invert these light output spectra and derive neutron energy spectra, relying on an accurate light output curve across a wide neutron energy range. The Birks formula for light output was used to fit measured light output from mono-energetic neutrons [?]. This study utilized the recoil proton light output curve inside the liquid scintillator as described by [?]:

$$E_e = 0.83E_p - 2.82 \cdot (1 - e^{-0.25E_p^{0.93}})$$

where E_e is the equivalent electron energy and E_p represents the deposited energy of the recoiled proton. Mono-energetic neutrons in 40 sets spanning an energy range from 5 to 200 MeV at 5 MeV intervals were simulated to study energy deposition of recoiled protons in the liquid scintillator, determining the light output corresponding to each mono-energetic neutron.

The detectors were calibrated by comparing simulated deposition distributions of maximum energy neutrons with scattering angles of 0° and incident energies of 75, 100, and 150 MeV against measured data. A response matrix $R(E, E')$ was employed to characterize measured neutron response spectra, enabling description of responses from various energies and fluxes. Neutron energies theoretically span a continuous spectrum, with total neutron response spectra expressed by the first-order Fredholm convolution equation [?]:

$$N(E) = \int R(E, E')\phi(E')dE'$$

where $\phi(E')$ represents the incident neutron energy spectrum. The continuous neutron energy spectrum was discretized into sufficiently small intervals treated as mono-energetic, simplifying the integral equation into matrix form:

$$\begin{bmatrix} R_{11} & R_{12} & R_{13} & \cdots & R_{1n} \\ R_{21} & R_{22} & R_{23} & \cdots & R_{2n} \\ R_{31} & R_{32} & R_{33} & \cdots & R_{3n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ R_{m1} & R_{m2} & R_{m3} & \cdots & R_{mn} \end{bmatrix}$$

where m and n represent energy intervals divided by detector response and incident neutron energy spectrum, respectively. N_m denotes the count in the m-th energy interval of the detector response spectrum, ϕ_n represents the flux of neutrons in the n-th energy interval of the incident neutron spectrum, and R_{mn} signifies the corresponding element of the response matrix.

The energy spectra of incident neutrons were resolved using the Maximum Likelihood Expectation-Maximization (MLEM) algorithm [?, ?, ?]. The MLEM algorithm demonstrates significant advantages in reconstructing neutron energy spectra from liquid scintillator measurements by systematically addressing inherent complexities of scintillator response and mixed radiation fields. Central to its efficacy is explicit integration of the scintillator' s energy-dependent light output characteristics into the algorithm' s system matrix, accounting for nonlinear quenching effects and proton recoil kinematics. The algorithm further adapts to the scintillator' s logarithmic energy response through dynamic binning strategies and regularization techniques, ensuring stable reconstruction over extended energy ranges. Implementation involves calibrating detector-specific response matrices via monoenergetic neutron sources and iteratively optimizing the energy spectrum against measured pulse height distributions. MLEM' s ability to reconcile first-principles scintillator physics with statistical optimization establishes it as a robust solution for neutron spectrometry in complex radiation environments, particularly where traditional methods struggle with nonlinear detector behavior and mixed-field interference. The likelihood function P increases steadily through each iteration as parameter estimates are updated toward the optimum solution, with final parameter estimates obtained when the likelihood function reaches its peak, expressed as:

$$P = \prod_i \frac{\lambda_i^{N_i}}{N_i!} e^{-\lambda_i}$$

where $\lambda_i = \sum_{j=1}^{n} R_{ij} \times \phi_j$, R_{ij} represents the detector response matrix element, ϕ_j is the neutron count in the j-th energy interval, and N_i represents the response count in the i-th energy interval of the detector neutron response spectrum.

In this study, each mono-energetic neutron response function derived from TOPAS simulation was divided into 50 energy intervals ranging from 0 to 200 MeV. Initial spectra obtained from TOPAS simulation were utilized as starting points and fed into the MLEM algorithm for optimum solution. The incident neutron spectra, ranging from 0 to 200 MeV, were divided into 40 uniform energy intervals, with the MLEM inversion algorithm iteratively computing the energy spectrum of the incident neutron.

Results and Discussion

A. Results of TOPAS simulation

The depth corresponding to 80% of the Bragg peak' s distal end, labeled as R_{80}, serves as a clinical indicator for describing the proton beam range. Fig. 2(a) displays the measured R_{80} ranges for each energy in water, while Fig. 2(b) depicts discrepancies in R_{80} ranges between simulated and measured IDD curves, which are observed to be within a margin of 0.3%. Fig. 2(c) illustrates the measured (blue curve) and simulated (red curve) IDD of proton beams using TOPAS for various incident energies in the water phantom. Fig. 2(d) shows the MU values calibrated using RayStation TPS, demonstrating that the number of protons per MU increases notably with higher proton energy because higher energy expands the proton beam' s range within the medium and increases the cumulative dose fraction toward the longer tracks near the front of the Bragg peak. This study investigated deviations associated with various proton beam spot sizes, and as illustrated in Fig. 2(e), the deviation observed in the model constructed using TOPAS in the central plane of the air was found to be less than 3.5%.

The proton pencil beam model in the TOPAS tool determined the number of protons per MU for incident energies of 75, 100, 150, and 200 MeV. Table 1 indicates that deviations between TOPAS and RayStation TPS for the number of protons per MU are within 3%.

By tuning the proton beam current in simulations, TOPAS can faithfully replicate the IDD curve of the proton beam in the water phantom, achieving an R_{80} error within 0.5%. Deviations between the simulated number of protons per MU and those calculated by RayStation TPS are within 3%, with this deviation increasing at higher energies as proton tracks extend further, particularly affecting positions within the Bragg peak. Higher energies enhance the likelihood of inelastic scattering and spallation processes, thereby amplifying neutron production in proximal regions. However, the evaporation neutron peak (1–10 MeV) in the simulated spectrum was submerged due to the wide distribution of high-energy neutrons.

The TOPAS toolkit was used to determine the angular distribution of secondary neutrons. As the energy of the incident proton beam increases, a noticeable shift of the secondary neutron peak from backward to forward angular directions occurs, as illustrated in Fig. 2(f). This shift corresponds to the increased range of protons in solid water with higher incident beam energies. The water phantom absorbs more secondary neutrons with forward angles for lower-energy protons, thereby reducing the secondary neutron flux outside the phantom.

The simulated secondary neutron spectra, as illustrated in Fig. 3, were generated through "Phase Space"scoring within the TOPAS framework. Two principal observations emerge from the analysis: (1) A marked elevation in the relative abundance of high-energy neutrons (>20 MeV) is evident as incident proton energy increases, aligning with expectations from nuclear interaction cross-section dependencies. (2) The angular distribution of these high-energy neutrons exhibits a pronounced forward bias, with a progressive shift toward smaller angles observed at higher proton energies. These trends are consistent with the physical mechanisms governing proton-nucleus interactions, where elevated beam energies enhance neutron production.

[Figure 3: see original paper]

The ambient dose equivalent values for proton energies of 75, 100, 150, and 200 MeV were simultaneously calculated within the Bragg peak area. The "Dose to Medium" scorer in TOPAS was utilized to output dose equivalent values for each grid point in the RW3 Slab Phantom, which was divided into 0.5 mm thick layers along the proton beam track. These results are presented in Table 2.

The angular distribution and energy spectra of secondary neutrons obtained from TOPAS simulations indicate a clear correlation between incident proton beam energy and the angular distribution of secondary neutrons. The Bragg peak was shallower with lower incident proton beam energies, resulting in a smaller total neutron yield. Additionally, due to the barrier effect of the thick solid water phantom, the number of neutrons scattered at angles less than 110° is significantly fewer compared to those at larger angles because neutrons in this direction were more shielded by the phantom. TOPAS simulations did not reveal prominent evaporation peaks in the secondary neutron spectra due to the absence of corresponding physical models and nuclear data, an omission that can lead to significant deviations in dose equivalent calculations. Neutron evaporation typically increases neutron flux with increased scattering angles.

B. The measured neutron energy spectra

The EJ301 detector demonstrates linear response to neutrons ranging from 0.5 MeV to 200 MeV and excels in particle discrimination. Recoiled protons are distinguished using pulse shape discrimination, and neutron energy spectra calculated via MLEM closely resemble those simulated by the TOPAS toolkit. However, TOPAS simulations show a significantly lower distribution of high-energy neutrons than measurements from the EJ301 detector.

Proton signals were selected and calculated using the MLEM method. Fig. 4 depicts neutron energy spectra with scattering angles of 0° and 135°. The energy spectra of secondary neutrons obtained from simulation and measurement exhibit similar trends, though the measured maximum energy was lower than the simulated value due to reduced detection efficiency at higher energies, indicating the need for a larger-volume detector.

[Figure 4: see original paper]

C. Ambient dose equivalent measurement

The neutron ambient dose equivalent distribution trend measured by the WENDI-II dosimeter was consistent with results from TOPAS simulations, as depicted in Fig. 5. The measured value at the 135° position is higher due to the influence of the nozzle in the measurement, which was not accounted for in the simulation.

A systematic comparison of neutron ambient dose equivalents derived from TOPAS simulations and WENDI-II measurements revealed consistent underestimations by the computational model across multiple angular positions. The divergence was particularly pronounced at lateral and backward angles, where experimental values exceeded simulated predictions. This discrepancy is hypothesized to originate from unaccounted neutron contributions arising from beamline components such as collimators and scattering foils, which were omitted in the simulation geometry. Additionally, EJ301 spectral measurements corroborated the WENDI-II findings, further emphasizing the necessity of refining neutron yield algorithms in Monte Carlo frameworks through empirical validation. These observations collectively underscore the importance of integrating facility-specific hardware configurations into simulation models to enhance their clinical applicability.

[Figure 5: see original paper]

Comparisons were performed between neutron ambient dose equivalent values per proton dose at various locations simulated by TOPAS and measurements from the WENDI-II dosimeter. Results indicated that TOPAS simulation yields substantially lower values, with measurements by the EJ301 detector and WENDI-II dosimeters suggesting inaccuracies in TOPAS simulation and highlighting the need for further calibration.

Conclusion

The spatial distributions of secondary fast neutrons during proton radiotherapy were investigated using an EJ301 liquid scintillation detector and a WENDI-II dosimeter. It was revealed that measured ambient dose equivalents of secondary neutrons were notably higher than those predicted by TOPAS simulations. When the proton beam energy is higher, the equivalent dose of secondary neutrons becomes much higher, and the dose to tissues behind the target area is significantly higher than in other locations. The EJ301 liquid scintillation detector demonstrated robust performance in resolving high-energy neutron spectra, leveraging its superior pulse shape discrimination capabilities to isolate neutron-induced signals from gamma-ray backgrounds. This precision positions the detector as a vital tool for quantifying secondary neutron exposures in organs at risk, such as the thyroid and bone marrow, where stochastic radiation effects are of particular concern in pediatric populations. Furthermore, its ability to capture real-time neutron fluence during beam delivery offers practical advantages in monitoring accidental exposures, thereby enhancing operational safety in clinical proton therapy. The detector’ s limitations in thermal neutron sensitivity, however, necessitate complementary dosimetric approaches for comprehensive risk assessments. Due to the wide energy range of secondary neutrons, more measurements are needed to obtain more accurate energy spectra, and a more accurate curve of EJ301 for recoil proton light output is needed.

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