ORIGINAL ARTICLE

Assessment of Photon Beam Skyshine Dose Equivalent Rate of a 4 MeV Radiation Therapy Bunker Using Analytical and Monte Carlo Methods

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Abstract

Purpose: Skyshine radiation dose equivalent dose rate is known as scattered radiation by the room above air to points at the ground level points outside the Linear Accelerator (LINAC) room. Our aim was to estimate skyshine around the LINAC-based radiotherapy by a 4MV LINAC photon beam.

Materials and Methods: Monte Carlo (MC) MCNP code calculation was conducted to skyshine at the control room, ^{60}Co treatment room, physics, and simulator rooms. National Council on Radiation Protection and Measurements (NCRP) 151 was also used and it reported analytical formulation methods for photon beam calculation. A Flattering Filter (FF) equipped and Flattening Filter-Free (FFF) LINACs photon beams were derived and differences and agreements were discussed.

Results: The results showed high skyshine for FF equipped relative to FFF LINACs. This effect may be attributed to photon beam hardening by FF in the LINAC head and higher transmission through the ceiling shield and more presence of photons on the roof above the air. NCRP 151 method results were higher than MC simulated photon beam skyshine dose equivalent dose rate and it may be the cause of the inflexible analytical method in contrast to MC simulation. Finally, FFF and FF-equipped LINACs result in skyshine compared and they compared to NCRP 151 report. MC simulation performed reasonably in estimation in different conditions.

Conclusion: Our results showed that FF-equipped skyshine is higher than FFF LINAC and NCRP 151 is an inflexible method that does not take some effective parameters into account and calculates skyshine higher.

Keywords: Monte Carlo; Skyshine Dose; Photon; Linear Accelerator.

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1. Introduction

In the medical Linear Accelerator (LINAC) based photon beam teletherapy, the physical phenomenon, "Skyshine", arises from the LINAC photon beam scattering by atmosphere molecules above the room's roof toward the ground level points outside of the radiotherapy bunker. Some treatment rooms are designed with a little shield above the LINAC in the ceiling shielding and photon beam from the medical LINAC can transmit from the ceiling shield and be scattered to the LINAC housing around points. National Council on Radiation Protection and Measurements (NCRP) No. 151 [1] has defined the radiation skyshine as the LINAC photon beam scattered to the points at the radiotherapy room at the ground level points outside the radiotherapy treatment room by the atmosphere molecules above the room roof air. Nowadays, megavoltage LINACs are being used frequently in cancer radiotherapy worldwide besides surgery and chemotherapy so the International Atomic Energy Agency (IAEA) in safety report No. 47 predicted an increase and has estimated that approximately 2500 megavoltage radiation therapy machines were in use in 1998 in developing countries and that 10^3 such megavoltage teletherapy machines may be needed by 2015 [2]. Radiation skyshine is important, especially from a radiation protection point of view that can contribute to the patients and staff additional received doses which may be the cause of secondary malignancies risk and increase the secondary cancer risk. NCRP report No. 144 [3] has introduced some computer-based developed codes for the skyshine calculation from the MeV and GeV energy accelerators in the radiological facilities. EGS4 code system, FLUKA and, MCNP Monte Carlo (MC) simulation code, SHIELD11, SKYSHINE-KSU, SKYSHINE-III, and some other computer-based calculation programs are some of the recommended computational codes. MCNP MC code, FLUKA, and, EGS4 codes are the codes that are widely used for medical LINAC radiation simulation [3-8]. In the literature, there are no sufficient studies and data on the medical low energy 4 MeV LINAC photon beam skyshine dose equivalent rate [9-29]. However, in the publications, comprehensive studies can be found on the photon beam skyshine dose equivalent rate from the LINAC photon beam above the 6MeV up to 21MeV photon beam skyshine dose equivalent rate by the experimental direct measurements, NCRP empirical calculation, and MC simulation methods. Chaocheng *et al*. [30] carried out a study on the photon beam skyshine dose equivalent rate from the 9MeV, 15MeV, and 21MeV LINACs photon beam skyshine dose equivalent rate and concluded that MC simulation is a powerful tool for complex geometries and complicated radiation physics problem-solving. LINAC head materials such as targets also were their study subject and dependence of the photon beam skyshine and energy of the photon on the skyshine dose equivalent rate in a wide range of distances. They also reported a good coincidence reasonably comparing the results derived by the MC simulation method but deviated from the results given by empirical NCRP formulas [30]. De Paiva's [31] publication on the photon beam revealed that the skyshine dose equivalent rate, besides the drawbacks of the NCRP analytical method which was employed for the photon beam skyshine doses equivalent rate estimation, can be applied as a preliminary photon beam skyshine doses equivalent rate estimation of near the outside of radiotherapy facility room. They discussed also the photon beam hardening effect by the LINACs structures. Gossman *et al*. [14] conducted a study on the survey measurements using different field sizes and at some different distances from the LINAC room primary barrier which have enabled them in the study to identify skyshine dose equivalent behavior in comparison to other energies such as photon beam of a 6MV LINAC. Their conclusion was to recommend the largest field size as suitable for skyshine estimation in comparison to the small field sizes and reported that a peak of skyshine occurs as a function of the calculation position distance to the barrier for the LINACs X-ray energies. They attributed the skyshine dependence on the skyshine behavior that appeared in their study to the increase in the scattering cross-sectional variable when the scattering angle subtended is decreased. De Paiva *et al*. [12], in a study surveyed photon equivalent dose rates from the 6MV and 10MV medical LINACs and observed a poor agreement of the NCRP 151 calculation method derived results, direct measurements calculation, and declared that the observed differences between the results that deviated in one or more order of magnitude comparing the measured and NCRP 151 predicted results [32]. They also stressed that there is a lack of data on the skyshine radiation characterization, so new reported data on this type of radiation play an important role in the understanding of the physical skyshine phenomenon itself. Patric M. [33] investigated NCRP 151 widely used empirical method and indicated that NCRP 151 analytical method is inadequate because it does not take different affecting parameters on the photon skyshine dose rate into accounts such as the used field size and proportion of Ω (solid angle) as $\Omega^{1.3}$. Their main conclusion was that evidence has shown that at intermediate distances the skyshine declines as one over the distance (d_s) and not one over the distance squared (d_s^2). Estimations of skyshine dose rates depend critically on a deep knowledge of the roof transmission factor (B_{xs}). Rostampour *et al.*'s [26] study conclusion showed a poor agreement between the NCRP 151 calculated skyshine dose equivalent rate and measured values on the photon beam skyshine from 9 MeV and 18 MeV LINACs. McGinley [34] calculated the skyshine dose equivalent rate from an 18MV LINAC and observed the peak effect on the skyshine dose equivalent rate occurred at 13.6 m from the LINAC X-ray source to the isocenter. They also discussed field size dependence of skyshine dose rate and it was concluded that the peak of photon skyshine dose occurs at a different position depending on the barrier for accelerator photon beam energies and also they revealed that the photon skyshine peak position is a function of the LINAC field size in the examination. Additionally, they concluded that skyshine behavior may be because of an increase in the scattering cross-sectional variable when the photon beam scattering angle subtended was decreased [14]. Different studies have been conducted on the LINAC photon beam or gamma-ray dose equivalent rate estimation using the MC simulation, direct measurement, and NCRP 151 empirical methods [12; 13; 16; 17; 19; 20; 25-28; 35-38]. Measuring and comparing the head scatter factor for 7 MV unflattened and 6 MV flattened photon beams using a homemade designed mini phantom. Ashokkumar *et al.* [39] measured and compared the head scatter factor for 7 MV unflattened and 6 MV flattened photon beams using a homemade designed mini phantom. According to Grady F'O *et al*. [40], the combination of in vivo and phantom measurements establishes that there is a significant increase (10%-15%) in superficial dose for whole breast irradiation with Halcyon compared with a standard 6X LINAC with flattening filter. Mizonu H *et al*. [41] dose-response of a radio-photoluminescent glass dosimeter for Tomo-Therapy, CyberKnife, and Flattening Filter-Free (FFF) LINAC output measurements in dosimetry audit. In Tsiamas P *et al*. [42], for dose rate increasing in the radiotherapy, some radiotherapy employs FFF LINAC photon beam. There are enormous publications on the FFF LINAC photon beam and features of its characteristics. When the flattening filter is removed from the LINAC, the material should be replaced due to electron radiation removed from the produced photon beam. They replaced a metal plate consisting of 6 mm Cu and 2 mm Al in the 6MV LINAC head. Electron contamination in the FFF with the metal plate can be removed [43]. In the current Monte Calo simulation of the photon beam skyshine from the Flattering Filter (FF) equipped LINAC and FFF LINAC and NCRP 151 recommended analytical method calculation. According to Bersolin A *et al*. [44], for absolute dosimetry of FFF beams by FC65-P IBA, the k_s correction is necessary. They also stated that for absolute dosimetry of FFF beams by FC65-P IBA, the k_s correction is necessary. SJ Yoo *et al* [45] comprehensively studied FFF and FF LINACs photon beam and characterized the machines and reported that the FFF dose rate can be two times higher than FF equipped LINAC dose rate. In this study, the authors aimed to calculate the FF-equipped LINAC skyshine dose equivalent and compare the FFF photon beam skyshine equivalent dose rate at points around the room and the results compared to NCRP 151 recommended analytical method derived results.

2. Materials and Methods

Monte Carlo N-Particle transport code, MCNPX version (2.6.0) of the MC simulation method was used in this study for the photon beam skyshine dose equivalent rate at the points outside the cancer radiotherapy treatment LINAC facility. MCNP code of the MC simulation method has been developed by the Los Alamos National Library (LANL) [46] and includes rich physical phenomena data and cross-sections and is capable of complex geometries and complicated radiation physics simulation. The code is an all-purpose photon and particles transport code that can transport photon, electron, neutron, and coupled electron/photon, neutron/photon, or neutron electron and, different particles in the wide energy range through different materials. Additionally, the composition of the materials and isotopes also can be simulated by the use of the MCNP MC code. The main parts geometry and the materials composition of a 4MV Varian LINAC with and without FF were simulated using the MC simulation method for photon beam skyshine study. Gaussian distributed symmetric electron beam along the X and Y axes with Full Width in Half of the Maximum (FWHM) modeled with 0.8 mm, target and target supporting and electron stopping small piece, collimation system, flattening filter, and movable jaws, as well as the LINAC heavy and massive with a complex shield were the main parts of the simulated LINAC for the 4MeV photon beam simulation. The manufacturer has reported a photon beam at a point 1m in height on the photon beam central axis as 180 Gy/h for FF-equipped LINAC. The FFF dose rate at the same point on the photon beam axis was calculated by MC simulation. Additionally, the LINAC photon beam simulated for FFF and FF equipped conditions for the photon beam skyshine dose rate assessment and investigation of the effect of the photon beam flattening on the skyshine dose equivalent rate. As NCRP 151 recommended, in the MC modeling, LINAC was positioned upward so that ceiling was irradiated vertically in the largest 40cm × 40cm field size. For speeding up the calculations and reduction of the statistical error a surface at 2m above the roof in the air composition (in the density of 1.24×10^{-03}) was simulated as the Phase-Space Distribution (PSD) file registered in a surface at the 2m above the roof, registered history of the radiation transmits from the ceiling and is been scattered by the atmosphere molecules in the air. The PS surface registered 13MB in size saved all radiations history crossing on it and the file of the registered history was created and in the next step was used as a primary radiation source and LINAC was removed from the geometry. A treatment room was modeled with dimensions and layout shown in Figure 1. The modeled room was made of ordinary concrete (in the density of 2.35 g/cm^3) room walls were embedded by a 5cm lead layer (in the density of 11.34 g/cm^3) for avoiding the scattered and leakage photons reaching the points of skyshine calculation. Running the MC programmed input file considering the PS surface containing the history of all radiation as the primary radiation source, the skyshine dose equivalent rate was estimated in Sv/h per initial source particle using the MCNPX (2.6.0) capabilities. Then, the photon beam skyshine dose rate was estimated at the points of calculation outside the room for FFF LINAC and FF-equipped LINAC photon beams at points shown in Figure 2. NCRP 151 recommended the latest methods for the photon beam skyshine dose equivalent rate as the following Equation:

$$H = 2.5 \times 10^7 \times D_0 \times \Omega^{13} \times B_{xs}/(d_i d_s)^2 \quad (1)$$

In the above Equation 1, the constant 2.5×10^7 includes a conversion factor to nSv/h and other terms are the same as Equation 2.

$$B_{xs} = 10^{-\{1+\left[\frac{t-TVL_1}{TVL_e}\right]\}} \quad (2)$$

Where B_{xs} is the shielding transmission factor for the certain photon energies, Ten Value Layer $(TVL)_1$ and TVL_e are the ceiling shield materials as first and equivalent Tenth Value Layer, respectively. According to the NCRP 151 data, ordinary concrete TVL_1 and TVL_e for the energy endpoint of 4MV were reported as 30cm and 35cm, respectively. B_{xs} obtained from data as 0.01389 and Ω was derived by Gossman *et al.*'s [47] formula as 0.1539 (Sr). Skyshine dose equivalent rate was calculated by MC simulation and NCRP empirical method for a 4MV FFF and FF-equipped LINAC photon beam. In the current study, the results of calculations were compared to the other works results and agreements and differences were

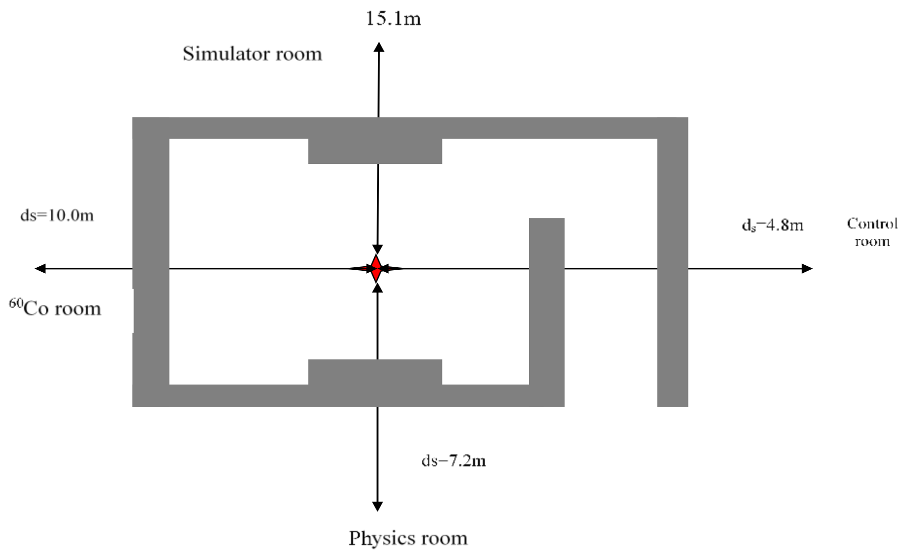

Figure 1. Monte Carlo (MC) simulated room with height of 3.68 m and its cross-sectional layout and dimensions

discussed. Additionally, the effect of the photon beam flattening was discussed.

3. Results and Discussion

We used MCNPX code calculation for photon beam of a 4MV FFF LINAC and FF-equipped LINAC photon beams skyshine dose rate around the LINAC-based radiation therapy treatment room. Our results showed that the photon dose equivalent rate estimated at a point of 1m in height on the central axis by MC simulation is in good agreement and 178 Gy/h was the value of 235 Gy/h for FF-equipped and FFF-LINACs that MCNPX estimated, respectively. In addition to dose rate, the number of photons crossing on the point at the isocentre was obtained as 2.419×10^5 photons and 4.723×10^4 photons for the ceiling inner surface. Then 5.1217 times reduction in the photon numbers at the ceiling surface compared to the isocenter may be attributed to the photon scattering in the room air and scattered photons by the room air. 2.619×10^4 number photon fluence distributed in the 0 MeV to 4 MeV photon derived at the isocenter while this value estimated as 5.5651×10^3 at a cell air-filled 30cm below the ceiling inner surface. MC code calculation showed the photon fluence at the FF-equipped LINAC isocenter at 2.329 times lower than fluence at a cell positioned 30cm below the ceiling inner surface. Photon fluence at the isocenter was shown in Figure 2 for FFF and LINAC flattened photon beams. Energy deposited by the LINAC flattened photon beam estimated as 2.59×10^{-2} MeV per initial source particle and energy of 1.99×10^{-2} at the isocentre and 0.634 MeV for photon beam in the 30cm below the small cell filled by the air composition for FF-equipped and FFF LINACs 0.687 and 0.548 and MeV, respectively.

3.1. NCRP 151 Approach

The method of NCRP 151 is an analytical and inflexible calculator. According to the NCRP 151 for data calculation of skyshine, Tables 1 and 2 showed that FF-equipped skyshine is higher than FFF LINAC photon beam. It may be more scattering by the atmosphere of the air inner the room, low transmit from the ceiling shield, and low photon presence photons at the room ceiling while the flattened photon beam with low attenuation in the room air, high transmitted factor, and reach a high number of photons at the room roof above the atmosphere. The results are in agreement with other works' results. Our results in the high energy skyshine higher for FF-equipped compared to FFF agrees with de Paiva D who calculated 6MV and 10MV LINAC photons beam skyshine. Apart from the large discrepancies found between NCRP 151 calculations and direct measurements of photon dose equivalent rate, analytical calculations have shown the dependency between skyshine radiation and treatment bunker geometric quantities. Good

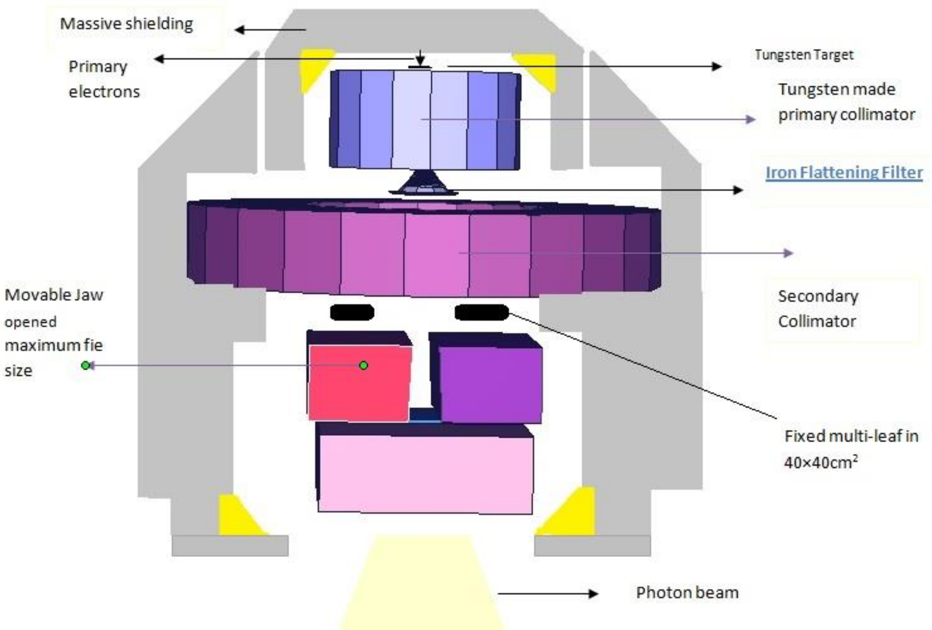

Figure 2. Monte Carlo (MC) simulated Linear Accelerator (LINAC) head main parts for study with Flattering Filter (FF). In Flattening Filter-Free (FFF) simulated FF piece removed and a plate made of Cu and Al positioned to avoid electron contamination

Table 1. MC derived parameters of FFF photon beam in nSv/h.

Photon fluence			
Photon number at isocenter	The photon dose rate at the isocenter	Number of photons crossing on ceiling	
1.8801×10^5	235 Gy/h	2.899×10^4	
Photon beam skyshine derived by NCRP 151 (nSv/h)			
Control room	Simulator room	^{60}Co treatment room	Physics room
4.8×10^{-5}	3.5×10^{-5}	1.8×10^{-5}	0.01×10^{-5}

Table 2. Photon beam estimated by MC simulation

	MC derived photon beam skyshine for FF equipped LINAC in nSv/h			
Positions Of skyshine calculation	Control room	Simulator room	^{60}Co treatment room	Physics room
	0.43	0.36	0.50	0.48
	MC derived photon beam skyshine for FF equipped LINAC in nSv/h			
	Control room	Simulator room	^{60}Co treatment room	Physics room
	0.15	0.98	5.4	0.15

agreement can be seen in our calculations comparing to the literature, [3; 10-12; 14; 16; 18; 19; 22; 24-27; 29; 32; 36; 37; 47].

4. Conclusion

Our MC estimations using MC for FF-equipped and FFF LINACs showed a poor agreement with other works' reports. Although the low energy photons are scattered more than high energy photons, hardened photon beams with high energy with low attenuation and scattering in the room inside air and low transmission from the ceiling shield and consequently the presence of lower photons with the low photons may be the main cause of the lower skyshine equivalent dose rate comparing to the FF-equipped LINAC. We concluded that although the high dose rate from the FFF LINAC and FF-equipped LINAC beam, scattering, or skyshine from the FFF the LINAC photon beam was shown lower than FF-equipped LINAC photon beam skyshine and NCRP 151 estimates high skyshin compared to the MC derived results. The authors propose future strong studies on the issue to reveal skyshine dose equivalent dose rate based on NCRP formulation and purposed an improved formulation.

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