ORIGINAL ARTICLE

Skyshine Dose Estimations for an 18 MeV Photon Beam Using MCNPX Code: A Comparison of Flattened and Flattening Filter-Free Beam

Mohammad Mohammadzadeh [1,2], Hosein Ghiasi [1,*]

[1] *Medical Radiation Sciences Research Team, Tabriz University of Medical Sciences, Imam Hospital, Tabriz, Iran*

[2] *Department of Radiology and Radiotherapy, School of Medicine, Tabriz University of Medical Sciences, Tabriz, Iran*

*Corresponding Author: Hosein Ghiasi
Email: hoseinghiasi62@gmail.com

Received: 04 March 2021 / Accepted: 17 May 2021

Abstract

Purpose: The current study aimed to estimate photon skyshine dose rate from a Varian linac equippedwith a Flattening Filter (FF) and its FF-Free (FFF) mode. The skyshine photons from a Linac bunker can influence the radiation dose received by personnel and the public in radiation therapy centers.

Materials and Methods: In the current study skyshine dose from the conventional flattened beam and the flattening-free beam were compared. The MCNPX Monte Carlo code was used to model an18 MeV photon beam of Varian linac. The skyshine radiation was calculated for FF and FFF linac photon beams at the control room, parking, sidewalk, and corridor around the linac room.

Results: For the conventional beam, the skyshine dose rates of 0.53, 0.42, 0.45, and 0.50 mSv/h were estimated for the control room, corridor, sidewalk, and parking, respectively. While for the FFF beam, dose rates of 0.21, 0.20, 0.20, and 0.23 mSv/h were estimated for the same positions, respectively. The results indicated that the empirical method of NCRP 151 can not distinguish between FF and FFF beams in skyshine dose calculations. Our results found a 50% lower level dose rate from the FFF beam at distant and nearby locations.

Conclusion: The findings of current can be helpful in the radiation dose calculations and the radiation protection designation of radiation therapy bunkers.

Keywords: Photon; Skyshine Dose; Flattening Filter-Free; Radiation Protection; Radiotherapy.

DOI: https://doi.org/10.18502/fbt.v8i3.7117

1. Introduction

Report no. 151 of the National Council on Radiation Protection and Measurements (NCRP) is widely used in the design of shielding in radiological facilities [1]. A contaminant and undesirable radiation, the so-called radiation skyshine, was investigated in the literature for the radiotherapy treatment room by different researchers. According to NCRP 151, skyshine radiation is the radiation scattered by air above the room to the points at the ground level around the radiation source house [1,2].

A guideline was formulated for the skyshine affecting parameters and introduced an empirical formula in report 51 and by some modifications, it was presented in the recent report no. 151 [1,2]. Overestimation of the proposed method was the conclusion of different publications [3-16]. Different researchers examined it by the Monte Carlo (MC) code calculations, direct measurements, and different linacs with energy range from 6MV to 25MV [6-16].

Paiva *et al.* [6] used 6MV and 10MV photon beams for the measurement and calculation of skyshine dose rate. NCRP 151 recommendation was employed to skyshine calculation and experimental measurement was conducted in their study. In conclusion, the linac leakage photon beam was less than 1% and only one of the uncontrolled locations received a dose rate more than the permissible dose. Also, a poor agreement between measurements and the NCRP method was obtained. Gossman *et al.* [12] conducted a study on the photon skyshine and their main conclusion was that the maximum value of the skyshine was seen in a maximum field of 40×40 cm^2 and 4.2m from the barrier. They recommended the use of maximum field size in the calculation of the skyshine dose rate. In another study [13] they discussed the skyshine dose rate and its dependence on the other parameters such as distance and solid angle. Rostampur *et al.* [14] employed NCRP formalism to skyshine detection around the linac house and reported overestimation of NCRP in comparison to measured skyshine dose rate. Different researchers conducted MC simulation, direct measurement, and analytical or methods together and concluded NCRP method overestimation comparing to other methods [3, 8, 10, 12, 13-19].

We aimed to evaluate the impact of a flattening filter on the photon beam skyshine dose rate around a concrete-made linac house. We used the MC simulation and NCRP 151 recommended method to investigate the skyshine dose rate for the 18 MV flattened and unflattened photon beams.

2. Materials and Methods

MCNPX Monte Carlo code (version, 2.7.0) was employed for simulations and calculations in the current study. A variety of particles and photons with a wide energy range can be transported by MCNPX code and microscopic properties of the materials and radiation interactions can be simulated. The MCNPX code is capable of simulating different and complex surfaces and geometries as well as materials compositions. Rich physics libraries of the code allowed us to simulate photon and other particles' interactions with the materials and estimate radiation characteristics. In total, 9×10^{10} primary electrons were initiated to bombard the tungsten target for bremsstrahlung X-ray production. Thin target with its support and electron stopper, primary and secondary barrier, FF, Beryllium mirror, ionization chamber, multi-leaf collimators, and movable jaws were simulated according to manufacturer's provided data. Primary electrons distribution was modeled as Gaussian with FWHM of 1mm along the X and Y axes. The linac model was validated by deriving Percentage Depth Dose (PDD) and Photon Beam Profile (PBP) curves in the water phantom with the dimension of 50 × 50 × 50 cm^3 and comparing the results to the measurements. The verified linac head model was in an upward direction so that it irradiated the room ceiling with a central axis perpendicular to the ceiling surface.

NCRP no.151 report was followed to estimate skyshine dose rates from the linac photon beams. As the report recommended, the photon beam was irradiated in its maximum field size (40 × 40 cm^2) and the dose rate of the photon beam was derived at the isocenter located at the distance of 1m from the X-ray source. A standard room made of ordinary concrete and 60 cm ceiling was simulated and inside and outside of the treatment room were filled by dry air.

According to the NCRP no.151 definition, photon skyshine radiation arises from the air molecules above the room which scatter the impinging photons to the points at the ground levels around the room as shown in Figure 1.

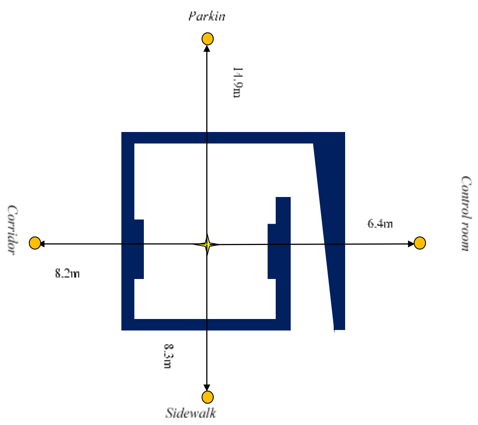

Figure 1. The schematic representation of the simulated 18MV linac treatment room and skyshine dose rate estimations by detectors at different distances from the X-ray source

The analytical method recommended for photon beam skyshine calculation is as follows (Equation 1) [2].

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

Where, $\dot{H}$and $\dot{D}$ represent photon skyshine dose rate in (nSv/h) and photon dose rate at 1m from the X-ray source in (Gy/h). Ω is the solid angle from the maximum field size d_i and d_s stands for distance from the X-ray source to a *hypothetical* point on the linac central axis and 2m above the roof and detector, respectively. B_{xs} is the shielding transmission factor for photon beams. The constant value includes the conversion of the result to nSv/h. B_{xs} was recommended to be calculated from the shielding first and Tenth Value Layer (TVL) according to the Equation 2.

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

TVL_1 and TVL_e were obtained and by inserting t the shielding thickness, B_{xs} was calculated for FF and FFF photon beam spectra (Figure 2).

Monte Carlo estimation was conducted to calculate the photon beam dose rate at 1m from the linac target. To convert the results into Sv/h per initial source particle (Sv/h/e_0), the input file was manipulated and parameters of "ic" and "iu" for scoring tally were set as 40 and 2, respectively. Then, ICRU report no. 74 was used and ambient dose equivalent conversion factor was applied to calculate the results in terms of Sv/h e_0. A surface was simulated at a distance of 1m above the roof to register all photons and particle histories. This Phase-Space surface was used as the primary source in the second program running. Photon skyshine dose rates were scored for both FF-equipped and FFF photon beams at the points around the room with a statistical error of ≤ 1% which is acceptable in photon dosimetry. As shown in Figure 1, the points of calculation and distances of the detectors from the linac head were represented. The results of both methods for photon skyshine dose rates at the shown points were tabulated in Table 1.

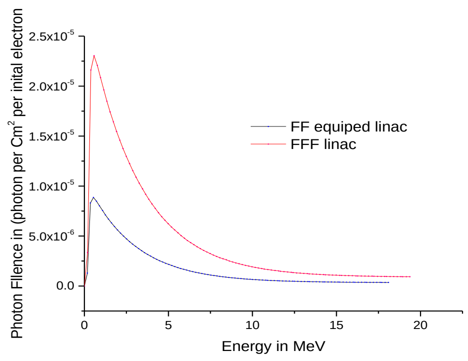

Figure 2. MC derived FF and FFF linac photon beam spectra. The photon beams spectra derived at 1m from the upward positioned linac for each FF

3. Results and Discussion

Our modeling had been verified in our previous works and in this investigation the benchmarked and verified linac model was applied to calculations. MC code calculations and empirical approaches (NCRP no.151) were employed to characterize skyshine dose rate from the FF-equipped and FFF 18MV linac at the points on the ground level around the room. Photon dose rates for FF-equipped and FFF linacs were estimated at 1m from the X-ray source for a field size of 40 × 40 cm^2 as 8.08 × 10^{-13} Sv/h/e_0 and 1.45×10^{-13} Sv/h/e_0 respectively. According to the results, removing the FF from the photon path increased the dose rate by as much as 1.80 times compared to the flattened beam. The number of photons crossing on the surface at the distance of 1m from the target and at the inner surface of the ceiling scored as 2.81×10^{-2} and 5.52×10^{-3} photons / initial e_0 for flattened and FFF modes, respectively. MC-derived photon spectra of FF and FFF photon beams revealed a slight photon energy shift to higher energies in the FF-equipped mode. The ratio of photons crossed the surface at 1m from the X-ray source relative to the inner surface of the ceiling was approximately 5. It means a significant attenuation and decrease in the fluence of photons was received by the ceiling.

Photon skyshine dose rates were estimated at different points and their distances are shown in Figure 1 for FF and FFF 18 MeV photon beams. According to Equation 2, Bxs was calculated by inserting the concrete first and second TVLs as 45cm and 43cm and ceiling thickness, and then Bxs was calculated to be 0.044. The photon dose rate at 1m was considered as 174 cGy/min or (104.4 Gy/h) in the empirical calculations according to the manufacture's provided data. As photon dose rate and skyshine dose rate were estimated per initial electron, then we present the skyshine results in nSv/h in MC simulation. Both MC and NCRP calculated skyshine dose rates were presented in Table 1.

According to the MC-derived results, the photon dose rate of FFF mode at 1m increased by a factor of 1.8 times compared to FF-equipped mode that shows our FFF and FF linac photon beam modeling was accurate enough for calculations [15]. The linac modeling was verified by comparison of MC-provided PDD and PBP dataset with measurements and our modeling accuracy was verified and benchmarked in our previous work [11]. There were several studies on photon skyshine calculation and measurement. Their results indicated inaccuracy of the NCRP method compared to measured values [6 -9, 15-21]. Photon beam skyshine has been assessed for different linacs photon beams with different energies [1, 4, 5, 14, 20, 22-25]. Chaocheng *et al*. calculated photon skyshine dose rate from 9MV, 15MV, and 21MV linacs and, according to their results derived by MC simulation, analytical NCRP calculation and, experimental methods, it can be deduced that photon skyshine has been affected by photon beam spectrum and characteristics and, linac structure and materials. They revealed the effect of the "spectrum-hardening" effect and photon beam average energy on the photon skyshine dose rate from the linacs. Linac massive shielding, the average energy of photons, and the "spectrum hardening" effect reported as some parameters affecting the linacs skyshine at a point [21].

McDermott investigated the widely used formula for the prediction of photon skyshine presented by NCRP 151 and it was shown by the researcher to be very inaccurate by comparison with numerous measurements so that discrepancies of up to an order of magnitude have been observed [22]. The poor agreement of NCRP 151 formula calculation results is the conclusion of different publications [6, 12, 14, 23-26]. The physical phenomenon, the skyshine scatter component was reported to increase to a peak dose value at 4.6 m from the maze barrier for the largest field size and according to their measured skyshine dose rate derived for the field sizes from the fully closed field size for the leakage photon dose rate estimation to the highest 40×40cm^2 field size and they recommended that the largest field sizes be used in the field for the description of skyshine effect and recommended that the peak value be further examined and analyzed specifically in the shielding design considering [12]. According to their study and results, it can be seen that the peak value of photon skyshine occurs around 1m closer for the highest field size comparing to the fully closed field size and skyshine is higher for the largest field size [12].

McDermott [22] characterized photon scattering from a point above the ceiling to the point of photon skyshine dose calculation as a function of the number of scattering centers, fluence rate, or the number of incident photons per unit area per unit time, and, the differential cross-section for Compton scattering. They formalized photon

Table 1. MC simulated and analytical calculated FF and FFF photon beam skyshine dose rate in(mSv/h) from an 18MV Varian 2100 Clinac

Location	Control Room	Corridor	Sidewalk	Parking
NCRP calculation for FF photon beam	25.74	8.50	8.29	13.52
MC estimation for FF photon beam	0.53	0.42	0.45	0.50
NCRP calculation for FFF photon beam	9.19	3.03	2.96	4.82
MC estimation for FFF photon beam	0.21	0.20	0.20	0.23
MC/NCRP ration for FF photon beam	0.02	0.04	0.05	0.03
MC/NCRP ration for FFF photon beam	0.02	0.06	0.06	0.04

scattering from the air atmosphere small volume unit as the relation is given by the Equation 3 [22].

$$\Delta\dot{N}_s = n\dot{\varphi}\frac{d\sigma}{d\Omega}\Delta\Omega \quad (3)$$

Where, $\Delta\dot{N}_s$ shows the number of photons scattered per unit time toward a point of photon skyshine dose rate calculation that is determined by the number of scattering centers (n), photons fluence rate at a point above the room donated by $\dot{\varphi}$, and differential cross-section for Compton scattering as shown by $\frac{d\sigma}{d\Omega}\Delta\Omega$. As photon skyshine description by McDermott [22], scattering centers are small volumes centers that photon scattering originates from the volume units above the roof in the air atmosphere. Considering the Equation 3 description, n or number of photon scattering centers may increase by more transmission of photons from the ceiling shield to the air atmosphere above the roof. The photons' capability of penetration and transmission from the ceiling shield depends on the energy of the photon and increasing the photon beam average energy, photons transmission through the ceiling material increases and consequently the number of photons scattered per unit time toward a point of photon skyshine dose increases. It may be concluded that MC simulation has made complicated calculations and the effect of the photon spectrum hardening, field size, dose rate and, other parameters affecting photon skyshine have been considered in the calculations together. Decreasing of FFF skyshine may be attributed to the photons' low energy, decrease in scattering centers at air atmosphere above the roof, consequently, decrease in photon fluence rate at the air above the roof dose determines scattering level toward the skyshine calculation point at time unit. On the other hand, MC calculated result is the result of different microscopic phenomena considering in the calculation and is complicated.

In these studies, the effect of field size, distance from the X-ray source, and some modifications such as solid angle definition were reported. They revealed that by increasing the field size, the photon skyshine dose rate rises, and the maximum dose rate was reported for 40×40 cm^2 field size.

Our results of photon beam skyshine for the FF linac showed a good agreement with the literature. Overall, a higher dose rate of FFF at the isocenter and higher intensity of low-energy photons at the isocenter was in agreement with the previous publications [17, 25-44]. It is completely attributed to the absence of a flattening filter which its presence removes the soft and low energy photons consequently causes "beam hardening" in the photon energy spectra. In Table 1, it is clear that the FFF photon beam skyshine is considerably lower than that of the FF photon beam. The contribution of more low-energy photons in the FFF mode can be the cause of the lower skyshine dose rate found around the treatment room. In other words, softer energy spectra of FFF mode are highly attenuated by the ceiling. Considering the microscopic interactions of photons with atmosphere molecules, shielding materials atoms, and other complicated physical phenomena, it may be said that the skyshine phenomenon consists of complex parameters and only the resultant of the effects has been reported in the calculations. It seems that an increase in the photon's average energy due to the spectrum-hardening effect by FF, removing the low-energy photons from the spectrum, and the presence of FF in the linac collimation system maybe some of the effective parameters in the photon skyshine difference. Our calculations revealed 1.51 and 1.48 times higher scattering in FF mode at 30cm and 50cm below than ceiling lower surface comparing to FFF mode of the linac irradiation. On the other hand, the number of photons scored by the F_1 tally of MCNPX code showed 1.98 times increasing in the number of photons that transmitted from the ceiling shield at 30cm above the roof in FF mode of the machine irradiation in the upward mounted position comparing to the FFF mode of the linac irradiation in same conditions. Increasing in the photons below the ceiling may be attributed to the photons scattering and backscattering due to the ceiling shield and 1.98 times higher photons number at 30 cm may also be because of photon beam high average energy in FF mode irradiation due to FF photon beam spectrum hardening. The presence of FF in the photon beam path may be considered a scattering source as a part of the linac collimation system and cause photon beam spectrum hardening effect. Then, this study revealed that FF in the linac increases photon beam scattering and average energy.

4. Conclusion

In this study, MC simulation and the analytical method of NCRP 151 were employed to skyshine doses from FF and FFF photon beams. Our results revealed the overestimation of the NCRP 151 analytical method, while MC simulated results showed a good agreement in FF mode comparing to previous similar studies. Additionally, in FFF mode, the dose rate at the isocenter was higher than the FF mode of the linac. In contrast, FF skyshine was higher than the FF mode of the linac operation. These results may be attributed to beam hardening of the FF mode and more attenuation of the FFF beam by the ceiling shield due to lower energy photon beam spectra. If it is considered a simple interaction and only dose rate or energy of photon beam be considered, the result may not be sufficiently accurate. Then, we should take different effects of FF on the photon beam characteristics into account, and complex interactions and consequently resultant of complicated physical phenomena determines the FF presence and absence effect.

The findings of the current study can be useful in the designation of new bunkers for linacs with FFF modes. Also, by confirmation of our findings through experimental evaluations, it would provide fruitful information for preparing new guidelines for the estimation of skyshine radiation and its protection.

References

1-A. ARONSON and R.L.FRENCH, "Air, Ground, and Structure Scattering of Radiation, Reactor Handbook, Shielding,", *Wiley-Interscience, New York, New York*, 2, ed.,1962.

2-Bethesda, MD. "Structural Shielding Design and Evaluation for Megavoltage X- and Gamma Ray Radiotherapy Facilities." *NCRP*, 151, 1-257, 2005.

3-Choi CH, Park SY, Park JM, Chun M, and Kim JI. "Monte Carlo simulation of neutron dose equivalent by photoneutron production inside the primary barriers of a radiotherapy vault." *Medical Physics*, 48, 1-5. 2018.

4-E. de Paiva and L. A. R. da Rosa, "Skyshine photon doses from 6 and 10 MV medical linear accelerators," *J Appl Clin Med Phys*, 13, 3671, 2012.

5-dePiva Elderado. "A Comment On The Photon Skyshine Radiation In The Vicinities Of Radiotherapy Facilities Rooms." *International Journal of Engineering Inventions,* 7(4), 28-13, 2018.

6-dePaiva E and da Rosa LAR. "Skyshine photon doses from 6 and 10 MV medical linear accelerators." *Journal of Applied Clinical Medical Physics*, 13, 215-219, 2012.

7-Dowlatabadi H, Mowlavi A A, and Ghorbani M. "Monte Carlo Simulation of Siemens Primus plus Linac for 6 and 18 MV Photon Beams." *J o Biomedical Physics and Enginering*, 7[4], 333-346, 2017.

8-Eduardo De Paiva. "A Comment On The Photon Skyshine Radiation In The Vicinities Of Radiotherapy Facilities Rooms." *International Journal of Engineering Inventions,* 7[4], 28-32, 2018.

9-Elder DH, Harmon JF, and Borak TB. "Skyshine radiation resulting from 6 MV and 10 MV photon beams from a medical accelerator." *Health Physics*, 99[1], 17-25, 2010.

10-Elder DH, Harmon JF, and Borak TB. "Skyshine radiation resulting from 6 MV and 10 MV photon beams from a medical accelerator." *Health Physics*, 99, 17-25, 2010.

11-H. Ghiasi and A. Mesbahi, "Monte Carlo characterization of photoneutrons in the radiation therapy with high energy photons: a Comparison between simplified and full Monte Carlo models," *Int J Radiat Res*, 8, 187-193, 2010.

12-Gossman MS, McGinley PH, Rising MB, and Pahikkala AJ. "Radiation skyshine from a 6 MeV medical accelerator." *Journal of Applied Clinical Medical Physics*, 11, 259-264, 2011.

13-Gossman MS, Pahikkala AJ, Rising MB, and McGinley PH. "Providing solid angle formalism for skyshine calculations." *Journal of Applied Clinical Medical Physics*, 11, 278-282. 2010.

14-M. S. Gossman, P. H. McGinley, M. B. Rising, and A. J. Pahikkala, "Radiation skyshine from a 6 MeV medical accelerator," *J Appl Clin Med Phys*, 11, 259-264, 2010.

15-GUI AA, hultis JK, and AW RE. "Neutron Skyshine Calculations with the Integral Line-Beam Method." *NUCLEAR SCIENCE AND ENGINEERING*, 127, 230-237, 1997.

16-Hertel NE, Sweezy JE, Shultis JK, Warkentin JK, and Rose ZJ. "A comparison of skyshine computational methods." *Radiat Prot Dosimetry. Radiation Protection Dosimetry*, 116[1-4], 525-533, 2005.

17-John Meyer, "IMRT, IGRT, SBRT: Advances in the Treatment Planning and Delivery of Radiotherapy," *Karger Medical and Scientific Publishers*, 2011.

18-Joo-Hee O, Nam-Suk J, Hee-Seock L, and Seung-Kook K. "New estimation method of neutron skyshine for a high-energy particle accelerator." *Journal of the Korean Physical Society*, 69, 1057-1064, 2016.

19-Kong C, Quanfeng L, Huaibi C, and *et al.* "Monte Carlo method for calculating the radiation skyshine produced by electron accelerators." *NuclInstr Methods Phys Res*, B. 234, 269-274, 2005.

20-M. LADU, M PELLICCIONI, P. PICCHI and G., "A CONTRIBUTION TO THE SKYSHINE STUDY." *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms,* 62, 51-56, 1968.

21-C. Kong, Q. Li, H. Chen, T. Du, C. Cheng, C. Tang, L. Zhu, H. Zhang, Z. Pei, and S. Ming, "Monte Carlo method for calculating the radiation skyshine produced by electron accelerators," *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, 234, 269-274, 2005.

22-P. N. McDermott, "Photon skyshine from medical linear accelerators," *J Appl Clin Med Phys*, 2020/03/01, 108-114, 2020.

23-P. N. McDermott, "Photon skyshine from medical linear accelerators." *J Appl Clin Med Phys*, 2020/03/01, 108-114 2020.

24-McDorrmot. "Photon skyshine from medical linear accelerators." *Journal of Applied Clinical Medical Physics,* 21[3], 108-114, 2020.

25-McGinley PH. "Radiation skyshine produced by an 18 MeV medical accelerator." *Rad Prot Mgmt,* 10[5], 59-64, 1993.

26-McGinley PH, "Shielding Techniques for Radiation Oncology Facilities," *Madison, WI: Medical Physics Publishing*; 2002.

27-McGinley PH, "Special Topics," pp. 1-182, 2002.

28-"NCRP. Radiation Protection Design Guidelines for 0.1-100 MeV Particles Accelerator Faciilies; 51." *National Council on Radiation Protection and Measurements,* 1977.

29-"NCRP. Structual Shielding Design for Medical X-Ray Imaging Facilities.", *National Council on Radiation Protection and Measurements.* 147, 2005.

30-Patrick N.McDermott. "Photon skyshine from medical linear accelerators." *RADIATION ONCOLOGY PHYSICS,* 2020.

31-Quianquian Xu *et al.* "Time and frequency to observe fiducial markers in MLC-modulated fields during prostate IMRT/VMAT beam delivery.", *Physica Medica,* 79, 142-149, 2020.

32-Ren-DihSheu RD, Chui CS, and Jiang SH. "The integral first collision kernel method for gamma-ray skyshine analysis." *Radiation Physics and Chemistry,* 68[5], 727-744, 2003.

33-Rindi A and Thomas RH. "Skyshine-A Paper TIGER?" *Particle Accelerators,* 7, 23-39, 1975.

34-Rostampour N, Jafari S, Saeb M, Keshtkar M, Shokrani P, and Almasi T. "Assessment of skyshine photon dose rates from 9 and 18 MV medical linear accelerators." *International Journal of Radiation Research,* 16, 499-503, 2018.

35-Matthew A, Hamilton IS., "RADIATION STREAMING AND SKYSHINE EVALUATION FOR A PROPOSED LOW-LEVEL RADIOACTIVE WASTE ASSURED ISOLATION FACILITY," *Health Physics*, 85, 494-499, 2003.

36-Shultis JK, FAW RE, and DENG X, "Improved Response Functions for Gamma-Ray Skyshine Analyses," *Sandia National Laboratories*, 1992.

37-Shultis JK, FAW RE, and Khan FA. "SKYNEUT: A Code for Neutron Skyshine Calculations Using the Integral Line Beam Method 9503." *Institute for Computational Research in Engineering and Science, Kansas State University*, CCC-6460SKYSHINE-KSU, Radiation Shielding Information Center, Oak Ridge National Laboratory, 1995.

38-Sitti Yanni and *et al.* "EGSnrc application for IMRT planning." *Report of Practical Oncology and Radiotherapy,* 25[2], 217-226, 2020.

39-Vassiliev ON, Titt U, Kry SF, Mohan R, and Gillin MT. "Radiation safety survey on a flattening filter-free medical accelerator." *Radiation Protection Dosimetry,* 124[2], 187-189, 2007.

40-Vassiliev ON, Titt U, Ponisch F, Kry SF, Mohan R, and Gillin MT. "Dosimetric properties of photon beams from a flattening filter free clinical accelerator." *Physics in Medicine and Biology,* 51[7], 1907-1917, 2006.

41-Vassiliev ON, Vassiliev ON, Titt U, Kry SF, Mohan R, and Gillin MT. "Radiation safety survey on a flattening filter-free medical accelerator." *Radiation Protection Dosimetry*, 124[2], 187-190, 2007.

42-Ying Xiao and *et al.* "Flattening filter-free accelerators: a report from the AAPM Therapy Emerging Technology Assessment Work Group." *Journal of Applied Clinical Medical Physics*, 16[3], 12-27, 2015.

43-Zefkili S, Kappas C, and Rosenwald JC. "On-axis and off-axis primary dose component in high energy photon beams." *Medical Physics,* 21[6], 799-808, 1994.

44-Zeghari A, Saaidi, and R.C Moursli. "Monte Carlo Study of A Free Flattening Filter To Increase Surface Dose on 12 Mv Photon Beam." *International Journal of Radiation Research*, 18[2], 307-313. 2020.