Assessment of Surface and Build-up Doses for a 6 MV Photon Beam using Parallel Plate Chamber, EBT3 Gafchromic Films, and PRIMO Monte Carlo Simulation Code

Mamta Mahur[1,2], Munendra Singh[3], Om Prakash Gurjar[4], Manoj Kumar Semwal[5]*

[1]MSc, Department of Radiation Oncology, Delhi State Cancer Institute, Dilshad Garden, Delhi, India
[2]MSc, Department of Physics, School of Basic Sciences and Research, Sharda University, Greater Noida, Uttar Pradesh, India
[3]PhD, Department of Physics, School of Basic Sciences and Research, Sharda University, Greater Noida, Uttar Pradesh, India
[4]PhD, Government Cancer Hospital, Mahatma Gandhi Memorial Medical College, Indore-452001, India
[5]PhD, Department of Radiation Oncology, Army Hospital (Research & Referral), Delhi Cantonment New Delhi-110010, India

ABSTRACT

Background: Accurate assessment of surface and build-up doses has a key role in radiotherapy, especially for the superficial lesions with uncertainties involved while performing measurements in the build-up region.

Objective: This study aimed to assess surface and build-up doses for 6 MV photon beam from linear accelerator using parallel plate ionization chamber, EBT3 Gafchromic films, and PRIMO Monte Carlo (MC) simulation code.

Material and Methods: In this experimental study, parallel plate chamber (PPC05) and EBT3 Gafchromic films were used to measure doses in a build-up region for 6 MV beam from the linear accelerator for different field sizes at various depths ranging from 0 to 2 cm from the surface with 100 cm source to surface distance (SSD) in a solid water phantom. Measured results were compared with Monte Carlo simulated results using PENELOPE-based PRIMO simulation code for the same setup conditions. Effect of gantry angle incidence and SSD were also analyzed for depth doses at the surface and build-up regions using PPC05 ion chamber and EBT3 Gafchromic films.

Results: Doses measured at the surface were 14.78%, 19.87%, 25.83%, and 31.54% for field sizes of 5×5, 10×10, 15×15, and 20×20 cm^2, respectively for a 6 MV photon beam with a parallel plate chamber and 14.20%, 19.14%, 25.149%, and 30.90%, respectively for EBT3 Gafchromic films. Both measurement sets were in good agreement with corresponding simulated results from the PRIMO MC simulation code; doses increase with the increase in field sizes.

Conclusion: Good agreement was observed between the measured depth doses using parallel plate ionization chamber, EBT3 Gafchromic films, and the simulated depth doses using PRIMO Monte Carlo simulation code.

Citation: Mahur M, Singh M, Gurjar OP, Semwal MK. Assessment of Surface and Build-up Doses for a 6 MV Photon Beam using Parallel Plate Chamber, EBT3 Gafchromic Films, and PRIMO Monte Carlo Simulation Code. *J Biomed Phys Eng*. 2022;12(5):455-464. doi: 10.31661/jbpe.v0i0.2101-1274.

Keywords

Chamber; Dosimetry; Monte Carlo Method; Radiotherapy

Introduction

In radiotherapy, the accuracy of measurement in surface doses is important to achieve the desired outcome of radiation treatment, especially when treating superficial tumors, due to the secondary charged particles, such as electrons; these charged particles are mainly produced during the interaction of photons with air, in linear accelerator beam defining system, i.e. collimator and the scattering materials in the path of the beam [1-3].

*Corresponding author:
Manoj Kumar Semwal
Department of Radiation Oncology, Army Hospital (Research & Referral), Delhi Cantonment New Delhi-110010, India
E-mail: manojsemwal@yahoo.co.in

Received: 30 January 2021
Accepted: 25 May 2021

According to the International Commission of Radiation Protection report 59 (ICRP-59) [4] and the International Commission of Radiation Units and Measurements (ICRU-39) [5], the skin depth is considered at the depth of 0.07 mm, corresponding to the depth of interface between the dermis and epidermis layers of the skin [6]. The accurate and precise measurements at such depths are not only difficult but also challenging due to the high dose gradient in the superficial region and without any charge particle equilibrium [2, 6].

However, extrapolation chambers are the best selection for the measurement of surface dose [7], their unavailability at most clinical facilities and time-consuming procedure in measuring doses leads to the impractical use of extrapolation chambers in clinical setups [6].

A parallel plate chamber (PPC) with fixed separation of electrodes as an alternative has been used for the measurement of the surface dose and build-up region dose. However, factors, such as cavity perturbation are necessary to improve the accuracy of such measurement [7-9].

Monte Carlo (MC) simulation method is widely regarded as a benchmark for dose estimation in radiotherapy [10, 11]. Various authors have evaluated the buildup region doses by EGSnrc and BEAMnrc MC simulation codes [6, 12, 13]; however, these simulations require long computational time/computational resources.

This study aimed to measure the surface and build-up region doses using the available parallel plate chamber (PPC), EBT3 Gafchromic film and to compare their results with MC simulated results using PENELOPE based PRIMO MC Code.

Material and Methods

Measurements using parallel plate chamber

An experimental study was conducted to assess the surface and build-up doses for a 6 MV photon beam from a linear accelerator using a Parallel plate ionization chamber, EBT3 Gafchromic films, and PRIMO Monte Carlo simulation code. PPC model PPC05 from IBA Wellhofer (IBA Dosimetry GmbH, Schwarzenbruck, Germany) is a commonly used detector for photon and electron absolute and relative dose measurements. This PPC05 chamber has a small collecting volume with 0.1 mm entering window thickness, 0.6 mm plate spacing, 9.9 mm diameter, and 3.4 mm wide guard ring which enables excellent resolution in the measurement of depth doses; this chamber was waterproof and vented through a silicon sleeve. Using this chamber along with a DOSE1 electrometer (IBA, GmBH, Scanditronix Wellhofer, Germany) point dose measurements were carried out on a Varian Clinac 600 C (Varian Medical Systems, Palo Alto, CA, USA) with a 6 Megavolt (MV) photon beam in a solid water phantom. The solid water phantom (CNMC Co. Nashville, TN, USA) had similar properties to that of water, such as relative electron density, effective atomic number, and similar interaction properties of absorption and scattering of radiation.

The PPC was embedded in a custom drilled slot on a 30×30 cm^2 piece of solid water phantom slab. A minimum of 10 cm of backscatter thickness was used to provide full phantom scatter equilibrium for these measurements for a 6 MV photon beam. Measurements were performed for depths of 0, 1, 3, 5, 7, 10, 12, 15, and 20 mm in the solid water phantom at source to surface distance (SSD) of 100 cm for field sizes of 5×5, 10×10, 15×15, and 20×20 cm^2 and gantry angles of 0°, 30°, and 60°.

The charge, collected by the ion chamber at both the polarities, i.e. +300 V and -300 V, was recorded, and the average value was then normalized to the dose maximum value as follows:

$$M_{avg} = \frac{M_+ + M_-}{2} \quad (1)$$

where M_{avg} is the average of accumulated

charge, M_+ and M_- are the electrometer readings obtained for accumulated charges at positive and negative polarity.

The readings obtained from the PPC were corrected for overresponse by applying Gerbi and Khan's method, which introduced a modified version of the correction factors of Velkely et al. to consider the effect of collector edge sidewall distance of the parallel plate chamber [7, 9].

$$P'(d,E) = P(d,E) - \xi(0,E) l e^{-\alpha\left(\frac{d}{d_{\max}}\right)} \quad (2)$$

$$\xi(0,E) = \left[-1.666 + (1.982IR)\right] \times (C - 15.8)(\%/mm) \quad (3)$$

where $P(d, E)$ is the measured percentage depth dose, $P'(d, E)$ is the corrected percentage depth dose at the depth 'd', 'E' is the energy of photon beam, 'l' is the plate separation, 'α' is constant with a value of 5.5, and $\xi(0, E)$ is the energy-dependent chamber factor, showing the overresponse per mm of chamber plate separation at the surface of the phantom. 'IR' represents the ionization ratio measured at depths of 20 cm and 10 cm for a field size of 10 cm × 10 cm at a fixed source-detector distance of 100 cm; 'C' is the sidewall-collector distance in mm, and 'd' is the depth of the chamber front window (d=0 for surface).

Gafchromic film measurements

Gafchromic film is a substantial dosimeter used in the measurement of surface dose due to its characteristics of high spatial resolution and low spectral sensitivity over a broad range of doses [6]. Comparison of doses from Gafchromic EBT films and parallel plate chambers were studied by Bilge et al. [14] and showed a difference between 5% for 6 MV and 3% for 18 MV photon beams.

In the current study, Gafchromic EBT3 film (International Specialty Product, NJ, US) was used, consisting of a 28 μm thick active layer sandwiched between two 125 μm matte-polyester substrates [15]. The active layer of the film contains the active component, such as a marker dye, stabilizers, and other components giving the film its near energy-independent response. The effective point of measurement was assumed at the geometric center along with the thickness of the exposed film.

All films used for measurements were obtained from the same lot (packet) (#09061602) and cut into squares of 4 cm × 4 cm. After irradiation, the films were scanned using an Epson 10000 XL flatbed scanner (Epson America, Inc. Long Beach, CA). After a 24-hour gap was considered between irradiation and scanning, leading to post-irradiation color changes. For scanning, transmission mode at a 72 dpi resolution and with 48-bits RGB format was used. As the optical properties of the Gafchromic film were sensitive to the scanning orientation of the film on the scanner bed, all the irradiated film pieces were scanned in the same orientation, which was in portrait mode [16]. Images were saved and analyzed using film QA Pro software (National Institute of Health, USA).

For calibration purposes, a set of EBT3 films from the same lot used for actual measurements were irradiated to establish the calibration curve. For irradiation, the film was placed at a depth of 5 cm in a solid water phantom and irradiated to doses ranging from 0 to 600 cGy at 100 cm SSD for a field size of 10×10 cm^2. After scanning, the optical density of the film was obtained from the red component of the RGB (red, green, and blue) images using Film QA Pro software. For buildup doses measurements, the film was placed at depths of 0, 1, 3, 5, 7, 10, 12, 15, and 20 mm in the solid water phantom; 200 MUs were delivered for each irradiation.

PRIMO

MC simulation technique involves the use of known probability distributions for the interaction of beam particles in various materials and simulating random trajectories of each particle. PRIMO is a new MC simulation sys-

tem (computer software) used for the effortless simulation of most Varian and Elekta linear accelerators, estimating dose distribution in phantoms and computed tomographic (CT) images; it also can use phase-space files in International Atomic Energy Agency (IAEA) format and import structures in the standard DICOMRT Structure format [17-19].

PRIMO simulation system includes as follows: (a) accurate physics from the PENELOPE code, (b) variance reduction technique significantly, reducing the computation time, and (c) a user-friendly graphical interface with tools for analyzing the generated data [18,19]. In PRIMO MC code, the simulation of the Linear accelerator (Linac) and the phantom set/CT images set can be performed in 3 segments (Figure 1): the first segment 's1' simulates the field–independent part of the Linear accelerator starting from an electron beam source to just above the moveable collimators, the second segment 's2' simulates field, defining part of the Linac, i.e. moveable jaws and multileaf collimator (MLC), and at the last, the segment 's3' simulates the dose distribution in the phantom or CT images set. In PRIMO, the primary electrons reaching the target are defined by a Gaussian distribution [18].

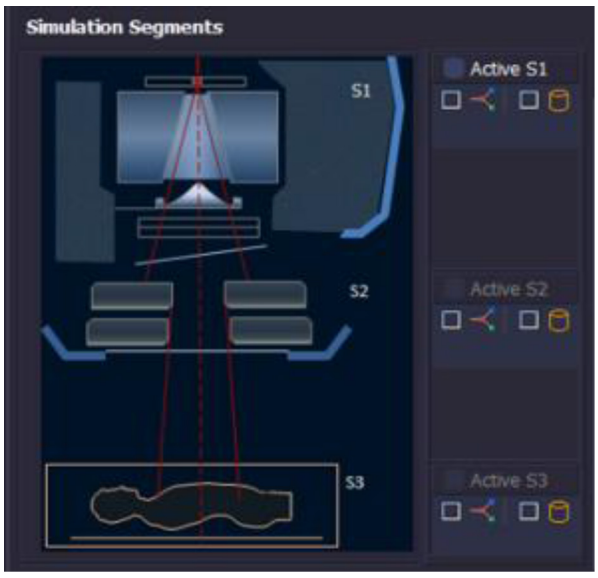

Figure 1: Segment s1, s2, and s3 of Primo Monte Carlo (MC) simulation code.

The latest released version (0.3.1.1772) of PRIMO on a desktop computer with specifications of 32GB RAM, Intel® CPU E5-2695 with a 64-bit operating system was used in this study. In PRIMO MC code, the default parameters of the 6 MV photon beam for the Varian Clinac 600 C model were defined with an electron beam of the initial energy of 5.4 mega electron volt (MeV) with energy FWHM of 0 MeV, the focal spot size of 0 mm, and a beam divergence of 0º.

Tuning of initial beam parameters in PRIMO

The primary beam parameters were adjusted to an acceptable difference with the measured data [19]. For tuning the 6 MV beam, the whole linear accelerator geometry was simulated at once to produce phase-space files in IAEA format. Initial beam energy parameters were changed from 5.4 MeV to 6.2 MeV in a step of 0.1 MeV until a good agreement for 5.8 MeV between measured and calculated percentage depth dose (PDD) for simulation of field size of 10 × 10 cm^2 in a water phantom at 100 cm SSD. FWHM and its energy, a similar approach to iterative adjustment, were applied by varying the initial values and repeating the simulation process to find the closest match for measured and calculated PDDs, profiles, and focal spot The focal spot size values were varied from 1.0 mm to 1.5 mm in a step of 0.1 mm, and FWHM energy was varied from 0.1 to 0.2 MeV; finally, the values for beam divergence were varied from 0.1º to 1º to determine the configuration, giving the highest gamma index passing rate using 1%/1 mm from the inbuilt analysis tool for comparing experimental and measured data in PRIMO code.

When simulating linear accelerator parts (s1 and s2), splitting roulette was selected. According to the authors of the PRIMO code, splitting-roulette was recommended for nominal energies below 15 MV, and rotational splitting was usually more efficient for nom-

inal energies above 15 MV [17, 18, 20, 21]. These applied variance reduction techniques and the geometry files used in the simulation were tested extensively by many researchers in the past [21-25].

The parameters of final beam values selected for simulation were as follows: initial energy of 5.8 MeV, energy FWHM of 0.18 MeV, the focal spot size of 1.2 mm, and the beam divergence of 0.2º for Linear Accelerator Varian Clinac 600 C after tuning of beam parameters in PRIMO. For the defined beam parameters, further simulation for 5×5, 10×10, 15×15, and 20×20 cm^2 field sizes were performed for tallying the dose in a homogeneous water phantom of size 30×30×30 cm^3 for a bin size of 2×2×1 mm^3 at SSD of 100 cm. More than 1×10^8 histories were simulated in PRIMO for each field size to reach the dose uncertainty below 1%.

Simulated depth dose curves were saved in a file in.txt format and normalized for the depth of maximum dose. The percentage difference between measured and simulated PDD values was evaluated statistically for each field size.

Results

In this paper, the buildup dose measured using PPC and Gafchromic films was compared and validated with MC simulated results from PENELOPE-based PRIMO code for the 6 MV photon beam from Varian Clinac 600 C. Figure 2 shows the PDD values in the buildup region measured with PPC as well as film and estimated with MC simulation for different field sizes.

The dose values measured with PPC, EBT3 film, and PRIMO MC simulated results for different field sizes at different depths as seen in Table 1.

The PRIMO simulated results shows that surface doses increases from 13.29% to 84.98%, 17.98% to 86.69%, 23.09% to 88.82%, and 28.47% to 90.17% in the first 5mm build-up depth and 13.29% to 97.93%, 17.98% to 98.62%, 23.09% to 99.16%, and 28.47% to 99.63% in the first 10 mm buildup depths for 5×5, 10×10, 15×15, and 20×20 cm^2 field sizes, respectively. Whereas measured results from PPC05 shows that surface doses increases from 14.78% to 86.83%, 19.87% to 88.1%, 25.83% to 90.32%, and 31.54% to 91.47% in the first 5 mm build-up depth and 14.78% to 99.17%, 19.87% to 99.14%, 25.83% to 99.70%, and 31.54% to 98.8% in the first 10 mm buildup depths for 5×5, 10×10, 15×15, and 20×20 cm^2 field size, respectively. Similarly measure-

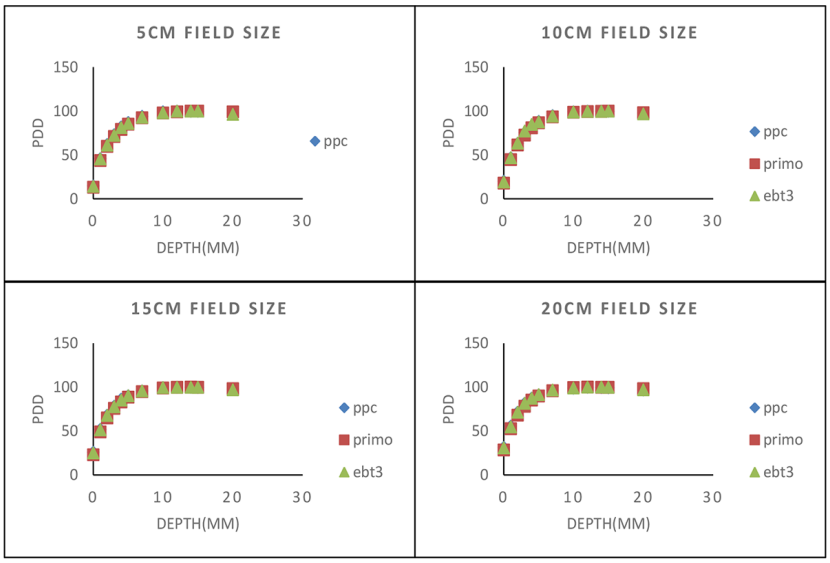

Figure 2: Comparison of percentage depth dose for 6 MV photon beam in the buildup region for 5×5, 10×10, 15×15, and 20×20 cm^2 field sizes at source to surface distance (SSD) 100 cm.

Table 1: Percentage depth dose measured/estimated from parallel plate chamber (PPC), EBT3 films, and PRIMO MC (Monte Carlo code name) for a 6 MV photon beam for 0° gantry angle.

Depth (mm)	PPC measured value				EBT3 Films measured value				PRIMO MC simulated results			
	5×5	10×10	15×15	20×20	5×5	10×10	15×15	20×20	5×5	10×10	15×15	20×20
0	14.78	19.87	25.83	31.54	14.20	19.14	25.14	30.90	13.29	17.98	23.09	28.47
1	45.84	46.92	51.96	55.70	45.55	46.69	51.50	54.76	43.55	44.74	49.26	52.92
2	61.96	63.24	68.13	71.50	61.21	63.56	67.89	71.65	59.94	61.48	65.06	68.18
3	73.14	75.46	78.20	81.75	72.29	77.39	77.92	81.59	70.99	72.50	75.85	78.23
4	82.03	82.83	86.37	87.63	81.21	84.87	85.41	87.56	79.21	80.98	83.19	85.27
5	86.83	88.10	90.39	91.47	85.82	87.70	90.32	91.72	84.98	86.69	88.62	90.17
7	93.94	94.72	95.74	96.26	93.01	94.31	95.80	96.81	92.49	93.31	95.04	95.96
10	99.17	99.14	99.70	98.80	98.13	98.98	99.62	99.10	97.93	98.62	99.16	99.63

PPC: Parallel plate chamber, EBT3: Brand name, PRIMO MC: Monte Carlo code name

ments from EBT3 films showed an increase in surface doses from 14.2% to 85.8%, 19.14% to 87.7%, 25.14% to 90.32%, and 30.90% to 91.72% in the first 5 mm build-up depth and 14.2% to 98.13%, 19.14% to 98.98%, 25.14% to 99.16%, and 30.90% to 99.1% in first 10 mm buildup depths for 5, 10, 15, and 20 cm field size, respectively. The effect of incident beam angle and SSD on surface and buildup doses are depicted in Figures 3 and 4.

Discussion

Based on the results, PDD values measured from PPC, EBT3 films, and simulated results using PRIMO MC were within 10% of the dose at 0.0 mm depth, 5% for the first 4 mm depths, and also 2% for measurements at depths beyond 4 mm. The maximum variation was observed for 0 mm and 1 mm depth among the measured and simulated results. Figure 2 shows that the PDD increased with an increase in field size as expected [26].

The measurements with EBT3 film showed more coherence with PRIMO MC simulated data. A maximum variation of 8.1% was observed at the surface and 4.3% at 1mm depth between PRIMO and EBT3 films results, while the maximum variation of 10.1% at the surface and 5.0% at 1 mm depth was observed for PPC and PRIMO MC simulated results. For PPC and EBT3 films, the maximum variation was observed at 3.9% at the surface and

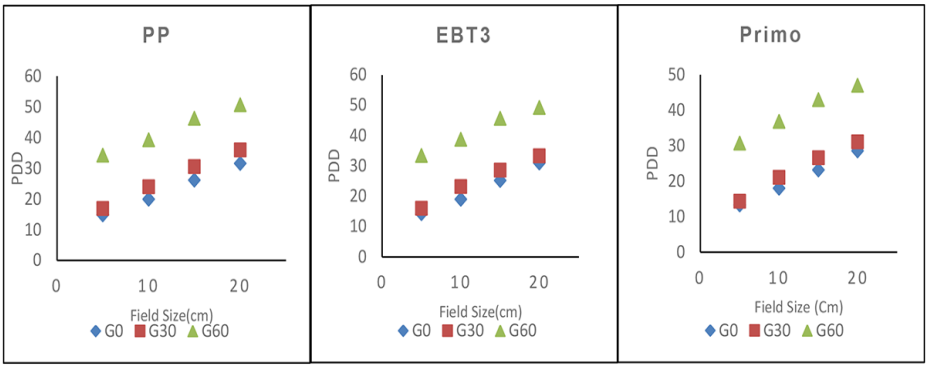

Figure 3: Variation of surface dose for field sizes 5×5, 10×10, 15×15, and 20×20 cm² for gantry angles of 0°, 30°, and 60°.

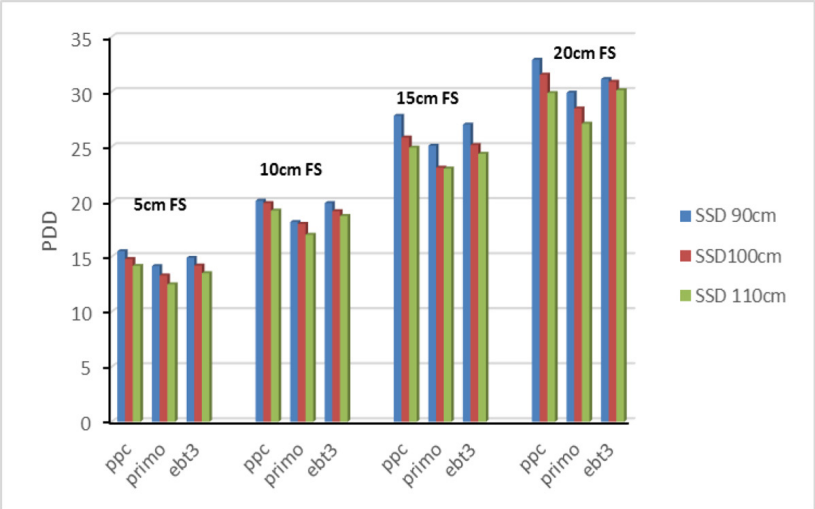

Figure 4: Effect of source to surface distance (SSD) on surface dose for field sizes of 5×5, 10×10, 15×15, and 20×20 cm^2 at 0^o degree gantry angle.

1.6% at 1 mm depth and showed consistent measurements with each other. However, the results of PPC and EBT3 films differ significantly from the dose obtained with PRIMO at the surface. For the rest of the buildup depth, there was good agreement among all the three modalities of dose estimation.

Furthermore, the obtained results are in agreement with the published literature. Jong et al. [27] reported the surface doses measured with Markus PPC for 6 and 10 MV photon beams from Varian Clinac 2100 C/D for 10×10 cm^2 field size within 15.8% and 11.8%, respectively. Qi et al. [28] measured PDD for 6 MV in water equivalent phantom with Attix PPC for Linear Accelerator Varian Clinac 600 C linear accelerator and also showed the values 12.9%, 18.9%, 29.1%, and 37.9% for 5×5, 10×10, 20×20, and 30×30 cm^2 field size at 100 cm SSD. Yu et al. [29] reported the surface doses of 16% and 13% for 10×10 cm^2 field size for 6 MV and 18 MV beam, respectively, in Varian Clinac 2100 C with Attix model 449 PPC.

Effect of Variation in the angle of incidence and SSD on surface doses

Figure 3 shows the PDDs values on the surface for 5×5, 10×10, 15×15, and 20×20 cm^2 field sizes for gantry angle incidence of 0^o, 30^o, and 60^o. For oblique incidence of 6 MV photon beam, i.e. for gantry angles of 30 and 60 degree, surface dose increased from 14.33% to 30.67%, 21.32% to 36.8%, 26.53% to 42.89%, and 31.01% to 46.95% for the 5×5, 10×10, 15×15, and 20×20 cm^2 field sizes, respectively. The surface dose increased with an increase in beam incidence angle due to the shift of charged particle equilibrium towards the surface. When the angle of the incident beam increased the depth of dose maximum shifted towards the surface due to increased electron contamination and higher photons interactions along the oblique path of the beam [30].

Figure 4 shows that the surface doses decreases as SSD increased; however, the effect was not much significant. It is known that the dose deposited on the surface of irradiation is due to not only the primary photon beam but also the contaminant electrons generated in the air and the collimator head, reaching the surface. However, the contribution to surface dose due to these contaminant electrons is not sufficient as the electrons produced in the accelerator head had relatively high energy. The

range of these electrons does not change significantly in phantom when required to travel 10 cm more or less in air. A similar situation is expected for photons when there is a change in traveling distance in air, as no considerable change in spectral components of photons is expected. [27, 31, 32].

Conclusion

In this present study, surface doses were analyzed for different field sizes at different gantry angles using three different tools, such as PPC, Gafchromic EBT3 films, and PRIMO MC simulation code. The simulated MC results from Penelope-based PRIMO software for 6 MV photon beam were in good agreement with the previously reported data for similar machines.

The difference between measurements by PPC, EBT3 films, and the simulated results by PRIMO MC code was reported within 10% at the surface and 5% for the first 5 mm depth. It shows that the comparison of Primo MC simulated results are in good agreement with the measured doses using PPC and EBT3 films and provides an accurate estimation of doses at the surface and buildup region. Also, this accurate estimation of doses at the surface and buildup region may help manage radiation-induced late skin toxicities.

Acknowledgment

The authors thank the Director, Delhi State Cancer Institute for permitting to carry out this study using the equipment of the institute.

Authors' Contribution

M. Mahur conceived the idea. The paper was written and designed by M. Mahur and M. Singh. M. Mahur and OP. Gurjar gather data and the related literature. M. Singh and MK. Semwal helped with the writing related works. The method implementation was conducted by M. Mahur. Analysis was conducted by M. Mahur and OP. Gurjar. The research work was proof read and supervised by MK. Semwal and M. Singh. All the authors read, modified, and approved the final version of the manuscript.

Ethical Approval

The permission from Delhi State Cancer Institute, Dilshad Garden, Delhi has been taken to conduct the research and use the resources needed.

Informed consent

This work didn't involve patients or data related to them.

Conflict of Interest

None

References

1. Kim S, Liu CR, Zhu TC, Palta JR. Photon beam skin dose analyses for different clinical setups. *Med Phys*. 1998;**25**(6):860-6. doi: 10.1118/1.598261. PubMed PMID: 9650173.
2. Nilsson B, Brahme A. Absorbed dose from secondary electrons in high energy photon beams. *Phys Med Biol*. 1979;**24**(5):901-12. doi: 10.1088/0031-9155/24/5/003. PubMed PMID: 117462.
3. Biggs PJ, Ling CC. Electrons as the cause of the observed dmax shift with field size in high energy photon beams. *Med Phys*. 1979;**6**(4):291-5. doi: 10.1118/1.594580. PubMed PMID: 113656.
4. ICRP Publication 59. The biological basis for dose limitation in the skin. A report of a Task Group of Committee 1 of the International Commission on Radiological Protection. *Ann ICRP*. 1991;**22**(2):1-104. PubMed PMID: 1812796.
5. International Commission on Radiation Units and Measurements. Determination of dose equivalents resulting from external radiation sources. ICRU Report 39; Washington DC: ICRU; 2020.
6. Devic S, Seuntjens J, Abdel-Rahman W, Evans M, Olivares M, Podgorsak EB, Vuong T, Soares CG. Accurate skin dose measurements using radiochromic film in clinical applications. *Med Phys*. 2006;**33**(4):1116-24. doi: 10.1118/1.2179169. PubMed PMID: 16696489.
7. Velkley DE, Manson DJ, Purdy JA, Oliver GD Jr. Build-up region of megavoltage photon radiation sources. *Med Phys*. 1975;**2**(1):14-9. doi: 10.1118/1.594158. PubMed PMID: 805358.
8. O'Shea E, McCavana P. Review of surface dose detectors in radiotherapy. *Journal of Radiotherapy in Practice*. 2003;**3**(2):69-76. doi: 10.1017/S1460396903000049.
9. Gerbi BJ, Khan FM. Measurement of dose in the

buildup region using fixed-separation plane-parallel ionization chambers. *Med Phys*. 1990;**17**(1):17-26. doi: 10.1118/1.596522. PubMed PMID: 2106611.

10. Nahum AE. Condensed-history Monte-Carlo simulation for charged particles: what can it do for us? *Radiat Environ Biophys*. 1999;**38**(3):163-73. doi: 10.1007/s004110050152. PubMed PMID: 10525953.
11. Abdel-Rahman W, Seuntjens JP, Verhaegen F, Deblois F, Podgorsak EB. Validation of Monte Carlo calculated surface doses for megavoltage photon beams. *Med Phys*. 2005;**32**(1):286-98. doi: 10.1118/1.1829401. PubMed PMID: 15719980.
12. Kim JH, Hill R, Kuncic Z. Practical considerations for reporting surface dose in external beam radiotherapy: a 6 MV X-ray beam study. *Australas Phys Eng Sci Med*. 2012;**35**(3):271-82. doi: 10.1007/s13246-012-0145-1. PubMed PMID: 22736310.
13. Apipunyasopon L, Srisatit S, Phaisangittisakul N. An investigation of the depth dose in the build-up region, and surface dose for a 6-MV therapeutic photon beam: Monte Carlo simulation and measurements. *J Radiat Res*. 2013;**54**(2):374-82. doi: 10.1093/jrr/rrs097. PubMed PMID: 23104898. PubMed PMCID: PMC3589935.
14. Bilge H, Cakir A, Okutan M, Acar H. Surface dose measurements with GafChromic EBT film for 6 and 18MV photon beams. *Phys Med*. 2009;**25**(2):101-4. doi: 10.1016/j.ejmp.2008.05.001. PubMed PMID: 18571964.
15. Ashland. Gafchromic Radiotherapy Films. Ashland, KY: Ashland; 2022. Available from: http://www.ashland.com/products/gafchromicradiotherapyfilms.
16. Menegotti L, Delana A, Martignano A. Radiochromic film dosimetry with flatbed scanners: a fast and accurate method for dose calibration and uniformity correction with single film exposure. *Med Phys*. 2008;**35**(7):3078-85. doi: 10.1118/1.2936334. PubMed PMID: 18697531.
17. Rodriguez M, Sempau J, Brualla L. PRIMO: a graphical environment for the Monte Carlo simulation of Varian and Elekta linacs. *Strahlenther Onkol*. 2013;**189**(10):881-6. doi: 10.1007/s00066-013-0415-1. PubMed PMID: 24005581.
18. Brualla L, Rodríguez M, Sempau J. PRIMO User's Manual Version 0.3.1.1770. Strahlenklinik, Hufelandstrasse; 2018. p. 55.
19. Bacala AM. Linac photon beam fine-tuning in PRIMO using the gamma-index analysis toolkit. *Radiat Oncol*. 2020;**15**(1):8. doi: 10.1186/s13014-019-1455-1. PubMed PMID: 31906977. PubMed PMCID: PMC6945657.
20. Sempau J, Sánchez-Reyes A, Salvat F, ben Tahar HO, Jiang SB, Fernández-Varea JM. Monte Carlo simulation of electron beams from an accelerator head using PENELOPE. *Phys Med Biol*. 2001;**46**(4):1163-86. doi: 10.1088/0031-9155/46/4/318. PubMed PMID: 11324958.
21. Brualla L, Salvat F, Palanco-Zamora R. Efficient Monte Carlo simulation of multileaf collimators using geometry-related variance-reduction techniques. *Phys Med Biol*. 2009;**54**(13):4131-49. doi: 10.1088/0031-9155/54/13/011 PubMed PMID: 19521002.
22. Rodriguez M, Sempau J, Brualla L. A combined approach of variance-reduction techniques for the efficient Monte Carlo simulation of linacs. *Phys Med Biol*. 2012;**57**(10):3013-24. doi: 10.1088/0031-9155/57/10/3013. PubMed PMID: 22538321.
23. Brualla L, Rodriguez M, Lallena AM. Monte Carlo systems used for treatment planning and dose verification. *Strahlenther Onkol*. 2017;**193**(4):243-259. doi: 10.1007/s00066-016-1075-8. PubMed PMID: 27888282.
24. Belosi MF, Rodriguez M, Fogliata A, Cozzi L, Sempau J, et al. Monte Carlo simulation of TrueBeam flattening-filter-free beams using varian phase-space files: comparison with experimental data. *Med Phys*. 2014;**41**(5):051707. doi: 10.1118/1.4871041. PubMed PMID: 24784373.
25. Hermida-López M, Sánchez-Artuñedo D, Calvo-Ortega JF. PRIMO Monte Carlo software benchmarked against a reference dosimetry dataset for 6 MV photon beams from Varian linacs. *Radiat Oncol*. 2018;**13**(1):144. doi: 10.1186/s13014-018-1076-0. PubMed PMID: 30086767. PubMed PMCID: PMC6081807.
26. Butson MJ, Cheung T, Yu PK. Skin dose delivered in megavoltage external beam therapeutic radiology. *Austral-Asian J Cancer*. 2006;**5**(2):101-4.
27. Jong WL, Wong JH, Ung NM, Ng KH, Ho GF, Cutajar DL, Rosenfeld AB. Characterization of MOSkin detector for in vivo skin dose measurement during megavoltage radiotherapy. *J Appl Clin Med Phys*. 2014;**15**(5):4869. doi: 10.1120/jacmp.v15i5.4869. PubMed PMID: 25207573. PubMed PMCID: PMC5711095.
28. Qi ZY, Deng XW, Huang SM, Zhang L, He ZC, Li XA, Kwan I, Lerch M, Cutajar D, Metcalfe P, Rosenfeld A. In vivo verification of superficial dose for head and neck treatments using intensity-modulated techniques. *Med Phys*. 2009;**36**(1):59-70. doi: 10.1118/1.3030951. PubMed PMID: 19235374.

29. Yu PK, Cheung T, Butson MJ. Variations in skin dose using 6MV or 18MV x-ray beams. *Australas Phys Eng Sci Med*. 2003;**26**(2):79-81. PubMed PMID: 12956189.
30. Jackson W. Surface effects of high-energy X rays at oblique incidence. *Br J Radiol*. 1971;**44**(518):109-15. doi: 10.1259/0007-1285-44-518-109. PubMed PMID: 4994161.
31. Yadav G, Yadav RS, Kumar A. Skin dose estimation for various beam modifiers and source-to-surface distances for 6MV photons. *J Med Phys*. 2009;**34**(2):87-92. doi: 10.4103/0971-6203.51935. PubMed PMID: 20098542. PubMed PMCID: PMC2805895.
32. Butson MJ, Cheung T, Yu PK. Variations in 6MV x-ray radiotherapy build-up dose with treatment distance. *Australas Phys Eng Sci Med*. 2003;**26**(2):88-90. PubMed PMID: 12956192.