Monte Carlo Investigation of Photon Beam Characteristics and its Variation with Incident Electron Beam Parameters for Indigenous Medical Linear Accelerator

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Abstract

Purpose: A Monte Carlo model of a 6 MV medical linear accelerator (linac) unit built indigenously was developed using the BEAMnrc user code of the EGSnrc code system. The model was benchmarked against the measurements. Monte Carlo simulations were carried out for different incident electron beam parameters in the study. **Materials and Methods:** Simulation of indigenously developed linac unit has been carried out using the Monte Carlo based BEAMnrc user-code of the EGSnrc code system. Using the model, percentage depth dose (PDD), and lateral dose profiles were studied using the DOSXYZnrc user code. To identify appropriate electron parameters, three different distributions of electron beam intensity were investigated. For each case, the kinetic energy of the incident electron was varied from 6 to 6.5 MeV (0.1 MeV increment). The calculated dose data were compared against the measurements using the PTW, Germany make RFA dosimetric system (water tank MP3-M and 0.125 cm^3 ion chamber). **Results:** The best fit of incident electron beam parameter was found for the combination of beam energy of 6.2 MeV and circular Gaussian distributed source in X and Y with FWHM of 1.0 mm. PDD and beam profiles (along both X and Y directions) were calculated for the field sizes from 5 cm × 5 cm to 25 cm × 25 cm. The dose difference between the calculated and measured PDD and profile values were under 1%, except for the penumbra region where the maximum deviation was found to be around 2%. **Conclusions:** A Monte Carlo model of indigenous linac (6 MV) has been developed and benchmarked against the measured data.

Keywords: Beamnrc, dosxyznrc, egsnrc code system, linear accelerator, measurement, monte Carlo

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Introduction

Linear accelerator (linac) has several advantages in comparison to telecobalt units.[1-5] Department of Science and Technology, Government of India, has entrusted the responsibility of development of indigenous linac to one of its constituent units, Society for Applied Microwave Electronics Engineering and Research (SAMEER) under Jai Vigyan National Science and Technology Mission. Due to its development under indigenous technology, the machine has the potential of delivering cost-effective radiotherapy treatments in India. The linac unit is named as Siddharth and is capable of producing photon beam energy of 6 MV. Details can be found at https://www.sameer.gov.in/linearaccelerators.

Benchmarking of photon beams generated from radiotherapy equipment are extensively carried out with the help of Monte Carlo radiation transport simulations.[6-13] The first step of dose calculation using Monte Carlo code is to develop the Monte Carlo beam model for the linac. Tuning of the incident electron beam parameters is an important task to benchmark the calculated dose data against the measured data.[14-17] Detailed studies by Sheikh–Bagheri and Rogers[14] showed that optimum tuning of the beam energy and its width can be performed by using PDD and in-air off-axis factors. A study by

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Lin *et al*.[18] found that it is possible to tune the beam width by the 10 cm × 10 cm beam profile measured in a water phantom. Verhaegen and Seuntjens[19] identified suitable electron beam width based on larger fields and shallower depths. Recently, Sangeetha and Surekha[20] used EGSnrc code system[21] to simulate Varian 600 C/D linac of photon energy 6 MV (for both with flattening filter and without flattening filter). Several studies on determination of incident beam parameters are reported in the literature.[15,22-29]

The purpose of the present study is to develop Monte Carlo model of 6 MV Siddharth linac unit using the Monte Carlo-based BEAMnrc user-code[30] of the EGSnrc[21] Monte Carlo code system and benchmark this model against the measured data. The calculated dose data are based on the DOSXYZnrc user code[31] of the EGSnrc code system.[21] In the study, simulations were carried out for different incident electron beam parameters.

Materials and Methods

Simulation of medical linear accelerator (Siddharth)

The geometry of the linac unit was simulated based on the manufacturer's detailed information using the BEAMnrc user code[30] of the Monte Carlo-based EGSnrc code system.[21] In this study, different components of the treatment head such as target, primary collimator, flattening filter, monitor chamber, mirror, and secondary collimator were modeled. Figure 1 shows the display of linac modeled in the present study using the BEAMnrc user code.[30] In this simulation, the z-axis is taken along the beam axis, and the origin is taken at the front face of the target.

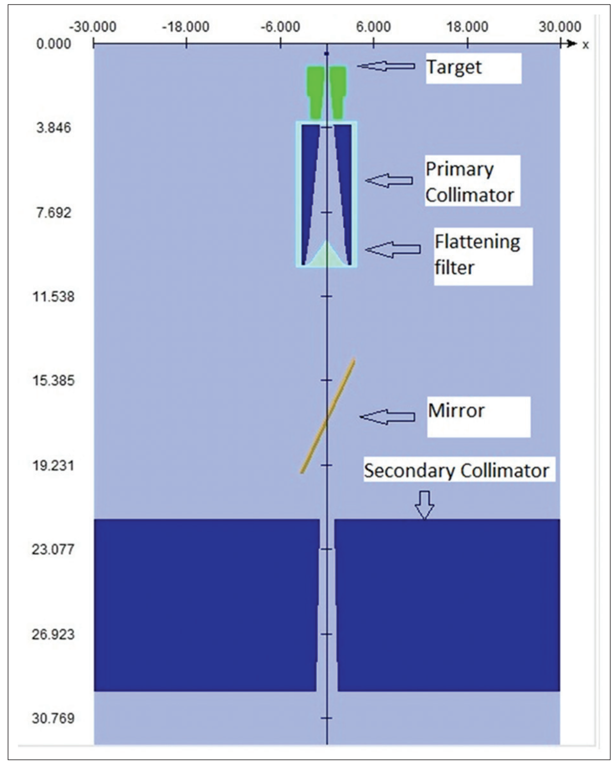

Figure 1: Detailed head structure of Siddharth medical linear accelerator. The dashed line is the Z-axis, with the positive X direction to the right and the Y direction coming out of the page. The origin is on the target surface at position 0. The linac head consists of six main component modules including the target, primary collimator, flattening filter, ion chamber, mirror, and secondary collimator

Incident electron beam parameters

Incident electron parameters play an important role in the dose distributions. To identify appropriate electron parameters, following three cases were studied. For each case, the kinetic energy of the incident electron was varied from 6 to 6.5 MeV (0.1 MeV increment).

Case 1

As per the manufacturer's specification, the electron beam is a point and divergent with a half-angle of 14°. The source is positioned on Z-axis and 4 mm above the target [Figure 2]. The radius of the beam at the target is 1 mm.

Case 2

In this case, the incident electron beam is a circular parallel beam with a diameter of 2 mm [Figure 3]. The electron beam is incident in the XY plane.

Case 3

In this case, the beam is circular, and the spatial distribution of electrons is defined by a Gaussian intensity distribution [Figure 4]. The Full Width Half Maximum (FWHM) of the incident beam is considered to be 1 mm in both X and Y directions.

BEAMnrc and DOSXYZnrc simulations

The Monte Carlo simulations were done in two steps. To identify the incident electron beam parameters, initial simulations were carried out for 10 cm × 10 cm field size and depth of 10 cm. In the first step, phase space file for each of the above cases was scored at 100 cm from the target using the BEAMnrc user-code.

In the BEAMnrc simulations, the electron transport cutoff (ECUT) and photon transport cutoff (PCUT) energies were set to 0.7 and 0.01 MeV, respectively. Secondary electron production cutoff (AE) and bremstrahlung production cutoff (AP) values were set to 0.521 and 0.01 MeV, respectively. Range rejection was turned on with ESAVE value of 0.7 MeV in the target and 2 MeV in other components of the linac.[14] The number of histories for Monte Carlo calculation was set 6×10^9 particles.

In the second step, the phase space data from aforementioned simulations served as the source for the simulations using the DOSXYZnrc user code. This user code is capable of performing 3D absorbed dose calculations in Cartesian coordinates in the water phantom. In DOSXYZnrc, the water phantom size was 50 cm × 50 cm × 50 cm and the phase space source was positioned on the water surface, i.e. at Z = 100 cm. Figure 5 represents the voxel phantom set up in the DOSXYZnrc simulations. The water phantom was divided into a number of voxels. For high-dose gradients regions, small voxel sizes were adapted.[32] For central axis PDD simulation, up to a depth of 2 cm, absorbed dose was scored in voxel dimension of 1.0 cm × 1.0 cm × 0.05 cm and for depths from

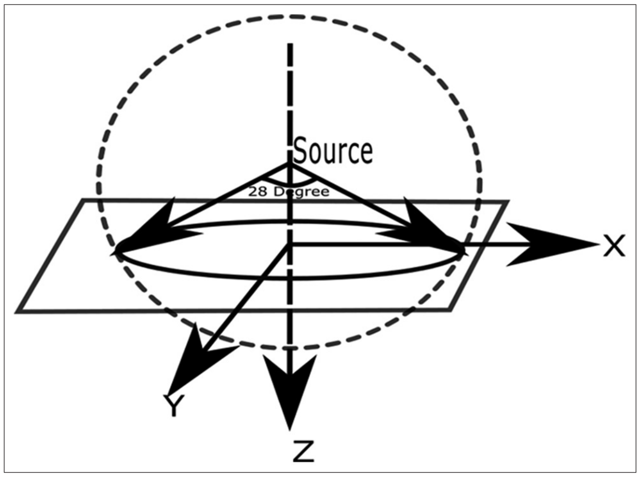

Figure 2: Point divergent source on Z-axis (Case 1) showing the electron beam divergence angle which is the half angle of the circular field at the point of incidence (14^o) and the directions of X, Y and Z axes. The beam is centered on the Z axis

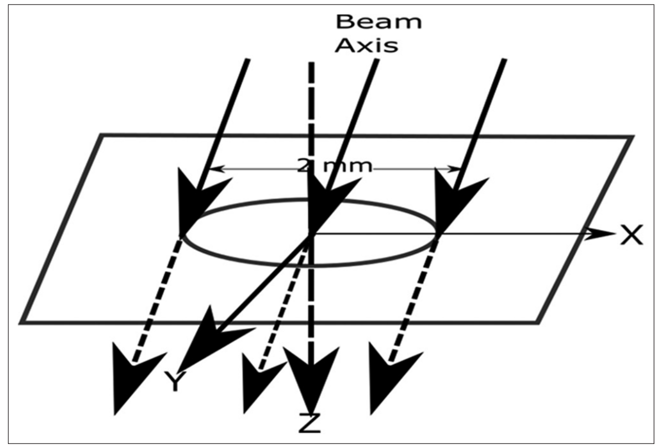

Figure 3: Parallel Circular Beam (Case 2) showing the beam diameter (2 mm) measured perpendicular to the beam central axis and the directions of X, Y and Z axes. The beam is along the Z-axis

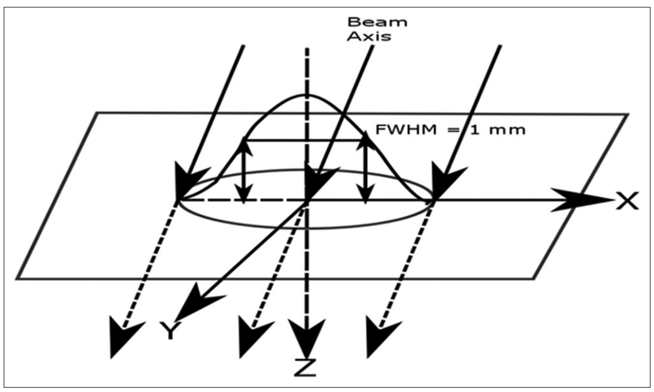

Figure 4: Circular Beam with Gaussian distributions in X and Y (Case 3). The shape of the circle is defined by FWHM (1 mm) of the Gaussian intensity distributions in the X-and Y-directions respectively

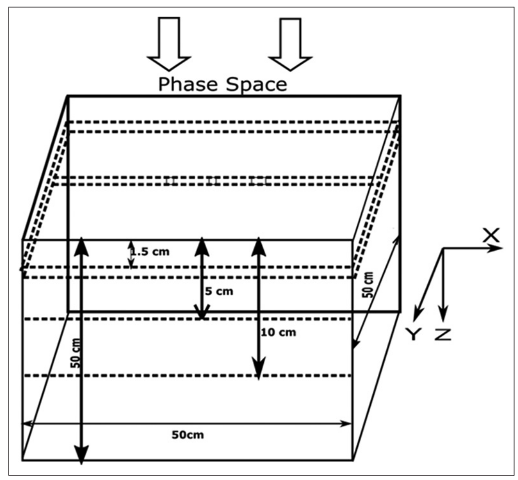

Figure 5: The voxel water phantom of dimension 50 cm × 50 cm × 50 cm used for DOSXYZnrc simulation. The size of voxels set for PDD and beam profile calculations (for 10 cm × 10 cm field size) are also shown

2 to 25 cm, voxel dimension of 1.0 cm × 1.0 cm × 0.1 cm were considered. The beam profiles (both X and Y directions) were calculated at three different depths such as d_{max} (1.5 cm), 5 cm and 10 cm. For beam profile simulations, different voxel dimensions were chosen for the shoulder, penumbra, and flattened regions. For example, for dose profile simulation in X-direction for a field size of 10 cm × 10 cm voxel dimensions of 0.1 cm × 1.0 cm × 0.1 cm (from −4.0 to +4.0) for flattened region and 0.05 cm × 1.0 cm × 0.1 cm for shoulder and penumbra regions (from −7.5 to −4.0 and +7.5 to +4.0) were used. The EGSnrc parameters set for DOSXYZnrc simulation were ECUT = AE = 0.521 MeV, PCUT = AP = 0.01 MeV.

All the simulations utilized PRESTA-II electron step length algorithm. Up to 6×10^9 particle histories were followed in the simulation. The statistical uncertainties associated with the absorbed dose values were <0.5%.

Measurement of photon beam dosimetric parameters

Dose measurements were carried out by a PTW MP3 Water Scanning System and ionization chamber (Semiflex 0.125 cm^3). The measurements were performed with 1 mm resolution for both PDD and beam profiles. Field sizes considered were from 5 cm x 5 cm to 25 cm x 25 cm at a SSD of 100 cm. Beam profiles were measured at three different depths, i.e. depth of maximum dose (d_{max}), 5 cm and 10 cm for both X and Y directions. The overall uncertainty in the dose measurement using the water phantom scanning system is estimated up to a maximum value of 2%. This uncertainty is attributed to positioning inaccuracy of the chamber up to 1 mm and fluctuations of chamber and electrometer, air pressure, and temperature during the time frame of one scan.

Results and Discussion

Incident electron beam characteristics

Analysis of central axis percentage depth dose (PDD) data for 10 cm × 10 cm suggests that for a given incident electron beam energy, PDD is almost insensitive to the incident electron beam parameters. PDD values also do not differ significantly with the investigated incident electron beam energies of 6–6.5 MeV. The relative difference between the calculated depth-dose distributions (10 cm × 10 cm field size) for beam energies 6 and 6.5 MeV was <1.5%. The PDD values at a depth of 10 cm, %dd (10), for a field size of 10 cm × 10 cm, corresponds to the beam quality.[33] Figure 6 presents the %dd (10) values for the investigated electron beam energies which have Gaussian distribution (FWHM = 1 mm). As the energy increases, there is a marginal increase in the value of %dd (10). The same trend was observed for the cases 1 and 2. For the incident electron beam energy of 6.2 MeV (Gaussian with FWHM = 1 mm), the calculated value %dd (10) is 66.3% which is in close agreement with the measured value of 67% carried out in the present study. The overall conclusion is that for the incident electron beam energy of 6.2 MeV, irrespective of the cases investigated (cases 1–3), the agreement between the calculated PDD values and the measurements is <1%.

However, the beam profiles are sensitive to the incident electron beam parameters. Figure 7a presents the comparison of Monte Carlo-calculated profile in X-direction for incident electron beam energies 6.0, 6.2, 6.5 MeV and measured data for a field size of 10 cm × 10 cm and at a depth of 10 cm for point divergent source (case 1). Figure 7b and c present the above comparison for the parallel circular beam (case 2) and Gaussian distribution (case 3), respectively. It was observed that beam profile horns were reduced as the incident electron beam energy increases. Lower energy beams produce horns at the edge of the radiation field while higher ones correspond to flat profiles. An energy difference of 0.1 MeV causes a dose difference at the edge of the field by about 1%. Above discussion demonstrates that the dose profile resulting from 6.2 MeV of electrons with Gaussian distribution (case 3) provides optimum agreement with the measurements. Figure 7d compares the investigated cases with incident electron beam energy of 6.2 MeV with measured data.

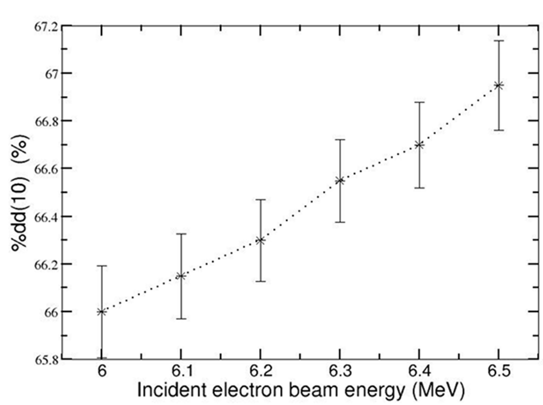

Figure 6: Comparison of percent depth dose value at a depth of 10 cm, %dd (10), in water, Monte Carlo-calculated values for various incident electron beam energies and measurement for a field size of 10 cm × 10 cm

For all the investigated cases, beam parameters such as left penumbra (LP), right penumbra (RP), beam flatness and beam symmetry were investigated. Table 1 presents these parameters analyzed from the calculated beam profiles of all the investigated electron beam parameters for the field size of 10 cm × 10 cm. Measured data are also included for comparison. For case 1, both RP and LP were <6 mm which is less than the measured values of 6.9 mm. Beam symmetry and flatness were observed to be higher than the measured as well as the tolerance values (103% and 106%) as quoted by the IEC protocol.[34] For case 2, both RP and LP were <5.5 mm which is less than the measured values of 6.9 mm. Beam flatness was observed to be higher than the measured as well as the tolerance values. However, beam symmetry was within the acceptable range for all the beam energies. For case 3, all the parameters such as RP, LP, symmetry, and flatness were in good agreement with the measured values at beam energy 6.2 MeV with the Gaussian distribution.

Figures 6 and 7 and Table 1 demonstrate that Monte Carlo calculations using the incident electron beam energy of 6.2 MeV with Gaussian distribution (FWHM = 1 mm) produce dose distributions which agree with the measurements. Table 2 presents the incident electron beam parameters concluded by the other investigators which result in dose distribution comparable to the measurements.

Measured and calculated photon beam dosimetric characteristics

Further Monte Carlo simulations were carried out for other field sizes such as 5 cm × 5 cm, 15 cm × 15 cm, 20 cm × 20 cm and 25 cm × 25 cm for a mono-energetic electron beam of kinetic energy 6.2 MeV with the Gaussian distribution of FWHM = 1 mm. PDDs were calculated for depths from 0 to 25 cm, and beam profiles (both X and Y directions) were calculated at three different depths of d_{max} (1.5 cm), 5 cm and 10 cm for the above field sizes. The calculated PDD and beam profiles for all the above field sizes were compared with the measured data and a good agreement was found.

The dose difference between the calculated and measured PDD values were under 1% for all the investigated field sizes. Both Monte Carlo-calculated and measured depth of d_{max} was found to be at 1.52 cm for a field size of 10 cm × 10 cm. The differences between calculated and measured values were <1% in the tail region and <0.5% in the superficial depth region for all the investigated field sizes. Calculated and measured PDD values are shown in Figures 8-10 for field sizes of 5 cm × 5 cm, 10 cm × 10 cm and 25 cm × 25 cm, respectively.

For beam profiles, the difference between calculated and measured dose values was <1%, except for the border points where the maximum deviation between calculated and measured dose values were found to be around 1.8%. Table 3 presents the comparison of Monte Carlo-calculated and measured beam profile parameters such as LP, RP,

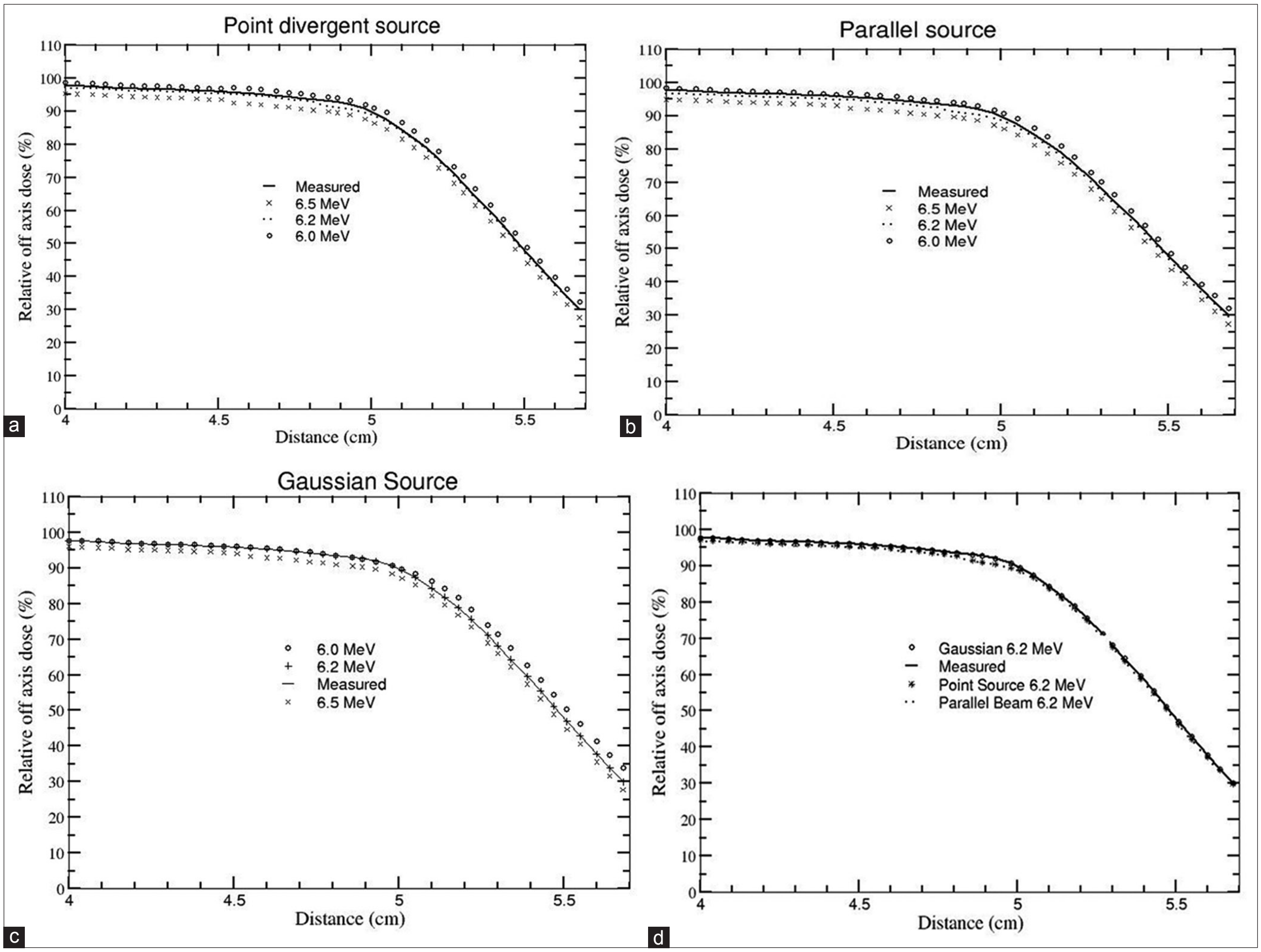

Figure 7: Comparison of Monte Carlo-calculated beam profiles and measured values for incident electron beam energies 6.0, 6.2, 6.5 MeV and measured data for a field size of 10 cm × 10 cm and at a depth of 10 cm (a) Point divergent source placed on the Z-axis (b) parallel circular beam (c) circular beam with Gaussian distributions. (d) Comparison of Monte Carlo-calculated beam profiles of all the investigated radial intensity distributions for incident electron beam energy 6.2 MeV and measured data

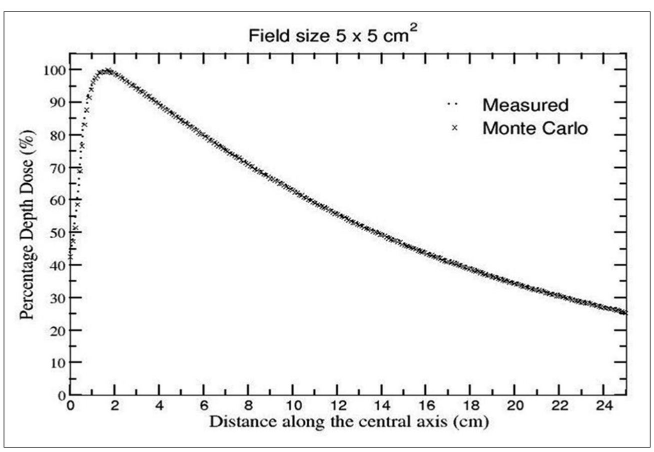

Figure 8: Comparison of Monte Carlo-calculated and measured percentage depth dose values for a field size of 5 cm × 5 cm

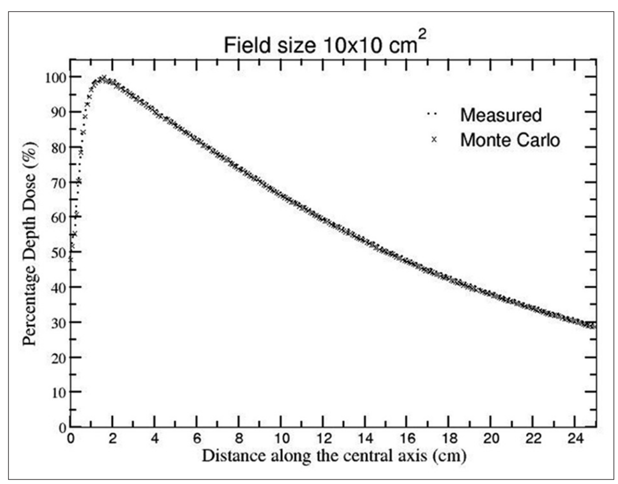

Figure 9: Comparison of Monte Carlo-calculated and measured percentage depth dose values for a field size of 10 cm × 10 cm

flatness, and symmetry for all the investigated field sizes. Monte Carlo-calculated values were found to be in excellent agreement with the measured values for the field sizes.

Calculated and measured X-profiles and Y-profiles for all the investigated field sizes at a depth of 10 cm are presented in

Table 1: The parameters analyzed from the beam profiles for all the combinations of incident electron beam parameters along with the measured parameters for a field size of 10 × 10 cm² and at a depth of 10 cm

Electron energy (MeV)	Gaussian source				Point source				Parallel beam source				Measured data			
	LP (mm)	RP (mm)	Flatness (%)	Symmetry (%)	LP (mm)	RP (mm)	Flatness (mm)	Symmetry (mm)	LP (mm)	RP (mm)	Flatness (mm)	Symmetry (%)	LP (mm)	RP (mm)	Flatness (%)	Symmetry (%)
6	6.5	6.4	106.4	101.2	5.3	5.4	108.1	102.2	5.6	5.7	109.2	103.3				
6.1	6.6	6.7	105.6	101.6	5.4	5.5	108.2	102.1	5.7	5.8	109.4	103.1				
6.2	6.8	6.7	104.6	101.5	5.5	5.6	108.4	102	5.9	5.8	109.5	102.9	6.9	6.8	104.9	101.2
6.3	6.6	6.7	105.7	101.7	5.4	5.5	108.6	102.7	5.7	5.8	109.4	103.2				
6.4	6.5	6.4	106.8	100.9	5.5	5.4	108.5	102.5	5.6	5.7	109.8	103.5				
6.5	6.5	6.6	106.9	101.4	5.3	5.4	108.3	102.8	5.6	5.7	109.9	103.7				

Left penumbra and right penumbra stand for left penumbra and right penumbra, respectively. LP: Left penumbra, RP: Right penumbra

Table 2: Comparison of incident electron beam parameters which resulted in good agreement with the measured dose profiles (published and this study)

Model of 6 MV Linac unit	Electron beam parameter	Reference
Varian 600 C/D	Electron energy - 5.7 MeV	[20]
	Gaussian distribution with FWHM 1.3 mm	
Elekta SL 25	Electron energy - 6.3 MeV	[14]
	Gaussian distribution with FWHM 1.1 mm	
Siemens KD	Electron energy - 6.8 MeV	[14]
	Gaussian distribution with FWHM 3.2 mm	
Elekta synergy	Electron energy - 6.45 MeV	[24]
	Gaussian distribution with FWHM 0.25 mm in Y and 1.0 mm in X plane	
Varian 2100 EX	Electron energy - 6.2 MeV	[22]
	Gaussian distribution with FWHM 1.3 mm	
Clinac 2100 C/D	Electron energy - 6.05 MeV	[29]
	Pencil beam with a diameter of 2 mm	
Present study	Electron energy - 6.2 MeV	-
	Gaussian distribution with FWHM 1 mm	

FWHM: Full Width Half Maximum

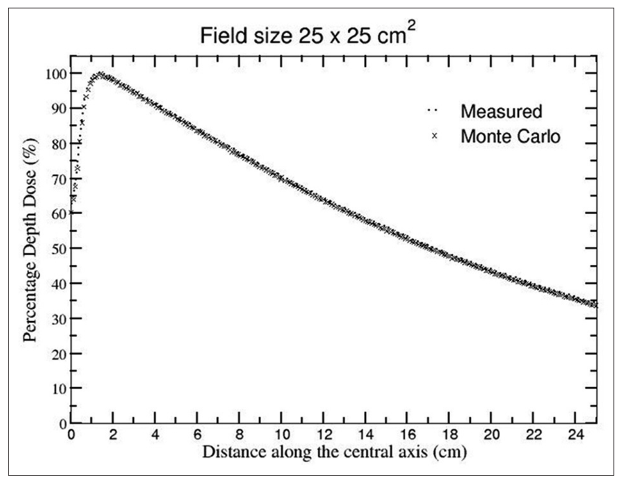

Figure 10: Comparison of Monte Carlo-calculated and measured percentage depth dose values for a field size of 25 cm × 25 cm

Figures 11 and 12, respectively. Statistical uncertainties on the calculated dose values for each voxel were mostly below 0.2% and about 0.7% for regions near field edge.

Conclusions

The indigenous linac unit Siddharth of photon energy 6 MV was simulated using the Monte Carlo-based BEAMnrc code. The dosimetric parameters such as PDD and beam profile were calculated using the DOSXYZnrc user-code of the EGSnrc code system, and the results were compared with the measured data. In the study of the influence of electron beam parameters on photon beam characteristics, five different incident electron beam energies (6-6.5 MeV) and three different type of radial intensity distribution of electron beam (case 1, 2 and 3) were chosen. It was found that the central axis relative depth dose

Table 3: Comparison of Monte Carlo-calculated and measured beam profile parameters such as left penumbra, right penumbra, flatness, and symmetry for the investigated field sizes for incident electron beam energy of 6.2 MeV with a Gaussian distribution of Full Width Half Maximum 1 mm

Field size (cm^2)	Monte Carlo calculated				Measured			
	LP (mm)	RP (mm)	Flatness (%)	Symmetry (%)	LP (mm)	RP (mm)	Flatness (%)	Symmetry (%)
5×5	6.3	6.2	103.2	101.5	6.2	6.4	104.2	101.4
10×10	6.8	6.7	104.6	101.5	6.9	6.8	104.9	101.2
15×15	7.6	7.7	104.2	100.7	7.8	7.7	103.6	102.3
20×20	8.3	8.4	103.5	101.3	8.4	8.5	103.2	101.6
25×25	9.1	9.3	104	103.2	9.2	9.2	103.5	103

Left penumbra and right penumbra stand for the left penumbra and right penumbra, respectively. LP: Left penumbra, RP: Right penumbra

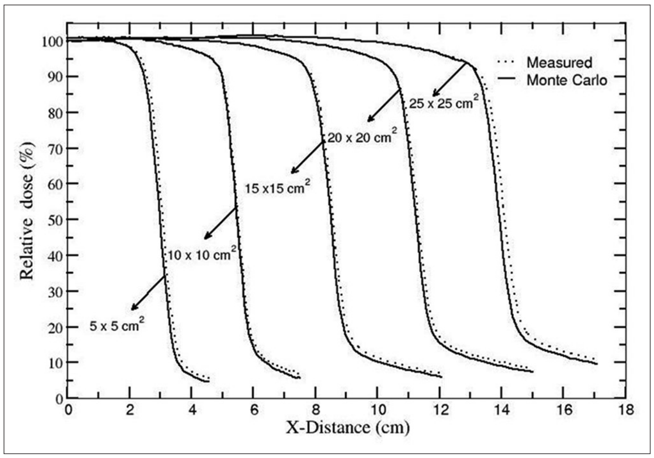

Figure 11: Comparison of Monte Carlo-calculated and measured X-profiles for all the investigated field sizes at a depth of 10 cm

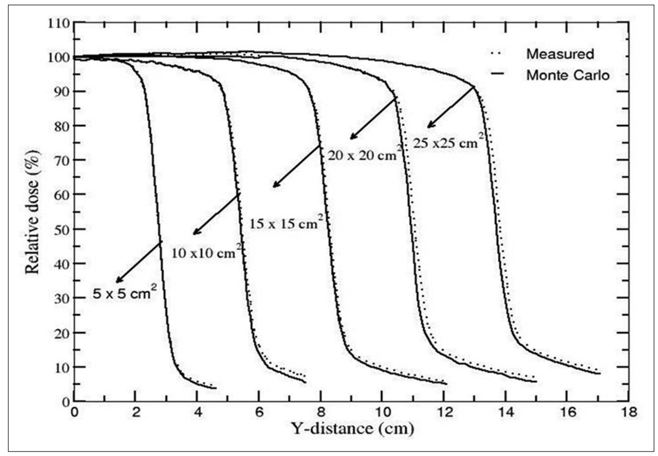

Figure 12: Comparison of Monte Carlo-calculated and measured Y-profiles for all the investigated field sizes at a depth of 10 cm

values, i.e. PDDs are quite insensitive to variations in the electron beam radial intensity distribution. However, the beam profiles are sensitive to the incident electron energy as well as the radial intensity distribution of the incident electron beam. The calculated PDD and lateral beam profiles for 5 cm × 5 cm, 10 cm × 10 cm, 15 cm × 15 cm, 20 cm × 20 cm and 25 cm × 25 cm field sizes were compared with the measured data and a good agreement was found when the calculated dose profiles utilized the combination of incident electron beam energy of 6.2 MeV and the Gaussian distribution with FWHM of 1.0 mm.

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Conflicts of interest

There are no conflicts of interest.

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