Evaluation of Skyshine Photon Dose Rates using Direct Measurement Method

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ABSTRACT

Background: Skyshine radiation refers to the scattered radiation above the ceiling of medical accelerator rooms that can return to ground level, resulting in potentially increasing the dose rate around the accelerator.

Objective: This study aimed to measure skyshine photon dose rate-based profiles from medical linear accelerator and to then compare measured dose rates with predictions based on the National Council on Radiation Protection and Measurements (NCRP)-151 formula to evaluate its accuracy and applicability.

Material and Methods: In this cross-sectional study, direct measurements were conducted using a survey meter dosimeter in both in-line and cross-line directions outside the accelerator room. An Elekta accelerator operating at energies of 6, 10, and 18 MV was utilized with the field size 40×40 cm². Skyshine radiation dose rates were directly measured under these conditions.

Results: The maximum skyshine dose rate significantly varied across different directions and distances from the accelerator room, while calculations based on the National Council on Radiation Protection & Measurements (NCRP-151) formula exhibited a continuous decrease with increasing distance. The energy range of skyshine photons observed around the treatment room was approximately 200–700 keV.

Conclusion: This study highlights that the skyshine dose rate from medical linear accelerators is highly dependent on beam energy and direction, showing notable deviations from NCRP-151 predictions. These findings underscore the importance of implementing site-specific shielding strategies.

Keywords

Radiation Dosimeters; Linear Accelerators; Radiation Dosage; Skyshine; Photons

Introduction

The equipment of radiation therapy should be designed with strict adherence to safety protocols, particularly regarding radiation protection in areas adjacent to the treatment room. Key factors include occupancy of surrounding spaces, beam direction, and determination of appropriate shielding thicknesses for walls and ceilings [1]. While conventional design practices primarily emphasize wall thickness to mitigate primary and secondary radiation exposure, ceiling shielding is often underestimated. Insufficient ceiling protection can result in elevated radiation levels around the facility, exceeding values predicted by standard shielding calculations. This phenomenon, known as skyshine radiation, is a growing concern in radiation safety [2].

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Skyshine radiation refers to stray radiation generated when high-energy photon beams from Medical Linear Accelerators (LINACs) scatter off the atmosphere above the treatment room roof. The scattered photons can be reflected back to ground level, potentially exposing nearby individuals to unanticipated radiation doses. This risk is especially significant when the gantry is directed upwards, as ceiling shielding may not be sufficient to prevent scattering [3].

The consequences of skyshine radiation are twofold: it can compromise occupational safety for staff and pose health risks to the public. To address this issue, the National Council on Radiation Protection and Measurements (NCRP) has proposed computational and empirical dose estimation methods in NCRP-151 [4]. Gossman et al. [5] further refined these approaches by introducing predictive models for estimating skyshine dose rates based on specific facility configurations. Although widely adopted, these models have been criticized for overestimating dose rates under practical conditions [1, 2, 5, 6].

Several studies have reported discrepancies between dose rates calculated by NCRP-151 formulas and actual measurements, suggesting that these models may not fully account for variables such as beam energy, direction, and shielding material properties [1, 5-13]. These limitations underscore the need for more accurate, site-specific methods to predict skyshine radiation, especially in facilities operating high-energy LINACs.

This study aims to bridge these knowledge gaps by providing detailed measurements of skyshine photon dose rates from medical LINACs operating at 6, 10, and 18 MV. The specific objectives are to measure skyshine dose rate profiles in all major directions outside the treatment room, to identify points of maximum dose rate to better understand the spatial distribution of skyshine radiation, and to compare measured dose rates with predictions based on the NCRP-151 formula for the evaluation of its accuracy and applicability.

This study differs from previous research in several key aspects, as follows: (a) comprehensive measurement approach: unlike earlier studies limited to select directions or simplified setups, this study assesses dose rate profiles across multiple directions and distances, offering a more complete understanding of skyshine distribution, (b) enhanced ceiling shielding: the treatment room features a composite ceiling comprising 125 cm of concrete plus 15 cm of lead, providing a higher level of shielding than typically studied and offering new insights into skyshine behavior in advanced shielding designs, and (c) beam energy variations: by analyzing skyshine dose rates at three photon energies (6, 10, and 18 MV), this study elucidates the relationship between beam energy and skyshine intensity.

The findings have important implications for radiation therapy facility design and safety. By identifying limitations of predictive models and providing empirical data on skyshine behavior, this study contributes to developing more accurate, site-specific shielding strategies essential for protecting staff and the public in high-energy treatment settings.

Material and Methods

A cross-sectional study was performed in one radiotherapy center equipped with Elekta LINAC to measure the skyshine photon dose rates.

a) Treatment room geometry

Measurements were performed for 6, 10, and 18 MV photon beams at a facility equipped with an Elekta Synergy linear accelerator. Figure 1 illustrates the measurement geometry and distances from the isocenter to surrounding walls. It should be noted that Intensity-Modulated Radiation Therapy (IMRT) techniques were not employed in this study.

b) Direct measurement

Skyshine photon dose rates were measured

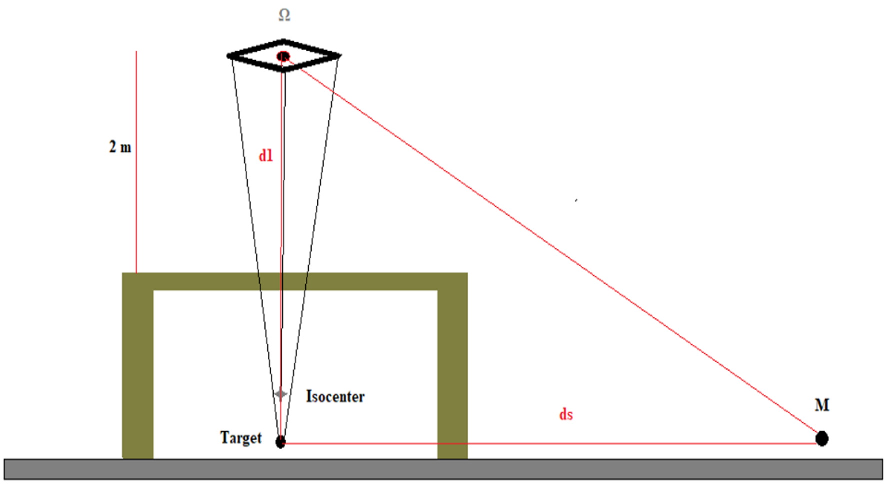

Figure 1: The geometry of treatment room to measure the skyshine photon dose rates.

using a multi-purpose survey meter, pressurized to 8 atmospheres, capable of detecting X-ray and gamma radiation above 25 keV with a dose rate range of 0.01 µSv/h to 50 mSv/h and a chamber volume of 230 cm^3. The device was calibrated for X-ray and gamma rays by the Iran Secondary Standard Dosimetry Laboratory (ISSDL), with an uncertainty better than 10% at a 95% confidence level.

All measurements were conducted at a height of 1 m above ground level near adjacent areas, including the rest room, emergency department, corridor, and physicist room. According to Figure 1, the wall lengths in the directions d_{s1}, d_{s2}, d_{s3}, and d_{s4} are 4.7, 3.9, 6.87, and 2.65 m, respectively.

To assess skyshine shielding, the minimum occupied area was defined as 3 m from the treatment room target, consistent with NCRP-151 recommendations. Measurements were performed on the side, where the dosimeter was closest to the outside wall, starting at a minimum distance of 0.3 m from the wall and increasing gradually. Dosimeter readings, calibrated by Iran Secondary Standard Dosimetry Laboratory (ISSDL), were multiplied by a calibration factor, and the background radiation was also considered.

The photon beam was directed vertically upward with the collimator fully opened (40 cm × 40 cm) at the isocenter for each photon energy. Figure 2 depicts the measurement geometry adapted from prior studies [2, 4-6], where ds represents the horizontal distance from the isocenter to measurement point M, and di is the vertical distance from the target to a point 2 m above the roof. Point M is the nearest point located outside the treatment room that an observer hypothetically located two meters above the roof in the central axis of the beam.

The solid angle Ω formed by the photon beam is calculated by equation 1 [4]:

$$\mathbf{\Omega = 4\sin^{-1} a^2/a^2+4h^2} \qquad (1)$$

where a is the field size side (40 cm), and h is the source-axis distance (100 cm).

Measurements were taken in 1 m increments along four directions (d_{s1}, d_{s2}, d_{s3} and d_{s4}) to explore relationships between dose rates and distance from lateral walls. Leakage dose rates were separately measured at a 0 cm × 0 cm field size, and skyshine dose was calculated by subtracting leakage from total readings.

c) Dose calculation

Dose-equivalent rates [H* (nSv/h)] at horizontal distance d_s from the isocenter were calculated using equation 2 [4, 5]:

$$\mathbf{H^{*}=2.5\times10^{7} B_{xs} D^{*} \Omega/(d_i d_s)^2} \qquad (2)$$

where B_{xs} is the roof shielding transmission

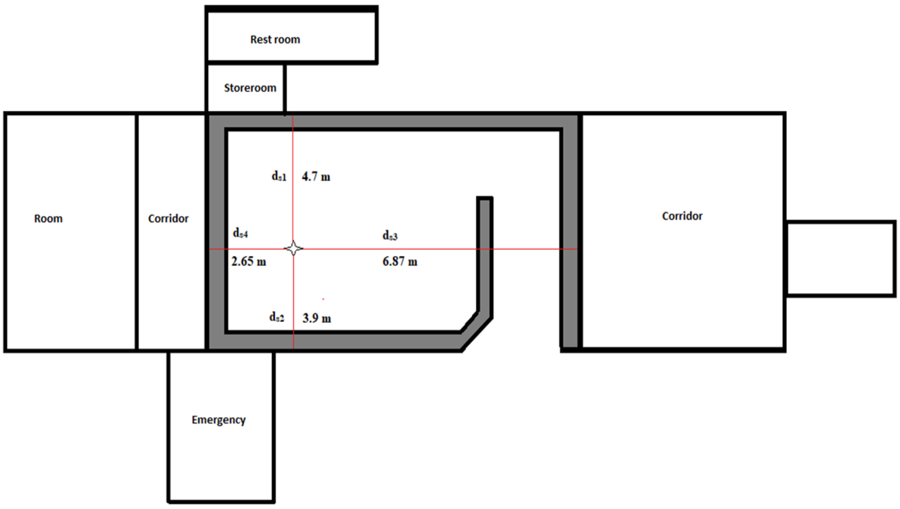

Figure 2: The geometry used to measure the skyshine radiation adjacent to the treatment room.

factor; D^* is the primary dose rate at 1 m from the target (Gy/h), set to 400 cGy/min for 6 and 10 MV, and 600 cGy/min for 18 MV; Ω is the solid angle from equation 1 (steradians); and 2.5×10^7 converts Gray to nano-Sievert (nSv).

The shielding transmission factor B_{xs} is calculated as (Equation 3):

$$B_{XS}=10^{-\{1+[(t-TVL_1)/TVL_e]\}} \quad (3)$$

where TVL_1 and TVL_e are the first and equilibrium tenth-value layers of concrete, respectively [5], and t is the shield thickness (125 cm concrete for walls; for the ceiling, 125 cm concrete plus 15 cm lead).

Dosimeter readings were recorded as dose rates (μSv/h) at varying distances outside the treatment room and converted to nSv/h for analysis. Calculated dose rates using NCRP-151 formula were also converted to nSv/h. Results of measured and calculated values are presented graphically for comparison.

Results

This study evaluated skyshine dose rates around a linear accelerator treatment room for photon beam energies of 6 MV, 10 MV, and 18 MV. Measurements were conducted in four horizontal directions corresponding to adjacent areas: cross-line right (d_{s1}), cross-line left (d_{s2}), in-line right (d_{s3}), and in-line left (d_{s4}), which represent locations, such as the rest room, emergency department, corridor, and physicist room, respectively. Dosimetry measurements were compared to calculations using the NCRP 151 formula. The measurement setup mirrored the NCRP-151 conditions, including a gantry angle of 180° with the beam directed vertically upwards and a maximum photon field size of 40 cm × 40 cm at the isocenter.

Table 1 presents the first and second tenth-value layers (TVL_1 and TVL_e) of concrete and lead for the respective photon energies, calculated using Equation 3. The treatment room ceiling consisted of 125 cm of concrete (density 2.3 g/cm³) plus a 15 cm lead layer. These parameters were used to calculate and measure skyshine dose rates at various points extending outward from the exterior walls in the four horizontal directions around the isocenter (Figure 1). The wall ends at distances of 4.7 m, 3.9 m, 6.87 m, and 2.65 m for d_{s1}, d_{s2}, d_{s3}, and d_{s4}, respectively. Unlike the standard NCRP-151 recommendation, measurements began 30 cm from the wall and increased progressively due to the unique accelerator positioning within the room. This study offers a comprehensive characterization of skyshine dose profiles across all directions outside the treatment room, as opposed to prior studies, which focused on limited distances (Figures 3-6). The main goal was to identify locations of maximum skyshine dose rates. Notably, IMRT was not used in this study, and the ceiling was substantially thicker, featuring a composite of concrete and lead compared to previous research.

Analysis of Results

A) 6 MV Photon Beam

Skyshine dose rates measured by dosimeters in all four directions initially increased with distance from the isocenter, reaching a peak before declining. In contrast, NCRP-151 calculations predicted a continuous decrease with distance. This discrepancy highlights the influence of treatment room geometry, ceiling

Table 1: TVL_1 and TVL_e of concrete and lead for 6, 10 and 18 MV photon energies

Energy (MV)	TVL_1 (m)		TVL_e (m)	
	Concrete	Lead	Concrete	Lead
6	0.37	0.055	0.33	0.053
10	0.41	0.056	0.37	0.054
18	0.45	0.056	0.43	0.054

TVL_1 and TVL_e are the first and second tenth-value layers of concrete & lead

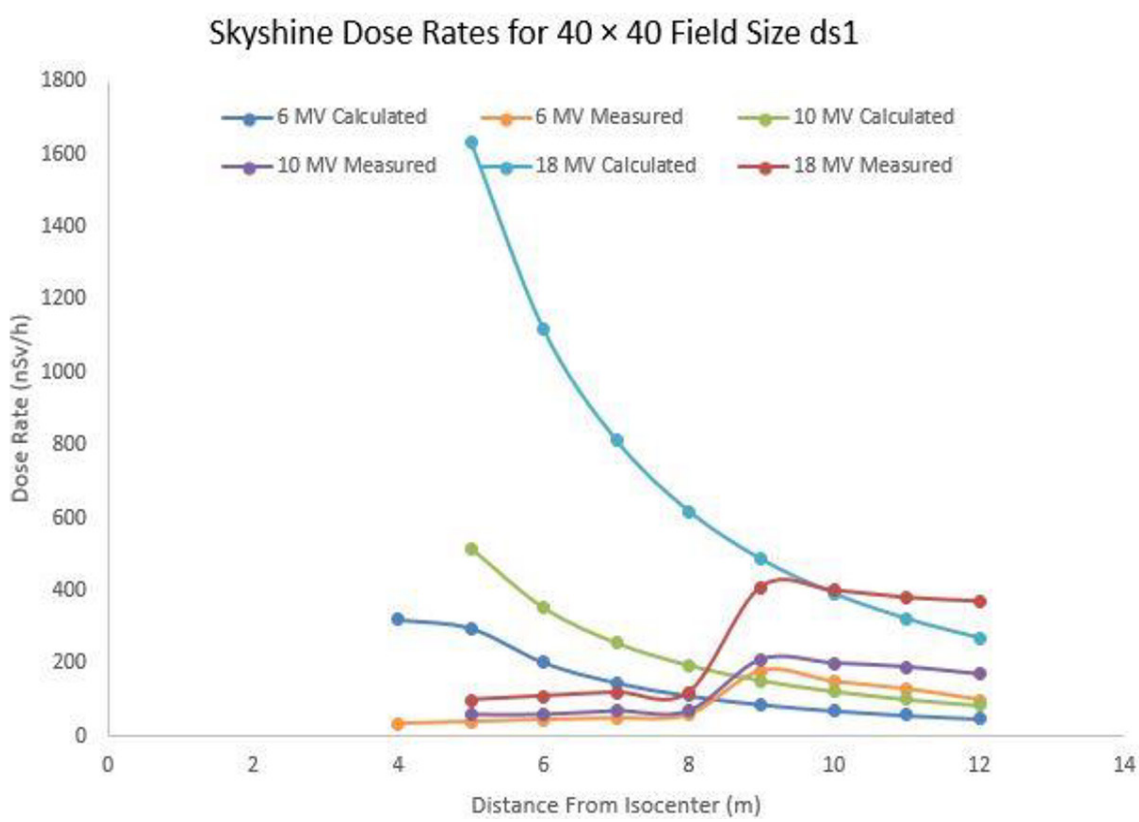

Figure 3: Skyshine dose rates calculated and measured at d_{s1} for 6, 10 and 18 MV and 40 cm×40 cm field size

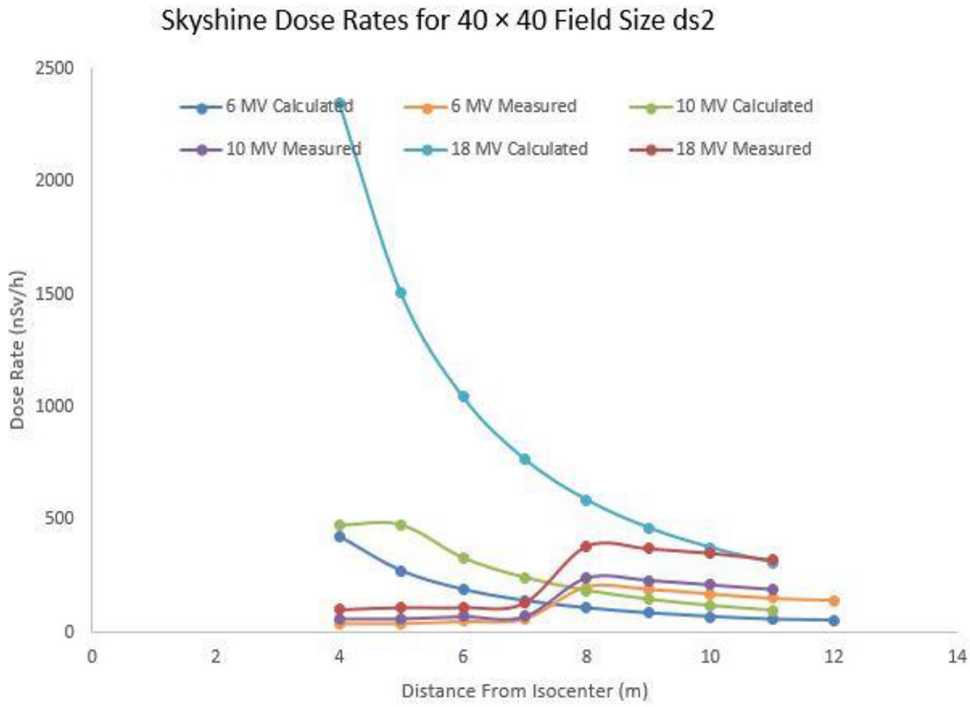

Figure 4: Skyshine dose rates calculated and measured at d_{s2} for 6, 10 and 18 MV and 40 cm×40 cm field size

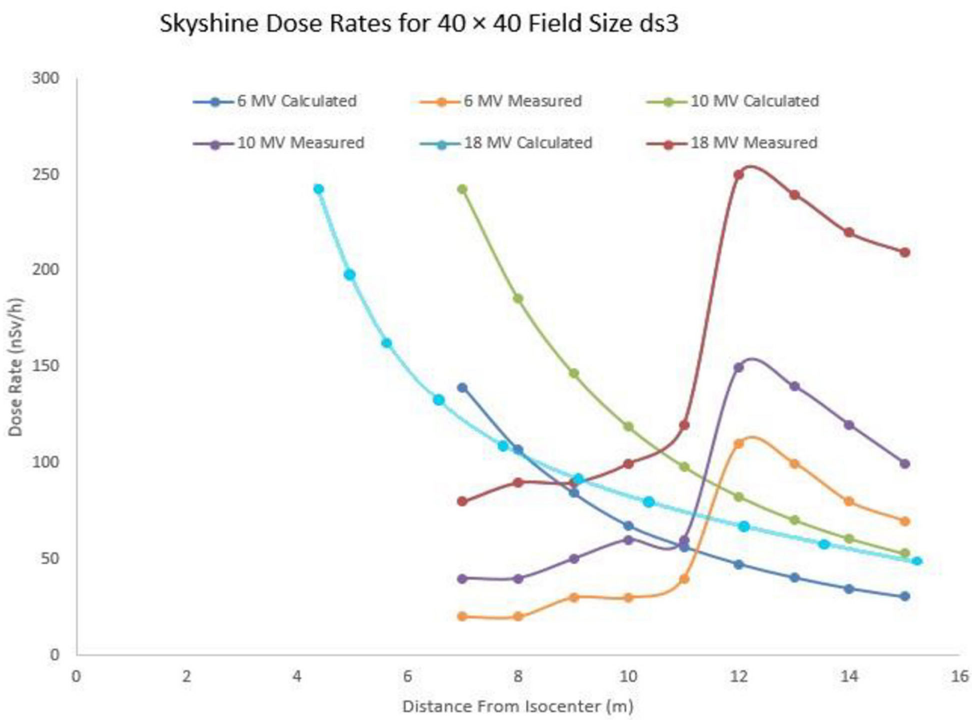

Figure 5: Skyshine dose rates calculated and measured at ds_3 for 6, 10 and 18 MV and 40 cm×40 cm field size

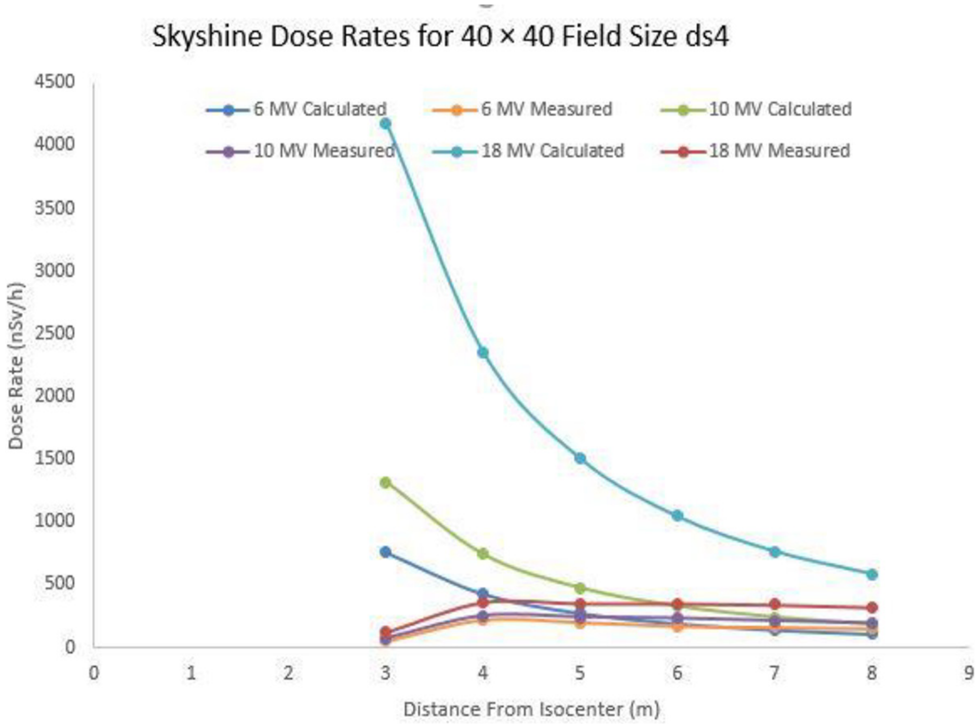

Figure 6: Skyshine dose rates calculated and measured at d_{s4} for 6, 10 and 18 MV and 40 cm×40 cm field size

thickness, and lead shielding. The maximum measured skyshine dose rate was 220 nSv/h at about 4.2 m outside the treatment room in the in-line left direction (d_{s4}). This is substantially lower than the 8640 nSv/h reported before for a 6 MV beam with a 51 cm concrete roof, likely due to the much thicker concrete and added lead shielding in the current study, which effectively attenuates primary and scattered radiation [5].

B) 10 MV Photon Beam

The maximum skyshine dose rate for the 10 MV beam was 250 nSv/h at approximately 4.2 m in the in-line left direction (d_{s4}), higher than the 6 MV results due to the higher transmission coefficient at this energy. Differences between measured and NCRP-151 predicted values likely reflect the specific room geometry. Elder et al. [1] reported a maximum skyshine dose of 20 µSv/h at 11 m, but roof thickness was not specified. The lower dose rates in their study might be related to thinner shielding compared to the 125 cm concrete plus 15 cm lead used here. Variations in roof transmission coefficients could also contribute to these discrepancies.

C) 18 MV Photon Beam

For the 18 MV beam, the highest skyshine dose rate measured was 410 nSv/h at about 8.8 m outside the treatment room in the cross-line right direction (d_{s1}). Again, significant differences were found between measured and NCRP-151 predicted values, likely due to room geometry.

Discussion

Charged particle accelerators play critical roles in research, industry and healthcare. During operation, secondary radiation is produced, which may pose risks to personnel and the public. Understanding the characteristics and quantification of this radiation is vital for ensuring safety. Accelerators are generally classified based on their secondary radiation production: electron accelerators and proton/heavy-ion accelerators. This study focuses on photon skyshine produced by medical linear accelerators.

Calculating photon skyshine equivalent doses is complex, influenced by beam energy, source characteristics, shielding, geometry, and scattering. NCRP Report No. 151 provides an empirical framework for dose estimation, yet these formulas often overestimate skyshine compared to measurements [5].

The following is a series of studies that explored various factors influencing skyshine radiation: Liang T. et al. (2020) showed skyshine decreases with distance approximately following an inverse square law [14]. Their Fluktuierende Kaskade (FLUKA) Monte Carlo simulations modeled neutron skyshine from a 4 GeV electron beam, demonstrating that larger scattering angles correspond to lower photon energies and reduced dose rates, while radiation near the beam direction contributes more to skyshine dose. Eghdam Zamiri et al. (2021, 2023) combined analytical and Monte Carlo methods to assess skyshine from 4 MeV radiation therapy bunkers, comparing Flattening Filter (FF) and Flattening Filter-Free (FFF) LINAC beams [15, 16]. They found higher skyshine doses with FF beams, attributed to beam hardening and increased photon transmission through shielding. Their Monte Carlo simulations provided more accurate dose estimates than NCRP-151, which tended to overestimate skyshine. Uddin et al. (2024) evaluated radiation safety and shielding of a newly installed LINAC in Bangladesh, reporting dose rates compliant with regulatory limits, confirming the shielding adequacy for both conventional and IMRT modes [17].

Other studies have characterized complex radiation environments in accelerator facilities, improving understanding of shielding requirements [18, 19]. Rostampour et al. (2018) and De Paiva (2018) emphasized the influence of beam energy, treatment parameters, and shielding on skyshine photon dose rates, advocating for site-specific assessments [6, 9].

Nariyama et al. (2018) have modeled neutron skyshine from medical LINACs, showing empirical formulas can underestimate neutron doses compared to Monte Carlo simulations and underscoring the need for improved modeling [20].

In this study, we only measured the photon dose rate in different energies because of lack of neutron dosimeter at the facility. Therefore, it was recommended that skyshine neutron dose rate be measured in next studies.

Conclusion

Empirical methods like NCRP-151 are useful but tend to overestimate skyshine doses due to their simplified assumptions. Monte Carlo simulations provide more precise, adaptable assessments, supporting the development of optimized shielding designs and enhanced radiation protection.

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Authors' Contribution

T. Almasi led the analysis and writing of the paper. S. Kasani led the measurements and analysis. G. Mahmoudi contributed to the analysis and interpretation, and N. Rostampour led the project and oversaw the project progress. All the authors read, modified, and approved the final version of the manuscript.

Ethical Approval

This study was approved by Kermanshah University of Medical Science Ethics Committee (IR.KUMS.REC.1398.499).

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Conflict of Interest

None

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