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SECONDARY NEUTRON PRODUCTION IN PROTON THERAPY

Annotation

This study focuses on the detailed characterization of secondary neutron production in proton therapy through Monte Carlo simulations using the GEANT4 toolkit. The primary objective is to analyze neutron yield, energy spectra, angular distribution, and the resulting dose deposited by these secondary particles in various clinical scenarios.

Key words: proton therapy, secondary neutrons, Monte Carlo Simulations, GEANT4, radiation dosimetry, Pencil Beam Scanning, Passive Scattering, Neutron Shielding, cancer treatment, Relative Biological Effectiveness (RBE)

ОБРАЗОВАНИЕ ВТОРИЧНИХ НЕЙТРОНОВ В ПРОТОННОЙ ТЕРАПИИ

Аннотация

Настоящее исследование посвящено детальной характеристике образования вторичных нейтронов в протонной терапии с использованием Монте-Карло моделирования в среде GEANT4. Основной целью является анализ выхода нейтронов, их энергетического спектра, углового распределения и дозы, создаваемой этими вторичными частицами в различных клинических сценариях.

Ключевые слова: протонная терапия, вторичные нейтроны, моделирование Монте-Карло, GEANT4, дозиметрия радиации, сканирование карандашным пучком, пассивное рассеяние, нейтронная защита, лечение рака, относительная биологическая эффективность (ОБЭ).

PRATON TERAPIYADA IKKILAMCHI NEYTRONLAR HOSIL BO‘LISHI

Annotatsiya

Ushbu tadqiqot GEANT4 vositasida Monte-Karlo simulyatsiyalaridan foydalanib, proton terapiyasida ikkilamchi neytronlar hosil bo‘lishini batafsil tahlil qilishga bag‘ishlangan. Asosiy maqsad neytron chiqishi, ularning energiya spektri, burchak taqsimoti va turli klinik holatlarda ushbu ikkilamchi zarrachalar tomonidan yutilgan dozani tahlil qilishdir.

Kalit so‘zlar: proton terapiyasi, ikkilamchi neytronlar, Monte-Karlo simulyatsiyasi, GEANT4, radiatsiya dozimetri, qalam nurlarini skanerlash, passiv tarqalish, neytronlarni himoya qilish, saratonni davolash, nisbiy biologik samaradorlik (RBE)

Introduction. Proton therapy has revolutionized cancer treatment by enabling precise dose delivery while minimizing radiation exposure to surrounding healthy tissues. Unlike conventional photon therapy, protons exhibit a Bragg peak effect, where energy deposition is concentrated at a specific depth, reducing the exit dose beyond the tumor. However, the interaction of protons with matter leads to nuclear reactions that produce secondary neutrons. These neutrons are highly penetrating and contribute to out-of-field doses, potentially increasing the risk of radiation-induced complications[1].

Secondary neutron production is particularly concerning in pediatric patients, as they are more sensitive to radiation-induced malignancies due to their longer post-treatment life expectancy[2]. The neutron yield depends on factors such as beam energy, delivery method, and treatment geometry. Passive scattering techniques tend to generate higher neutron flux compared to pencil beam scanning, as the former involves interactions with scattering foils and collimators [3].

This study employs Monte Carlo simulations using GEANT4 to systematically investigate secondary neutron production in proton therapy. The results provide insights into neutron energy spectra, spatial distribution, and potential mitigation strategies to enhance patient safety.

Proton Therapy and the Bragg Peak

Proton therapy relies on the unique physical properties of protons to deliver radiation doses with high precision. The energy deposition profile of protons follows a characteristic Bragg curve, where the majority of the energy is deposited at a well-defined depth, known as the Bragg peak (see Figure 1). This property makes protons particularly suitable for treating deep-seated tumors while sparing healthy tissues in front of and beyond the target volume[4].

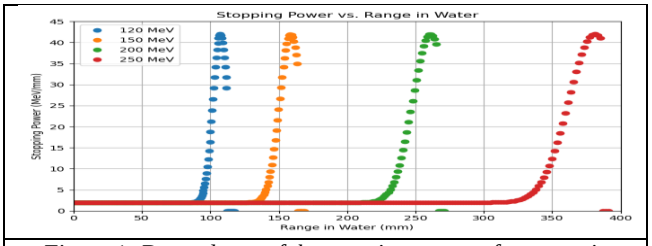

Figure 1: Dependence of the stopping power of protons in range for different energies.

When protons interact with atomic nuclei within the patient’s body or treatment components, nuclear reactions occur, leading to the production of secondary radiation, including gamma rays, charged fragments, and neutrons. The probability of these interactions depends on the proton energy, target material composition, and interaction cross-sections.

Secondary neutrons in proton therapy originate from several processes, including:

- Elastic Scattering: Neutrons scatter off atomic nuclei without causing nuclear reactions, leading to energy loss and angular redistribution.
- Inelastic Scattering: Protons interact inelastically with nuclei, resulting in neutron emission and nuclear excitation.
- Spallation Reactions: At higher energies, protons induce spallation reactions, where the target nucleus disintegrates, emitting multiple secondary particles, including neutrons.

Biological Impact of Secondary Neutrons

Unlike charged particles, neutrons do not directly ionize biological tissues but transfer energy through secondary charged particles created via neutron interactions. The relative biological effectiveness (RBE) of neutrons is significantly higher than that of photons, leading to a greater probability of radiation-induced damage[5]. This is particularly concerning for pediatric patients, as they have a longer post-treatment life expectancy and a higher susceptibility to secondary malignancies.

Proton therapy employs two primary delivery techniques:

1. Passive Scattering: Uses beam-modifying devices such as collimators and compensators to shape the proton beam, leading to increased neutron production due to multiple interactions with these structures.
2. Pencil Beam Scanning (PBS): Delivers narrow proton beams that are magnetically scanned across the tumor, significantly reducing the number of beam modifiers and, consequently, the secondary neutron yield.

Results and Discussion. The Monte Carlo simulations conducted in this study provide a comprehensive understanding of secondary neutron production in proton therapy under different beam delivery methods. The results highlight the significant differences in neutron yield, spatial distribution, and energy spectra between passive scattering and pencil beam scanning (PBS) techniques.

The simulations show that neutron production is highly dependent on the proton beam energy and target material composition (Figure 2). Higher-energy protons (above 150 MeV) tend to generate a more substantial number of secondary neutrons due to inelastic nuclear interactions and spallation reactions. The energy spectrum analysis indicates that:

- Low-energy neutrons (below 1 MeV) are predominantly produced inside the patient body due to elastic and inelastic scattering.
- Intermediate-energy neutrons (1–10 MeV) contribute significantly to out-of-field doses.
- High-energy neutrons (above 10 MeV) are primarily generated from interactions with beamline components, such as collimators and range modulators.

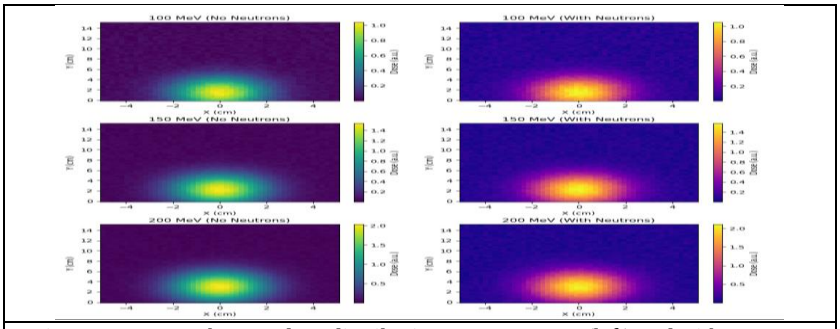

Figure 2: Proton therapy dose distributions: no neutrons (left) and with neutrons (right)

These secondary neutrons have a broad energy distribution, impacting both dose deposition and biological effectiveness. The neutron dose maps reveal distinct spatial distributions depending on the beam delivery technique: In passive scattering therapy, neutron production is concentrated near beam-modifying components such as collimators and scattering foils. This results in a higher neutron fluence outside the primary treatment field. In pencil beam scanning (PBS), neutron production is significantly lower because the beam is magnetically scanned across the tumor without the need for additional beam modifiers. The reduction in neutron dose is particularly beneficial for pediatric patients, where secondary malignancies are a significant concern.

The neutron dose decreases with increasing distance from the treatment field, but residual neutron exposure can still be observed up to several centimeters away from the target volume. This highlights the need for advanced shielding techniques in treatment planning.

The following key observations were made:

Using neutron-absorbing materials (e.g., borated polyethylene, high-density polyethylene) effectively reduces neutron dose contributions.

Increasing the distance between the patient and beamline components significantly lowers neutron fluence.

Optimizing collimation and treatment planning can further reduce unnecessary neutron exposure.

Conclusions. The results of this study emphasize the importance of mitigating secondary neutron exposure in proton therapy. The findings suggest that:

1.PBS should be prioritized over passive scattering whenever feasible, as it significantly reduces neutron production.

2.Shielding strategies must be optimized in clinical settings to minimize the out-of-field neutron dose.

3.Future proton therapy treatment planning should incorporate neutron dose considerations to enhance patient safety, particularly for pediatric and long-term cancer survivors.

REFERENCES

1. Newhauser, W. D., & Durante, M. (2011). Assessing the risk of second malignancies after modern radiotherapy. Nature Reviews Cancer, 11(6), 438-448.
2. Taddei, P. J., et al. (2008). Neutron production from beam-modifying devices in proton therapy. Physics in Medicine & Biology, 53(1), 236-257.
3. Hall, E. J. (2006). Radiobiology for the radiologist. Lippincott Williams & Wilkins.
4. Agostinelli, S., et al. (2003). GEANT4-a simulation toolkit. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 506(3), 250-303.
5. Paganetti, H. (2012). Relative biological effectiveness (RBE) values for proton beam therapy: Variations as a function of biological endpoint, dose, and linear energy transfer. Physics in Medicine & Biology, 57(11), R75.