

Survey of photoneutron emitted from 6MV, 10MV, and 15MV medical LINAC using nuclear track detection

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ABSTRACT

Background: Medical linear accelerators (LINAC) can produce unwanted photoneutrons that might cause tissue damage or cancer in other organs. The efficient techniques and detectors are importantly required to detect these harmful neutrons.

Objectives: This study aimed to measure photoneutrons produced from medical LINAC of 6, 10, and 15 megavolts (MV).

Materials and methods: Nuclear track detector (CR-39 detectors) were employed to quantify the number of neutrons from LINACs. The X-ray energies, doses, and radiation techniques were varied to compare the number of neutrons. The photoneutron productions inside the LINAC room were also examined.

Results: The results showed that there were no neutrons from medical LINAC 6 MV, whereas photoneutrons could be detected from 10 and 15 MV LINAC. Radiotherapeutic techniques with moving multi-leaf collimator (MLC) produced higher photoneutron than techniques without using MLC. The neutrons were detected on the walls of the LINAC room.

Conclusion: X-ray energy greater than 10 MeV generated undesired photoneutrons that can penetrate the shielding and increase the patient dose. For the safety of staff to re-enter the treatment room, delaying time should be considered for the neutron decay process.

Introduction

In 2020, the International Agency for Research on Cancer (IARC) reported the incidence of cancer of 19.3 million cases globally and around 10.0 million cancer deaths.¹ The cancer burden in Asia accounted for 49.3% of global cases.¹ Radiotherapy has been recognized as one of the effective cancer treatment methods. This treatment employs high-energy ionizing radiation such as X-rays, gamma

rays, and other particles to kill cancer cells. The radiation dose given to patients must be correctly calculated to destroy cancer cells with minimum damage to nearby normal cells. Thus, radiotherapy must be carefully planned for ensuring safety of the patients. Radiotherapy can be combined with surgery or chemotherapy, depending on characteristics, staging and location of cancer, and patients' health. There are two types of radiation therapy categorized by radioactive sources. First is brachytherapy, which is a treatment where a radioactive source is temporarily placed inside the body near the cancer cells. The radioactive sources might also be swallowed by the patient or injected into the patient's body. Second is teletherapy, which can be given by placing a radioactive material at 10 to 100 centimeters (cm) from the patient and using a collimator to control the radiation

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beam to the desired direction. Cobalt-60 machines and medical linear accelerators (LINAC) that generate photon beams with high energy ranging from 1 to 25 mega electron volts (MeV) are currently used for the teletherapy.² Recently, medical LINACs have been substituting for cobalt-60 machines because they do not require radioactive sources, more secure and easy for waste management. Consequently, LINACs are more practical to use. Integrating computer systems to control collimator leaf position according to the tumor shape helps alleviate radiation damage on cells surrounding the tumor and enhance the treatment efficacy to eradicate tumors by the high-energy photons. However, a photon beam with energy more than 10 MeV can interact with high atomic number materials, such as tungsten and lead. These elements are commonly used as components of the target and collimation system in LINAC's treatment head. As a result, high-energy neutron particles have been undesirably produced and they potentially pass through the protection device to the patient. Thus, the radiation dose to the patient is increased.³ Similarly, the high-energy neutrons contaminating the radiotherapeutic room and its wall can have an impact on operators.⁴ Hence, neutron protection needs to be considered while designing room structure. Besides, care should be taken of photon-induced radioactive material as it can capture neutron and produce undesirable high energy photons.⁵

Medical LINAC can produce photoneutrons that are generated by the interaction between high-energy X-rays and high atomic number substances such as tungsten and lead. The threshold energy of X-rays and lead interaction in producing photoneutrons is 7.4 MeV.⁶ Neutron particles have no electric charge and can move deeper through medium. It can directly interact with nuclei of the medium, then transfers most of its energy to nuclei of an element that has a similar mass to the neutron. The human body contains abundant hydrogen that has comparable mass with neutrons. Neutrons interact with human tissues and transfer the energy to hydrogen nuclei. This effect potentially causes genetic deterioration leading to cancer.

Apart from being one of the most effective cancer treatments, LINAC itself produces unwanted photoneutrons that might cause tissue damage or cancer in other organs. Therefore, the efficient techniques and detectors are importantly required to detect these harmful neutrons. Nuclear track detector has been used for measuring radiation dose and energy of photoneutrons from LINAC.^{3, 7, 8} CR-39 plastic nuclear track detector (CR-39 PNTD) is Polyallyldiglycol Carbonate ($C_{12}H_{18}O_7$) polymer. The material contains hydrogen and oxygen atoms, similar to human tissue. This property allows the study of interaction of neutrons and tissue. Neutron energy with the range of 1-20 MeV can be indirectly measured by the interaction of neutron and hydrogen atoms of CR-39. The size of the CR-39 detector is small and requires no electricity, so it is easy to place on patient's skin. It is sensitive to charged particles, but it does not respond to any photon.

This study aimed to examine the number of neutrons produced by 6, 10, and 15 MV LINAC and measure neutrons in the radiotherapy room using the CR-39 radiation detector.

Materials and methods

Two medical LINACs; 6 and 10 MV (LINAC#1) and 10 and 15 MV (LINAC#2) were used in this study. CR-39 PNTD is composed of boron nitride (BN) and polyethylene sheet (TASTRAK™ PADC, Track Analysis Systems Ltd (TASL), Bristol, UK). The former allows neutron-alpha (n, α) interaction for measuring neutron energy less than 1 MeV. The latter interacts with neutron energy of 1-10 MeV (or called fast neutron) via elastic scattering producing protons.

Etching process started with immersing the CR-39 plastic detector into NaOH aqueous solution of 6.25% concentration at 70 °C in a water bath. After 15 hours, CR-39 were rinsed in distilled water and dried at room temperature. The nuclear tracks were magnified and visualized under 100x-400x microscope as dark circles (Figure 1). The etched CR-39 detectors were manually counted under optical microscope with 400x to obtain the number of nuclear tracks.

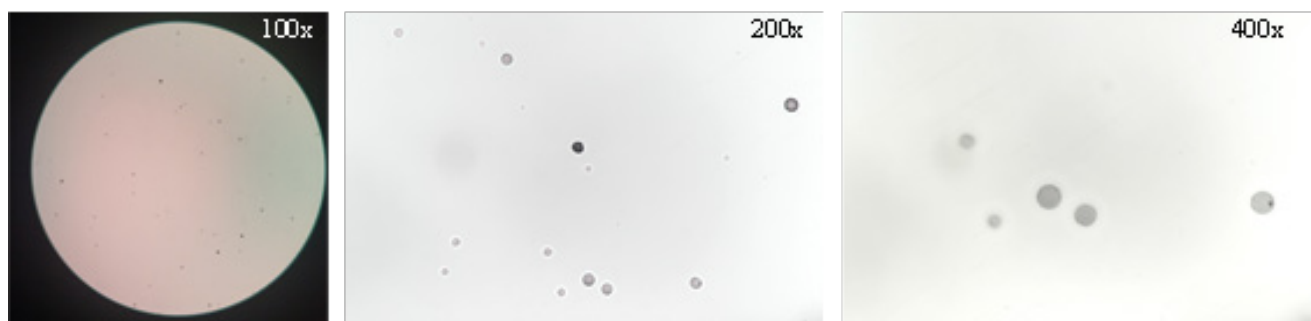


Figure 1. Nuclear tracks on CR-39 detectors.

Calculation of neutron equivalent dose

The dose conversion graph and equation for the calculation of neutron equivalent dose were provided by the secondary standards dosimetry laboratory (SSDL), the office of atomic for peace (OAP). CR-39 detectors were irradiated with ($^{241}\text{AmBe}$ neutron source) neutrons equivalent dose of 0.5, 1, 5 and 10 mSv. These neutrons equivalent doses were traceable to Primary Standard Dosimetry

Laboratory at Korea Research Institute of Standard and Science (KRISS). After etching process, the nuclear tracks were automatically counted. The relationship between the number of tracks and radiation equivalent dose were plotted (Figure 2) and the neutron equivalent dose was calculated from equation (1) as follows:

$$y = 0.0199x + 0.7862 \dots (1)$$

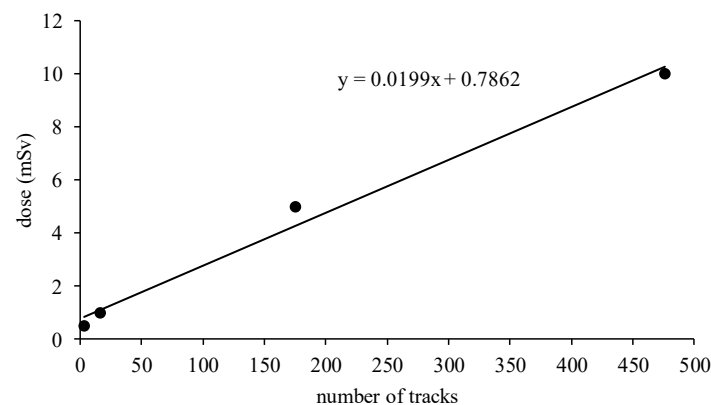


Figure 2. Dose conversion graph and equation for the calculation of neutron equivalent dose.

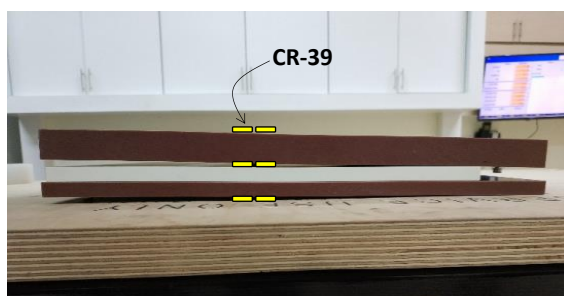
Measurement of neutron using phantom

The amount of neutron equivalent dose produced by two different LINACs with different energies were compared. LINAC#1 produced X-ray beams from accelerating electrons with 6 and 10 MV and LINAC#2 with 10 and 15 MV. The radiation dose of 200 cGy and 990 cGy were set to irradiated CR-39 detectors. This study also compared the number of neutron equivalent dose from different irradiation techniques, which were intensity-modulated radiation therapy (IMRT), volumetric modulated arc therapy (VMAT), 3-dimensional radiotherapy (3D-RT), and 2-dimensional radiotherapy (2D-RT).

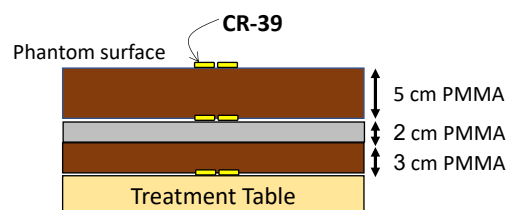
The irradiation conditions for LINAC#1 were to compare the potential difference of 6MV and 10MV, assigning a dose of 200 cGy and 990 cGy (calibrated at 1 Monitor unit = 1 cGy), using two radiation techniques; 3-Dimensional radiotherapy (3D) and Intensity-modulated radiation therapy

(IMRT). Two of 5-centimeter polymethylmethacrylate (PMMA) phantoms were placed on the LINAC's table at 100 cm source-to-surface distance (SSD) with 15 cm² field size. Six of CR-39 detectors were used to measure neutron particles. Two of CR-39 detectors were placed isocenter at the top of the phantom, while another two were inserted between the phantom, and another two were underneath (Figure 3A).

Whereas LINAC#2 has a higher energy range of 10MV and 15MV. The phantom thickness was increased by adding two of 5-cm PMMA sheets under the Anthropomorphic pelvic phantom. The total thickness became 32 cm mimicking a large patient. Two CR-39 detectors were placed at isocenter on top of the phantom, and another two were underneath (Figure 3B). The radiation dose was 200 cGy using 2-Dimensional radiotherapy (2D) technique and volumetric modulated arc therapy (VMAT) technique.



(A) Medical LINAC 6MV and 10MV



(B) Medical LINAC 10MV and 15MV

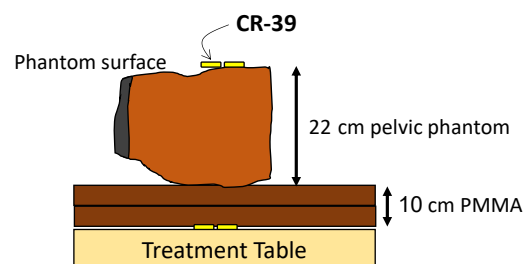


Figure 3. CR-39 detectors were placed on phantom to measure neutrons from the two LINACs.

Measurement of neutron around the LINAC room

Background radiation was measured by keeping the two CR-39 detectors in a non-radiation environment area. Then the number of radiation nuclear tracks from the background will be subtracted from the experiments.

CR-39 detectors were placed inside and outside both LINAC rooms. Two detectors were used to survey and measure neutrons at each position. In LINAC#1 (6MV and 10MV) room, CR-39 detectors were placed on the wall of

three locations 1) the junction between LINAC vault and maze, 2) the maze way, and 3) the entrance door inside the LINAC room (Figure 4A). In LINAC#2 (10MV and 15MV) room, CR-39 detectors were placed on the wall of six locations 1) the bunker inside LINAC vault and maze, 2) the bunker between LINAC vault and maze, 3) the maze way, 4) the entrance door inside the LINAC room, 5) the entrance door outside the LINAC room, and 6) the operation room (Figure 4B).

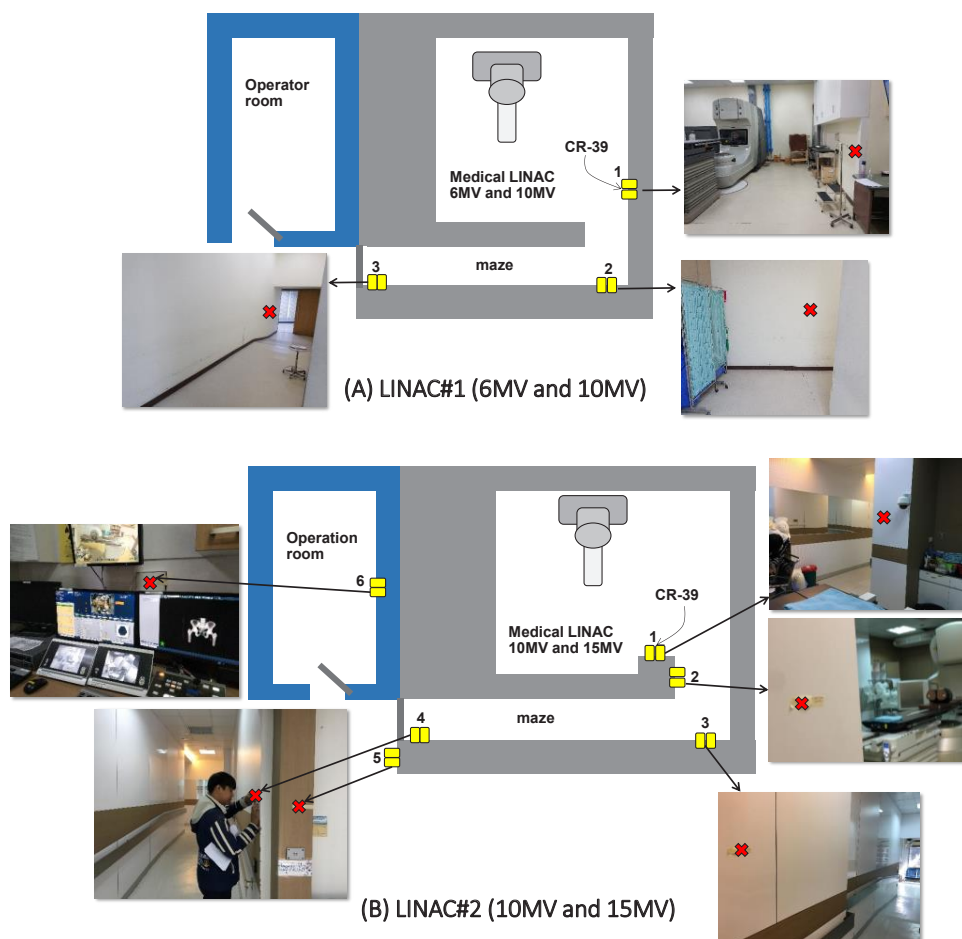


Figure 4. CR-39 detectors located in both LINAC's room to survey neutron particles.

Results

Neutron particles produced from medical LINACs

Table 1 shows the number of neutrons produced when varying energies, radiation doses, and radiation techniques. For 6 MV LINAC#1, the number of nuclear tracks is similar to that of the background radiation, implying that no neutron particles from the 6MV acceleration were found. Increasing the radiation dose and changing the radiation techniques did not enhance the number of tracks. However, when increasing the acceleration potential to 10 MV, the number of tracks was higher than background radiation. The results also showed that the number of nuclear tracks increased with the radiation doses. The center of phantom presented a higher number of tracks than those at the top and bottom. The IMRT technique, using a multileaf collimator (MLC), produced more radiation tracks than 3D techniques without MLC.

For 10 and 15 MV LINAC#2, it was found that both energy levels generated the number of neutron tracks. The higher the energy was used; the more tracks were produced. The VMAT technique, using a multileaf collimator, produced more radiation tracks than 2D techniques without MLC. The bottom of phantom presented a higher number of tracks than those at the top.

Radiotherapeutic parameters are generally used at 6, 10, or 15 MV depending on patient thickness with a dose of 200 MU. The mean neutron radiation doses were calculated using equation (1). The results revealed that the radiation dose that used 6 MV LINAC was about 0.8 mSv. The use of 10 MV LINAC associated with MLC yielded a radiation dose range of 1.4 - 4.6 mSv. The highest neutron equivalent dose of 7.7 mSv was from 15 MV LINAC with VMAT (Table 2).

Neutron around the radiotherapy room

The survey results found neutron particles in the interior of 10 MV, 900 MU LINAC room. The highest radiation dose was 1.2 mSv at the junction between LINAC vault and maze. The farther the accelerator, the lesser number of nuclear tracks produced. At the door, the amount of neutron radiation was similar to the amount of natural background radiation.

The survey results inside LINAC rooms showed that the location near the accelerator had the highest number

of tracks. The calculation of radiation dose inside 10 MV, 200 MU LINAC room was 1.2 mSv. Increasing the voltage to 15 MV, 200 MU, the radiation dose inside the LINAC room was increased to 8.3 mSv. The CR-39 detectors, that were placed at the front door outside the irradiated room, can detect the nuclear tracks and the calculated dose was 1.3 mSv. Nuclear tracks on the detectors placed at the junction point between the control room and the LINAC room were also found. (Table 3)

Table 1 Number of nuclear tracks produced from neutron particles.

No.	Parameters		200MU			990MU		
			top	middle	bottom	top	middle	bottom
LINAC#1	6MV	3D	2	1	2	0	0	0
		IMRT	6	0	1	8	5	1
	10MV	3D	27	129	72	168	379	324
		IMRT	47	193	176	330	666	610
LINAC#2	10MV	2D	21	n/a	32	n/a	n/a	n/a
		VMAT	31	n/a	56	n/a	n/a	n/a
	15MV	2D	37	n/a	78	n/a	n/a	n/a
		VMAT	327	n/a	348	n/a	n/a	n/a

n/a: not available

Table 2 Neutron equivalent dose in mSv.

No.	Parameters		200MU		
			top	middle	bottom
LINAC#1	6MV	3D	0.8	0.8	0.8
		IMRT	0.9	0.8	0.8
	10MV	3D	1.3	3.3	2.2
		IMRT	1.7	4.6	4.3
LINAC#2	10MV	2D	1.2	n/a	1.4
		VMAT	1.4	n/a	1.9
	15MV	2D	1.5	n/a	2.3
		VMAT	7.3	n/a	7.7

n/a: not available

Table 3 Number of nuclear tracks and the number in parenthesis is neutron equivalent dose in mSv.

		Location					
		#1	#2	#3	#4	#5	#6
LINAC#1 (6MV,10MV)	10MV 900MU	22	1	0	n/a	n/a	n/a
		(1.2)	(0.8)	(0.7)	n/a	n/a	n/a
LINAC#2 (10MV,15MV)	10MV 200MU	20	21	4	0	6	3
		(1.2)	(1.2)	(0.9)	(0.8)	(0.9)	(0.8)
	15MV 200MU	376	278	117	38	24	22
		(8.3)	(6.3)	(3.1)	(1.5)	(1.3)	(1.2)

n/a: not available

Discussion

The high-energy medical LINAC has been widely used to generate X-rays and electrons for treating cancer patients. However, the machine also produces neutron particles. This unintentional byproduct increases unnecessary exposure to radiation of patients. Besides, the neutron particles can disperse beyond tumor cells, making it difficult to protect the harmful effect of neutron radiation.⁹ This study aimed to determine neutrons generated from the LINAC by varying X-rays energy levels, radiotherapy techniques, and radiation doses. In terms of X-rays energy levels, the 6, 10, and 15 MV accelerations are commonly used to treat cancer patients. The results showed that none of the neutron particles occurred when using the X-rays energy lower than 6 MeV. The neutron particles were detected from the 10 and 15 MeV X-rays and the increase in X-rays energy led to the increase in the number of neutron particles. Our findings were in line with various theories and studies that neutron particles are generated from the interaction between high-energy photons and materials of the LINAC head, air, and patient's body. Since, the LINAC head contains high-atomic number metals such as lead, tungsten, copper, and iron, these metals have threshold energy for neutron emission at 7.37, 7.41, 10.85, and 11.19 MeV, respectively.^{7,9} This real-world evidence has proven the potential risk from detectable photoneutrons occurring from routine clinical practice. Thus, thorough measures for neutron radiation protection should be developed and strictly implemented in hospital radiology departments to prevent overexposure of patients and healthcare personnel.

Various advanced radiotherapeutic techniques were developed with the aims of improving target volume coverage and minimizing the effect on normal cells, such as intensity modulated radiation therapy (IMRT) and volumetric modulated arc therapy (VMAT) that can control a multileaf collimator (MLC) at the LINAC head. However, moving the collimator increases the chance of its high-atomic number metals to interact with the high-energy X-rays. Thus, IMRT and VMAT can produce a higher level of neutron particles compared to radiation techniques without the collimator movement such as 3-dimensional radiotherapy (3D-RT) and 2-dimensional radiotherapy (2D-RT).¹⁰ Additionally, the highest average neutron equivalent dose was detected in the middle of the phantom when using 3D-RT and IMRT techniques. It might be a result of the increasing number of neutron particles due to X-rays emission through the phantom and some particles interacted with CR-39 detector.

This study examined neutron contamination inside and outside the radiotherapy room. At above 10 MeV X-rays, the neutron particles were detected near the LINAC more than other areas, while the 15 MeV X-rays directly affected the increasing number of neutron particles. The results highlighted that room size, devices, medical supplies, shelves, furniture, and materials for walls and floors should be considered when designing a LINAC radiotherapy room.¹¹

Besides, medical staff must avoid the dangers of the high-energy neutron decay inside the irradiation room. Staff should delay room entry times after previous treatment. A study proposed that the waiting time of 7 to 11 minutes

should be appropriate for allowing the neutron decay based on the employed techniques.¹² Moreover, the waiting time depends on the energy level of X-rays, radiation techniques, components of the LINAC head, and materials of the collimator.^{12,13}

Conclusion

The neutron particles were detected from X-rays of above 10 MeV. The number of neutron particles in the radiotherapy room and their effect on people in such an area should be further examined. The decay of contaminated neutrons in the treatment room from various radiation techniques could be another matter of investigation. This evidence can raise radiation safety awareness and be used to develop related preventive procedures.

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Conflict of interest

There are no conflicts of interest to disclose.

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