ORIGINAL ARTICLE

A Comparison of Conventional Empirical Formula and MCNPX Code in the Estimations of Photon and Neutron Skyshine Rates for an 18MV Radiotherapy Bunker

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Abstract

Purpose: A physical phenomenon, scattering the radiation by the atmosphere above the room to the points at ground level around the linac treatment room is known as skyshine radiation. This study aimed to estimate photon and neutron skyshine from a linac in a high-energy radiation therapy facility.

Materials and Methods: The empirical method of NCRP report 151 and MC simulations were employed to estimate skyshine radiation dose from the 18MV linac photon beam. A linac and its bunker were modeled and skyshine dose equivalent from photons and secondary neutrons were derived and compared in the control room, corridor, sidewalk and, parking.

Results: The photon skyshine dose rates calculations by the MC method varied from 0.43 µSv/h at the sidewalk to 6.2 µSv/h at the control room. The ratios of NCRP to MCNP calculations varied from 3.58 for the corridor to 16.14 for the control room. For the neutron skyshine dose rate at distances shorter than 20m, it was found to be 10.4 nSv/h and the ratios of the NCRP to MCNP were 1.26 at the control room and 3.34 at the sidewalk.

Conclusion: It was concluded that the empirical method overestimates photon and neutron skyshine dose rates in comparison to the MCNPX code. The refinement of the proposed empirical method of NCRP 151 and application of MC methods are strongly suggested for more reliable calculations of skyshine radiations.

Keywords: Skyshine; Monte Carlo; Photon; Neutron.

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1. Introduction

The term "radiation skyshine" refers to the scattered radiation by the air atmosphere molecules above the radiation source room to the points at the ground level around the radiation therapy facility. The skyshine radiation consists of the scattered radiation by the air molecules above the roof and strays to the points around the radiation facility at the ground level. National Council of Radiation Protection and Measurements (NCRP) has explained radiation skyshine in its report No.151 [1] and proposed empirical methods for the photon and neutron skyshine calculations in the radiotherapy facilities.

For medical Linacs operating at energies above 10 MV, (γ,n) and (γ,n) nuclear reactions occur inside the facility. Consequently, secondary neutrons and capture gamma-rays are produced and contaminate the useful therapeutic beam as well as propagating around the linac inside the room [2, 3]. Secondary neutron production in radiotherapy with high energy photon beams through (γ,n) nuclear reaction has been extensively characterized by the researchers [4-10]. According to the reports on the secondary cancer risk estimation, due to the neutron in the X-ray linac radiotherapy, neutron skyshine calculation may be as important as photon skyshine in the radiotherapy facilities [11-15].

There are enormous publications on the skyshine dose rate calculations in megavoltage radiotherapy facilities in the literature [16-27]. Monte Carlo (MC) code calculations [28], NCRP 151 recommended empirical method [3], and experimental measurements are the methods employed for the skyshine calculations in the publications [17, 23, 28-31]. de-Paiva [17] studied NCRP 151 method [3] and focused on the angular dependence of the radiation skyshine and on some terms that appear in the NCRP 151empirical method for skyshine dose rate estimation. de Paiva and da Raso [16] carried out a study on skyshine dose from 6MV and 10MV linacs photon beam. In their study, measured dose-equivalent rates were compared with calculations, and differences between them deviated in one or more order of magnitude. Chaocheng *et al.* [29] used photon beams of the 9MV, 15MV, and 21MV linacs to calculate photo beam skyshine dose rate. They applied an empirical approach, experimental and MC simulation methods. They reported that the measured skyshine dose rate agreed reasonably with the MC method, but a relatively high difference was shown between MC computational results and empirical formulas calculations. McDermott [32], discussed the widely used NCRP 151 formula for the prediction of photon skyshine and showed its shortcoming for photon skyshine dose rate evaluation. They investigated the performance of the NCRP 151 method in photon skyshine dose rate estimation and stated that neutron skyshine must be evaluated separately for estimation of accurate results in the neutron skyshine dose rate. Poor agreement between the skyshine methods is the conclusion of different studies and one or more order of magnitude discrepancy has been reported by different researchers [16, 18, 22, 23, 25, 29, 30, 33]. Rostampour *et al.* [34], assessed skyshine dose rate for two 9MV and 18MV linacs and compared the NCRP method results with the measurements. They reported a considerable disagreement between the measured and the calculated values and stressed the requirement of caution while using the equations available in NCRP 151.

Ladu M *et al.* [35] conducted an investigation and discussed the 5MeV neutron point source skyshine and concluded that the applied formulations and derived results were satisfactory and simple to be used for estimating the neutron lateral emission. They concluded that for a 5 MeV point source, the lower angles counted more neutron fluence than others.

In the current study, the authors aimed to study the photon and neutron skyshine dose rate from the 18MV linac around the linac-based radiotherapy facility and comparing MC simulation results and the NCRP 151 formula.

2. Materials and Methods

NCRP 151 is recommended as an analytical method for the photon skyshine dose-equivalent rate calculation. The method is given in the following Equation.

$$H_M = \frac{2.5\times10^{7}\times\dot{D}\times\Omega^{1.3}\times B_{xs}}{d_i^2 d_s^2} \quad (1)$$

Where HM (nSv/Gy) is the photon and γ-ray skyshine dose-equivalent rate when the field size was set as its maximum size 40×40 cm^2. The gantry orientation is upward so that linac irradiates the ceiling vertically. *D* (Gy/h) shows the linac dose-equivalent rate at 1m in height from the linac X-ray source on the linac central axis. B_{xs} represents the shielding material transmission factor for a photon beam in a certain energy. The shielding transmission factor was calculated by Equation 2.

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

In Equation 2, t and TVLe are the shielding thickness and shielding material equivalent Tenth Value Layer (TVL). The parameter di is the vertical distance from a hypothetical point at 2m above the roof to the linac X-ray source. Additionally, ds is the point of skyshine dose-equivalent rate calculation horizontal distance from the upward linac X-ray source. The constant 2.5×10^7 is a conversion factor of gray (Gy) to nanosievert (nSv). The solid angle in Stradiante is shown as Ω and is calculated by the following Equation.

$$\Omega = 4\, arcsin \frac{a^2}{a^2+4h^2} \quad (3)$$

Where "a" and "h" are the angle between the linac movable jaws side and the central axis of the linac in 40×40 cm^2 and upward mounted gantry, respectively.

2.1. Neutron Skyshine

Application of the high-energy linacs operating at energies higher than 10MV is associated with the secondary photo-neutron production that propagates around the room and contaminates photon beam, out-of-field radiation, and the maze. Secondary neutrons and capture gamma-rays are produced through the (n, γ) and (γ, n) nuclear reactions and contribute to the patient and stuff additional dose-equivalent. NCRP 151 has discussed neutron skyshine and recommended a method for calculation of neutron skyshine dose-equivalent. The method is given below (Equation 4).

$$\dot{H}_n = \frac{0.85\times10^5\times H_{ns}\times\phi_0\times\Omega}{d_i^2} \quad (4)$$

In Equation 3, H_n is the neutron dose-equivalent rate (nSv/h) skyshine when the movable jaws set a 0×0 cm^2 field size for the maximum photoneutron production by downward pointed linac head. H_{ns} in Equation 3 is the ratio of the dose-equivalent 2m beyond the ceiling shield to the neutron fluence incident at the ceiling ($Svcm^2/n$). Additionally, ϕ_0 represents the neutron fluence rate at 1 m from the target (n/cm^2 per h) and the constant 0.85 × 105 includes a conversion from sievert to nano-sievert. Equation 3 was recommended for ds≤20m by NCRP 151. d_i and ds description are the same as the photon skyshine calculation method (Equation 1). Photo-neutron fluence at the linac isocentre (≈1m) is calculated as follows (Equation 5):

$$\varphi = \varphi_{dir} + \varphi_{scatt} + \varphi_{th} = \frac{aQ}{4\pi r^2} + \frac{5.4Q_N}{S} + \frac{1.26Q_N}{S} \quad (5)$$

ϕ_0 includes the direct and fast neutron fluence, and φ_{dir} can be calculated from the linac apparent neutron strength (QN) from Equation 4, and then it is inserted in Equation 3 for estimation neutron skyshine dose rate.

2.2. Monte Carlo Simulation

The MCNPX MC code (version, 2.6.0) [28] was utilized for photon and neutron skyshine dose-equivalent calculations. The main parts of an 18MV Varian 2100Clinac were modeled according to the manufacture's provided data [36, 37]. Target, electron beam, primary and secondary collimators, mirror, heavy bending magnet, flattening filter, and ionization chamber as well as the linac head massive and complex shielding were simulated. Percent Depth Dose (PDD) and Photon Beam Profile (PBP) of the linac beam in 10×10 cm^2 standard field size derived by MC simulation and compared to dataset measured in the water phantom department. For PDD, in the build-up region, the difference of the MC code derived and measured dataset was 1%, at depth of maximum dose (d_{max}) difference reduced to 0.07% and at descending region maximum difference obtained as 1.78%. In the flat part of PBP, dataset difference observed as 0.04%-0.08% and in penumbra site, dataset difference obtained 2%. The linac modeling has been verified in our previous works using the measured data from a real Linac [38]. The linac's bunker also was modeled and using the beam features of NCRP 151, photon and neutron skyshine dose-equivalents were derived. Ordinary concrete (density= 2.35 g/cm^3) was simulated for the bunker's wall and ceiling in the given dimensions. Several calculation points were considered at the control room, sidewalk, parking, and corridors around the linac, and then skyshine dose equivalent rates were tallied. The MC code (MCNPX 2.6.0) internally applies a conversion factor and gives results in terms of Sv/h per initial source particle. The statistical errors of MC results were less than 1% for all simulations. The MC input files were manipulated so that the conversion factors were chosen from International Commission on Radiological Protection (ICRP 74) [39] for neutron and ANSI/ANS 6.1.1 [40] for the photon beam.

3. Results and Discussion

3.1. Photon Skyshine

According to NCRP report 151, TVL1 and TVL_e are the first and equivalent tenth-value layers of the used ordinary concrete (density of 2.35g/cm^3) and in our calculations, their values were obtained as 0.45 m and 0.43 m, respectively [3]. The Bxs was derived for 18 MV linac photon beam as 0.044. Also, Equation 3 was employed for the solid angle calculation considering the field size of 40×40cm^2 and the upward irradiation, the value of 0.1539 Steradian was calculated. The machine's manufacture provided a dose-equivalent rate at a point 1m above the X-ray source as 104.4 Gy/h [37]. Thus, for di parameter, the value of 5 m was taken into account according to the geometry of the simulated treatment room geometry (Figures 1, 2).

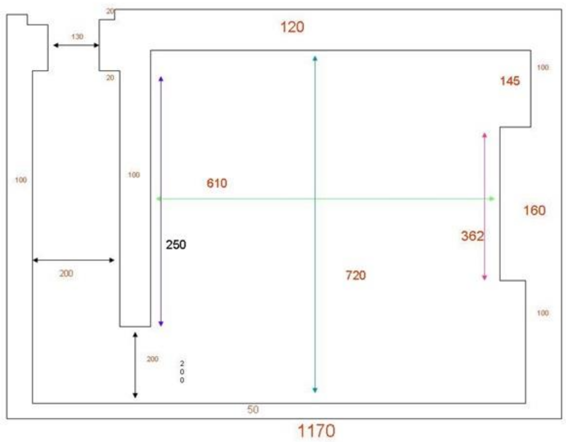


Figure 1. MC simulated treatment room (cross-sectional view), layout, and dimensions in m

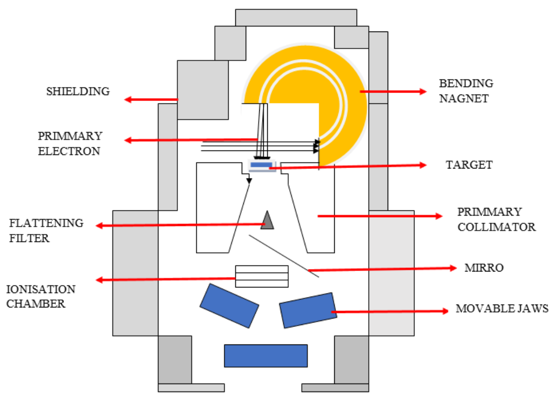


Figure 2. MC modeling of the 18MV Varian 2100C linac for the skyshine dose rate calculation

Equation 1 was used to calculate photon beam skyshine for the control room, sidewalk, corridor, and parking of the facility. MC simulations were performed also for the same locations and data was tabulated in Table 1. According to Table 1, the ratios of NCRP results to MCNP were 16.14, 3.58, 14.2 and, 13.56 for the control room, corridor, sidewalk and, parking of the 18MV linac facility, respectively. It can be seen that the lowest and highest photon skyshine dose rate ratio was obtained for the corridor and control room, respectively. Our MC calculated results were in good agreement with the MC findings of Rostampour *et al.* On the other hand, our NCRP calculations were in line with their NCRP results [34]. The obtained agreements are attributed to the close similarities in photon energy and simulated geometry used in both works. For instance, in an MC study by Chaocheng *et al.* [41], for 9MV, 15MV and, 21MV linacs, the photon beam skyshine rates of 0.270 µGy/h, 1.059 µGy/h and, 0.153 µGy/h were reported respectively for the points inside the distance of 20m from the linac. According to their data, the low dose rate of 21MV linac at 1m from the target may be the cause of the low skyshine dose rate. Our results were in close agreement with the photon skyshine dose rate for 15MV linac in their work [41].

Table 1. Photon skyshine dose rate (µSv/h) around the 18MV linac treatment room calculated by NCRP 151 and MC simulation method

Point of Calculation	MCNP	NCRP	NCRP/MCNP
Control room:6.8m	0.62	10.01	16.14
Corridor:15.1m	0.51	1.83	3.58
Sidewalk 8.4m	0.43	6.03	14.02
Parking:8m	0.46	6.24	13.56

Our results were also very close to the study of Gossman *et al.* [18] in which they concluded that the photon skyshine dose rate rises outside the lateral wall to a maximum and then decreases gradually after the maximum value. da-Rosa and de-Paiva [16] set up an investigation on skyshine dose-equivalent rates for 6MV and 10MV linacs. They measured and calculated the skyshine dose-equivalent rates and differences up to one or more orders of magnitude were found between measurements and calculations. Significant discrepancies between NCRP calculated and measured or MC derived skyshine dose-equivalent were the conclusion of some other publications [16, 18, 22-24, 29, 33, 42] which confirms our results.

3.2. Neutron Skyshine

Neutron source strength (QN) was obtained as 1.3×10^{12} for the simulated linac and it was employed for skyshine dose rate calculations in our study. The calculated neutron source strength was in good agreement with the previous publications [43]. Then, Equation 5 was used and φ_{dir} was calculated from the relation between fluence rate and neutron source strength. H_{ns} was derived from the NCRP report 151 [3] as 3.29×10^{-10} Sv/cm^2 and solid angle was considered as 1 for fully closed field-sized. Because the calculations were made for the same treatment room as photon skyshine derived, the same di was applied for neutron skyshine. The method of NCRP provides neutron skyshine dose equivalent calculation for the points inside the distance 20m from the linac X-ray source. In this work, all points of the calculation were located at shorter distances less than 20m.

MC simulation estimated the neutron skyshine dose-equivalent rates for all locations as 0.23-0.35μSv/h and the highest value was obtained for the control room. Neutron skyshine dose rate was lower at the locations on the outer side of the wall, then, it increased to a maximum value and, where it started to decrease and reached a plateau.

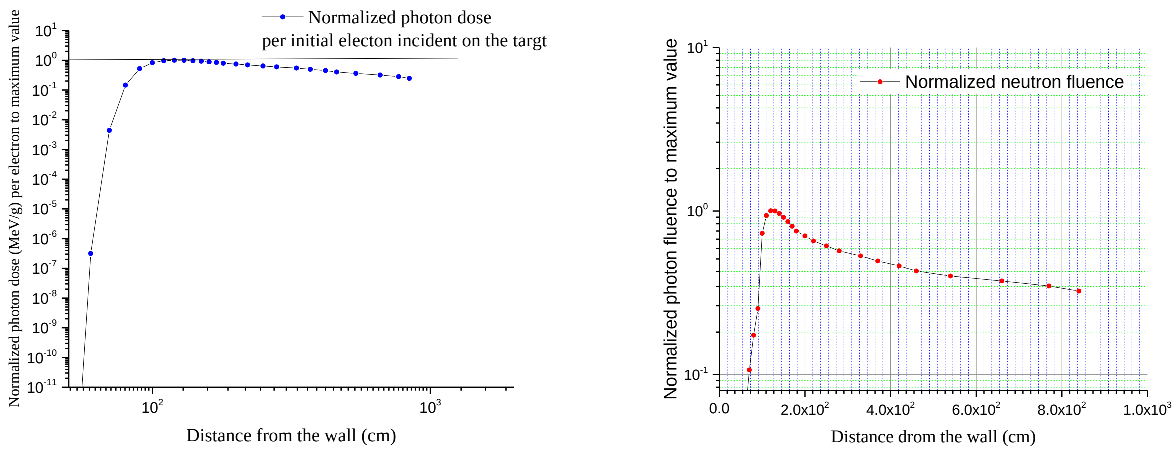
Table 2 shows the skyshine dose rates calculated by the NCRP method and the results obtained by MC modeling. Figure 3 shows the variation of photon and neutron skyshine dose rates outside the room. It was seen that the NCRP method was very simple to implement for the neutron skyshine calculations and it showed a fair agreement with the results of Ladu *et al.* [35].

Table 2. Neutron skyshine dose rate (μSv/h) around the 18MV linac treatment room calculated by NCRP 151 and MC simulation method

Point of Calculation	MCNP	NCRP	NCRP/MCNP
Control room: 6.8m	8.24	10.4	1.26
Corridor:15.1m	3.11	10.4	3.34
Sidewalk8.4m	7.99	10.4	1.30
Parking:8m	7.91	10.4	1.31

4. Conclusion

Photon and photoneutron skyshine dose rates were estimated by MC simulations and the NCRP 151 method. It was found that the empirical method of NCRP 151 is a reliable estimator for rough calculations. However, the NCRP method overestimated the skyshine dose rates remarkably compared to the MC estimations. It can be concluded that the NCRP151 method needs more development and enhancements by adding new parameters for accurate skyshine dose rate estimations. The results of the current study suggest the application of the MC simulations by MCNPX code for skyshine dose rate estimation.



(a) (b)

Figure 3. a) Normalized neutron skyshine trend from the barrier wall derived by MC simulation, b) Normalized photon skyshine trend from the barrier wall derived by MC simulation

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