Assessment the photo-neutron contamination of IMRT and 3D-conformal techniques using thermo-luminescent dosimeter (TLD)

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Abstract
In radiation therapy with high-energy photon beams (E > 10 MeV) neutrons are generated mainly in linac head thorough (ɣ,n) interactions of photons with nuclei of high atomic number materials that constitute the linac head and the beam collimation system. These neutrons increase the out-of-field radiation dose of patients undergoing radiation therapy with high-energy photon beams. The purpose of the present work is to evaluate the dependence of photo-neutron production on field size, depth in phantom and distance from isocenter and also to calculate the equivalent neutron doses for PTV and OAR of IMRT and 3DCRT techniques using TLD (600/700). The results showed that; the measured photo-neutron decreases from 0.2 mSv/Gy to 0.09 mSv/Gy as increases field sizes from 2x2 cm^2 to 20x20 cm^2. The measured photo-neutron was maximum at d_{max} =0.15 mSv/Gy and decreases gradually as increases the depth in phantom reaches to 0.07 mSv/Gy at 10cm depth in phantom. The measured photo-neutron decreases from 1.5 mSv/Gy to 0.02 mSv/Gy when measured at isocenter and at 100cm along the patient couch. Using 3DCRT for PTV and OAR were ranging from 0.027 to 0.39 mSv per photon Gy and for IMRT were 0.135 to 2.34 mSv per photon Gy. In conclusion the photo-neutron production is decreases as increases field size and distance from isocenter along patient couch while increases with depth in phantom up to d_{max} and decreases gradually as increases depth in phantom. IMRT requires longer beam-on time than 3DCRT leading to worse OAR sparing and increase the production of photo-neutrons than 3DCRT.

Keywords: photo-neutrons, 3DCRT, IMRT, TLD.

1.Introduction

Radiotherapy means to convey a radiation dose (therapeutic dose) to kill all tumor cells which may cause harm to other sensitive organs, these organs called in the radiotherapy the organ at risk (OAR). Modern radiotherapy techniques using high-energy linear accelerators aim to achieve better tumor control for deep-seated tumors. However, they also impose certain risks that must be assessed and weighed against their benefits. In particular, the risk of radiation-induced second primary cancers after external-beam radiotherapy is a debated topic among scientific and medical groups [1].

According to the International Commission on Radiological Protection (ICRP), it is necessary to estimate all the sources of doses inside and outside the Planning target volume (PTV) to justify radiation doses to patients treated with radiotherapy (RT). The primary concern with out-of-field radiation is that even relatively low doses outside the target have the potential to induce second cancers (stochastic effects) [2]. Medical linear accelerator (Linac) with high-energy photon beams (>10 MV) provide more deep penetration for greater depth dose, decreasing skin and peripheral doses due to less scatter than lower-energy beams. However these high-energy photons can also produce unwanted neutrons. The production of photo-neutrons mostly generated by the giant dipole resonance reactions (γ, n) with high-Z material inside the head of the accelerators as the target, the flatting filter, collimator and multi-leaf collimator [3]. A non-negligible production of photoneutrons can be generated in low-Z materials like C, N and O, in particular in the patient body and materials in the treatment hall when linear accelerators operate in the photon mode (i.e. via bremsstrahlung process) above 10 MV [4]. The dose from neutrons that produced during the therapy with high energy photon beams is un- accounted dose which may induce secondary cancer, the knowledge of the extra dose from neutrons in the vicinity of patient position is an important goal from the radiation protection point of view [5].Three-dimensional conformal radiotherapy (3DCRT) is one of the radiotherapy treatment techniques that are based on 3D anatomic information and utilize dose distributions that acclimate as nearly as possible to the planning target volume (PTV) regarding adequate dose to the tumor and minimum dose as possible to the surrounding normal tissue. Intensity-modulated radiation therapy (IMRT) is another treatment technique of radiotherapy which provide non-uniform adequate dose to the patient from many different angles of the treatment beam to optimize the composite dose distribution [6]. A thermo-luminescent dosimeter (TLD) used to determine the equivalent dose of the neutron. Neutrons cannot produce direct ionization in a detector but they produce charged particles such as protons and alpha particles that thus cause ionization [7-8]. Other passive detectors adequate for those installations can be consulted in the literature [9-10-11].

Neutron dose produced from high-energy photon beams (>10 MV) Linac that contaminate the therapeutic beams is not detailed in routine treatment planning though this information is potentially important for better estimates of health risks including secondary cancers. This work aims to assess the photo-neutron contamination for 15MV photon mode linac with different variables and also assess the photo-neutron contamination using 3DCRT and IMRT treatment techniques that used in our hospitals in Egypt.

2. Methods and materials

2.1 Thermoluminescence dosimeters (TLD Chips)

In the present study, the TLDs used were 6LiF: Mg, Ti (TLD600) which is sensitive to neutrons and 7LiF: Mg, Ti (TLD700) more sensitive to photons. These TLDs (TLD600 with 95.6% 6LiF and TLD700 with 99.9% 7LiF) are in the form of chips with dimension of 3.2 x 3.2 x 0.9 mm manufactured by Harshaw chemical company. The purpose of measuring the Element Correction Coefficient (ECC) for each chip to ensures that the entire population of TLDs were respond almost the same, all the chips irradiated with a single known dose 200 cGy using Siemens Linac 6 MV, the irradiations were performed with a field size of 10x10 cm^2 and Source to Surface Distance (SSD) of 100cm. The ECC is performed using the following equation:

$$\mathrm{ECCn} = \frac{<\mathrm{TLR}>}{\mathrm{TLRn}} \qquad \text{eq.1}$$

Where the TLR is the average read-out of the TLD chips and TLRn is the read-out of the TLD number n [12].

This step has been repeated three times during this work.

Since TLD response is energy dependent, it is better to calibrate the TLD chips by the energy which is used in experiment [12]. Therefore, gamma calibration was performed by 15 MV photon beams.

2.1.1Gamma and Neutron calibration

The gamma calibration was done by two methods; Using 15MV Linac to irradiate all TLD chips, the chips were divided into 6 groups exposed to definite doses of (100, 130, 160, 190, 220, 250) cGy. The irradiations were performed in a RW3slab phantom 30x30x30cm^3 with a field size of 10x10cm^2 and max depth in phantom (d_{max} =3) at zero angle. The other method of calibration presented in table 1. The TLDs were read out using PCL3 readout system (automatic reader) has been used for TLD measurements. After each use all the chips were annealed in a dedicated oven at 400^{o}C for one hour followed by 100^{o}C for two hours. Fig.1 shows the gamma calibration curve. Using 15MV Linac to irradiate all TLD chips as previous but using tungsten plates in front of the point of measurement serve as a moderator and to thermalize the fast neutron.

The neutron calibration was performed by A 5 Ci Am-241-Be source. All chips were placed at 1m distance from the source using 6 cm polyethylene as moderator in front of the chips. Data of calibration represented in table2.

Name	Type	Manufacturer	Cal. on
Cal. Source	^{137}Cs		
UNIDOS meter	App. Nr. 10001-10522	PTW, Freiburg	May/ 2017 (BIPM)
Ion chamber 30 cc	NE2530 (#424)	NE 2530	May/ 2017 (BIPM)

Table1. Standard/ Reference/ Major used data of gamma calibration

Name	Type	Manufacturer	Cal. on	Results	St. Dev. 0.565
Cal. Source	Am-Be				**Correction factor** 0.066
Neutron monitor	NM2	NE., LTD.	Mar.2016 (PTB)		

Table2. Standard/ Reference/ Major used data of neutron calibration

2.2 Assess the neutron contamination for 15MV photon mode with different variables.

In this step all the TLD chips (600 and 700) exposed to a single dose 200cGy with different variables as seen in the following figs (4, 5, 6, and 7). The equivalent dose H_T for neutron was calculated by the equation 2.

H_T = =Wr x D_T eq. 2 (ref ICRP 60).

Where: H_T= Equivalent dose (Sv), D_T= Absorbed Dose (Gy), Wr = Radiation weighting factor war calculated using ICRP-60 recommended formula (ICRP, 1991) [13-14].

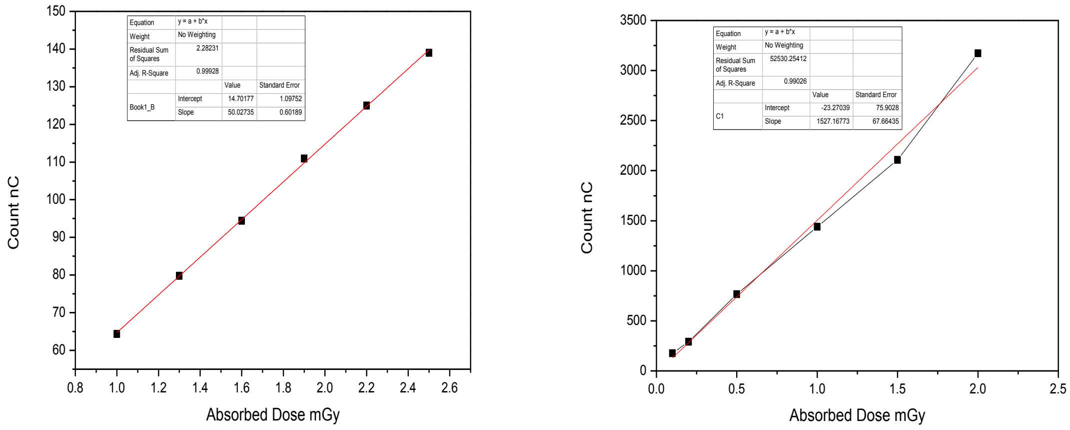

Fig. 1 The relation between gamma absorbed dose (mGy) and TLD reading (count in nC) with 15 MV photon irradiation on the left, and with ionization chamber on right side.

2.3 Treatment planning system

5 prostate cancer cases were selected in this study for patients completed their courses of radical radiotherapy to the prostate with high energy beam (15MV) Linear accelerator Siemens Oncor impression, Germany, installed at Nasser Institute- Oncology Center. The OARs were bladder, rectum and femur. Using both 3DCRT and IMRT treatment plans. Once the plans were completed, there were copied from a patient onto the RW3 slab phantom. The phantom scanned firstly using Toshiba CT machine providing 4 multi-slices per rotation. The phantom images then transferred to XIO TPS (planning system) via the network. On the TPS, all fields of both treatment plans are transferred to the phantom, the total prescribed dose for each plan was 2.2Gy per 30 sessions to deliver total prescribed dose of 70Gy. A 5-field conventional 3D conformal plan has been used The gantry angles for the 5-field conventional 3D conformal were 0°, 45°, 90°, 270°, and 315°. A standard 5-field treatment was calculated for the slab phantom, as shown in (fig.2). The total numbers of Monitor Units (MU) for each angle were 77, 54, 70, 77, and 44 respectively irradiated per fraction resulting in a total dose to the PTV of 70 Gy. 7radiation fields used in IMRT plan with angles 0, 51, 102, 153, 204, 255, and 302 (fig.3). The total numbers of MUs for each angle were 52, 63, 87, 96, 53, 128, and 73 respectively. The plans were optimized to reduce the dose to the OARs to a minimum, while the dose to the PTV was maintained in accordance with the ICRU 83 Report [15].

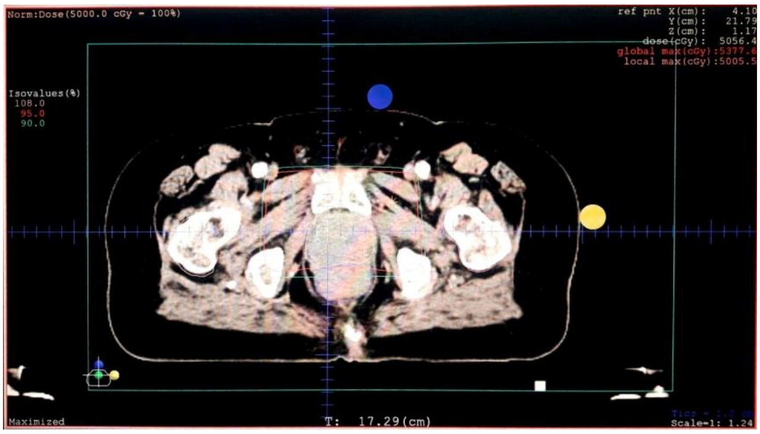

Fig.2. A standard 5-field treatment was calculated for the slab phantom.

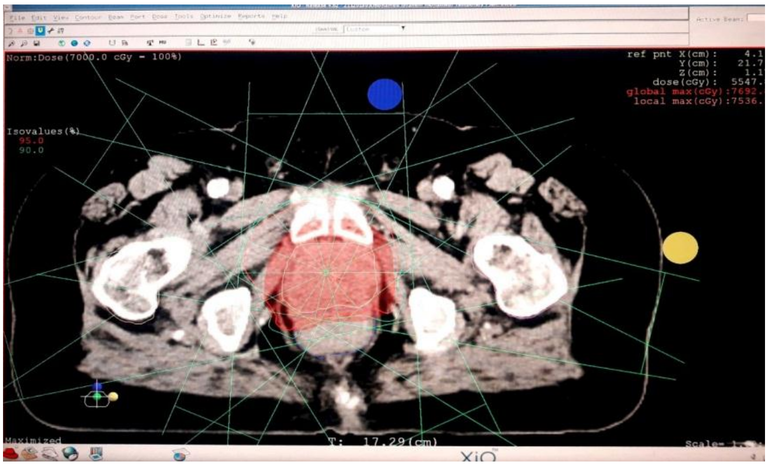

Fig. 3. Shows the dose distribution of 7-field IMRT plan.

2.4 Results and Discussion

In the step of assessing photo-neutron production at different variables, the equivalent neutron doses in mSv per photon Gy is expressed with (mSv/Gy).

From fig.4 noticed that the equivalent neutron dose decreased with increase field sizes from 0.2 to 0.09 mSv/Gy with field size changed from 2x2 cm^2 20x20 cm^2, this result has agreement with the previous published work [16] in which the equivalent neutron dose decreased with increase field sizes from1 to 0.6 mSv/Gy using 18 MV Linac .
The measured data in fig.5 showed that the largest equivalent neutron dose was at isocenter 0.15 mSv/Gy reached to 0.02 mSv/Gy at 100cm. this data correlated with the previous published works [17-18-19]. In reference [17] the equivalent neutron dose is greater at the isocenter 1.35 mSv/Gy and decreases gradually with the distance away from the isocenter 0.0469 mSv/Gy at 75 cm, and decreased from 1.288mSv/Gy at the isocenter to 0.062mSv/Gy at 100cm as found in reference [19].
The variation of equivalent neutron dose with depth in phantom showed in fig.6. The equivalent neutron dose increased reach to maximum at d_{max} =0.15 mSv/Gy and decreased gradually as increased the depth in phantom reached to 0.07 mSv/Gy at 10cm depth in phantom. This result showed good agreement with the previous published work [20] in which the highest equivalent neutron dose was at d_{max} = 0.67 and decreased to 0.4 mSv/Gy at phantom's depth= 10cm.

Table 3 represented the summary of findings from previous studies which correlated to the present one.

Medical Accelerator Energy (MV)	**Reference**	**Field size (cm^2)**	**Distance (cm)**	**Depth in Phantom (cm)**	**The measured Equivalent neutron dose (mSv/Gy)**
Elekta (18MV)	[16]	Changed from 5 x5 to 30 x40			Decreased from1 mSv/Gy to 0.6 mSv/Gy
Varian (15MV) Elekta (15MV)	[17] [19]		Changed from isocenter to 75cm Changed from isocenter to 100cm		At isocenter =1.35 mSv/Gy, at 75cm= 0.0469 mSv/Gy At isocenter =1.28 at 100cm= 0.062 mSv/Gy
Varian (18MV)	[20]			Changed from surface to 10cm depth in phantom	Hgistet value at d_{max} = 0.67 mSv/Gy decreased to 0.4 mSv/Gy at 10cm depth

Table3. A summary of the measured equivalent neutron dose (msv/Gy) from other studies.

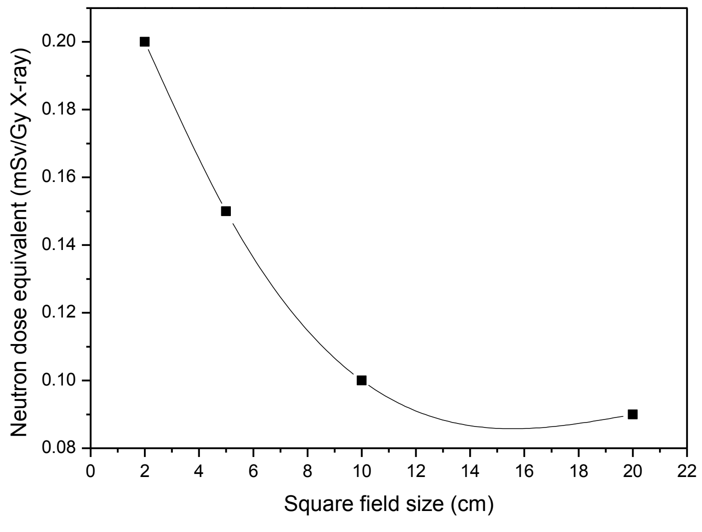

Fig.4. Equivalent neutron doses at the isocenter with SSD =100cm and zero angle using different field sizes (2x2, 5x5, 10x10, 20x20) cm^2.

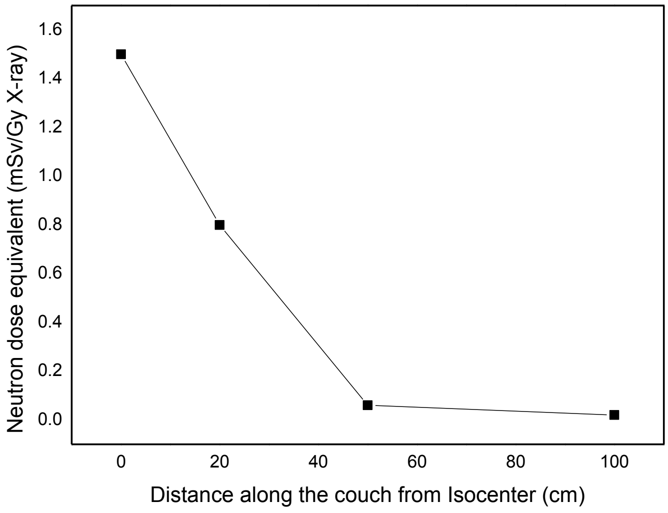

Fig.5. Equivalent neutron doses at four selected positions (Isocenter =0cm, 20cm, 50cm and 100cm) along the patient couch with FS (10x10) cm^2, SSD = 100cm at zero angle using TLD chips.

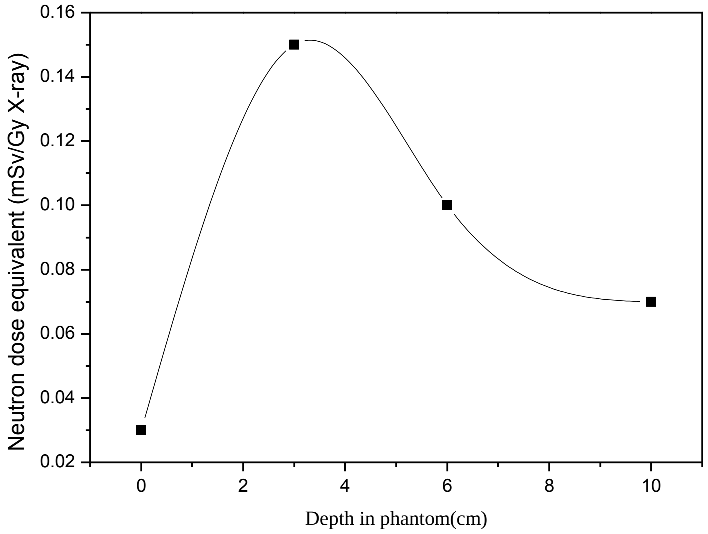

Fig.6. Equivalent neutron doses for different depths (Surface= 0, 3, 6 and 10) cm in phantom with FS (10x10) cm^2, zero angle at isocenter.

The measured equivalent neutron doses using 3DCRT for PTV and OAR were ranging from 0.027 to 0.39 mSv per photon Gy with average value 0.20 mSv per photon Gy (i.e. for 70 Gy treatment dose, the equivalent neutron dose was 1.89 to 27.3 mSv). For IMRT the measured equivalent neutron doses for PTV and OAR were ranging from 0.135 to 2.34 mSv per photon Gy with average value 1.23 mSv per photon Gy (i.e. for 70 Gy treatment dose, the equivalent neutron dose was 9.45

to 163. 8 mSv) as described in table 4 and fig.7. These finding correlated with the published data [21], the neutron equivalent doses ranged between 0.5 and 3.6mSv per photon Gy (i.e. for a 74 Gy treatment, the neutron equivalent dose range was from 37 to 263 mSv).

In 3DCRT the dose to bladder was nearly equal to the dose to the prostate that's because the location of the bladder is close to the prostate, while rectum received dose nearly equal to 40% from PTV dose. Rt. femur the dose was equal to 6% from PTV dose. In IMRT the doses at OARs were larger than doses with 3DCRT except for bladder the dose is larger than dose with IMRT that's due to the bladder in 3DCRT was located within the radiation field while in IMRT it was located partially in the field. These findings correlated with the published data [22].

Organ	**3DCRT (mSv/Gy)**	**IMRT (mSv/Gy)**
Prostate (PTV)	0.39±0.007	2.34±0.001
Bladder (OAR)	0.3± 0.005	0.28±0.003
Rectum (OAR)	0.19±0.04	1.1±0.058
Rt. Femur (OAR)	0.027±0.01	0.135±0.02

Table 4. Equivalent neutron doses for PTV and OAR using IMRT and 3D-CRTtechniques.

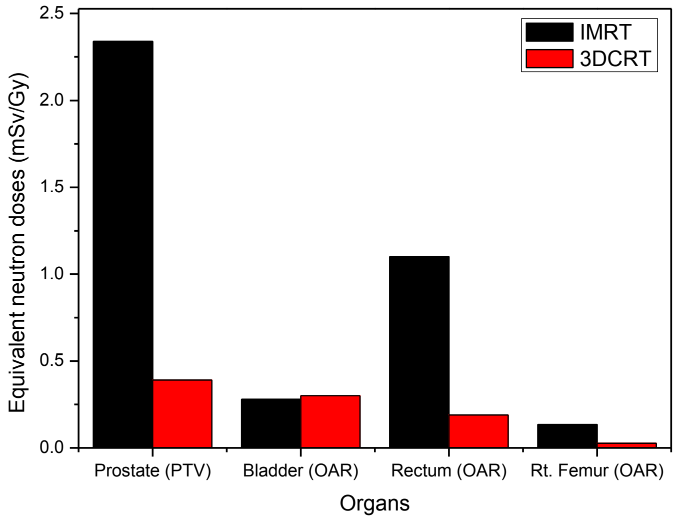

Fig.7. represents the equivalent neutron doses for PTV and OAR for IMRT and 3D-CRT techniques using TLD Chips.

2.5 conclusions

In conclusion: the photo-neutron production is varying with field size, gantry angle, depth in phantom and distance from isocenter along patient couch The contamination of therapeutic dose from neutron delivered to the patient during the therapy is not negligible dose which reach to 2% with 3D-CRT and 39% with IMRT. IMRT has more complex design with more scattering elements than 3DCRT so increases radiation risk induces secondary cancer. Treatment Planning System doesn't designed for measure dose from neutron then more research using Monte Carlo Simulation (MC) is required to measure the contamination of the therapeutic radiation dose with neutron when using high energy linac.

Acknowledgments

Another study using GEANT-4 MC is under preparation. MC simulations can be used for evaluation of dose from a variety of particles produced in photo-nuclear reactions inside patient body. This dose has not generally been calculated before for radiation therapy treatments.

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