

The Influence of Brass Compensator Thickness and Field Size on Neutron Contamination Spectrum in 18MV Elekta SL 75/25 Medical Linear Accelerator with and without Flattening Filter: A Monte Carlo Study

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ABSTRACT

Background: One of the most significant Intensity Modulated Radiation Therapy treatment benefits is a high target to normal tissue dose ratio. To improve this advantage, an additional accessory such as a compensator is used to deliver doses. Compensator-based IMRT treatment is usually operated with an energy higher than 10 MV. Photoneutrons, which have high linear energy transfer and radiobiological effectiveness, are produced by colliding high-energy photon beams with linear accelerator structures, then they deliver the unwanted doses to patients and staff. Therefore, the neutron energy spectra should be determined in order to calculate and reduce the photoneutron risk.

Objective: We have conducted a comprehensive and precise study on the influence of brass compensator thickness and field size on neutron contamination spectrum in an Elekta SL 75/25 medical linear accelerator with and without the flattening filter by Monte Carlo method.

Material and Methods: MCNPX MC Code version 2.6.0 was utilized to simulate the detailed geometry of Elekta SL 75/25 head components based on Linac's manual. This code includes an important feature to simulate the photo-neutron interactions. Photoneutrons spectrum was calculated after the Linac output benchmarking based on tuning the primary electron beam.

Results and Conclusion: Based on the Friedman and Wilcoxon nonparametric tests results ($P < 0.05$), photoneutron fluence directly depends on the field size and compensator thickness. Moreover, the unflattened beam provides lower photoneutron fluence than the flattened beam. Photoneutrons fluence is not negligible in compensator-based IMRT treatment. However, in order to optimize treatment plans, this additional and unwanted dose must be accounted for patients.

Keywords

Photoneutron, Spectrum, MCNP, Compensator, Field Size

Introduction

Today, cancer is the most common cause of death in the world [1]. More than 50% of all cancer patients receive radiation therapy [2]. One of the routine radiotherapy techniques is Intensity Modulated Radiation Therapy (IMRT). IMRT delivers high radiation doses

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to tumors and then provides a high target to normal tissue dose ratio [3]. In this technique for achieving a field of variable intensity, multi-leaf collimator (MLC) or compensator IS utilized. Basically, variations of compensator are based on their continual intensity, and are made of materials with different densities. In contrast with MLC, compensator-based IMRT has some advantages like simplifying quality assurance, treatment delivery and dose calculation [4]. Photon beams with energies higher than 10 MV are used in compensator-based IMRT. When these high energy photon beams collide with nuclei of high atomic number materials which are located along the path of the beam including linear accelerator (Linac) head structures (target, primary collimators, flattening filter and jaws), neutrons are produced by (γ, n) and ($e, e'n$) interactions and contaminate therapeutic beam. The cross-section for (γ, n) interaction is approximately 137 times higher than ($e, e'n$) interaction; as a result, ($e, e'n$) interaction generates negligibility neutrons versus (γ, n) interaction [5]. The average threshold energy for photoneutron interactions is 8 MV. Thus, photoneutrons are generated when photon energy is higher than threshold energy [6]. According to NCRP 116 recommendation, the quality factor for neutrons with energy range 0.1-2 Mev is 20 [7]. These particles have a high linear energy transfer (LET) and radiobiological effectiveness (RBE) delivering an unwanted dose to patients and personals which are induced secondary cancers [8]. In order to calculate and reduce the photoneutron risk, neutron energy spectra should be determined [9]. Photoneutron spectrometry is a very complex task due to the type of its interaction with matters; this is while, there are several methods to assess the neutron spectrum such as multi-sphere measurements, nuclear recoil, threshold methods, Monte Carlo (MC) calculation, etc. [10]. Nevertheless Monte Carlo calculations is an alternative method in this field of research. Various studies have been carried out for dif-

ferent problems related to the neutron spectrometry. Some researchers investigated the MLC, wedge filters, flattening filter (FF) and field size effects on the neuron spectrum. In addition, other researchers reported it at different points around many types of Linac by employing the Monte Carlo method in most of their projects. Based on all publications, we can conclude that the contaminated neutron spectrum depends dominantly on the field size, the energy beam, type of Linac, treatment room geometry, the wall composition of the room and the position of the measurement point. Due to disagreements on the influence of field size on the neutron spectrum in articles and the lack of the study about compensator effects on the neutron spectrum, we have conducted a comprehensive and precise study on the influence of brass compensator thickness and field size on neutron contamination spectrum in an Elekta SL 75/25 medical linear accelerator with and without flattening filter by Monte Carlo method.

Material and Methods

Linac's Head Simulation

MCNPX MC Code version 2.6.0 was used to simulate the detailed geometry of Elekta SL 75/25 head components based on Linac's manual. This code includes an important feature that can simulate photo-neutron interactions [11]. Linac is operated by an 18 MV photon beam. As shown in Figure 1, the main structures of Linac's head consist of target (90%W and 10%Re), primary collimators (96%W, 3.75%Ni and 1.25%Fe), flattening filter (steel), ion chamber (Maylar), upper jaws (96%W, 3.75%Ni and 1.25%Fe), lower jaws (96%Pb and 4%Sn), and shielding (96%W, 3.75%Ni and 1.25%Fe). In order to tune the simulated Linac, the percentage depth dose (PDD) and beam profile data derived from MCNP calculation should match the experimental dose data in a water phantom within 1%. This Linac was validated in our previous

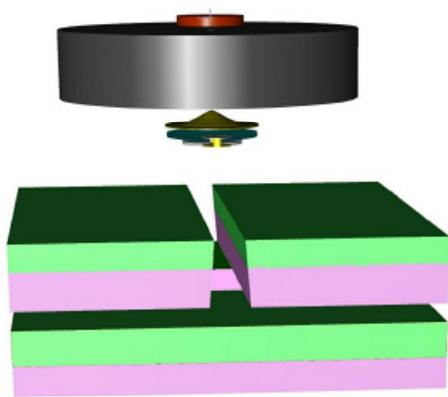


Figure 1: The Geometry of Linac's Head

study [12]. To determine the percentage depth dose and beam profile data in the source-surface distance (SSD) of 100cm, a water phantom with dimensions of $60 \times 60 \times 50 \text{ cm}^3$ was simulated. To achieve differences less than 1% between measurement and calculation data, the characteristics of incident primary electron beam such as mean energy, radial distribution and energy distribution were adjusted [13]. The cut-off energy for electron and photon were selected as 10 Kev and 700 Kev, respectively. Also, to calculate dose data *F8 tally was used. A water phantom (RFA-300) and a Farmer ionization chamber (FC65-P, volume= 65 cm^3) were utilized to gather experimental data. The number of primary electrons was selected to be 1×10^9 .

Calculation of Photoneutron Spectrum

Photoneutron spectrum was calculated after Linac output benchmarking according to tuning the primary electron beam. To calculate the photoneutron spectrum, the code was slightly modified. The photoneutron production does not occur lower than 7 MeV. Therefore, the cut-off energy for electron and photon was altered to 7MeV. The fourth entry of PHYS: P card is ispn that controls photonuclear particle production. This entry must be chosen as -1 for

an analogue photonuclear production. To carry out this calculation, a void sphere cell with a dimension of 10 cm diameter was modelled in SSD=100 from the target. The photoneutrons crossing the void cell were accounted by F4 tally, which is used for the determination of flux average over a cell. The geometry of the brass compensator as a cylinder with 21 cm diameter and a variable height (0.5, 1, 2,3,6 and 8 cm), was defined in 67.2 cm from the target. The brass compensator compositions are 3% Pb, 61.5% Cu and 35.5% Zn with the density of 8.22 gr/cm^3 . Photoneutron spectrum was investigated and calculated for the following cases: (a for flattened and unflattened 18-MV photon beam in different field sizes (5×5 , 10×10 , 15×15 and 20×20) and b) in the presence of compensators with thickness 0.5, 1, 2, 3, 6 and 8 cm for different field sizes in flattened and unflattened 18-MV photon beam. To correctly compare the photoneutron spectrum in different cases, the neutron spectrum was obtained for the same absorbed dose in an isocenter. The uncertainty for photoneutron spectrum and dose calculation was less than 2% and 1%, respectively.

Results

Linac Validation

Linac validation was conducted by comparing MC calculation and practical measurement data for the open field. Figure 2 shows that the difference between two PDD curves resulting from MC and empirical measurement is within 1% for the depths after 3 cm (build-up depth). Difference less than 2% is seen for the points located in the flat region in beam profiles (Figure 3). Our validation results are in agreement with other studies and are in accordance with our previous study [12]. Finally, we have chosen the features of incident primary electron beam based on the validation results (mean energy=17.8 MV, radial distribution=0.35 cm and Gaussian energy distribution with FWHM=7%).

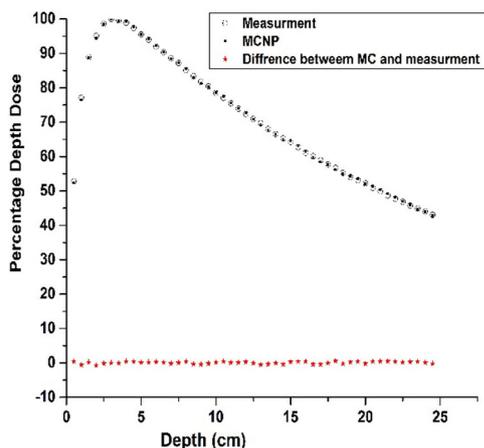


Figure 2: Percentage depth dose curves difference between empirical measurements and MC calculation for $10 \times 10 \text{ cm}^2$ field size

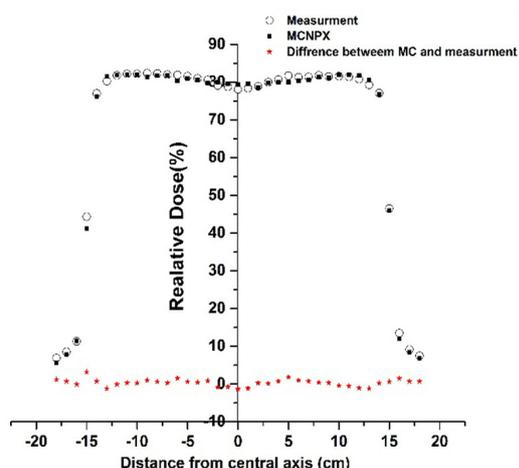


Figure 3: Beam profiles difference between empirical measurements and MC calculation for $30 \times 30 \text{ cm}^2$ field size.

Photoneutrons spectrum

The results of MC calculation to observe the effect of flattening filter on photoneutron spectrum are shown in Figure 4. Based on Wilcoxon's nonparametric test results ($P < 0.05$), Photoneutrons fluence reduced with removing FF. Photoneutron fluence was 72.8%, 71.7%,

70.4%, 70.2%, 69.5%, 68.8% and 64.6% lower for unflattened beams in $10 \times 10 \text{ cm}^2$ field size for the open field and compensator field with 0.5, 1, 2, 3, 6 and 8 cm thickness, respectively. The photoneutron fluence is listed in Table 1 for the unflattened and flattened beams in different field sizes and different thicknesses of the Brass compensator. We performed Friedman's nonparametric test to assess the effect of field size on photoneutron spectrum, and found that photoneutron fluence increased when field size increased for all simulated cases ($P < 0.05$). The ratio of photoneutron fluence for $20 \times 20 \text{ cm}^2$ field size to photoneutron fluence for $5 \times 5 \text{ cm}^2$ field size is approximately 1.3 for the flattened beam in open field and compensator field with different thicknesses. This proportion is approximately 1.2 for the unflattened beam. As the results of Friedman test ($P < 0.05$) show, it can be concluded that there is a significant difference among photoneutron fluences in different thicknesses of the compensator. Figures 5 and 6 reveal that photoneutron fluence increased by the increment compensator thickness and this effect is the same for the unflattened and flattened beams. As a case in point, when the compensator thickness increases from 0.5 cm to 8 cm, the photoneutron fluence increases 4.5 times for flattened beam in $5 \times 5 \text{ cm}^2$, $10 \times 10 \text{ cm}^2$, $15 \times 15 \text{ cm}^2$ and $20 \times 20 \text{ cm}^2$ field sizes. This variation is 5.5 times for the unflattened beam.

Discussion

The effect of FF on Photoneutron Spectrum

According to our results, by removing FF, the shape of photoneutron spectrum does not considerably change, while the photoneutron fluence decreases notably. The main reason for this variation is that by removing FF photons, fluence increases in isocenter due to the lack of flattening filter attenuation effect. Therefore, to achieve the same dose in isocenter for unflattened and flattened beams, photon flu-

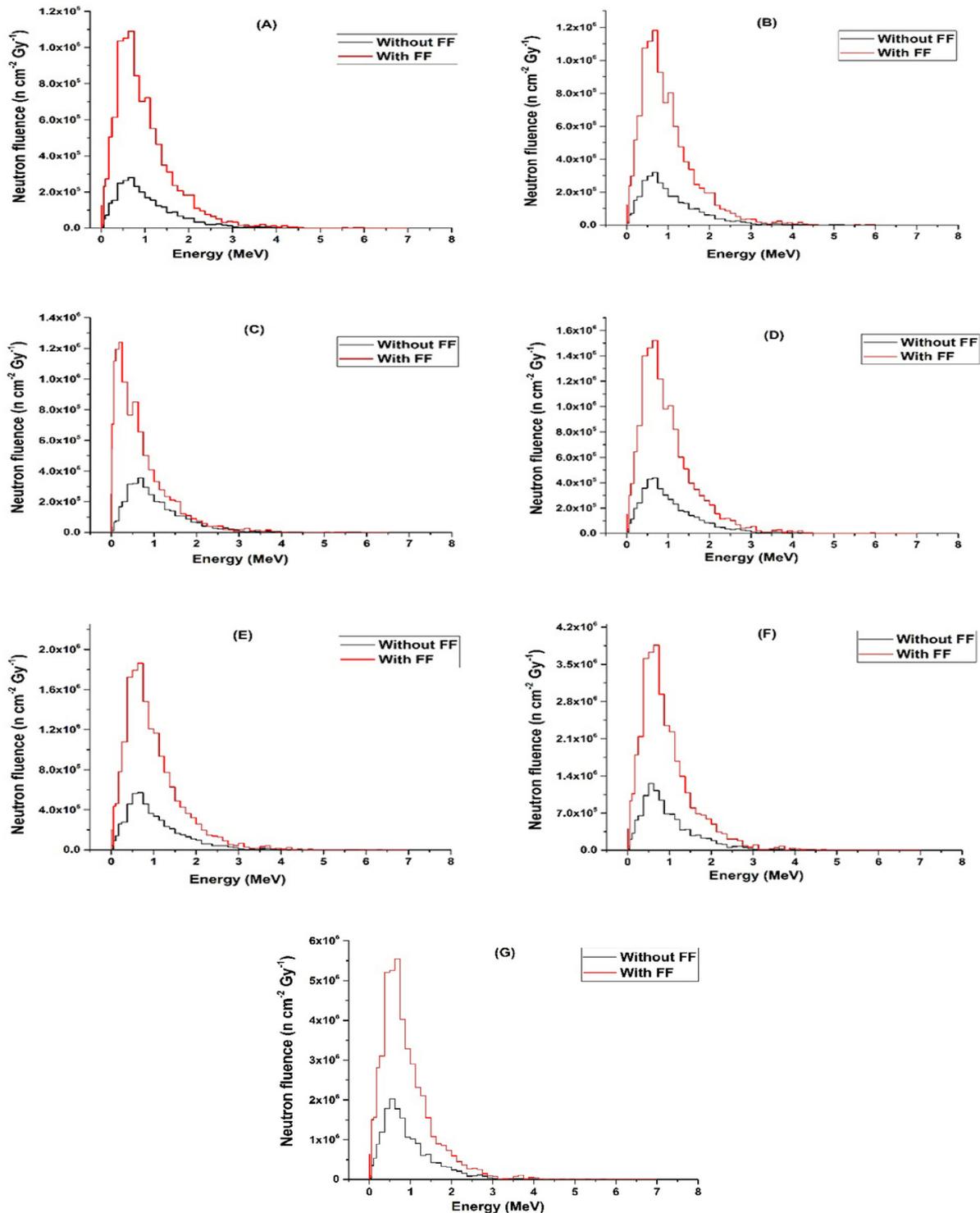


Figure 4: Compression of photoneutron spectrum for the unflattened and flattened beams in 10×10 cm² field size. A) Without compensator. B) Compensator with 0.5 cm thickness. C) Compensator with 1cm thickness. D) Compensator with 2cm thickness. E) Compensator with 3 cm thickness. F) Compensator with 6 cm thickness. G) Compensator with 8 cm thickness.

Table 1: Photoneutron fluence.

The thickness of compensator (cm)	Field size (cm ²)	Photoneutron fluence ((n/cm ² Gy)-((n/cm ² Gy ⁻¹)×10 ⁶))	
		flattened beam	unflattened beam
0	5×5	8.79±0.241	2.52±0.067
	10×10	10.3±0.275	2.80±0.071
	15×15	10.9±0.288	2.94±0.065
	20×20	11.6±0.299	3.02±0.075
0.5	5×5	9.82±0.269	2.78±0.094
	10×10	11±0.271	3.11±0.071
	15×15	12.4±0.275	3.21±0.820
	20×20	12.9±0.272	3.53±0.072
1	5×5	10.7±0.284	3.07±0.082
	10×10	11.7±0.295	3.46±0.080
	15×15	12.5±0.293	3.5±0.083
	20×20	13.3±0.297	3.66±0.084
2	5×5	12.9±0.385	3.8±0.102
	10×10	14.3±0.375	4.26±0.100
	15×15	15.5±0.413	4.41±0.106
	20×20	16.6±0.432	4.57±0.111
3	5×5	15.7±0.252	4.88±0.127
	10×10	17.5±0.280	5.34±0.130
	15×15	19±0.294	5.7±0.133
	20×20	20.6±0.532	6.09±0.125
6	5×5	30.5±0.879	9.52±0.262
	10×10	34.3±0.993	10.7±0.240
	15×15	38.19±0.109	11.6±251
	20×20	42.6±0.116	12.2±0.356
8	5×5	43.3±0.522	15.2±0.433
	10×10	48.3±0.280	17.1±0.400
	15×15	53.1±0.294	18.5±0.440
	20×20	58.3±0.302	19.1±0.421

ence production decreases in the target for the unflattened beam. A main result of this study was that photoneutron interactions decreased in Linac's head structures which are made of high atomic number. Although our results are in agreement with the related publications [14, 15], different reasons were mentioned about

the photoneutron fluence reduction in the unflattened beam. One of these reasons is the flattening filter capability in photoneutron production [15]. As mentioned above, FF compositions are made of low-atomic-number materials in Elekta SL 75/2 Linac. Accordingly, due to their low photoneutron cross-section, the contribution of flattening filter in photoneutron production is negligible and is inconsistent with the results of the present study.

The effect of Field Size on Photoneutron Spectrum

As presented in Table 1, the photoneutron fluence decreases with a decrease in the field size in the open field, and the compensator field for with and without FF present in Linac's head; these variations can be explained by the contribution of secondary collimators in photoneutron attenuation. When field size decreases, the secondary collimators will be closed. Therefore, photoneutrons originated from the upper structures are attenuated by secondary collimators because of its thickness. In addition, the photoneutrons generated by secondary collimators will be stopped locally. Most probably, the secondary collimators have a significant attenuated effect. By increasing field size, the interval between secondary collimators increases. As a result, more photoneutrons will be received by the detector in isocenter without the attenuation effect of the secondary collimators. Additionally, the photoneutron fluence increases with the field size in the presence of Brass compensator with different thicknesses (0.5, 1, 2, 3, 6 and 8 cm). Based on the compensator compositions (3% Pb, 61.5% Cu and 35.5% Zn), as field size enlarges, a larger surface of the compensator is irradiated by high energy photons. Then, the photoneutron fluence increases by increasing the number of photon-neutron interactions in the compensator. Many authors have investigated the dependency of field size on the photoneutron spectrum [16-22]. Nevertheless, this investigation has become a controversial issue.

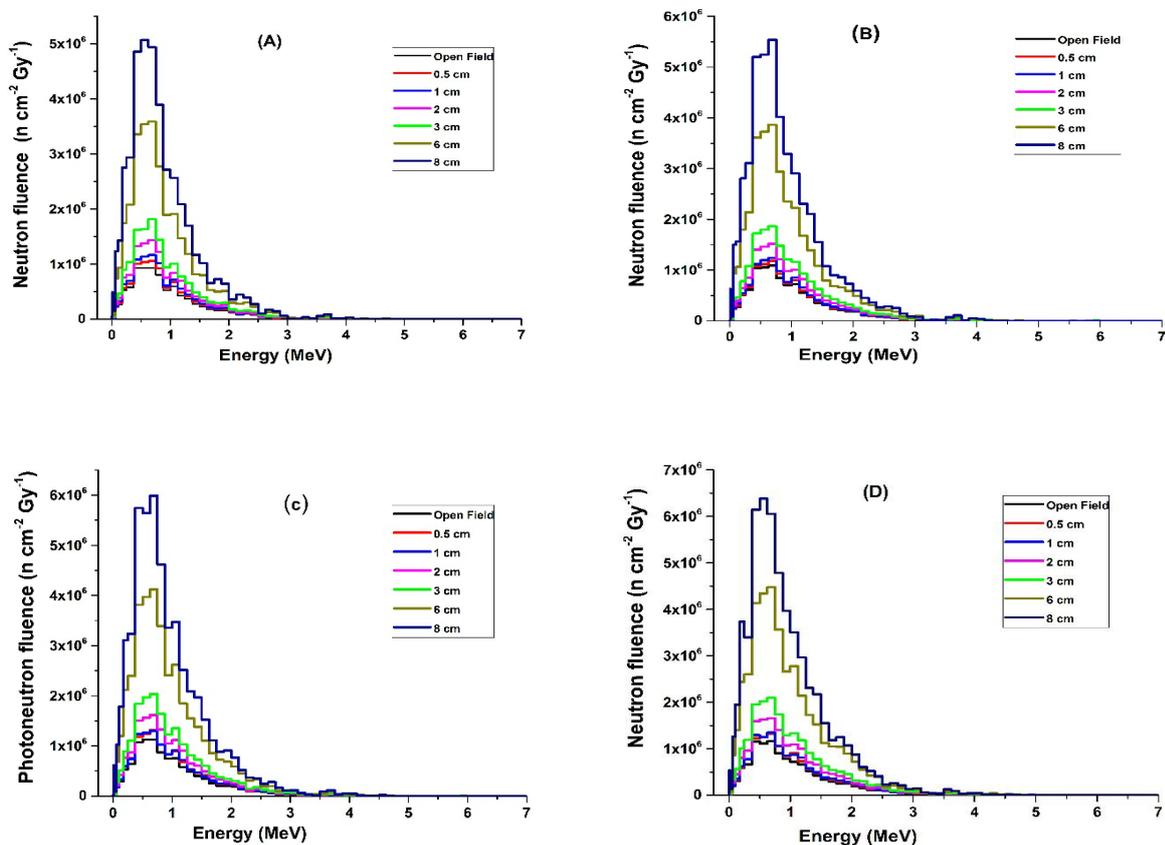


Figure 5: . Compression of photoneutron spectrum for different compensator thicknesses for flattened beam. A) 5×5 cm² field size B) 10×10 cm² field size C) 15×15 cm² field size D) 20×20 cm² field.

Our results are completely in agreement with several publications [16, 17, 19], but disagree with MC and experimental studies by several researchers [20-22]. It seems that high statistical uncertainty of publications has influenced the results. As mentioned previously, our MC calculation is performed with a statistical uncertainty less than 2%.

the effect of Compensator Thickness on Photoneutron Spectrum

The photoneutron spectrum shape does not change significantly with the increase in compensator thickness. Our results exhibited that photoneutron fluence increases with compensator thickness in the flattened and unflattened beams. The increase in the photoneutron flu-

ence with compensator thickness can be explained by the fact that photon beams are attenuated when the compensator is located in the beam path. Subsequently, the absorbed dose decreases in the isocenter. In order to achieve the same absorbed dose, the photon fluence should be increased. Hence, by an increase in the photon fluence with compensator thickness, the number of photoneutron interactions and, in turn, photoneutron fluence will increase. Recent investigations conducted on the aspects of IMRT treatment show an increasing neutron contamination in comparison with conventional treatments [23, 24].

Conclusion

In this study, the photoneutron spectrum was

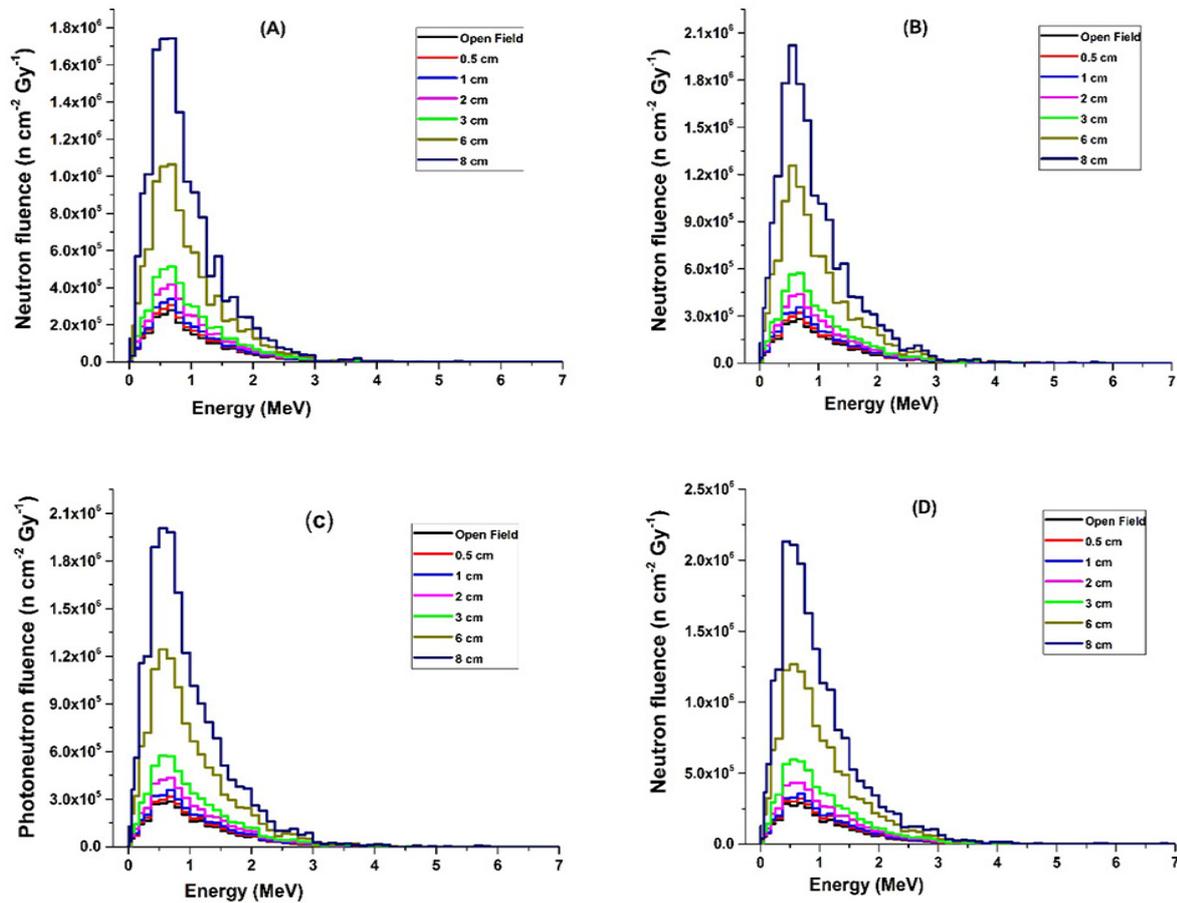


Figure 6: Compression of photoneutron spectrum for different compensator thicknesses for unflattened beam. A) $5 \times 5 \text{ cm}^2$ field size B) $10 \times 10 \text{ cm}^2$ field size C) $15 \times 15 \text{ cm}^2$ field size D) $20 \times 20 \text{ cm}^2$ field size

calculated through MC method by mounting different thicknesses of brass compensator on the head of ELEKTA SL75/25 Linac. Although experimental methods are usually associated with uncertainties, MC method presents accurate calculations. The application of compensator and FF leads to enhanced photoneutron fluence and increased field size. The radioprotection recommendations indicate harmful biological effects of contaminated neutrons on patients and personnel. A careful study of this work can improve the benefit-risk ratio of IMRT-based compensator treatment by photoneutron spectrum determination.

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Conflict of Interest

None

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