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ORIGINAL ARTICLE

Capture γ-Ray Dose Equivalent at Double-Bend Maze Entrance: Monte Carlo Simulation and Analytical Methods and Measurements

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Abstract

Purpose: The production of the secondary neutron in the high-energy megavoltage medical accelerator machines has been extensively studied. In this study, MCNP5 MC code and two analytical methods, the proposed method and International Atomic Energy Agency (IAEA) 47 proposed method were used to capture γ-ray dose equivalent calculation.

Materials and Methods: MCNP5 code of the MC simulation method was used for code calculation in this study. The main components of a Varian 2100Clinac were simulated as well as a 30×30×30 cm^3 water phantom, in a Source to Surface Distance (SSD) of 100cm. Apparent neutron source strength (QN) was obtained using F1, *F8 tallies, and a small scoring cell at the isocenter with a mass equal to 0.625g.

Results: QN was obtained as 1.25 n/Gy X for the simulated Linear Accelerators (linac) head and was used in the other calculations. In the simulated double-bend maze treatment room with first and second lengths of the maze as 7m and 3m, the proposed method calculated capture γ-ray dose with 6.2% and 60% differences compared with MC simulation and IAEA 47 methods, respectively.

Conclusion: We concluded that Ghiasi and Mesbahi's proposed method performed better in capturing γ-ray dose equivalent calculation compared to IAEA 47 report. The proposed method reduced the difference from 60% to 6.2%.

Keywords: Monte Carlo; Capture Gamma-Ray; Dose Equivalent; Photon; Neutron.

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1. Introduction

Megavoltage photon beam of the Linear Accelerators (linac) has been employed widely for cancer radiotherapy worldwide. When the energy of X-ray photons produced in the linac head is higher than the linac head materials Giant Dipole Resonance (GDR), secondary radiations will be emitted such as neutron, proton, α particles, and other heavy particles to return the nucleus to its stable energy state [1;2]. Different materials GDR characteristics have been listed in the extensive study on the semi-microscopic description of the GDR by Ishkhanov *et al* [2]. Secondary photoneutron emission from the medical linacs has been reported to have a close to isotropic pattern and the secondary neutrons spectrum reported as consisting of an evaporated neutrons peak in the range of 0.2-0.7 MeV and around 0.1 of the total spectrum [3]. The National Council on Radiation Protection and Measurements (NCRP) report 144 reported average energy of the medical linacs produced secondary neutrons energy up to 3 MeV with an average energy of 1.5 MeV [4]. International Atomic Energy Agency (IAEA) in report 47 characterized photoneutron from the medical linacs, its shielding methods and stated that in the linac radiotherapy facilities higher than 10MV, neutron shielding should be conducted as same as photon shielding the linac housing [5]. Enormous publications can be found in the literature on photoneutron production from medical linacs and characterization of the secondary photoneutron produced by linac [6-13]. Naseri and Mesbahi [8] published a review on photoneutron production and characteristics and discussed the reported results. Ghiasi [10] evaluated characteristics of the photoneutron and subsequent neutron capture γ-ray in the radiotherapy with a medical 18MV linac. In Ghiasi's [10] study, (n,γ) and (γ,n) nuclear reactions were characterized and stated that photoneutron and prompt γ-ray spectra in different points in the room revealed thermalization of the fast neutron so that photoneutron energy changed from about 0.6 MeV at the isocentre to around 10–08 MeV at the outer door position. In another study carried out by Ghasemi and Ghiasi [12], they applied Phase-Space (PS) file and Monte Carlo (MC) simulation for the (n,γ), (γ,n) nuclear reactions simulation and linac leakage photons study in a megavoltage linac-based radiotherapy room. They concluded that using PS file and MC simulation method with controlling parameters reduced simulation time significantly and application of PS file allowed them to estimate photoneutron and capture γ-ray as well as leakage photon dose and fluence at different distances from the linac with acceptable statistical error. IAEA 47 [5] and NCRP 151 [14] discussed photoneutron and capture γ-ray characteristics and proposed some analytical methods for photoneutron and γ-ray dose equivalent calculation from the linac for adequate shielding against the secondary neutrons and capture γ-ray. Some analytical methods for the secondary neutron and consequently neutron capture γ-ray dose equivalent have been proposed by researchers in the literature. Kersey [15] method, French and Well [16] method, McCall [16;17], and Wu-McGinley [16;18] analytical methods were proposed for photoneutron dose equivalent calculation. IAEA 47 [5] reported analytical methods for photoneutron and capture γ-ray dose estimation for straight mazes and stated that for double-bend mazes, there is no method proposed and users can use the straight maze formula for double-bend mazes for capture γ-ray dose equivalent calculation at the maze entrance. Ghiasi and Mesbahi [19] proposed an analytical formula for neutron capture gamma dose equivalent calculation which reduced the difference with MC simulation to 2-11% from 36-38% using the proposed method instead of IAEA 47 [5] proposed calculation method. They derived a proposed formula from 40 mazes having different dimensions and lenghs. The proposed method by Ghiasi and Mesbahi [19] was as below (Equations 1, 2).

$$D_g = 1.114 \times 10^{-16} \times \varphi_A \times (\sqrt{S} \times e^{-\left(\frac{d_2+d_3}{3.89}\right)} + e^{-\left(\frac{d_2+d_3}{4.00}\right)}) \quad (1)$$

$$\varphi_A = \frac{Q_N}{4\pi d^2} + \frac{5.4Q_N}{2\pi S} + \frac{1.26Q_N}{2\pi S} \quad (2)$$

Where S is the radiotherapy room's total inner surface area in m^2, d1 shows the distance of isocenter to a point at the inner room entrance and, d_2 and d_3 stand for the length of the maze and double-bend maze in m. Apparent neutron source strength (QN) has been defined by IAEA 47 [5] as the number of secondary neutrons produced by the linac per absorbing 1Gy from X-ray at the isocenter in n/Gy X at isocenter. IAEA 47 [5] proposed method for capture γ-ray dose calculation in straight mazes was as below given method (Equation 3).

$$D_g = 5.7 \times 10^{-16} \times \emptyset_A \times 10^{\frac{(-d_2)}{6.2}} \quad (3)$$

Where d^2 was the straight maze length in m. The application of analytical methods for photoneutron and measurement using bubble-detector was conducted by Walter *et al.* [20]. They reported that the population of the neutrons in the maze entrance had energies below

200keV. Their main conclusion was to take the energy dependence of detectors into the account in neutron measurement and the flexibility and power of MC simulation in the problems simulation. Linac simulation preciseness and components effects on the photoneutron and γ-ray dose equivalent at the maze entrance for adequate shielding against neutron are important [21]. Ghiasi and Mesbahi [21] compared simplified linac head modeling and full linac head modeling employment for the photoneutron dose characterization. In calculating the neutron and capture γ-ray dose equivalent, the simplified model overestimated (9-47%) and (20-61%), respectively for photoneutron and capture γ-ray dose equivalent calculation compared to the full simulated linac head modeling. However, a good agreement was observed between the models for a standard field size of 10 × 10 cm^2 while in other field sizes significant differences were observed. In the fluence estimation, 5-53% difference was seen while in standard 10 × 10 cm^2 field size the simplified linac head modeling can be applied for the neutron and γ-ray dose equivalent calculation for rough estimation and speed calculation of the results. Different studies were conducted for photoneutron and capture γ-ray dose equivalent estimation by MC, experimental and analytical characterization of the neutron and capture γ-ray dose equivalent calculation [6, 9, 10, 12, 18, 19, 22-27]. In the current study, the authors aimed to calculate capture γ-ray dose equivalent using MC simulation and a proposed analytical method for double-bend maze entrance. The calculation was conducted using a Varian 2100Clinac and a standard treatment room. The results were discussed for agreements and differences.

2. Materials and Methods

The MCNP5 MC code was used for simulations and calculations for the entire work. The code, using its rich physical cross-sections for different interactions and other data in the libraries can transport a variety of photons and particles with a high energy range through different materials. The main components of an 18MV Varian 2100Clinac were simulated precisely using the manufacturer-provided data and literature useful data. Primary electron was simulated with a Gaussian symmetric distribution on X and Y axes with Full-Width at Half Maximum (FWHM) of 0.5 mm in the Axes on (-Z) axis or downward. The thin target and target supporting piece, flattening filter primary and secondary collimators with movable jaws, mirror, and ionizing chamber were the simulated parts of the head components. A 30 × 30 × 30 cm^3 water phantom in the Source to the Surface Distance of 100 cm (SSD) was modeled. Energy cut-off for photon and electron were set as 0.02 MeV and 0.5 Mev to take low photons into account. The application of F1 tally of MCNP5 MC code and the number of photo-neutrons crossing on it were scored. while *F8 tally was applied for estimation of energy released to a small water cell (with the mass of 0.625 gr) and then the absorbed dose was converted to J/kg or Gy at the isocentre. For calibration of MC simulation, in standard 10×10 cm^2, QN for the linac head modeling was obtained in n/Gy X. For the MC simulation calibration, the number required for absorbing 1Gy from the linac photon beam was obtained. A standard room with walls made of ordinary concrete w Primary electron was simulated with a Gaussian symmetric distribution on X and Y axes with FWHM of 0.5 mm in the Axes on (-Z) axis or downward. The simulated room and maze layout were shown in Figure 1. Secondary neutrons doses and fluencies in different field sizes were derived at the isocenter using MC simulation and F4 and F6 tallies of the employed code. The obtained result and inserting QN value, Equation 2, and MC simulation results were compared. The results of empirical and MC computational methods were compared. Four Thermoluminesances (TLD 100) were calibrated and provided with Secondary Standard Dosimetry Laboratories (SSDLs) and were used for points 1-3 and point of the strait maze entrance, and also double maze entrance. After exposing, the reading process was carried out by the Iranian SSDLs organization, and, the results were tabulated in Tables 1, 2. The TLDs were positioned at the inner entrance of the room, middle of the maze, and outer maze entrance.

The simulated linac geometries with its components were shown in Figure 2.

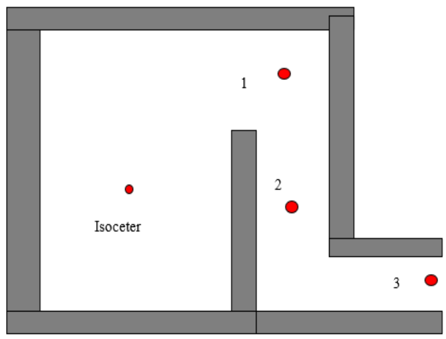

Figure 1. MC simulated room and maze layout and the points in which capture γ-ray dose equivalent was calculated by MCNP5 MC simulation code

Table 1. Neutron capture γ-ray dose equivalent calculated by MCNP5 MC simulation code, IAEA 47 proposed method, TLD 100 measurements, and Ghiasi and Mesbahi proposed analytical methods (Sv/Gy X)

Location	MCNP5 code calculation	IAEA 47 proposed for straight maze for a double-bend maze	Ghiasi and Mesbahi method	TLD measurement
Point 1	2.01×10^{-3}	2.78×10^{-3}	8.00×10^{-3}	2.29×10^{-3}
Point 2	3.59×10^{-4}	4.40×10^{-4}	4.76×10^{-4}	3.47×10^{-4}
Point 3	8.57×10^{-7}	1.17×10^{-4}	9.79×10^{-5}	8.01×10^{-7}

Table 2. Neutron capture γ-ray dose equivalent differences calculated by the MCNP5 MC simulation code, IAEA 47 proposed method, and Ghiasi and Mesbahi purposed method with TLD 100 measurements

Location	MCNP5 code calculation	IAEA 47 proposed for straight maze for a double-bend maze	Ghiasi and Mesbahi Method	TLD Measurement
Point 1	1.39×10^{-1}	$3.83\times10^{+1}$	$2.43E\times10^{1}$	2.29×10^{-3}
Point 2	3.34×10^{-2}	$2.26\times10^{+1}$	7.54×10^{1}	3.47×10^{-4}
Point 3	6.53×10^{-2}	$1.36\times10^{+4}$	8.66×10^{-1}	8.01×10^{-7}

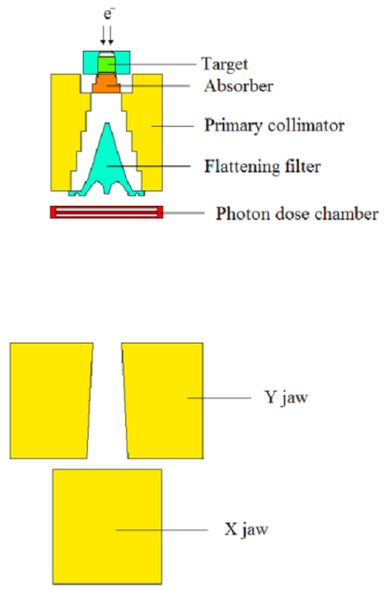

Figure 2. The simulated linac geometries with its components

3. Results and Discussion

In the current study, Ghiasi and Mesbahi's [19] method for the capture γ-ray dose equivalent, and MCNP5 code calculation were used and compared. The simulated linac head was verified for neutron calculation using QN estimation. Employment of F1 and *F8 tallies of the code, the value of 1.25 n/Gy X at isocenter was obtained for neutron the apparent source strength. Comparing the obtained value to the literature reported values showed a good agreement which verified our head simulation. The fluence of the neutron at the isocenter at standard field size and standard 10×10 cm^2 was 1.07×10^7 n/cm^2. Kase *et al.* [15] and Zabihzadeh *et al.* [28] calculated the fluence of the neutron at the isocenter at standard field size as 1.2×10^7 n/cm^2, and 1.09×10^7 n/cm^2. There is a good agreement between our result and others in neutron fluence calculation at the isocenter for the same energy and linac model. The values of 9.00×10^{-9} n/cm^2, 8.43×10^{-9} n/cm^2 and 7.80×10^{-9} n/cm^2 were derived as neutron fluence at isocenter in 10×10 cm^2, 20×20 cm^2 and 40×40 cm^2 field sizes. A reduction in the neutron fluence with field size increase is seen which may be attributed to the more interactions between photons and linac head materials in the small field sizes which leads to an increase in the yield of photoneutron. In points 1,2 1nd 3, the neutron capture γ-ray dose equivalent was obtained by MC simulation, IAEA 47 [5], and the proposed Ghiasi and Mesbahi's [19] methods as seen in Tables 1, 2. The φA value was estimated by MC simulation as 7.79×10^9 n/m^2 and Equation 2 calculated it as 7.85×10^9 n/m^2. A negligible difference was seen in the φA determination. For d_2 = 7m and d_3 = 3, the empirical proposed method that calculated the captureγ-ray dose equivalent was calculated as 2.43×10^{-4} mSv/Gy X, while the cross-section of the maze was 2m. The proposed [19] method also calculated capture γ-ray dose equivalent at the maze entrance as 9.79×10^{-5} mSv/Gy X. 6.2% difference was observed between the analytical method proposed by Ghiasi and Mesbahi [19] while IAEA 47 [5] method calculated it as 1.03×10^{-5} mSv/Gy X and 60% difference was calculated between MC estimated value and analytical method calculation. It can be seen that compared to MCNP code calculation, the proposed method [19] reduced the difference from 60% to 6.2%. The method performed well and the application of the method is proposed in the shielding calculations. The measured values showed more agreement with MCNP estimations and Ghiasi and Mesbahi proposed method at double-bend maze entrance rather than the maze middle. Our purposed method is for maze entrance and agreement between MCNP estimations, the purposed analytical method calculation and the direct measurement approves Ghiasi and Mesbahi's method. Higher values calculation with IAEA method may be attributed to scattering the linac photons as well as phantom scattering and its aim that was for calculation for strait maze without additional bending.

4. Conclusion

We concluded that the method proposed by Ghiasi and Mesbahi performed better compared to other analytical methods and agreed with MC estimation and measurement results, especially in double bend maze entrance calculation of capture γ-ray dose equivalent. We recommend the employment of the proposed method instead of the IAEA 47 [5] method in the shielding calculations. However, the authors recommend more studies to verify the applied analytical method for double bend mazes neutron capture γ-ray dose equivalent calculation.

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