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The measurement of photoneutron dose around an 18 MV Varian linear accelerator by TLD600 and TLD700 dosimeters inside the polyethylene sphere of neutron probe LB 6411

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ABSTRACT

Bremsstrahlung X-rays from high-energy linear accelerators (Linacs) produce neutrons as a result of photonuclear reactions mainly with the different materials constituting the accelerator head. The neutrons produced during high energy radiotherapy should be considered in terms of protection and ose escalation. Due to the very intense photon component in the Linac field causing pulse pile-up and dead-time effects in detectors, measurement of the corresponding neutron dose by active dosimeters is extremely troublesome. In this study, the neutron probe LB 6411, which active detector of ^{3}He proportional counter tube was replaced with the passive detectors of TLD600 and TLD700, has been used to perform neutron measurements at four points around the 18 MV Varian 2100C Linac facility. The neutron dose equivalent at the distance of 1 and 2 m from the isocentre on the patient couch was obtained 2.2 and 0.75 mSv.Gy^{-1} respectively. According to the results, the dose equivalent from emitted photoneutrons is not negligible and therefore treatment conditions should be optimized. The results of this study emphasized that TLD600 and TLD700 dosimeters inside the polyethylene sphere of neutron probe LB 6411 is an appropriate choice for studying photoneutron production in the vicinity of the accelerator.

Indexing terms/Keywords

Photoneutron; TLD600; TLD700; dosimetry; neutron probe LB 6411.

Academic Discipline And Sub-Disciplines

Medical physics

SUBJECT CLASSIFICATION

Medical physics

TYPE (METHOD/APPROACH)

Experimental study of neutron dose measurements

1. INTRODUCTION

Radiotherapy with high energy photon and electron beams is the most widely used technique to control and treat tumors. Therefore, medical linear accelerators, also known as Linacs, are greatly utilized. The advantages of high energy X-rays over lower energy photons are: lower skin dose, higher depth dose and smaller scattered dose to tissues outside the target volume that led high energy Linacs to be the standard fixture of radiotherapy clinics (1, 2 and 3).

In spite of clinically usefulness photon and electron beams, high energy linacs operating at energies higher than 8 MV, produce secondary particles such as neutrons which are the most important secondary particles causing dose escalation on account of their high range in ordinary matter and the high LET of their by-products. Photoneutrons are produced by the giant dipole resonance reactions, (γ, n), when the incident photon energy is above the threshold energy of the (γ, n) reaction. This threshold is around 8 MeV for high atomic numbers (7.42 MeV for tungsten) and higher for low atomic numbers (16 MeV for oxygen) (1, 4 and 5).

Neutrons are generated in the accelerator head (target, collimators, flattening filter and shields), treatment room structures (bunker walls, floor and ceiling), couch and patient’s body. Since, the accelerator head is constituted of high *Z* materials and these materials have the highest (γ, n) cross sections, photoneutron production is mainly due to (γ, n) reactions in the accelerator head. Moreover, the high *Z* materials present in the accelerator head have low neutron absorption cross sections for the generated neutron energies. Therefore, the produced neutrons will escape from the Linac head and reach the patient (1, 2, 3, 4, 5 and 6).

All the produced neutrons in the accelerator head are fast. They lose their energy by elastic and inelastic collisions inside the treatment room and present a complex energy spectrum with an average energy in the range of 0.2–2 MeV (7). These neutrons have the maximum radiation weighting factor of (w_R=20) in calculations of dose equivalent and effective dose and thereby are the most biologically damaging particles(8 and 9). This undesired additional neutron dose delivered to the patient increases the possibility of associated risks of secondary cancers after radiotherapy. Hence, photoneutron field evaluation is of high priority to optimize the treatment conditions (10).

Neutron dose measurement inside the treatment room is highly difficult if active detectors are used. The very intense gamma irradiation, the pulsed time structure of the neutron fields and the high frequency electromagnetic fields distort the operation of active detectors. In some of these detectors like ^{3}He, the separation of gamma and neutron component is on the basis of pulse height discrimination. In some places where the gamma irradiation is very intensive, such as linacs , dead-time effects and pulse pile-up affect the discrimination and falsify the results (11, 12, 13, 14 and 15). Therefore, as several authors have pointed out, passive detectors such as activation foils, bubble detectors, CR-39 nuclear track detectors (NTDs) and thermoluminescent dosimeters (TLDs), are the basic dosimeters for characterizing neutron beams inside the treatment room (11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21 and 22).

TLDs have been significantly be interested because of their small size and their tissue-equivalence. Since TLDs are sensitive to gamma, it is not possible to determine the neutron dose with a single TLD. As described in the ICRU report 26 (23), dosimetry in a neutron-gamma mixed field like the Linac field needs at least two dosimeters, one sensitive to gamma and the other sensitive to neutrons. The dosimeters applied in this study are TLD600 (^{6}LiF: Mg, Ti) and TLD700 (^{7}LiF: Mg, Ti). TLD600 contains 95.6% ^{6}Li which has a high thermal neutron capture cross-section (about 940 barn), whilst TLD700 contains only 0.01% ^{6}Li. Therefore, TLD600 is much more sensitive to thermal neutrons, whereas the gamma sensitivities of both TLDs are approximately the same (14, 15, 19, 20, 21 and 22).

The goal of the present study is to estimate the neutron dose equivalent around an 18 MV Varian Linac by TLD600 and TLD700 pairs inside the polyethylene sphere of neutron probe LB 6411.

2. MATERIALS AND METHODS

2.1. TLD pairs and TL measurements

Dosimeters are commercial TLD600 (^{6}LiF:Mg,Ti) and TLD700 (^{7}LiF:Mg,Ti) manufactured by Harshaw Chemical Co., in the shape of chips and dimensions of 3×3×0.9 mm^3. All the TLD chips were annealed before each irradiation following the producer instructions. Annealing was performed at 400 °C for 1 h, gradually cooled down to room temperature and heated to 100 °C for 2 h. Then they were analyzed with a TLD reader model 7102 made in Iran. The instrument software represents the glow curve and the TL intensity (area under the glow curve). The reading cycle (time temperature profile) used in the study is given in table 1.

Table 1. Time temperature profile used for reading TLDs .

Preheat temperature (°C)	50
Preheat time (s)	0
Heating rate (°C/s)	25
Maximum temperature (°C)	300
Acquire time (s)	12
Anneal temperature (°C)	300
Anneal time (s)	0

As explained, simultaneous use of TLD600 and TLD700 is an appropriate solution to discriminate the neutron and gamma components in a mixed radiation field. The response of TLD600 and TLD700 to a neutron-gamma mixed field is given through the following equation:

$$R_{600}^{n+\gamma} = R_{600}^{n} + \frac{\alpha_{700}^{\gamma}}{\alpha_{600}^{\gamma}} R_{700}^{\gamma} \qquad (1)$$

Where $R_{600}^{n+\gamma}$ and R_{700}^{γ} are the TLD600 and TLD700 total responses to the mixed field, α_{600}^{γ} and α_{700}^{γ} are TLD600 and TLD700 gamma calibration factors and R_{600}^{n} is the neutron contribution.

Since neutron sensitivity of TLD600 is about 10^3 times that of TLD700 (24), no neutron sensitivity was assumed for TLD700.

Gamma and neutron doses, D_γ and D_n, in a mixed radiation field can be deduced through these equations**:**

$$\begin{cases} D_\gamma = \alpha_{700}^{\gamma} R_{700}^{\gamma} \\ D_n = \alpha_{600}^{n} R_{600}^{n} = \alpha_{600}^{n} R_{600}^{n+\gamma} - \dfrac{\alpha_{600}^{n}\alpha_{700}^{\gamma}}{\alpha_{600}^{\gamma}} R_{700}^{\gamma} \end{cases} \qquad (2)$$

To obtain D_γ and D_n the user must know the gamma and neutron calibration factors. To determine these factors, gamma and neutron calibrations of the TLDs were performed.

2.2. Gamma and neutron calibration

Gamma calibration of TLD chips was performed by ^{60}Co machine (Theratron 780, MDS Nordion) which is used for radiotherapy treatments. TLDs were positioned in a Perspex phantom 30×30×30 cm^3, at the depth of 0.5 cm, with a 20×20 cm^2 field size and the source to surface distance (SSD) of 80 cm. Thirty TLD pairs were exposed to definite gamma doses in the range of 50 to 300 cGy. Five TLD pairs were used for each irradiation, meanwhile two pairs were devoted to measure the background in all irradiations.

The most important parameter in TLD pairs measurements is neutron dose calibration in characterized neutron field. Neutron calibration was done by ^{241}Am-Be 20 Ci source (in the Tehran university of medical sciences). First, neutron dose equivalent rate at definite distance from the source was determined by neutron probe LB 6411 and then the active detector of ^{3}He proportional counter tube inside the LB 6411 was replaced with the passive detectors of TLD600 and TLD700. Neutron probe LB 6411[1] manufactured by Berthold Co. is designed for the measurement of the ambient dose equivalent rate. It consists of a cylindrical ^{3}He counter tube with external dimensions of Ø 4 cm × 10 cm and active volume of 45 cm^3, surrounded by a polyethylene moderator sphere which has a diameter of 25 cm. This detector is sensitive to neutrons from thermal energies up to 20 MeV and the measuring range is from 100 nSv/h up to 100 mSv/h. Am-Be sources are widely used in neutron calibration, due to the similarity between the spectra of Am-Be emitted neutrons and the neutrons produced in Linacs (25).

In order to do the calibration, TLD pairs were located at the center of the polyethylene sphere of neutron probe LB 6411. Neutron source was placed on lead Blocks at 1 m hight. The distance of TLDs from the neutron source was chosen 1 m. Neutron dose rate at the point of TLDs was measured 700 µSv/h using neutron probe LB 6411. Neutron irradiations were carried out in several different time intervals; from 12 to 70 h by five TLD pairs for each irradiation. The neutron doses measured by neutron probe LB 6411 were correlated to the TL responses to determine the calibration curve.

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[1] Berthold company, www.berthold.com

Since the Am-Be emission is accompanied with photons radiation, the TLD600 signal is due to both neutrons and photons. Therefore, gamma component must be subtracted from the total TLD600 signal. As mentioned, TLD700 neutron sensitivity was presumed zero. Consequently, gamma dose component measured by the TLD700 dosimeters was substracted. The neutron calibration curve for TLD600 dosimeters was estimated as follows:

$$D_{\mathrm{n}} = \alpha^{\mathrm{n}} I_{\mathrm{n}} \qquad (3)$$

Where I_n represents the TL intensity due to thermal neutrons and α^{γ} is the neutron calibration factor.

2.3. The experimental setup

Medical linear accelerator investigated in this study was Varian Clinac 2100C at Cancer. The energy of the photon beam was 18 MV and it was collimated to an area of 20×20 cm^2 at the isocentre (SAD=100 cm). Linac was set to deliver 150 cGy at the isocentre (~300 MU), and this was done at a rate of 300 MU/min. The analysis of neutron doses was performed at four points around the accelerator in the patient plane. Fig. 1shows the schematic layout of the irradiation points . Points 1 to 3 are located at 1 m from the isocentre, at the couch angles of 0°, 90° and 270° respectively, while point 4 is 2 m away from the isocentre, at 0° couch angle.

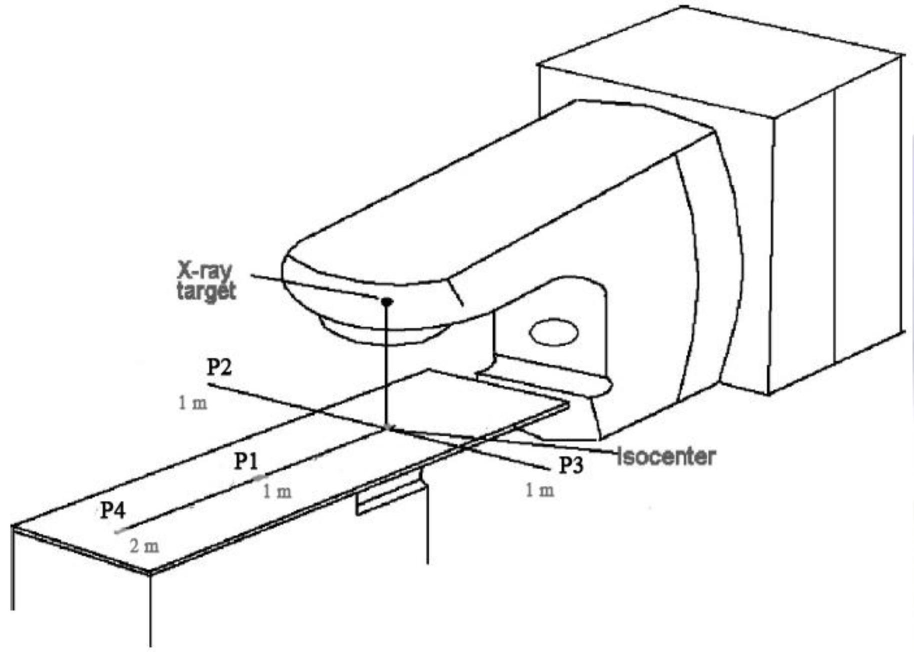

Fig. 1. Experimental arrangement showing the measurement points around the accelerator. Points 1 to 3 (0°, 90° and 270° couch angles) are at 1 m and point 4 (0° couch angle) is at 2 m from the isocentre.

As shown in Fig. 2, five TLD pairs in the center of LB 6411 polyethylene sphere were used for each irradiation.

Fig. 2. Linac, LB 6411 polyethylene sphere, and the sites where the neutron doses were measured. Five TLD pairs are located in the center of LB 6411 polyethylene sphere.

3. Results

The TL response of the two dosimeters (TLD600 and TLD700) versus ^{60}Co gamma dose is shown in fig. 3. Fig. 4 represents the TL signal, I_n, as a function of thermal neutron dose for the TLD600 dosimeter.

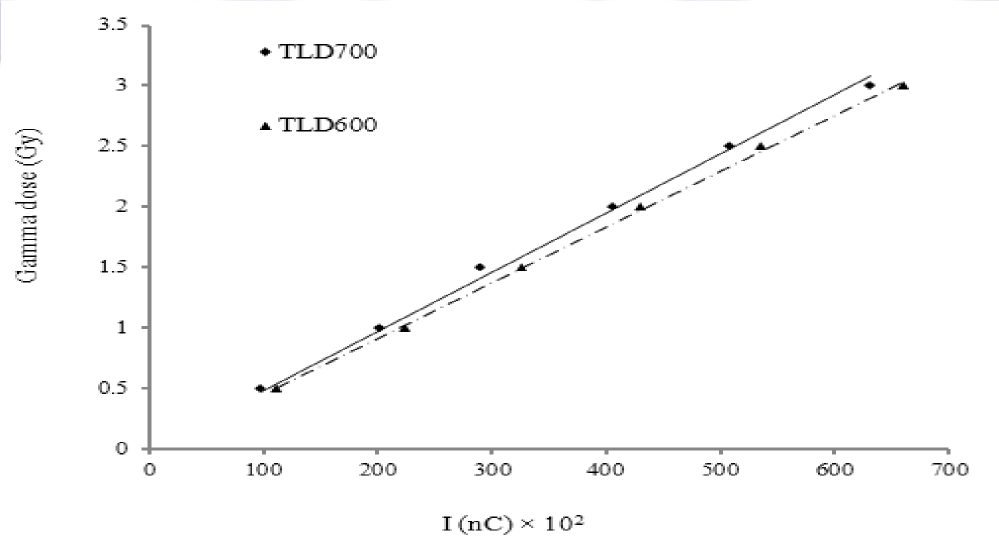

Fig. 3. TLD600 and TLD700 gamma calibration curves.

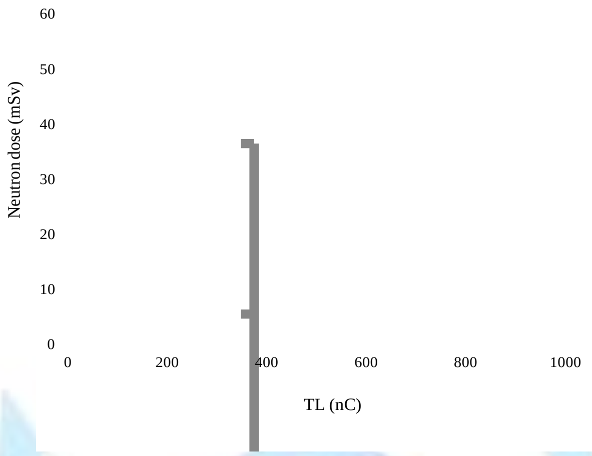

Fig. 4: TLD600 neutron calibration curve .

Table 2 illustrates the gamma and neutron calibration factors of the dosimeters. The standard deviations (σ) of the calculated quantities are also given. As it can be considered from this table, gamma calibration factors of the dosimeters are of the same order of magnitude. Nevertheless, gamma sensitivity of TLD600 is a bit more than that of TLD700. Neutron sensitivity of TLD600 is more higher than TLD700 because of the large neutron capture cross-section of the nuclei of ^{6}Li in this dosimeter.

Table 2. The results of the linear gamma and neutron calibration curves of the two dosimeters.

Dosimeter	$\alpha^{\gamma} \pm \sigma \left(\frac{mGy}{TL}\right)$	R^2	$\alpha^{n} \pm \sigma \left(\frac{mSv}{TL}\right)$	R^2
TLD600	$(4.59 \pm 0.03) \times 10^{-2}$	0.9992	$(5.77 \pm 0.09) \times 10^{-2}$	0.9991
TLD700	$(4.88 \pm 0.06) \times 10^{-2}$	0.9998	_	_

Table 3 indicates the neutron and gamma dose equivalent values at points 1 to 4 around the accelerator calculated by equations (2). The positions of these points were displayed in fig. 1. Because of the unit quality factor of the gamma radiation, the gamma dose is reported in terms of mSv.Gy^{-1}. The results are normalized to the dose of 1 Gy at the isocentre.

Table 3. The peripheral neutron and gamma dose equivalent values at points 1 to 4 per unit photon dose at the isocentre.

Points	$D_{\gamma} \pm \sigma$ (mSv.Gy^{-1})	$D_{n} \pm \sigma$ (mSv.Gy^{-1})
1	0.57 ± 0.11	2.17 ± 0.23
2	0.55 ± 0.07	2.27 ± 0.28
3	0.61 ± 0.14	2.13 ± 0.29
4	0.33 ± 0.04	0.74 ± 0.18

According to this table, the peripheral neutron dose equivalent at point 1 which corresponds to the position of normal organs is about 2.17 mSv.Gy^{-1}. It decreases with the distance from the isocentre and gets the value of 0.74 mSv.Gy^{-1} at point 4. As it can be seen, there is no significant difference (about 6%) between the neutron dose values at different directions but the same distance from the isocentre (1 m).

The neutron doses around the accelerator are much higher than the gamma doses. It means that the gamma dose values are more concentrated around the isocentre (confined to the field size), whilst the neutron dose values are more extended. So the peripheral neutron doses are not negligible.

4. DISCUSSION

Several studies have been devoted to the evaluation of the photoneutron dose in the vicinity of the accelerator (2, 3, 4, 5, 6, 12, 13, 14, 15, 16, 17, 18, 25 and 26]. However, no similar work has been done by TLD pairs inside the polyethylene sphere of neutron probe LB 6411.

In spite of the fact that the results of ohotoneutron production depend on the photon energy and the type of the Linac, we can compare them with the published data. Table 4. shows the measured neutron ambient dose equivalent values at 1 and 2 m from the isocentre in 18 MV photon energy determined by different authors.

Table 4. Neutron dose equivalent values $(H^*(10))$ per unit photon dose at the isocentre in 18 MV photon energy determined by different authors.

Manufacturer	Model	$H^*(10)$ (mSv.Gy^{-1})	
		at 1 m from the isocentre	at 2 m from the isocentre
Varian	2100C	2.17 (this study), 2.3[17]	0.74 (this study)
	1800	1.02–1.6[29]	
Elekta	Precise	0.60[14], 0.61[14]	
Siemens	KDS	0.50[15], 0.37[25]	
	Primus	0.35[25]	

Neutron dose equivalent at 1 m from the isocentre measured by Vanhavere et al. (17) using BD-PND and BDT bubble detectors for an 18 MV 2100C Varian Linac and a 10×10 cm^2 field at the isocentre was 2.3 mSv.Gy^{-1} which shows a reasonable agreement with that of ours, found in this study (2.17 mSv.Gy^{-1}).

Barquero et al. (15) used TLD600 and TLD700 pairs at the center of a 25 cm diameter paraffin sphere to measure the photoneutron ambient dose around a 40×40 cm^2 beam of 18 MV Siemens KDS Linac. For the calibration of this instrument, the neutron doses were determined at several distances from the ^{241}Am–Be neutron source by ^{6}LiI(Eu) scintillator crystal inside a 25 cm diameter polyethylene sphere. Their work resulted in 0.5 mSv.Gy^{-1} 1 m away from the isocentre, as against 0.37 and 0.35 mSv.Gy^{-1} for a 10×10 cm^2 beam of 18 MV Siemens KDS and Siemens Primus respectively, obtained by Rivera et al. (25) using bubble detectors.

Esposito et al. (14) evaluated the neutron production of 18 MV Elekta Precise Linac by activation gold foils and TLD600 and TLD700 pairs inside bonner spheres. The measurements were done for a 15×15 cm^2 field size. They found the ambient dose equivalent about 0.60 mSv.Gy^{-1} by gold foils and 0.61 mSv.Gy^{-1} by TLD pairs at 1 m from the isocentre.

As it can be seen there is a significant difference between the neutron dose equivalent values achieved for Varian Linacs and those obtained for Elekta and Siemens accelerators. Some studies have mentioned the considerably more photoneutron production in Varian Linac compared to Siemens and Elekta accelerators in the same energy [10,27,28]. This more production is related to the geometry of the materials used in the Linac head configuration and the maximum energy of electrons striking the target.

The NCRP (7) reports the neutron dose measurements for 18 MV Linac between 0.8 and 2.5 mSv.Gy^{-1} at 50 cm distance from the isocentre. Bourgois et al. (9) reported lower neutron doses between 0.5 and 1.7 mSv.Gy^{-1} at different distances.

Rebello et al. (26) calculated the neutron dose in a 5×5 cm^2 field of 18 MV 2300C Varian Linac at 2.83 m from the isocentre about 0.65 mSv.Gy^{-1} using Monte Carlo code, MCNPX, which is comparable with our 0.74 mSv.Gy^{-1} at 2 m from the isocentre.

As the results indicate, the neutron dose values even at large distances from the isocentre (1 and 2 m distance) is considerable and despite the advantages mentioned for high energy radiation, it is imperative to determine the unwanted dose delivered to normal tissues. The American Association of Physicists in Medicine (AAPM) and the NCRP report 79 have emphasized on the importance of quantitative evaluation of neutron dose outside the tumor volume (7 and 31).

5. Conclusion

Firstly, The comparison of the results with other published data showed a coherent agreement, confirming the dosimetric system used in this work to be a reliable tool for photoneutron dose measurements in the vicinity of the accelerators.

Secondly, the measurements with TLD dosimeters instead of ^{3}He counter tube of neutron probe LB 6411 allowed the problems of active detectors to be overcome.

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