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Assessment of the photo-neutron contamination in 3D-conformal technique using Thermo-luminescent Dosimeter (TLD) and GEANT4 Monte Carlo simulation

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In radiation therapy with high-energy photon beam modalities (E > 10 MeV), neutrons are generated. The main source of these neutrons is the Linac head. Neutrons are produced via the (γ,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 calculate the equivalent neutron doses for planning target volume (PTV) and OAR of the 3DCRT technique by using TLD chips (600/700), and GEANT4 based Monte Carlo simulations. The results showed that; the measured equivalent neutron doses using 3DCRT for PTV and OAR were ranging from 0.04 to 0.24mSv per photon Gy with average value of 0.15mSv per photon Gy, also there were great agreement between the doses measured by TLD and calculated by MC.

Keywords: photo-neutrons, 3DCRT, TLD, GEANT4.

INTRODUCTION

Radiotherapy delivers high doses of radiation to the planning target volume (PTV). These doses are highly toxic, even to tumor cells. This leads to the main challenge in radiotherapy; applying high doses to PTV and decreasing the harm effect that may occur to the sensitive organs, these organs called in radiotherapy the organ at risk (OAR) (Takam et al., 2011) Modern medical linear accelerators have two operation modes: electron mode and photon mode. In electron mode primary electrons are used for treatment, in photon mode photons are produced for treatment.

Medical linear accelerator (Linac) with high-energy photon beams (>10 MV) have several benefits than lower-energy beams such as: more deep penetration for greater depth dose, decreasing skin and peripheral scatter doses to OARs. However this modality can produce unwanted neutrons. The main source of photo-neutrons production is the giant dipole resonance reactions (γ, n) with the high-Z materials inside the head of the accelerator as the target, collimator, multi-leaf collimator and the flatting filter (Sandipan et al., 2018).These neutrons that produced during the therapy with high energy photon beams are not taken into account by the staff during the measuring of therapeutic doses for each patient. So neutron doses are un-accounted doses which may induce secondary cancer. Measuring the un-wanted neutron doses in the vicinity of patient position is an important goal of radiation protection (Haluk et al., 2016).Three-dimensional conformal radiotherapy (3DCRT) technique is based on 3D anatomic information to conform the prescribed dose distribution to the 3D target volume (tumor) shape with decreasing the dose to the surrounding normal tissues as possible. 3DCRT technique includes both the physical and biological rationales to meet the desired clinical results(Ben et al., 2013).Thermo-luminescence detector (TLD) is a suitable detector that measures the ionizing radiation exposure by measuring the amount of visible emitted light from a crystal in the detector when the crystal is heated above 100 to 200°C. TLD chips are chosen in this work 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 cause ionization (Barquero et al., 2002) and (Noramaliza et al .,2010) Other passive detectors adequate for those installations can be consulted in the literature (Castillo et al., 2014), (Robert et al., 2016) and (Lavine et al., 2012)

The Monte Carlo code Geometry and Tacking Version 4 (GEANT4) is a general purpose Monte Carlo radiation transport code that tracks nearly all particles at nearly all energies. Geant4 is a software package composed of tools which are used to accurately simulate the passage of radiation particles through matter for a very wide energy range. GATE is a MC simulation application based on GEANT4 and is dedicated for the simulation of imaging, RT and dosimetry in the same environment. The simulation process includes the detailed geometry of the Linac Head as Jaws, Flatting Filter and MLCs, etc…, and the produced particles as gammas and neutrons. This was the motivation of choosing GATE as the simulation code in this work. The present study aims to assess the photo-neutron contamination with the 3DCRT technique by using the TLD chips and the Monte Carlo code GEANT4/GATE.

MATERIALS AND METHODS

Thermo-luminescence Dosimeters (TLD Chips)

Suitable pairs of dosimeters are used, ^{6}LiF: Mg, Ti (TLD-600) is sensitive for both neutrons and photons, ^{7}LiF: Mg, Ti (TLD-700) is sensitive to photons only. The TLD Calibration for gammas and neutrons was presented in good details in our previous work (Mohamedy et al., 2019).

A PCL3 readout system is used for TLD measurements manufactured by FIMEL Company, and Fisher Scientific oven model is used to anneal the TLD chips.

2.2 Linear accelerator

Siemens ONCOR impression linear accelerator with multi-energies, 6 and 15MV, is used in the present work. The Multi-leaf Collimator (MLC) delivery system replaces the lower movable jaws inside the linear accelerator head. The simulation of the Linac head is based on the details of each component which is provided from the manufacturer shown in table1, and figure1. There are two stages of simulation processes. The first stage is phase space (PhS) stage and the second stage is dose calculation stage as shown in figure 2 (a and b).

2.3 Geant4

GEANT4 application for Tomographic Emission (GATE) is macro-structured software built from the GEANT4 toolkit in C++ by the Open GATE collaboration. GATE is used for RT and dosimetry applications. The purpose of using GATE is to develop a MC tool for researchers in the medical fields. GEANT4 can model geometries in motion, such as the rotating parts of an Intensity Modulating radiotherapy (IMRT) beam line and dynamic Multi Leaf Collimators (MLCs). GEANT4 is used in this study to compare the photo-neutron doses with the experimental results Geant 4 (2012),

2.4 3DCRT

A Rectum cancer planned with a 4-field conventional 3Dconformal plan using the same anatomic data from a CT scan. PTV was the rectum, and OARS were Rectum, Bladder and left Femur. The gantry angles for the 4-field plan were 0°, 90°, 180° and 270°. A dose of 230 monitor units (MU) were irradiated per fraction to deliver 72 Gy as total dose to the Rectum. The RW3 slab phantom designed for high energy radiation therapy with dimensions 30cm×30cm×30cm used in this work. The total number of slices used was 11 slices from total 30 slices. The phantom was transected horizontally and scanned with CT without TLDs, and then the phantom images were transferred to XIO treatment planning system (TPS) via the network.

The Slab phantom was simulated by defining its dimensions and height of each slice. The voxels size were 1cm×1cm×1cm in all dimensions. For the Rectum case simulated; the following data were simulated by GEANT4:

1. Isocenter Z position under the surface of the phantom was 5cm.
2. Field size was 14 x9.5 cm.
3. Beam angles were 0°, 180°, 270°, and 90° (Anterior, Posterior, LT lateral, and RT lateral).
4. Beam times for all angles were15 sec., 17sec. respectively.

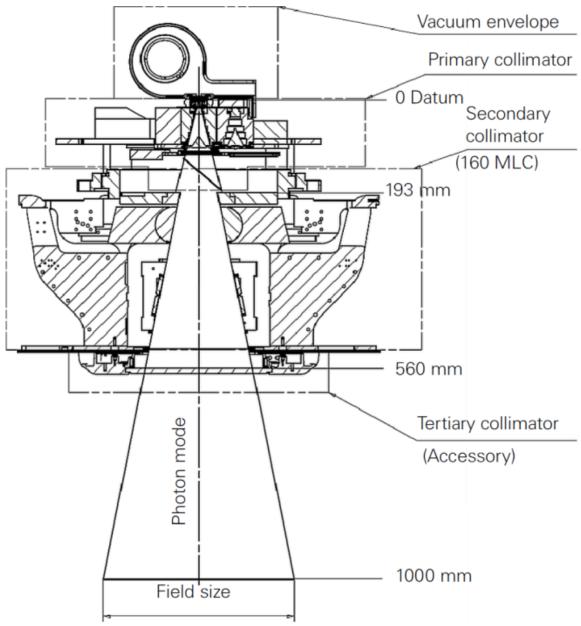

Figure 1: The main components of the Linac head.

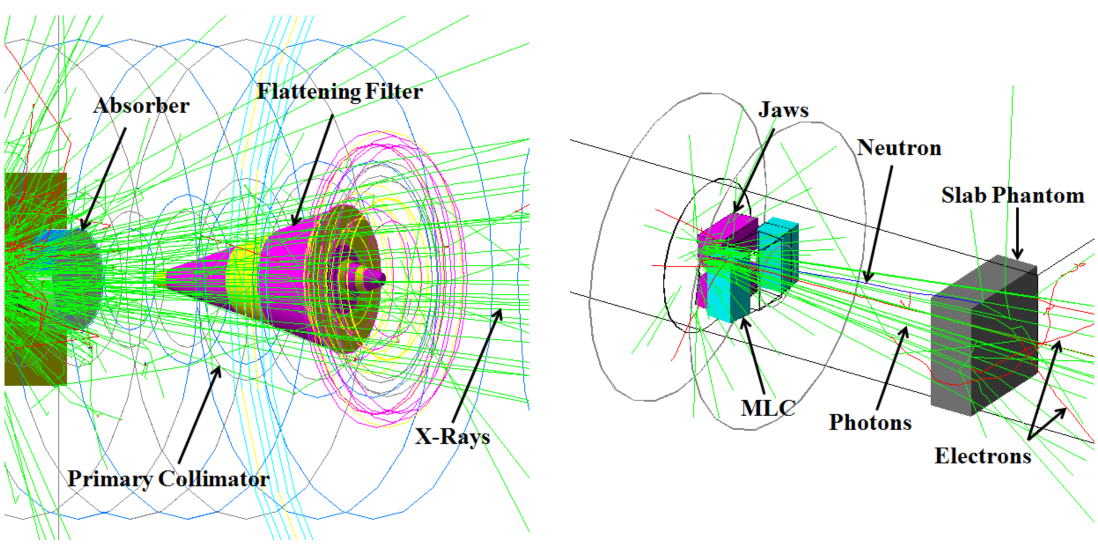

Figure 2: The stages of the simulation process: phase space (PhS) stage (Left), and dose calculation stage (Right).

Table1: The components inside the Linac head

	Shape	Material	Thickness (cm)	Position (cm)
Exit Window	Box	Titanium	0.0050	−0.42150
		Water	0.0660	−0.38600
		Titanium	0.0050	−0.35050
		Air	0.4650	−0.11550
Datum	-	-	0.0000	0.00000
Target	Box	Tungsten	0.0640	0.14900
		Nickel	0.0040	0.13800
		Gold	0.0110	0.19050
		Cupper	0.1650	0.27850
		Nickel	0.0015	0.36175
		Gold	0.0035	0.36425
		Stainless Steel	0.1020	0.41700
		Graphite	1.0160	0.97600
		Stainless Steel	0.0040	1.48600
Primary Collimator	Cylinder	Tungsten	1.1900	2.29500
			1.1200	3.45000
			1.2400	4.63000
			1.2650	5.88250
			1.550	7.29000
			1.1930	8.66150
Flatting Filter	Cone	Stainless Steel	0.3100	7.91000
			0.7635	8.44675
			0.4295	9.04325
	Cylinder		0.0720	9.29400
	Cone		0.3100	9.48500
			0.4054	9.533270
Monitor	Cylinder	Ceramic	0.1520	10.8100
		Nitrogen	0.1840	10.9780
		Ceramic	0.1520	11.1470
		Nitrogen	0.1840	11.3150
		Ceramic	0.1520	11.4830
Mirror	Box	Glass	0.2090	16.4985
Secondary Collimators	Y-Jaws	Tungsten	7.7980	23.5840
	X-Jaws		7.4930	32.0420

RESULTS AND DISCUSSION

The phase space stage ROOT data file includes all the information of the generated particles from the Linac head, as type of particles, Direction of all particles, 3D coordinates, production process, energy and weight before the secondary collimators.

Different types of particles were generated from the Linac head as neutrons, photons, positrons... etc., shown in figure 3. Figures 4 and 5 represent the distribution of photons and neutrons.

The highest contribution of neutrons to the total treatment dose was close to the phantom surface and distant from the central axis. This is due to scattered photon dose is minimal at these points.

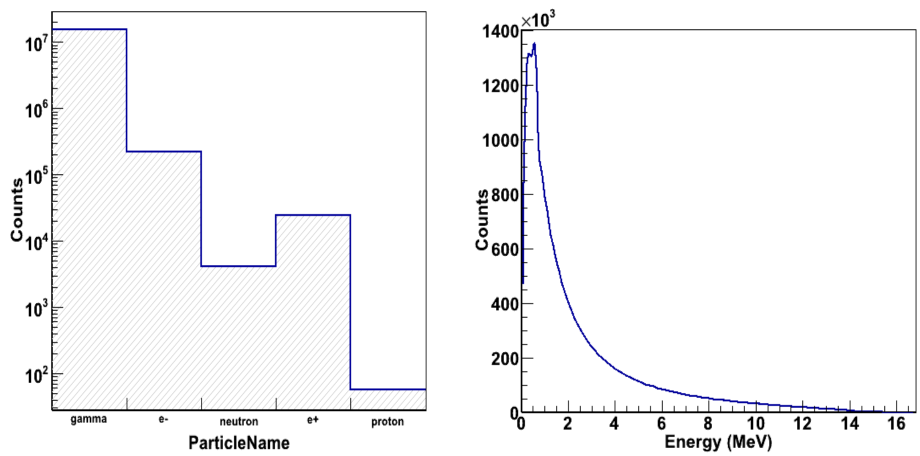

Figure 3: Particles types produced from the Linac head (Left), and photon spectrum (Right).

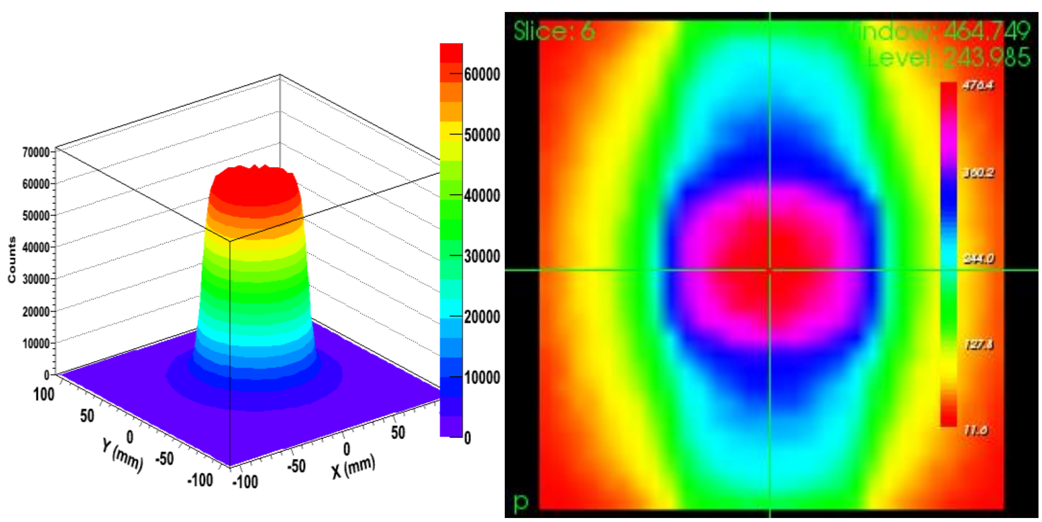

Figure 4: Photons distribution (Left), and dose (Right).

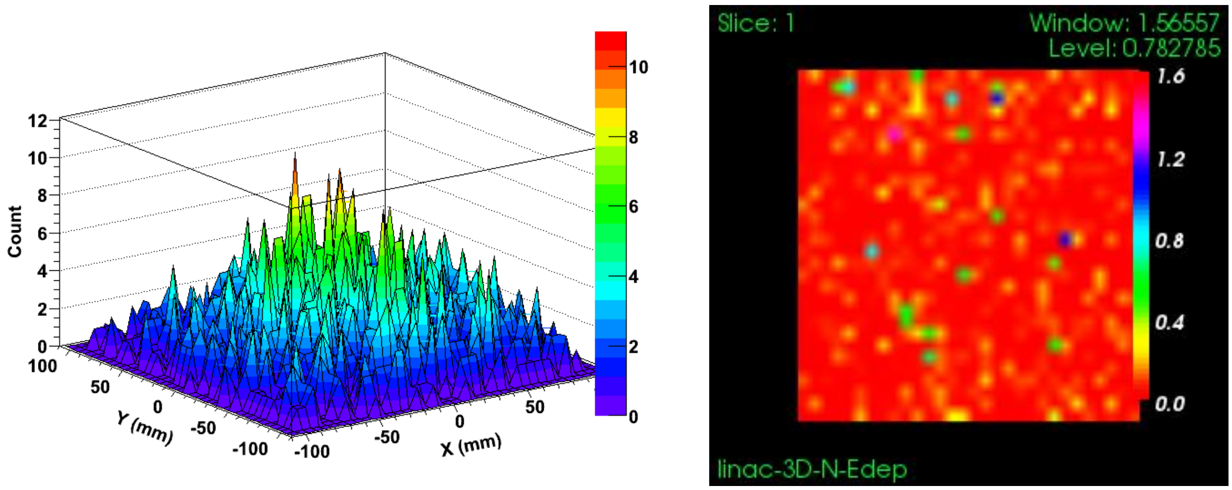

Figure 5: Neutrons distribution (Left), and dose (Right).

Equivalent neutron doses for both PTV and OAR using the 3DCRT technique were measured by TLD chips and calculated by the Simulation are presented in table 2. The measured equivalent neutron doses with TLD chips using 3DCRT for PTV and OAR were ranging from 0.04 to 0.24mSv per photon Gy with average value of 0.15mSv per photon Gy (i.e. for 70Gy treatment dose, the equivalent neutron dose was 2.8 to 16.8mSv), these findings show agreement with the previous published data (Rahim et al., 2018) and (Anna et al., 2017) As noticed from table 2 there is an excellent agreement between the calculated and measured equivalent neutron doses.

Table 2: Equivalent neutron doses for PTV and OAR using 3DCRT technique measured by TLD chips and calculated by the MC Simulation.

Organ	TLD (mSv/Gy)	MC (mSv/Gy)	Difference between measured and calculated dose
Rectum (PTV)	0.306±0.009	0.3±0.001	≤0.006
Bladder (OAR)	0.14± 0.0010	0.138±0.001	≤0.002
LT Femur (OAR)	0.04±0.004	0.038±0.008	≤0.002

CONCLUSION

The equivalent dose at tissues or organs adjacent to the treatment field due to photo-neutrons could be up to 10% of the total peripheral dose. Therefore, photo-neutrons should be taken into account when accurate dose calculations are required to sensitive tissues that are adjacent to the therapeutic X-ray beam. The study showed that Monte Carlo simulation can be applied in radiotherapy which offers reliable results. So MC is a valuable tool for photonuclear dose studies.

CONFLICT OF INTEREST

The authors declared that present study was performed in absence of any conflict of interest.

ACKNOWLEGEMENT

The Linac Siemens ONCOR impression, Germany is installed at Nasser Institute-Oncology Center, Cairo, Egypt. The TLDs were provided by the National Institute of Standards (**NIS**), Giza, Egypt.

AUTHOR CONTRIBUTIONS

EMM and NLH prepared the TLD ships for neutron and gamma measurements. EMA choose the Treatment Planning technique, HFI performed the simulation and data analysis, WMK wrote the manuscript. All authors reviewed the manuscript, read and approved the final version.

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