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Original research article

Safe bunker designing for the 18 MV Varian 2100 Clinac: a comparison between Monte Carlo simulation based upon data and new protocol recommendations

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ABSTRACT

Aim: The aim of this study was to compare two bunkers designed by only protocols recommendations and Monte Carlo (MC) based upon data derived for an 18 MV Varian 2100Clinac accelerator.

Background: High energy radiation therapy is associated with fast and thermal photoneutrons. Adequate shielding against the contaminant neutron has been recommended by IAEA and NCRP new protocols.

Materials and methods: The latest protocols released by the IAEA (safety report No. 47) and NCRP report No. 151 were used for the bunker designing calculations. MC method based upon data was also derived. Two bunkers using protocols and MC upon data were designed and discussed.

Results: From designed door's thickness, the door designed by the MC simulation and Wu–McGinley analytical method was closer in both BPE and lead thickness. In the case of the primary and secondary barriers, MC simulation resulted in 440.11 mm for the ordinary concrete, total concrete thickness of 1709 mm was required. Calculating the same parameters value with the recommended analytical methods resulted in 1762 mm for the required thickness using 445 mm as recommended by TVL for the concrete. Additionally, for the secondary barrier the thickness of 752.05 mm was obtained.

Conclusion: Our results showed MC simulation and the followed protocols recommendations in dose calculation are in good agreement in the radiation contamination dose calculation. Difference between the two analytical and MC simulation methods revealed that the application of only one method for the bunker design may lead to underestimation or overestimation in dose and shielding calculations.

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1. Background

In the high energy external photon beam radiotherapy, unwanted and undesirable secondary particle emission is a penalty for better quality and outcome of cancer treatment. Secondary particle production in the megavoltage linac based radiotherapy is mainly governed by Giant Dipole Resonance (GDR).[1] Among the produced particles are neutrons with zero electrical charge which are not influenced by the Columbic force originated from the surrounding atoms. Neutron can be transmitted from the massive linac shielding and may be found at the maze and the maze entrance. International Commission on Radiological Protection (ICRP) publication 103[2] reported a high (up to 20) radiation weighting factor (W_R) for photoneutrons produced in high energy medical accelerators. On the other hand, nearly isotropic emission has been reported for photoneutrons by researchers.[3] The isotropic emission pattern, high W_R and low attenuation have made the neutrons more important to be shielded. Maze wall degrades the energy of photoneutrons and capture them by releasing gamma ray photons with energy up to 8 MeV.[4] In the literature, two main peaks at 200 and 700 KeV have been shown in the secondary neutrons spectra.[5] Photoneutrons spectra around the linac head have been extensively studied and analyzed by researchers.[5–9] International Atomic Energy Agency (IAEA) No. 47[2] and National Commission of Radiation Protection and Measurements (NCRP) No. 151[10] have recommended that photoneutron production becomes important in the bunkers with linacs operating at the energy above than 10 MV. Additionally, it was stated that shielding against neutrons must be considered as well as photons in linacs with energy above 10 MV.[3] Photoneutron dose equivalent has been reported at the isocentre as 0.006, 0.016, 0.147, 0.231 and 0.261 mSv/Gy X for 9, 10, 15, 18 and 20 MV linacs, respectively.[11] Kim et al.[12] studied the neutron dose equivalent around a 15 MV linac and found the neutron dose equivalent as 3.49 mSv/Gy X at 1 m from the target in horizontal configuration while 0.63 mSv/Gy X was calculated at 1.41 m from the target in diagonal configuration of the gantry. However, Wu and McGinley[13] measured the value of photoneutron dose equivalent as 0.79–1.3 mSv/Gy X at the 1.41 m from the target. Mesbahi et al.[14] simulated 18 MV Varian 2100Clinac and four different rooms including two straight and two double-bend mazes and evaluated the analytical methods for the photoneutron dose calculation in different maze layouts. They found the Wu–McGinley method the best estimator among the other methods. In the case of the capture gamma ray dose equivalent calculation, their method showed up to 90% difference with MC simulation in the case of double-bend mazes while a good agreement was reported in the straight mazes. Ghiasi and Mesbahi[15] simulated and studied 40 different rooms and proposed an analytical method for the capture gamma ray dose equivalent calculation in double-bend mazes which reduced the difference to lower than 10%. Recently, NCRP No. 151[10] and IAEA No. 47[3] have recommended analytical methods for the shielding calculation against photon, photoneutron and capture gamma ray radiations in the high energy radiation therapy facilities. Additionally, NCRP No. 144[1] has recommended the MC simulation as a reliable method for the shielding calculations. In the current study, two bunkers were designed using the protocols recommended data and MC simulation based upon data without using any of the recommended data.

2. Aim

The aim of this study was to compare two bunkers designed by only protocols recommendations and Monte Carlo (MC) based upon derived data for a 18 MV Varian 2100Clinac accelerator.

3. Materials and methods

The latest protocols released by the IAEA (safety report No. 47)[2] and NCRP report No. 151[10] were used for the bunker designing calculations. It was recommended to take into account the scattering of X-ray with the patient, walls and leakage radiation from the linac head to the maze during the bunker designing. For the linac orientation whereby the gantry rotation axis is perpendicular to the maze wall, total dose at the maze entrance D_d is calculated as in Eq. (1).

$$D_d = \sum D_P \sum f \times D_W \sum D_L \sum D_T \tag{1}$$

Linac photon beam was considered as downward in the entire work. D_p, f, D_w, D_L and D_T are doses from the patient scattering, primary radiation transmitted from the patient, primary radiation scattered by the walls into the maze, leakage radiation scattered down the maze, leakage radiation transmitted from the maze wall and patient scattered radiation to the maze, respectively. When gantry rotates over the axis parallel to the maze axis, explanation of D_d is the same as Eq. (1) expects that radiation transmission to the maze must be added to the scattering radiation to the maze. In this paper, gantry rotation axis was considered as perpendicular to the maze wall. Several analytical calculation methods were also proposed and recommended for the photoneutron shielding calculation. Total photoneutron fluence at the point A in Fig. 2 is given by the following equation:

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

φ_A is a total neutron fluence at the inner maze entrance or point A, in $n^0 m^{-2}$ per Gy of X-ray at the isocentre. Q_N is the neutron source strength that represents the total number of produced neutrons per Gy X-ray at the isocentre. d_1 is the distance from the isocentre to the inner maze entrance (point A) in m and S is a total inner surface area of the treatment room in m^2.

Wu–McGinley[13] method has been reported as the best estimator for the neutron dose calculation in the high energy radiotherapy room.[14] Photoneutron dose equivalent is calculated by the method in (Sv per Gy of isocentre) as the following formulation:

$$D_n = 2.4 \times 10^{-15} \times \varphi_A \times \sqrt{\frac{A_r}{S1}} \times (1.64 \times 10^{-d_2/1.9} + 10^{-d_2/T_N}) \tag{3}$$

where D_n is the neutron dose equivalent at the maze entrance in Sv/Gy X-ray at the isocentre, φ_A is the neutron fluence given by Eq. (2), A_r and S_1 are cross-sectional areas (in m^2) of the inner and outer maze entrance, respectively. d_2 is the distance from point A (in m) to the door position and T_N is the length of the maze that attenuates neutron dose by factor of 10. Wu–McGinley reported method was recommended by the IAEA No. 47[2] and NCRP No. 151[10] for use in the shielding calculations.

It has also been reported by the mentioned protocols that neutron capture gamma ray dose equivalent along the maze can be obtained as Eq. (5) in Gy/X of the isocentre.

$$D_{\varphi} = 5.7 \times 10^{-16} \times \varphi_A \times 10^{-d_2/6.2} \quad (4)$$

The weekly dose due to neutron and capture gamma ray is obtained from multiplying the dose equivalent to the weekly workload. The workload considered as the recommended value for an 18 MV standard radiotherapy department as 600 Gy for a 5 day week (40 patients in a 5-day week and dose rate of the linac was 3 Gy/min). The readers can find the methods in detail in the protocols used.

MCNPX code of MC[16] was used for modelling an 18 MV Varian 2100Clinac and a typical treatment room. The code is a general purpose MC code and can transport electron, photon, and neutron and coupled radiations. Additionally, it is possible to simulate the photoneutron production from photon and materials interactions and capture gamma ray production from the photoneutrons interactions with the materials found in the linac head, treatment room walls and patient body. LA150U library file of the MCNPX code[16] was used for the photoneutron production throughout the entire simulation process. The simulated linac model was validated in our previous works.[17–20] Tuning the energy with comparison between the measurement and simulated percent depth dose (PDD), primary electrons energy was set as 18.3 MeV. Additionally, the comparison of beam profiles (BP) and PDDs in different field sizes verified and benchmarked the modelled linac. Fig. 1 shows derived PDD and BP using MC simulation and direct measurement. At d_{max}, the difference between MC and measurement PDD was 0.99% and in the case of BP the difference was seen up to 3% in the lateral sides. Simulated treatment room and the linac head components are shown in Figs. 2 and 3, respectively. The walls were simulated by the ordinary concrete materials with NCRP 144 recommended composition and density of 2.3 g/cm^3. Composition of walls was 0.013 H, 1.165 O, 0.737 silicon, 0.194 Ca, 0.04 Na, 0.006 magnesium, 0.107 Al, 0.003 sulfur, 0.045 K, 0.29 Fe. The room dimensions were 10.97 m × 12.65 m with walls and 4.2 m in height. In addition, the maze length was 9.90 m. Photon beam spectrum was derived at the primary and secondary barrier location. Then, the simulated ordinary concrete tenth value layers (TVLs) were calculated simulating the "good geometry". Narrow beam and adequate distance of the simulated detector for avoiding the scattered radiation detection were the conditions considered in the good geometry simulation. Calculating the concrete TVLs, required thickness of the primary and secondary barriers to be determined. MC derived photon spectra at the primary and secondary barriers were shown in Figs. 4 and 5. Useful, scattered and leakage photon

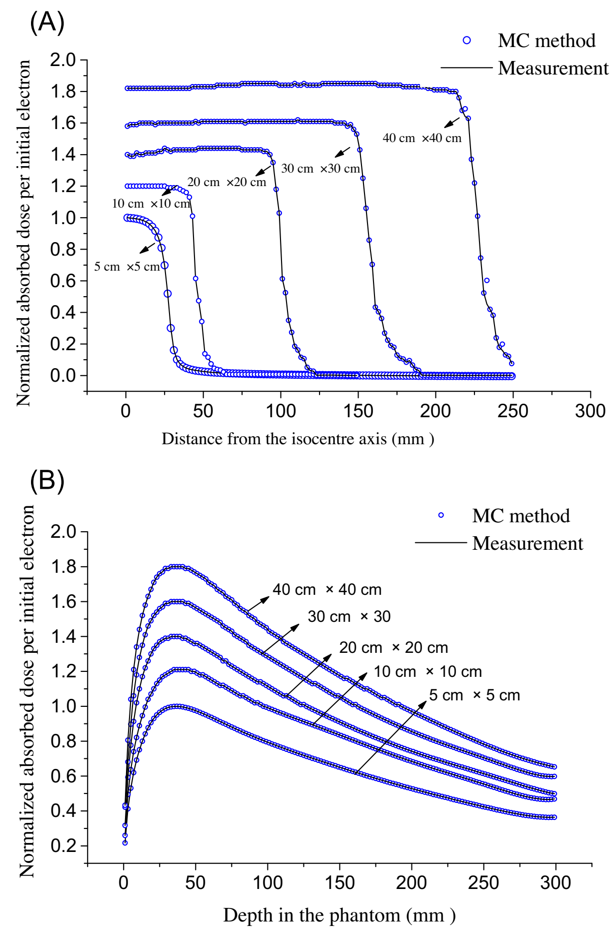

Fig. 1 – (A) Normalized BP derived by MC simulation and measurements data in different field sizes. (B) Normalized PDD derived by MC simulation and measurements data in different field sizes.

beam components were included in the spectra at the barriers positions. The spectra at the maze entrance door were also calculated for the photons from the linac, secondary produced photoneutrons and capture gamma ray due to the photoneutrons. Using the obtained spectra under the "good geometry", TVLs for the lead and BPE were calculated. Photon dose per initial electron at the maze entrance was calculated. Then, the required initial electrons for delivering 1 Gy dose to the isocentre were calculated. Using the number of the initial electrons required to 1 Gy photon dose delivery to the isocentre, total photon dose at the maze entrance per Gy of X-ray at the isocentre was calculated. Application of the full MC simulations to perform photoneutron calculations for the maze entrance neutron and gamma ray doses calculation requires long run time and the results are associated with unacceptable statistical uncertainty. To speed up the MC calculations for point dose calculations at the end of the maze, the full model was run and the neutron source strength (Q_N) value (n^0Gy^{-1}) and photoneutron spectra around the head were calculated. The calculated photoneutron and photon spectra were shown at the isocentre in Figs. 6 and 7. For variance reduction, a point like source with isotropic emission was positioned at the room

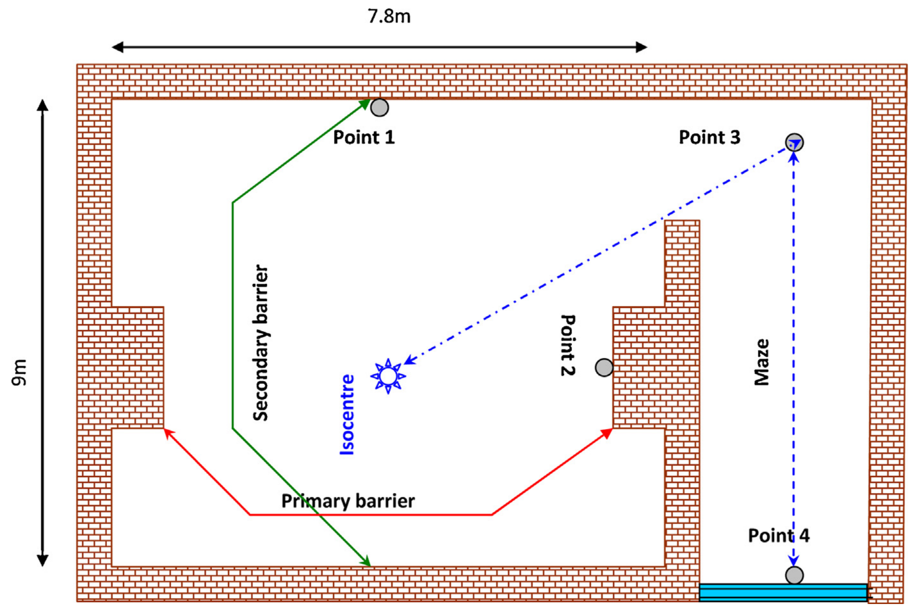

Fig. 2 – Simulated dimensions and room layout for the calculations. The points in which dose and spectrum were calculated also is shown

centre with the derived photoneutron spectra at the isocentre and the calculated Q_N was used for the MC calculations. The Q_N calculation method was explained in our previous work.[21] Using the isotropic photoneutron source, compromising the statistical error and dose resolution, photoneutron dose and spectra were calculated at the maze entrance at a spherical water cell 4 cm in radius. It should be stated that the photons from the linac and produced by the capture gamma ray dose and spectra at the same cell were derived separately. The photoneutrons and photons deposited energy was calculated in terms of MeV g^{-1} per initial particle using a f6 tally in the simulation program's data card. The number of the initial electrons for absorbing 600 Gy (weekly delivered dose) dose at the isocentre was calculated according to the number of initial

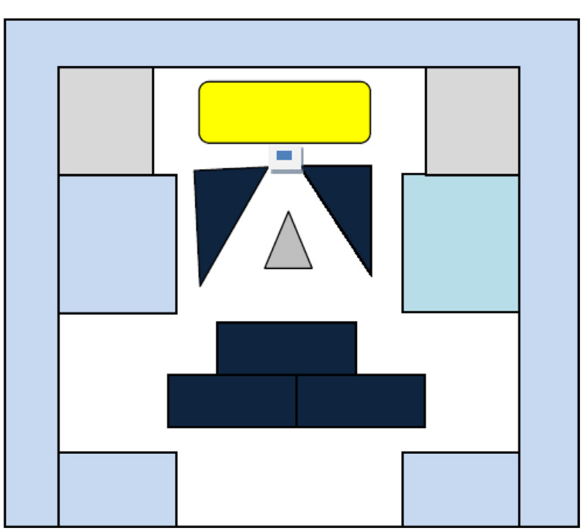

Fig. 3 – The simulated linac. Shielding assembly, primary and secondary collimators, jaws, flattening filter, target and electron stopper was shown.

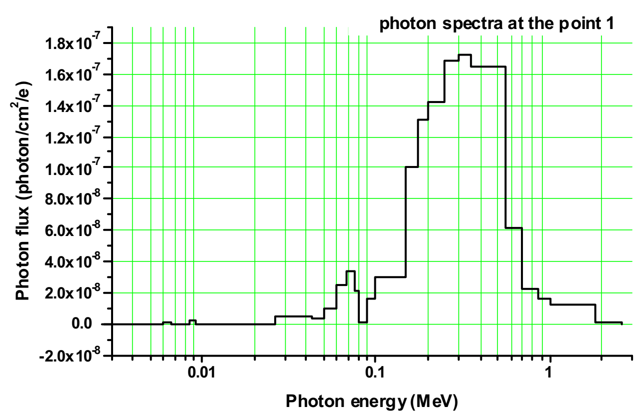

Fig. 4 – Photon spectra at the point 1 (secondary barrier position).

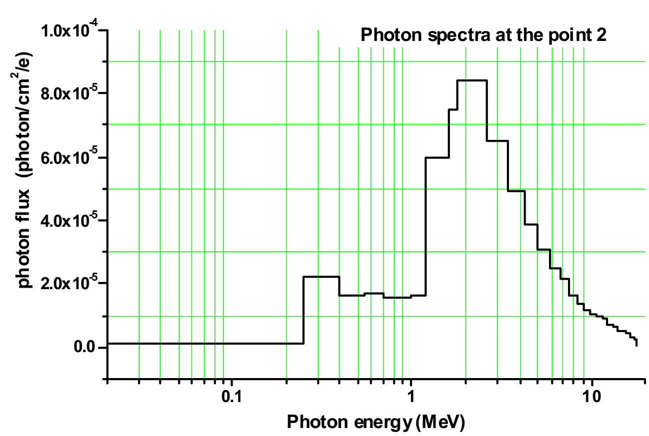

Fig. 5 – Photon spectra at the point 2 (primary barrier position).

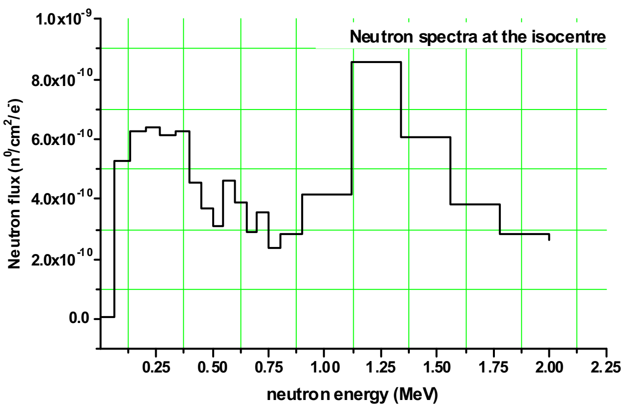

Fig. 6 – Photoneutron spectra at the isocentre derived from full simulated linac.

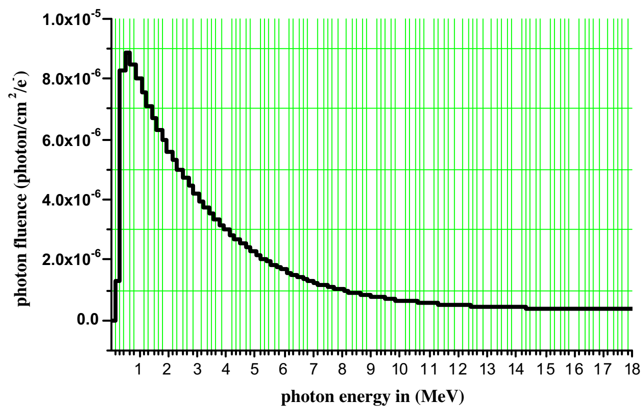

Fig. 7 – Photon spectra at the isocentre derived from full simulated linac.

electrons required to deliver 1 Gy dose from the linac photon beam at the isocentre. Additionally, the calculated Q_N value was used to the calculation of total neutron dose per Gy of X-ray at the isocentre. The scored values were associated with uncertainty less than 1%. In the full MC running for Q_N calculation, biased photonuclear production enabled by setting the forth entry of PHYS:P card (which controls the energy and physical aspect of photoneutron production) as 1 to speed up the calculations. Additionally, BNUM in the PHYS:E card was optimized. BNUM controls the number of photons produced from the incidence of one initial electron on the target. Also, because the energy threshold of the photoneutron reactions for the main components of a linac is higher than 8 MeV, for the photoneutron production simulation the energy cut-off of 8 MeV was used for both electrons and photons. Capture gamma ray dose calculation was performed in a separate run and the energy cut-off for photons and electrons was inactivated for scoring the full energy range of capture gamma rays produced at the end of the maze. Calculating the photon and neutron spectra at the primary and secondary barriers and door position and using the obtained spectra for deriving TVLs of the concrete, lead and borated-polyethylene (BPE), the thickness of the barriers and the thickness of required maze door materials were calculated. Then, the thickness of shielding materials including concrete, lead and BPE was considered according to the total radiation spectra at the position and the designed bunker was an only MC upon designed bunker.

4. Results

As shown in Fig. 2, the distance from the isocentre to point A was obtained as 6.4 m and total room surface was calculated as 236 m^2. In D_p calculation for the modelled linac produced photon beam, IAEA No. 47 recommended value was used for the scatter fraction of dose by the patient.[6] Dose albedo considered according to the recommendations and maximum field size of $40 \times 40\,\text{cm}^2$ was opened for taking the maximum photon dose level into account. But in the case of the photoneutron and capture gamma ray dose and fluence calculations, fully closed field size ($0 \times 0\,\text{cm}^2$) was modelled in order to obtain maximum photoneutron production by the linac head.[19] Considering the recommended values for the D_w and D_{wT}, doses from the walls scattering and beam transmissions to the maze were calculated. Additionally, fraction of 0.001 (0.01% of the useful beam) was applied to the head leakage at the isocentre and transmission radiation dose calculation at the maze entrance. Workload of 600 Gy per week was considered throughout the calculations. Maximum values for all of the components in Eq. (1) were calculated. Furthermore, the coefficient of 2.64 was inserted for calculations in the case of the gantry rotation perpendicular to the maze axis according to the IAEA safety report No. 47 recommendation.[2] Additionally, 0.25 was applied for the use factor in the calculations for all of the four components in Eq. (1) (Fig. 8).

Using the values in the analytical method of dose equivalent calculation, all components of D_P, D_φ and D_n were calculated. Design dose limit for the occupational location was considered as 20 mSv/year. We considered an occupancy factor for our study equal to 1/16. Distance from the isocentre to point A in Fig. 2 and the distance from point A to the door position were 6.4 and 9.9 m, respectively. Area of the wall that reflected radiation to the maze in the inner maze entrance was calculated from the room dimensions and 11.8 m^2 obtained. Applying the values, dose arising from the patient scattering was calculated. After the calculation of the patient scattering dose, walls scattering dose was calculated according to

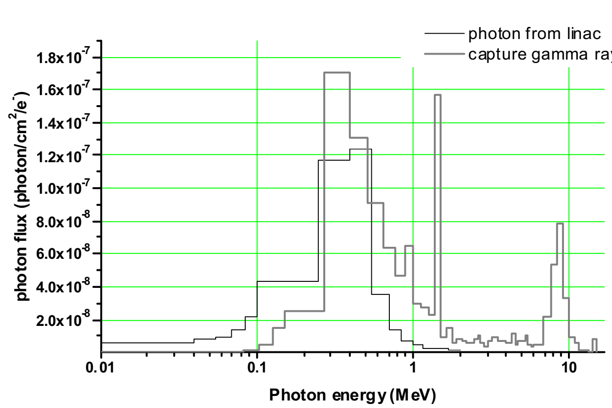

Fig. 8 – Photon from the simulated linac and capture gamma ray spectra at the maze entrance.

Table 1 – Neutron, photon and capture gamma ray dose equivalent at the maze entrance door (mSv/Gy X isocentre).

Method	Wu–McGinley	IAEA No. 47	NCRP No. 151	MC simulation
Neutron dose equivalent	8.31E−04	8.31E−04	8.31E−04	7.25E−04
Capture gamma ray dose equivalent	1.93E−04	1.93E−04	1.93E−04	1.01E−04

the IAEA and NCRP recommendations. Most probable angle of reflection considered in the calculations and the scatter fraction of 8.64×10^{-4} was applied for the concrete reflection in 45°. By applying the IAEA No. 47[6] recommended coefficients for the 18 MV beam and calculating the required dimensions from the room dimensions, dose from the walls scattering was also obtained. For calculating the linac head leakage radiation and its scattering to the maze, dimensions and recommended coefficients were applied. Table 1 shows the calculation results for the analytical methods.

In calculation of total neutron fluence of photoneutrons at point A in Fig. 2, Q_N was set as 1.22×10^{12} n^0/Gy X of the isocentre. Using the distance of point A to the door position, d_2, neutron capture gamma ray dose equivalent at the maze entrance was also calculated (Fig. 9).

In the Wu–McGinley method, A_r and S_r values were obtained as 10.2 and 8.76 m^2, respectively, from the simulated room dimensions. Importing the data in Wu–McGinley analytical method, neutron dose equivalent was calculated in Sv/Gy-X at the isocentre. Weekly dose from the neutron and capture gamma ray was obtained using the workload and dose equivalent.

Running the MC simulation input file, 2.25×10^{-15} Gy/initial e^0 dose was absorbed at the isocentre. For adsorbing 1 Gy dose to the isocentre, 4.44×10^{14} initial electrons were required. At the maze entrance, 2.32×10^{-22} Gy/initial e^0 dose from photons was absorbed and considering the number of electrons needed for the absorbing of 1 Gy/Gy-X at the isocentre, 6.19×10^{-8} Sv/week dose from the linac photons was obtained. Q_N for our model was obtained as 1.3×10^{12} n^0/Gy X at the isocentre. Photoneutron fluence at point A in Fig. 2 was obtained as 5.96×10^{-3} n^0/m^2 per initial particle and applying the Q_N value, the fluence value was determined as 7.55×10^9 n^0/m^2/Gy X at the isocentre. Additionally, neutron

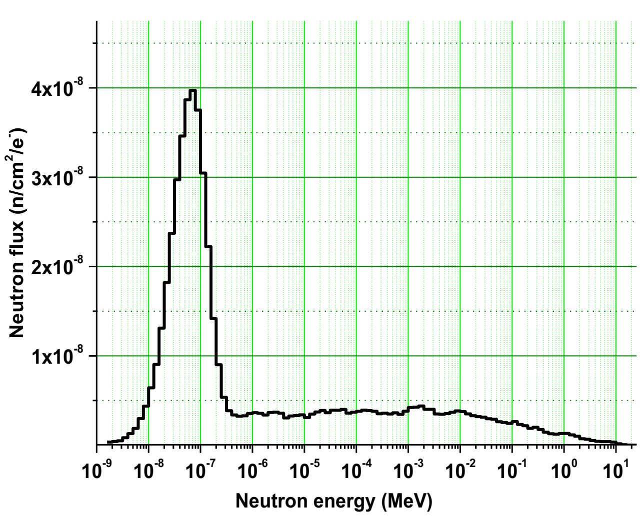

Fig. 9 – Photoneutron spectra at the door position derived from full simulated linac.

and neutron capture gamma ray dose equivalent at the maze entrance (applying the ICRP 103 recommended radiation weighting factors)[2] were obtained as 7.25×10^{-7} Sv/Gy X at the isocentre and 1.01×10^{-7} Sv/Gy-X at the isocentre, respectively. Results of the calculations were shown in Table 1. Calculating the total dose at the maze entrance and according to the shielding materials attenuation characteristics, an optimized door for the room can be designed. NCRP No. 151[10] and IAEA No. 47[3] presented some materials for the photon and neutron shielding materials and their TVLs. Calculating dose level at the door position, according to the material TVLs, required thicknesses were calculated for the maze door design. TVL for lead and BPE were recommended as 6 and 445 mm, respectively. Required concrete thickness was calculated from the equation[3,10]:

$$\text{no.TVLs} = \log_{10}\left(\frac{1}{B}\right) \tag{5}$$

Considering that the maze entrance and door are located in the controlled area and the recommended design limit for the controlled area, 0.1 mSv/week,[6] required lead and BPE thicknesses were calculated from Eq. 6 as the protocols recommendation for the reduction of total dose equivalent to 0.1 mSv/week,

$$\text{no.TVLs} = \log_{10}\left(\frac{DE(\text{mSv week}^{-1})}{0.1\left(\text{mSv week}^{-1}\right)}\right) \tag{6}$$

The analytical calculated door was designed in a sandwich configuration so BPE was considered in the centre. As for designed door's thickness, the door designed by the MC simulation and Wu–McGinley[13] analytical method was closer to both BPE and lead thickness. In the case of the primary and secondary barriers, MC simulation resulted in 440.11 mm for the ordinary concrete, total concrete thickness of 1709 mm was required (Fig. 10). Calculating the same parameters with the recommended analytical methods resulted in 1762 mm for the required thickness using 445 mm as recommended TVL for concrete. Additionally, for the secondary barrier thickness 752.05 mm was obtained. Required concrete thickness for reducing the dose at point 1 to the acceptable value, MC calculation resulted in 747.25 mm. In the current study, two bunkers were designed by two different methods. Firstly, only MC based upon data was applied to design a safe bunker. In the other method, IAEA[3] and NCRP[10] recommended analytical methods and data were used for a safe bunker design for the same linac. In the MC-based method, all of the required data were derived by simulations. However, a good agreement was seen in the derived data and designed bunker with the protocol recommendations and calculated barriers. The primary barrier designed according to the protocol method used was 3% thicker than the barrier designed according to MC. Additionally, the secondary barriers of the bunker were 0.6% thicker

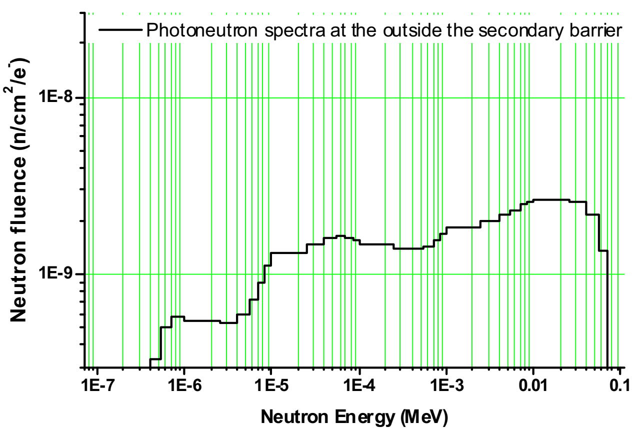

Fig. 10 – Photoneutron spectra outside the secondary barrier.

using the protocol recommended method. Comparing the photoneutron and capture gamma ray dose equivalent at the maze entrance, we can see 12% and 47% difference. Difference in the case of the neutron dose may be attributed to the fact that the analytical methods do not take the microscopic interactions into the account. Photoneutron and capture gamma ray productions occur by the multiple scattering of the radiation, molecular and atomic scale interactions. On the other hand, the analytical methods have proposed only to calculate dose by distances and source term, while the composition of the wall materials plays a significant role in the neutron production and capturing. In our previous work,[17] we proposed an analytical method for the capture gamma ray dose equivalent at the maze entrance which reduced the difference with the MC simulation from 90% down to 10%. The readers can see our proposed method in detail in our previous work.[17] Additionally, we studied this effect in detail in the previous work. In that work, we studied photoneutron contamination at the different concrete compositions and up to 46% difference was obtained. The result of this study was obtained for a room made of ordinary concrete. We sensitized the analytical methods by the introduction of Q_W representing the walls neutron source term. On the other hand, MC simulation was associated with some fluctuations in the results. In this study, we reduced the fluctuations. Our results were obtained with the statistical error below 0.008 in all of the data derived. But the accuracy of the simulations may be a source of errors. Our previous work[18] introduced the Wu–McGinley method[13] as the best of the proposed methods. The thickness of lead and BPE calculated by the MC simulation was 28% and 32% lower than the protocols calculated. Although the MC simulation may be associated with some errors, the protocols method overestimates the dose and, consequently, the thickness of the shielding materials. There are studies comparing the MC simulation method and analytical methods in terms of photoneutron contamination in a high energy radiotherapy room.[17] According to the studies, the studied analytical methods overestimate the dose. But in this study, we deduced that the application of both MC simulation and Wu–McGinley method[13] with our modified formulation of Eq. (2) can decrease overestimation or underestimation. Specially, the author proposes the application of the method taking the wall material into account. Our proposed formulation for the capture gamma dose equivalent and modified formulation of Eq. (2) is strongly proposed.

5. Conclusion

Our results showed that MC simulation and the followed protocol recommendations in dose calculation are in good agreement in the calculation of radiation contamination dose. Difference between the two analytical and MC simulation methods revealed that the application of only one method for the bunker design may lead to underestimation or overestimation in dose and shielding calculations. Underestimation can be hazardous[20] for the staff due to the poor protection and may cause radiological problems and, on the other hand, overestimation can impose additional costs and technical problems. Our results showed that the application of different methods in the shielding calculations and bunker designing can optimize bunker designing and improve the radiation protection while lowering the costs. It can be concluded that MC simulation is a reliable and useful method in the shielding calculation while in the radiotherapy departments those cannot use MC simulation for shielding calculations, the applied protocol recommended methods can be followed. MC simulation is time consuming and needs an expert user to conduct a precise code calculation, but its capability in taking the microscopic and macroscopic aspects of the problem has made it a powerful method in radiation physics calculations. Finally, the author proposes using both MC and the protocol methods with our modifications and proposed method for optimizing the bunker designing.

Conflict of interest

None declared.

Financial disclosure

None.

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