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Developing a Novel Method for Photon Skyshine Dose Estimation in Radiation Therapy Facilities Compared to the NCRP151 Approach

M. Robatjazi[1], F. Koosha[2], M. Molazadeh[3,4*]

[1] *Department of Medical Physics and Radiological Sciences, Sabzevar University of Medical Sciences, Sabzevar, Iran*
[2] *Department of Radiology Technology, School of Allied Medical Sciences, Shahid Beheshti University of Medical Sciences, Tehran, Iran*
[3] *Medical Radiation Sciences Research Center, Tabriz University of Medical Sciences, Tabriz, Iran*
[4] *Department of Medical Physics, Faculty of Medicine, Tabriz University of Medical Sciences, Tabriz, Iran*

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ABSTRACT

This study aimed to enhance the accuracy of estimating photon beam skyshine dose rates by refining the National Committee on Radiation Protection (NCRP) 151 method. Simulations were conducted using the MCNPX Monte Carlo (MC) code for 6, 10, and 18 MV photon beams of Varian 2300 C/D linear accelerators to estimate the skyshine dose rates of photon beams. The analytical methods of NCRP 151 and our proposed formulation were used to estimate the skyshine dose around the vault. The results of the three methods were compared and analyzed. Our modified method demonstrated improved accuracy compared to the NCRP method and agreed with the MC method under similar conditions and geometries for the linac photon beams. The ratio of skyshine dose rates calculated by NCRP 151 to MC simulation results ranged from 5.39 to 16.59 for 18 MV, 2.25 to 19.20 for 10 MV, and 3.33 to 22.50 for 6 MV linacs. However, employing our derived formula reduced these ratios to 0.91 to 1.22 for 18 MV, 0.92 to 1.10 for 10 MV, and 0.12 to 1.40 for 6 MV machines. Our modified method exhibited good agreement with MC modeling across various conditions. Application of the novel method in different situations and comparison with measurements are recommended for further use in radiation therapy and radiation protection calculations.

INTRODUCTION

Monitoring photon beam dosimetry outside the high-energy megavoltage linear accelerator (linac) bunker presents considerable challenges. These difficulties arise from several factors, including the presence of low-energy and highly scattered radiation, the complexities involved in measurement setup. The need to select appropriate dosimeters that provide adequate responses in these radiation fields, and the occurrence of mixed radiation fields that include low-energy photons and capture gamma rays generated from secondary neutron production [1-4].

Furthermore, ensuring personnel protection from radiation necessitates a thorough understanding of radiation dosimetry. In addition to radiation contamination around the megavoltage linear accelerators, there is considerable concern about the scattering of the primary photon beam from the materials of the roof and walls, as well as from the air, towards peripheral areas of the facility. Addressing these complexities is crucial in radiation protection, and the calculation of skyshine doses has been an important part of radiation safety around radiotherapy facilities [4-9].

In some radiation facilities, minimal shielding is implemented in the ceiling above the accelerator. This can result in radiation scattering through the atmosphere, reaching ground-level points outside the treatment room. This scattered radiation is commonly referred to as skyshine, and methods for calculating skyshine for accelerator facilities are provided by NCRP report No. 151 [4].

*Corresponding author.
E-mail address: mikaeel.mollazadeh@gmail.com
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Researchers in radiological protection and radiation oncology, medical physicists have taken a keen interest in studying the skyshine phenomenon and the photon radiation involved. In the field of radiation protection, various approaches have been utilized, including experimental measurements, Monte Carlo (MC) simulations, empirical calculations, and the formulation of experimental equations [10,11]. These methods aim to enhance the understanding and quantification of the skyshine phenomenon, thereby improving radiation safety practices [3, 12-17].

Chaocheng *et al.* [16], used the MCNP4C MC code for the characterization of the skyshine radiation dose rate estimation produced by linacs in photon energies of 9, 15, and 21 MV. Their primary conclusion pertained to comparing the reported NCRP 51 [6] empirical method with its modified version. They found a significant alignment between the MC results and the measurement data, indicating the validity of their approach. Additionally, they examined the impact of the linac head spectrum hardening effect on the calculation results of skyshine photon beam spectra.

Sheu *et al.* [18] conducted a study on a simplified "integral first collision kernel" method for analyzing gamma-ray skyshine. Their conclusion highlighted the effectiveness of this method as another simple yet accurate technique for skyshine calculations. They emphasized that this method could be easily programmed, further enhancing its practical utility [16]. Paiva *et al.* [10] investigated the photon skyshine from 6 and 10 MV photons by using the NCRP 151 recommended method. They conducted measurements of skyshine photon dose rates from eight different 6 and 10 MV medical accelerators. Each measurement was conducted outdoors, with the beam directed upwards, positioned at a horizontal distance from the target, and using a maximum photon field size of 40 cm × 40 cm at the accelerator isocenter. Comparisons between measured dose-equivalent rates and those calculated from an empirical formula revealed discrepancies that varied by one or more orders of magnitude. Rostampour *et al.* [3] also adhered to NCRP 151 guidelines and conducted measurements to characterize photon skyshine from 9 and 18 MV photon beams. They reported a significant lack of agreement between the calculations and measurements, with the calculated-to-measured ratio ranging from 3 to 16.

Existing literature lacks comprehensive reports on sky shine-measured doses, often showing poor agreement with empirical calculations. Then, in this work, we aimed to improve of NCRP 151 method to modify the method so that its calculated results are reasonably close to measurements and MC results.

METHODOLOGY

The NCRP 151 method

According to NCRP 151, skyshine radiation is defined as the scattering of radiation by atmospheric molecules located above a radiology facility, which can reach ground-level points outside the radiation source room. Various methods, including those recommended by NCRP 151, have been proposed for empirically calculating the air scattering dose beyond the primary source room. Particularly in linac-based radiation therapy, the scattering of photons from the atmosphere above the ceiling to the ground holds significance for the radiation protection of both public and staff working in adjacent areas such as control rooms or corridors. The method recommended by NCRP 151 uses a geometry that was shown schematically in Fig. 1. As illustrated, NCRP 151 suggests that air-scattered photons penetrate from the ceiling to the scoring point outside the room. However, this approach has limitations, as only a portion of the photons is scattered into the scoring point, rather than all photons, and not exclusively at the 2 m elevation above the roof.

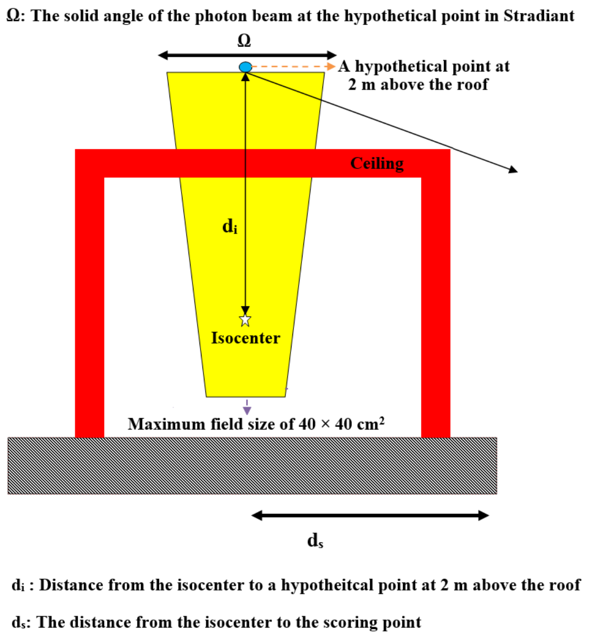

Fig. 1. The simulated geometry of photon skyshine, following NCRP 151 guidelines. It features a linac photon beam directed vertically upward, with a maximum field size of 40 × 40 cm². Key components include the distance from the machine isocenter to a point 2 m above the roof, the solid angle in steradians **Ω**, and the distance to the scoring point.

Skyshine dose equivalent rate at distance d_s is given by Eq. (1):

$$\dot{H} = \frac{2.5 \times 10^7 (B_{xs} \dot{D}_0 \ \Omega^{1.3})}{(d_i d_s)^2} \quad (1)$$

where the constant 2.7×10^7 is the conversion factor of dose equivalent rate ($\dot{H}$) from mSv/h to nSv/h. d_i is the X-ray source vertical distance to a hypothetical point at 2 m above the room roof. $\dot{D}_0$ is the dose rate at a vertical distance of 1m from the X-ray source. $\dot{D}_0$ is geometry independent, and the linac or source characteristic determines it.

B_{xs} and Ω are photon transmission factors for a certain energy and solid angles between the field size side and the vertical central axis, respectively. B_{xs}, according to the NCRP 151 report, is calculated from Eq. (2).

$$B_{xs} = 10^{1+[\frac{(t-TVL1)}{TVLe}]} \quad (2)$$

where TVL_1 and TVL_e are the first and second tenth-value layers of concrete, respectively, and t stands for the ceiling thickness.

Table 1. Modified method and MC calculated photon skyshine, including the ratio of proposed results to MC results

Energy	6 MV		10 MV		18 MV		Eq.4/MCNP 6 MV	Eq.4/MCNP 10 MV	Eq.4/MCNP 18 MV
Method	**Eq. 4**	**MCNP**	**Eq. 4**	**MCNP**	**Eq. 4**	**MCNP**			
Control room **M1:** **d$_s$**=6.3m	0.037	0.3	8.892	8.31	0.696	0.57	1.22	1.07	0.12
Corridor **M2**: **d$_s$**=16.3m	0.018	0.02	0.463	0.50	0.256	0.28	0.91	0.92	0.90
Parking **M3**: **d$_s$**=8m	0.028	0.02	0.674	0.61	0.577	0.60	0.96	1.10	1.40
Side walk **M4**: **d$_s$**=8.1m	0.01	0.02	0.279	0.3	0.564	0.59	0.96	0.93	0.50

Table 2. Photon skyshine calculation with NCRP 151 and MC simulation method for 18 MV linac (mSv/h).

Horizontal distance from the target to the point of calculation	NCRP 151	MCNP5	NCRP 151 /MCNP5 ratio
Control room **M1: d$_s$**=6.4m	9.46	0.57	16.59
Corridor **M2**: **d$_s$**= 16 m	1.51	0.28	5.39
Parking **M3**: **d$_s$** = 8.3m	5.62	0.60	9.36
Side walk **M4**: **d$_s$** = 8.2 m	5.76	0.59	9.76

Target distance to 2 m above the roof (d_i) calculated to be 5.1 m

Table 3. Photon skyshine calculation with NCRP 151 and MC simulation method for 10 MV linac (mSv/h).

Horizontal distance from the target to the point of calculation	NCRP 151	MCNP5	NCRP 151 /MCNP5 ratio
Control room **M1**: **d$_s$** = 4.8 m	18.76	8.31	2.25
Corridor **M2**: **d$_s$** = 10.1 m	4.23	0.50	8.46
Parking **M3**: **d$_s$** = 7 m	5.62	0.61	9.21
Side walk **M4**: **d$_s$** = 15 m	5.76	0.30	19.20

Target distance to 2 m above the roof (d_i) calculated to be 4.2 m.

Utilizing the aforementioned empirical method, we calculated the photon skyshine dose rate ($\dot{H}$) at points M1-M4. The results for photon energy of 6, 10, and 18 MV are presented in Tables 1, 2, and 3. In empirical calculations, TVLs and B_{xs} values are adopted from NCCRP 151. $\dot{D}_0$ value of 104.4 Gy/h cGy/min) was considered, and distances d_i and d_s were also derived from room geometry.

d_i in the room of the 18 MV linac was 5.1 m, and for the 10 and 6 MV bunkers was 4.2 m. Considering the maximum field size (side of 40 cm) and upward position of linac, the solid angle Ω in Steradian (Sr) obtained a constant value of 0.1539 for all calculations. The first and second tenth-value layers (TVL_1 and TVL_e) for 18 MV endpoint X-ray energy reported by NCRP 151 and IAEA No. 47 as 0.45 m and 0.43 m, for 10 MV were 41 cm and 37 cm, and 37 cm and 33 cm for an endpoint energy of 6 MV, respectively. B_{xs} was calculated to be 0.001, 0.0306, 0.044 for 6 MV,10 MV, and 18 MV for 0.6m ceiling concrete shielding from the NCRP 151 recommended formula (Eq. 3), respectively.

Monte Carlo method for skyshine calculations

A MC simulation was conducted so that all parameters were derived from the simulation. The simulated linacs with different energy spectra were derived, and the photon beam spectra for the 6 MV, 10 MV, and 18 MV linacs were illustrated using the MCNP5 MC code, as shown in Fig. 2 (a-c). For spectra deriving F4 tally (particle fluence) of the MCNP5 MC code was used, and narrow bins of energy were defined in which the fluence of photons was estimated. The spectra were estimated 50 cm below the ceiling, and backscattered photons didn't score. In the spectra, only the room inside airattenuated by photons. MCNP5 MC code was employed to simulate a radiotherapy room and a linac model for Varian 2300 C/D. For dose calculations, several spherical cells with a diameter of 10 cm were simulated extending from the room wall to assess the dose rate at varying distances from the room. F6 tally (dose) for photons, which calculates the dose imparted in air in terms of MeV, was used to estimate the air-scattered photons at points peripheral to the bunker and at the points M1-M4.

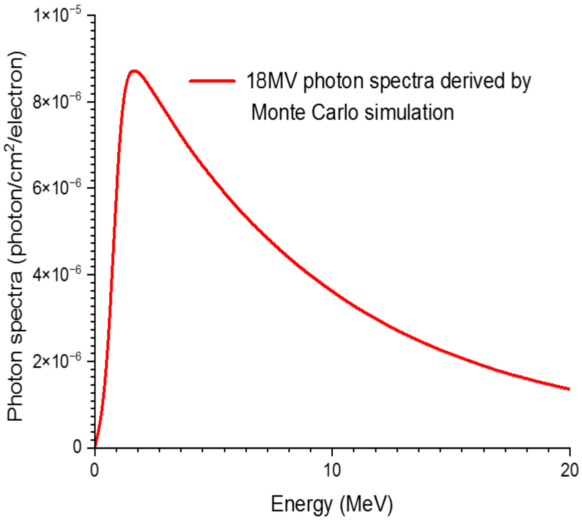

Fig. 2 (a): The 18 MV photon spectra employed by the MC. The MCNP code was used to calculate the photon beam spectra at the isocenter of an 18 MV linac.

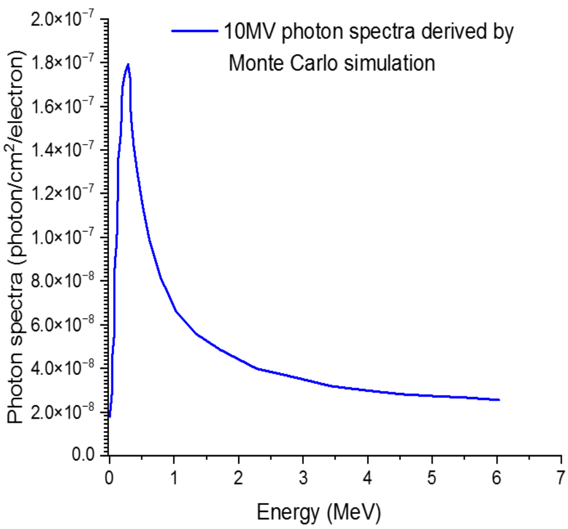

Fig. 2 (b): The 10 MV photon spectra employed by the MC simulation. The MCNP code was utilized to calculate the photon beam spectra at the isocenter of a 10 MV linac.

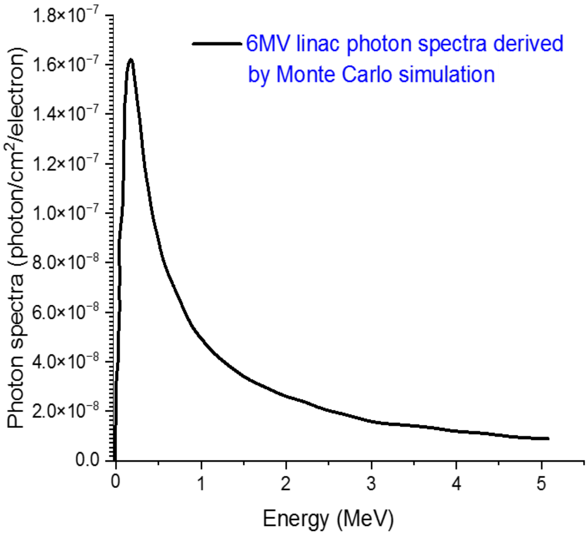

Fig. 2 (c). The 6 MV linac photon beam spectra employed by MC. The MCNP code was used to calculate the photon beam speactra at the isocenter of 6 MV linas.

The room dimensions were 7 × 7× 4 m^3, and the thickness of the primary and secondary walls was 2.8 and 1.5 m, respectively. The thickness of the ceiling was considered 60 cm to check the skyshine dose rate around the bunker. It is important to note that the thickness of the ceiling, serving as a primary barrier, is estimated to be between 2.5 and 3 meters, based on workload and other influencing factors.

The secondary collimators are positioned with a gantry angle of 180° directed toward the ceiling. The field size of 40 × 40 cm^2 was simulated at the isocenter. The point source of the linac irradiates the ceiling with photon energy spectra of 6, 10, and 18 MV, which derived from previous MC studies for the Varian linac.

The medium inside and surrounding the room was modeled as dry air, while the walls were represented as ordinary concrete, in accordance with the data provided by NCRP 144, which has a density of 2.35 g/cm^3. Dry air filling the room and outside simulated as C 0.0124 %, N 75.5267 %, O 23.1781 %, Ar 1.2827 % with the density of 1.20×10^{-3} g/cm^3.

Numerical approximation approach

We simulated the skyshine phenomenon in a typical radiotherapy room with a thin ceiling. Our new method consists of two main steps: a) identifying the effective portion of the air surface that scatters photons toward the calculation point, and b) assessing the attenuation of the forward-scattered photons along a direct path from the effective surface to the dose scoring point. One of the important goals of our numerical approximation method was to remove the part of the scattering air surface above the roof that scatters photons to the peripheral instead of forward. Then, the point of interest directs us to consider a forward scattered space opening by 30° as effective scattering. To achieve this, we utilized a MC simulation where a cylindrical surface recorded the number of photons crossing it in 5° radial bins. This was accomplished by importing Cs for F1 tally, which defines the radial bins by degrees, ranging from -180° to +180° in the input file. Then the ratio of the photons crossed on forward or six 5° bins, so 3 of them were located on each side of a straight line, and in 30° bins, to total scattered photons scattered from the roof above the surface. Derived and effective percent of the surface in forward scattering obtained by calculating the ratio to total photons. In Fig. 3, the is schematically illustrated the method susing the MC model to determine the effective portion of the 2 m upper air surface in forward scattering. Photon scoring was performed in defined small angular bins, with 5° and 30° accepted as this forward direction in this work. Photon spectra before and after transmission through the ceiling, made of ordinary concrete, as well as the attenuation of the ceiling material, were obtained using MC simulation. The result is shown in Fig. 4. In Fig. 4, the 18 MV linac spectra at 10 cm below the ceiling were scored, and backscattered photons were not scored by the code to estimate photons exiting from the linac fluence. Furthermore, the spectra of transmitted photons from the ceiling, measured 2 m above it, were also recorded using the code. This allows for the determination of the number and fluence of transmitted photons passing through the barrier (ceiling).

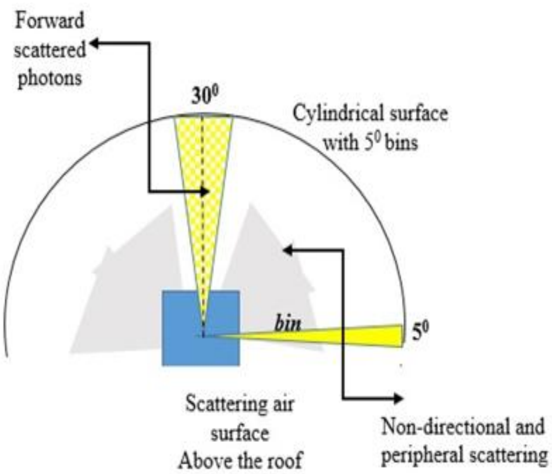

Fig. 3. Schematic view of modeling for forward-directed photons scoring in radial bins. Divergence of scattering at 30° is accepted as forward directed. As seen, F1 tally scored the number of photons in 5° bins and 30° are considered as the forward direction.

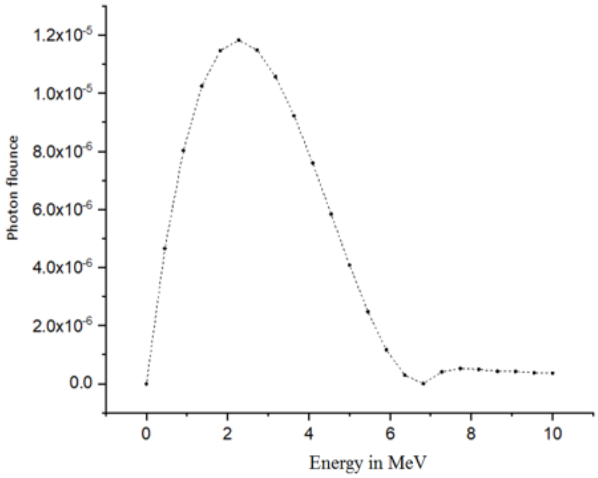

Fig. 4. The 18 MV linac spectra at 10 cm below the ceiling and backscattered photons didn't score.

RESULTS AND DISCUSSION

MC simulations and the empirical methods outlined in NCRP 151 were employed to calculate the photon skyshine dose rates for 6 MV, 10 MV, and 18 MV linear accelerator (linac) photon beams. The photon dose rate at 1 m from the X-ray source (target), denoted as $\dot{D}_0$ in Gy.h^{-1}, was derived from the manufacturer's specifications and incorporated into the analytical calculations. $\dot{D}_0$ for the linacs estimated by MC simulation as 104.09 Gy.h^{-1}, 143.00 Gy.h^{-1}, and 149.86 Gy.h^{-1} while NCRP 151 reported the values 104.4, 142.2, and 150.0 Gy.h^{-1}, and MC estimation difference with MC simulation-derived and NCRP-reported values was negligible.

MC simulation estimated the B_{xs} photon transmission factor for certain energies as 0.0014 (6 MV), 0.0310 (10 MV), and 0.0450 (18 MV) in the upward direction of linacs, with maximum field size 40 × 40 cm^2, and ordinary concrete of 0.6 m. By incorporating the distances d_i and d_s based on the room geometry, the calculated dose equivalent rate, or skyshine dose rate, was determined using data from NCRP 151. In contrast, in the MC code calculations for estimating the skyshine dose rate, all parameter values were derived from simulations, resulting in estimated outcome.

In Tables 1, 2, and 3, the NCRP 151 method calculated skyshine and MC-derived results for the studied energies are tabulated. Schematic view of simplified skyshine geometry and concept, photon beam spectra before and after transmission from the ceiling concrete shielding, and the effect of the concrete on the pattern are also shown in Fig. 4.

In assessing the effect of a 0.6 m concrete ceiling on the linac beam, our MC modeling indicated that 26 % of the linac photons interacting with the inner side of the roof crossed a rectangular surface defined by Ω, with the collimated photon beam exiting the roof shielding in an isotropic pattern. Because of visual tracking of the photons above the roof, we noticed that it may be true, considering half of Ω surface made for effective scattering to the side where the point of photon dose calculations is located. Then we considered the point-side half part of the scattering air surface for dose calculation in point skyshine dose rate estimation. In addition, the scoring of scattered photons, both peripheral and forward, was conducted by estimating values on a cylindrical surface centered at the midpoint and divided into 5° radial bins for F1 scoring. Fig. 3 illustrales the modeled setup used to identify and distinguish between peripheral scattering and scattering directed toward the scoring point. It revealed that around 26 % of total scattered photons crossed on the defined radial bins as forward (total 30° from -15° to +15°), then the effective part of the surface in forward scattering photons was 26 % and the remaining scattered to peripheral points. Considering that 26 % of the air within 2 m above the half of the roof contributes to scattering photons toward each point, a 30° divergences was accepted as the forward on each side. Based on the results, it was deem reasonable to treat 0.13 of the surface area adjacent to the point as the effective forward-scattering source for that point. For dose rate calculations, four points behind the walls were considered. Approximating the scattering from all four points, 0.03 of the surface area was treated as an effective photon source directed toward each point, with the remaining photons scattered to peripheral locations. In Tables 1, 2, and 3, NCRP 151 formulation calculated and MCNP code estimated values of atmosphere molecules scattered photons dose rate at certain points, so-called photon skyshine dose ($\dot{H}$) represented and the difference in methods results discussed.

The Ratio of the photons number with energy upper than 10 MeV to those with energy below 10 MeV obtained as 2.14×10^{-2}, then the photons may be negligible in the skyshine dose while a small dose rate is scored for them.

In Fig. 5, our results were compared to the studies of Paiva *et al.* [12] and Gossman *et al.* [15]. Table 5 shows a comparison of our proposed formulation with Rostampour *et al.* [3].

NCRP 151 recommended that empirical calculation and MC simulation were utilized to photon skyshine dose rate for 6 MV, 10 MV, and 18 MV end-point energies linacs produced photon beams. The parameters used in the calculations for each energy level were explained, and values were adopted from the NCRP report for the analytical approach, alongside MC-derived values for the simulation results. This facilitated a more straightforward comparison and evaluation of the method's capabilities, rather than requiring the same values to be used in both approaches. MC simulated linac operating in 6 MV, 10 MV, and 18 MV energies $\dot{D}_0$ obtained as 104.09, 143.00, and 149.86 $Gy.h^{-1}$ using the MC simulation. The values were in good agreement with the recommended values 140.4, 142.2, and 150.0 applied in analytical calculations, and it may show the precision of our modeling.

Tables 1, 2, and 3 show the MC simulation and the NCRP analytical method calculated photon skyshine for the energies and the linac's own room and distances. The ratio of the NCRP 151 formula calculated skyshine dose rate to MC simulation results for 18 MV observed as 5.39-16.59, 2.25-19.20, and 3.33-22.50 for 18 MV, 10 MV, and 6 MV, respectively. According to the Tabulated results in Tables 1, 2, and 3, our work revealed the NCRP 151 formulation's poor agreement, as some other studies in which the authors concluded that the NCRP 151 formula shows poor agreement with MC simulation and measurements [3, 12, 16, 18].

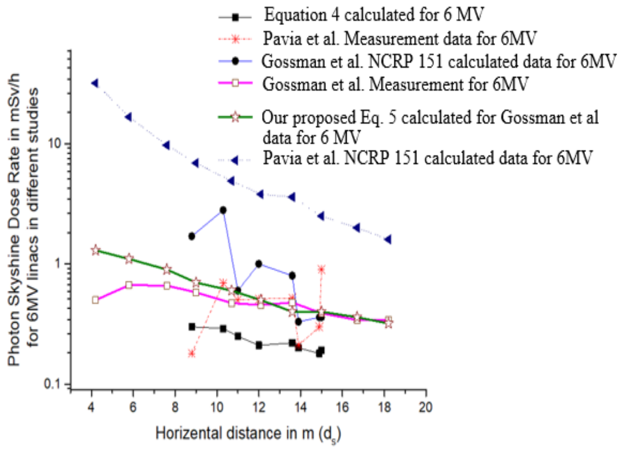

Fig. 5. Our proposed Eq.4 calculated result in photon skyshine dose rate in comparison with the other studied measurement or NCRP 151 calculated data in other works. The works of Paiva *et al.* [10] and Gossman *et al.* [15] were compared with our results.

Table 5. Comparison of our proposed formulation with Rostampour *et al.* [3], NCRP 151 calculated and measured data to compare the Eq. (4) performance for benchmarking it.

Our proposed formula calculated results with Eq. 4 for Rostampour *et al.* [3] data	**4.54**	**9.27**	**6.62**	**14.42**	d_s (m)
	0.9	0.5	0.7	0.2	**9 MV**
	6.3	**8.1**	**8.0**	**16.3**	d_s (m)
	0.7	0.6	0.5	0.3	**18 MV**
Rostampour *et al.* [3], measurement	**4.54**	**9.27**	**6.62**	**14.42**	d_s (m)
	0.6	0.5	0.5	0.4	**9 MV**
	6.3	**8.1**	**8.0**	**16.3**	d_s (m)
	0.6	0.4	0.4	0.5	**18 MV**
Rostampour *et al.* [3] calculated with NCRP 151	**4.54**	**9.27**	**6.62**	**14.42**	d_s (m)
	20.711	4.967	9.741	2.053	**9 MV**
	6.3	**8.1**	**8.0**	**16.3**	d_s (m)
	9.767	5.908	6.075	1.459	**18 MV**

Hertel *et al.* [14] studied skyshine computational and based on two concepts, and calculated by the hybrid method, including the concepts obtained a good agreement in skyshine dose rate calculation in low and high distances [14]. The concepts utilized in the referenced study focused on identifying the effective scattering source rather than applying the total surface area, while also considering a straight beamline for photon scattering to the calculation point. For effective source determination, they used the scattering surface sub-volume and polar angle dependence of scattering to determine escaped photons from the forward straight scattering. An array of 12 points, modeled as small sub-volumes, was characterized based on energy and polar angular scattering dependence, and this array was treated as an effective source of skyshine. By determining the straight beamline and applying these concepts, they achieved favorable results [14]. We believe that both Ω and the distances play significant role in achieving agreement with MC result. This is because Ω represents the scattering source, while the distances di and d_s determine photon attenuation and the path traveled by photons to reach the calculation point. On the other hand, the NCRP 151 formulation is very sensitive to distances, Thus the relation is proportional to $\frac{1}{d_i^2 \times d_s^2}$ in where ds is horizontal distance of linac to the point and its role is not clear in NCRP 151 recommended formula. Chaocheng *et al.* [16] calculated 21 MV and 15 MV photon skyshine, and the MCNP/Experimental ratio obtained around 0.91-1.62 and 1.25-2, respectively.

In Fig. 5, our results were compared to others, showing an overestimation by the NCRP 151 expression. It was concluded that the empirical formula (NCRP method) was not sufficiently accurate, whereas the MC results align well with measurement. In addition, they emphasized the use of MC simulation with variance reduction techniques in complex problems such as skyshine calculation.

In Eq. 1, $\frac{B_{xs}\dot{D}_0}{d_i^2}$ is clear phrase and shows the linac photon dose rate at distance of di after transmission from roof shielding. According to our computed numerical approximations, half of the solid angle contributes to the forward scattering of photons. Only 0.03 of the total surface area, represented by Ώ, was identified as the effective forward-scattering component, producing scattered photons diverging at 30°.

Then considering $\frac{Ώ}{2}$ instead of Ω may be more rational. For beamline, photons scattering from the effective scattering surface to point in straight route which is hypotenuse of triangle made by d_i and d_s. the route or straight beam-line can be calculated from the Eq. (3).

$$d_e = d_i + \sqrt{d_i^2 + d_s^2} \quad (3)$$

where d_e is the photon route from X-ray production to the skyshine calculation point, and photons in air attenuate as $(d_e)^{-2}$.

After considering the approximation and inserting the numerical approximation in the analytical formula, Eq. (4) was obtained, and photon skyshine was evaluated by the approximated method and MC simulation results.

$$\dot{H} = \frac{0.03 \times 2.5 \times 10^7 \times \dot{D}_0 \times B_{xs} \times \times \left(\frac{Ώ}{2}\right)^{13}}{d_e^2} \quad (4)$$

Calculation of photon skyshine by approximated method and MC simulation at the same points M1-M2 and parameter values such as distances and machine characteristics tabulated below in Table 4.

The ratio of the numerically approximated formula to the MC simulation results approaches 1, whereas for the 18 MV, 10 MV, and 6 MV energies, the ratios were higher, as shown in Tables 1, 2, and 3, where the NCRP 151 formula was applied. Our proposed method effectively reduced the discrepancy between the numerically approximated formula and the MC simulation results, making it suitable for use in radiation calculation applications. To verify of our proposed Eq. (4), in Fig. 5, data provided in different studies were used for comparison of the skyshine dose rate in mSv/h, and other reported measurements or calculated data by the NCRP 151 formula are shown in a figure. The figure showed that Eq. (4) proposed in this study is in good agreement with the other researcher's results in photon skyshine dose rate, and NCRP 151 results showed a poor agreement with our results and reported measurements in different distances and energies. Table 4 and Fig. 4 prove Eq. (4)'s better performance in photon skyshine dose rate calculation results and its agreement with measured and calculated data reported by other studies [12,17].

CONCLUSION

Our study presents a novel method for estimating photon skyshine dose rates that significantly outperforms the traditional NCRP 151 approach. The enhanced accuracy of our method can be attributed to improved modeling of scattering and a more thorough consideration of geometry dependence. By focusing on the effective scattering surfaces and the angular distribution of scattered photons, our method provides a more realistic estimation of dose rates in complex environments typical of radiation therapy facilities. This approach is particularly suitable for applications in medical facilities, where precise radiation safety assessments are critical. It can also be effectively utilized in the design of shielding solutions and in conducting comprehensive skyshine analyses to evaluate potential radiation exposure in surrounding areas. We recommend further validation of our method through real-world measurements in diverse clinical settings.

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ETHICAL STATEMENTS

The Research Ethics Committees of Vice-Chancellor in Research Affairs – Tabriz University of Medical Sciences approved the study protocol (Ethic code: IR.TBZMED.VCR.REC.1403.191).

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AUTHOR CONTRIBUTION

M. Robatjazi and F. Koosha equally contributed as the main contributors of this paper. M. Molazadeh is the main author of this research article. He is presently serving as Senior Medical Physicist at Madani Hospital (Radiation Oncology Department). All authors read and approved the final version of the paper.

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