The Characteristic of Profile and Depth Dose of Neutron Clinac iX 15 MV

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Abstract. Several previous studies described that radiation neutrons are produced by 10 MV X-ray beams operated linac. This study was performed to exercise the characteristic of profile and neutron depth dose for 15 MV X-ray beams and also to evaluate the contribution of neutron dose to the patient. The experiment used Linac iX with 15 MV X-ray beam, TLD-100, TLD-600, and phantom. The phantom was designed to evaluate the dose profile at cross-plane and diagonal axis. TLDs were calibrated separately by gamma and neutron sources. Gamma calibration was carried out using $^{137}$Cs source whereas neutron calibration was done using $^{252}$Cf source at BATAN Facility. Neutron dose equivalents were calculated on cross-plane and diagonal axis in 10 cm × 10 cm fields at 15 positions from the central axis, on the phantom surface and depths of 2 cm, 3 cm, and 15 cm. The percentage maximum neutron dose equivalent distributions were obtained around of 3 cm depth for cross-plane and diagonal axis. Furthermore, the dose profile of neutron at different depths and off-axis position are not symmetrical. Neutron dose in out-of-field had no significant response compared to the in-field. The relative neutron dose in out-of-field is 27% and 24% normalized to the maximum neutron dose at each depth on cross-plane and diagonal axis respectively.

1. Introduction

In radiotherapy for deeper types of tumors or cancers, high-energy photons are used. Linear accelerator (LINAC) which operates with high photon energy above 10 MV will produce neutrons when X-rays interact with the atomic elements of the accelerator head material. Neutrons are produced from photonuclear reactions through photodisintegration process. The production of neutrons in the LINAC head occurs in components with high mass numbers, which include X-ray targets, primary collimators, beam flattening filters, collimator jaws, transmission of ionization chambers, and light localizers. In addition to the LINAC head, other photoneutron sources are the patient’s body, air, and the treatment room’s wall. This neutron can cause an increase in the dose received by patients treated and staff accessing the treatment room, contributing to the risk of secondary malignancy in patients [1-3].

In low neutron equivalent, many dosimeters do not have sufficient sensitivity and ability to quickly detect very low neutron doses in the epithermal, thermal, and neutron regions. This limitation does not
make the production of neutrons from medical accelerators neglected, and neutron dosimetry in such conditions remains a challenging issue for research. Accurate determination of the neutron equivalent dose distribution both outside and inside radiation fields of high-energy medical linear accelerators are very important not only in neutron dosimetry for protecting the estimated cancer risk of the patient, but also for radiation protection.

Several studies have been conducted to measure exposure to neutron radiation as a secondary effect of treatment received by patients. Measurements using thermo luminescent dosimeter (TLD) have also been carried out, but measurements are only done on the isocenter, organs around the target irradiation, and around the patient [1-3]. Most of the studies have reported that the neutron dose is produced from the 18-MV photon beam which is higher than the photon energy in this study. Only a few reports have investigated the equivalent neutron dose produced by the 15-MV photon beam. For measurements, most studies used TLD to determine the neutron dose equivalent. Nedaie et al. [2] used TLD-600/TLD-700 dosimeters to measure the neutron dose equivalent and compared the results with the Monte Carlo simulation. The neutron dose equivalents reported in this study always concerned to the photon dose at the dose maximum position (Dmax= 3 cm) at the isocenter of the beam. Sohrabi & Hakimi [1] conducted a study on large photoneutrons along the dose profile in and out of the radiation field of high-energy radiotherapy treatment using polycarbonate track dosimeters (PCTD). The maximum epithermal and thermal neutron dose equivalent at the isocenter decreases to 20 cm from the isocenter. Thermal or epithermal neutron percentage depth dose (PDD) is at several depths along the dose profile where all peaks at a depth of 3 cm are consistent with other similar studies that are already on the isocenter. Sohrabi & Hakimi [1] stated that the neutron dose equivalent on the surface in the isocenter was 3.11 ± 0.17 mSv.Gy⁻¹, with details on fast neutrons of 2.17 ± 0.16 mSv.Gy⁻¹ and thermal neutrons of 0.77 ± 0.05 mSv.Gy⁻¹. Each photoneutron (PN) dose equivalent distribution profile on each of the three-axis of the multilayer polyethylene (MLPE) phantom has a symmetrical bell-shape with a maximum dose at the beam central axis. All positions studied on the three-stated axes at different depths, the maximum of the PN dose equivalent distribution occurs on the surface of the MLPE phantom and decreases as depth increases. On the other hand, PN dose equivalent falls rapidly as depth increases. The PCTD has some complexities of requiring high frequency-high voltage for detector processing [1] and to use low background track density PCTDs with a low minimum detection limit for such low PN dose equivalent determinations [1]. In this study, measurements were performed to determine the characteristics of neutron dose contamination on LINAC Varian Clinac iX planes at several depths and positions in and out of the radiation field. The necessity of the work is to estimate unwanted neutrons, which can be considered for tissue outside the target volume regarding the long-term health of cancer patients and due to the high biological effectiveness of neutrons with regard to cancer induction. Neutron depth dose equivalent distributions at different depths and positions from the beam central axis in or out-of-field in such high-energy X-ray beams of medical accelerators are of high importance for estimating patient doses for the risk of secondary malignancy in the patient in the future and medical physics points of view, which have not yet been well studied [1,4].

2. Materials and Methods

There are no TLDs available that are sensitive to only thermal neutrons [2, 3]. As explained in the International Commission on Radiation Units and Measurement report 26 [5], the use of a suitable pair of dosimeters, in which one is more sensitive to neutrons and the other one is more sensitive to photon, is needed to discriminate the contributions of gamma photons and neutrons in the mixed field [5]. TLD pairs used were TLD-600 which is sensitive to gamma and neutron and TLD-100 which is sensitive to gamma doped with Mg, Ti from the Harshaw Chemical Company. TLD-600 and TLD-100 were in the shape of chips and had dimensions of 3.2 × 3.2 × 0.89 mm³. The neutron dose equivalents were produced by 15 MV photon beams from Varian’s Linear Accelerator Clinac iX. Phantom water-equivalent white polystyrene (RW3) and acrylic slabs that were used had dimensions of 30 × 30 × 30 mm³ with 30 layers. The gamma and neutron calibrations of the TLDs were performed. For gamma calibration, the calibration was performed in two procedures. TLD-600 and TLD-100 were calibrated using the Cesium-
137 Source to obtain gamma calibration factor to know these sensitivity factors of components for each TLDs. Furthermore, the Californium-252 Source was used to obtain the neutron calibration factor. Irradiation used a standard gamma source of $^{137}\text{Cs}$ of 5 mSv with Source to Surface Distance (SSD) of 100 cm and $H_p(10)$ of 31868 µSv/hour for 9 minutes 25 seconds. A $^{252}\text{Cf}$ source using a graphite moderator was selected with a dose rate of $9 \times 10^{-5}$ mSv/hour. TLDs were exposed to definite doses of 0.0088 mSv for 98 hours 20 minutes 55 seconds. The used phantom had dimensions of $30 \times 30 \times 30$ cm$^3$ with a position on LINAC. Phantom was irradiated for 300 cGy with a field size of $10 \times 10$ cm$^2$, the dose rate of 400 MU/min and the SSD of 100 cm. All measurements were performed along the central axis and considered for the $d_{\text{max}}$ depth of 3 cm for 15 MV on the RW3. TLDs were placed at several depths (0, 2, 3 and 15) cm in the phantom as functions of distance from the beam axis for different situations such as transverse (X) (under MLCs) and diagonal axes. Each measurement point was filled in 1 group consisting of 3 pieces of TLD. After phases of phantom irradiation, TLD readings were performed. TLD was stored at room temperature for ± 24 hours so that the TLD becomes stable.

**Figure 1.** Schematic diagram of the study

Data processing methods adjusted for the type of TLD used. TLD-600 and TLD-100 responses in the neutron-gamma mixed radiation field were calculated with the following equation [2].

$$R_{600}^{\gamma+n} = R_{600}^n + \frac{\alpha_{600}^\gamma}{\alpha_{100}^\gamma} R_{100}^\gamma$$

where $R_{600}^{\gamma+n}$ and $R_{100}^\gamma$ is the total TLD-600 and TLD-100 responses from the mixed radiation field. $\alpha_{600}^\gamma$ and $\alpha_{100}^\gamma$ are gamma calibration factors on TLD-600 and TLD-100. $R_{600}^n$ is a neutron contribution. Gamma correction factor is a comparison of TLD-600 response to TLD-100 to gamma radiation. The correction factor is used to correct TLD response to gamma radiation in neutron irradiation. This equation was adapted from Nedaie et al. [2] with some modifications, which is using TLD600 and TLD700 to a neutron-gamma mixed field.

3. **Result and Discussion**

Neutron dose equivalent distributions at different depths and positions in and out of the field of high-energy X-ray beams were efficiently determined by TLD dosimeters in the water-equivalent white polystyrene (RW3) phantom as illustrated in Figure 2.
Figure 2. Relative dose at different depths and various distances from the isocenter on (a) cross-plane (The couch’s right is positive area and left is negative area) (b) diagonal axis (The closest side from gantry is negative area and the other one is positive area).

Figure 3. Relative dose at different depths and positions in the radiation field on (a) cross-plane and (b) diagonal axis.

Figure 2 shows neutron dose equivalent distributions at 4 different depths 0, 2, 3, and 15 cm in the RW3 phantom as functions of distance from the beam axis for different situations such as cross-plane and diagonal axis respectively. From the data shown in Figure 2 (a–b), each neutron dose equivalent distribution profile on each of the two axis of the phantom has an asymmetrical shape, with a maximum dose at the different positions of each depth. The same trend is shown at every depth. In this study, a dose of a neutron equivalent which is significant and tends to fluctuate at each depth is obtained at distances up to 4 cm from the isocenter as irradiation field. In this work, neutron percentage depth dose equivalents (PDDE) for 15 Gy X-ray doses in a 10×10 cm² field for different positions were determined.

Figure 3 (a–b) shows the neutron PDDE for different positions in-field versus beam central axis in cross-plane and diagonal axis respectively. As shown in Figure 3 (a – b), for all the positions in radiation field at different depths, the percentage of maximum neutron dose equivalent distributions are obtained around 3 cm depth for cross-plane and diagonal axis. It also appears that the lowest PDDE is obtained on the phantom surface compared to other depths. The PDDE neutron increases sharply at a depth of 2 cm and approaches the maximum at a depth of 3 cm, then decreases at a depth of 15 cm. By comparing the PDDE neutron response on the cross-plane and the diagonal axis given in Figure 2 sections a and b,
respectively, it can be seen that the PDDE neutron response on the isocenter and other positions included in the field is almost the same except the position at a distance of 6 cm from isocenter on the diagonal axis. The maximum neutron dose equivalent at a depth of 3 cm in the cross-plane is 0.298 mSv.Gy\(^{-1}\) and on the diagonal axis is 0.330 mSv.Gy\(^{-1}\) obtained at a distance of 4 cm from the isocenter.

The neutron dose in out-of-field had no significant responses compared to the in-field neutron dose. As seen in the curve, neutron dose equivalent in out-of-field decreases on each axis as the distance of each position from the beam central axis increases. The highest neutron response outside the irradiation field is at the measurement point at a distance of 6 cm from the isocenter for the cross-plane plane; while for the diagonal axis, it is at the measurement point at a distance of 8 cm from the isocenter. The high relative neutron dose in out-of-field is 27% and 24% normalized to the maximum neutron dose at each depth on cross-plane and diagonal axis. Doses decrease when the distance from the isocenter increases to 10 cm and 14 cm for cross-plane and diagonal axis, respectively. With a further increase in distance from the isocenter, the dose reaches a nearly constant.

Table 1. Neutron dose equivalents per Gy of X-ray dose at various distances from the isocenter and different depths in the phantom on cross-plane

| Positions from Isocenter | Neutron dose equivalent/X-ray dose (mSv.Gy\(^{-1}\)) |
|--------------------------|--------------------------------------------------|
|                          | 0 cm | 2 cm | 3 cm | 15 cm |
| 0 cm                     | 0.049 | 0.223 | 0.249 | 0.107 |
| 2 cm                     | 0.052 | 0.250 | 0.273 | 0.159 |
| 4 cm                     | 0.061 | 0.251 | 0.298 | 0.170 |
| 6 cm                     | 0.013 | 0.025 | 0.028 | 0.040 |
| 8 cm                     | 0.010 | 0.012 | 0.007 | 0.010 |
| 10 cm                    | 0.008 | 0.010 | 0.010 | 0.008 |
| 12 cm                    | 0.007 | 0.006 | 0.007 | 0.005 |
| 14 cm                    | 0.005 | 0.004 | 0.004 | 0.005 |

Table 2. Neutron dose equivalents per Gy of X-ray dose at various distances from the isocenter and different depths in the phantom on diagonal axis

| Positions from Isocenter | Neutron dose equivalent/X-ray dose (mSv.Gy\(^{-1}\)) |
|--------------------------|--------------------------------------------------|
|                          | 0 cm | 2 cm | 3 cm | 15 cm |
| 0 cm                     | 0.089 | 0.216 | 0.288 | 0.165 |
| 2 cm                     | 0.048 | 0.228 | 0.250 | 0.163 |
| 4 cm                     | 0.057 | 0.250 | 0.330 | 0.168 |
| 6 cm                     | 0.033 | 0.148 | 0.293 | 0.108 |
| 8 cm                     | 0.012 | 0.017 | 0.025 | 0.027 |
| 10 cm                    | 0.011 | 0.011 | 0.009 | 0.006 |
| 12 cm                    | 0.007 | 0.009 | 0.007 | 0.004 |
| 14 cm                    | 0.005 | 0.007 | 0.006 | 0.003 |

No similar studies are known to be carried out in the same accelerator used. Therefore, the dose was compared with other studies for the same X-ray energy and the same field size of various types of medical accelerators using various neutron dosimetry methods. When compared to the results of Sohrabi & Hakimi’s research [1], the thermal neutron dose obtained in this study was 8 for the cross-plane direction and 16 times smaller for the diagonal axis direction, this was due to the fact that the study used greater energy. The neutron dose equivalent on the phantom surface at the isocenter in our studies has a value of 0.049 mSv.Gy\(^{-1}\) and 0.089 mSv.Gy\(^{-1}\). Thekkedath et al. [3], using the TLD 600 and TLD 700 detectors on the Elekta medical linear accelerator, measured the neutron dose equivalent for the same energy on the phantom surface about 0.41 ± 0.01 mSv.Gy\(^{-1}\). The differences observed among the neutron
dose equivalents on the phantom surface at the isocenter of different accelerators are due to variations in the head component material and different type of neutron dosimetry methods applied [4]. The results obtained by Thekkedath et al. [3] showed that the value on the isocenter on the depth 3 cm is $0.32 \pm 0.01$ mSv.Gy$^{-1}$. This result shows a reasonable agreement with what we found in this study ($0.249$ and $0.288$ mSv.Gy$^{-1}$). The differences observed in different accelerators are due to variations in the head component material and the various types of neutron dosimetry methods used. The thermal neutrons increase to certain depth and then start decreasing. The lower energy neutrons reach thermal equilibrium and are captured at shallower depths, while the higher energy neutrons travel longer distances before being captured. Sohrabi & Hakimi [1] state that the dose profile tends to level off at a deeper depth than the surface. This statement is not in accordance with the curve at a depth of 15 cm obtained in this study where the dose on the isocenter tends to be low compared to the off-axis area around in the irradiation field. In the study performed Sohrabi & Hakimi [1], measured along the beam axis, has the maximum at 3 cm of the phantom and reduces exponentially with the depth and showed a similar trend. Nedaie et al. [2] suggest that neutron equivalent dose is nearly zero at build up region, because of the fact that TLD-600 is only sensitive to thermal neutrons and the majority of neutrons on the phantom surface and build up region are fast neutrons. TLD dosimeters cannot be relied upon as measuring devices in studies of neutron dose equivalents for patients on isocenter, because fast neutron doses on isocenter dominate, thus affecting TLD measurements that are only sensitive to thermal neutron energy [2]. The high inaccuracy of TLD to measure neutrons is due to the effect of gamma and neutron radiation as in LINAC, where the contribution of neutrons is very small compared to photons. The TLD on measurements in large central axis is uncertain, so TLD is only suitable for measurements on off-axis [3]. The comparison of results with other studies shows that TLD600 and TLD100 pairs do not seem to be a reliable tool in the study of doses to patients from emitted neutron along the beam axis. The neutron dose equivalent dependent on the dose rate, monitor units, patient treatment plans using 15 MV are not reported in this paper. According to the results of this work, the neutron dose equivalents at the entrance of the phantom grow up to the depths of 3 cm for cross-plane and diagonal axis, respectively and then decreases.

Conclusions

Dose profile and neutron percentage depth dose equivalents (PDDE) for different positions were determined. The percentage of maximum neutron dose equivalent distributions was obtained to be around 3 cm depth for cross-plane and diagonal axis. Furthermore, the neutron dose profile at different depths and off-axis positions are not symmetrical. The neutron dose in out-of-field had no significant response compared to the in-field neutron dose. The comparison between the measured and calculated neutron dose equivalent values is required to estimate the neutron production using Monte Carlo calculations. MCNPX code is an appropriate alternative for studying photoneutron production.

References

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