

Comparison of Measured and Monte Carlo Calculated Dose Distributions from Indigenously Developed 6 MV Flattening Filter Free Medical Linear Accelerator

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Abstract

Purpose: Monte Carlo simulation was carried out for a 6 MV flattening filter-free (FFF) indigenously developed linear accelerator (linac) using the BEAMnrc user-code of the EGSnrc code system. The model was benchmarked against the measurements. A Gaussian distributed electron beam of kinetic energy 6.2 MeV with full-width half maximum of 1 mm was used in this study. **Methods:** The simulation of indigenously developed linac unit has been carried out by using the Monte Carlo-based BEAMnrc user-code of the EGSnrc code system. Using the simulated model, depth and lateral dose profiles were studied using the DOSXYZnrc user-code. The calculated dose data were compared against the measurements using an RFA dosimetric system made by PTW, Germany (water tank MP3-M and 0.125 cm³ ion chamber). **Results:** The BEAMDP code was used to analyze photon fluence spectra, mean energy distribution, and electron contamination fluence spectra. Percentage depth dose (PDD) and beam profiles (along both X and Y directions) were calculated for the field sizes 5 cm × 5 cm - 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 3%. **Conclusions:** A Monte Carlo model of indigenous FFF linac (6 MV) has been developed and benchmarked against the measured data.

Keywords: EGSnrc code system, flattening filter free, linear accelerator, Monte Carlo

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INTRODUCTION

Conventional medical linear accelerators (linac) are equipped with a flattening filter (FF) which is primarily designed to produce a flat beam profile at a given depth by compensating for the nonuniformity of photon fluence across the field. However, FF decreases the output considerably and produces quality changes within the primary beam by scattering and absorption of primary photons.^[1] The requirement to have a flattened beam profile for treatment delivery is not necessary when a certain type of advanced modality treatments such as intensity-modulated radiation therapy (IMRT) or intensity-modulated arc therapies is used. In IMRT, the patient dose distribution can instead be shaped by the multileaf collimator (MLC) to create the desired clinical effect. In principle, the FF can be removed, and the leaf sequences can be adjusted accordingly to produce fluence distributions similar

to those of a beam with an FF. The removal of FF with its associated attenuation from X-ray beam path increases dose rate.^[2] The other possible effect is substantial reduction in head scatter, as the FF is the major source of scattered photons. FF-free (FFF) beams in radiotherapy thus have the advantage of shorter treatment delivery time and lower out-of-field dose compared to conventional flattened beams.^[3] For small field sizes, unflattened fields have dose profiles similar to those of a flattened beam. This, along with the higher dose rate in FFF mode, will increase the efficiency when delivering stereotactic

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radiosurgery.^[4-6] For larger clinical targets, the desired photon fluence could be modulated using the MLC and movable jaws allowing FFF beams to be a useful approach for the delivery of radiotherapy treatments.^[7-11] Further, the vault design for FFF linac has shown lesser shielding requirements in comparison to FF linac.^[12]

SAMEER (Society for Applied Microwave Electronics Engineering and Research), Mumbai, India has developed an indigenous linac unit named as “SIDDHARTH” which is capable of delivering cost-effective radiotherapy treatment in India. Presently, the linac unit is being used clinically at various hospitals in India in FF mode with photons of energies 4 and 6 MV. Recently, Subhalaxmi *et al.* have reported the dosimetric characteristics of this unit using Monte Carlo method as well as by measurement.^[13] However, due to the increase in interest of operating the linac in FFF mode, the feasibility study has been carried out for the same unit in FFF mode. The objective of this study is to evaluate the dosimetric characteristics of indigenously developed linac in FFF mode using Monte Carlo method and verify the results with the measured data. It may be noted that the measured data were generated in linac service mode to find the feasibility for clinical use of this linac in FFF mode.

Monte Carlo method has become a powerful tool in radiotherapy dose calculations, and many studies have been performed using this method for studying beam characteristics of linac.^[14-18] Several Monte Carlo studies of FFF treatment machines have been published.^[19-23] In this study, Monte Carlo simulation of indigenously developed linac unit of photon energy 6 MV in FFF mode was carried out, and the data were verified with measurement for its clinical use. For this purpose, the user-codes BEAMnrc^[24] DOSXYZnrc^[25] of the EGSnrc code system^[26] were used to study its dosimetric characteristics. The calculated dose data were then compared with the measured data. The BEAMDP^[27] (BEAM Data Processor) user-code of the EGSnrc code system was used to analyze the phase-space files and to extract the spectra of particles such as photons and electrons reaching the plane at the source to surface distance (SSD) of 100 cm. This study reports the percentage depth dose (PDD), TPR 20/10, beam profiles, surface dose, build-up dose, mean energy, photon fluence, and contaminant electron fluence spectra for the 6 MV FFF beam.

MATERIALS AND METHODS

Monte Carlo simulation

Simulation of medical linear accelerator using BEAMnrc code

The geometry of indigenously developed linac was simulated using the BEAMnrc^[24] user-code of EGSnrc^[26] code system based on the detailed design specification provided by the vendor. Different components of the linac head such as target, primary collimator, monitor chamber, and secondary collimator were accurately modeled. Figure 1 shows the linac modeled in

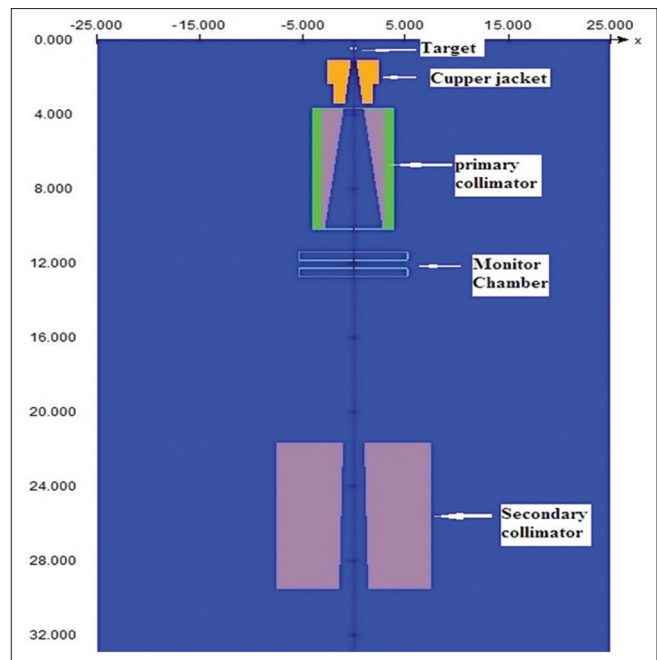


Figure 1: Structure of the indigenous flattening filter-free medical linear accelerator considered in the Monte Carlo calculation. The dashed line is the Z-axis, with the positive X direction to the right and the Y direction coming out of the page. The origin is on the target surface at position 0. The main components of linac head consist of the target, primary collimator, ion chamber, and secondary collimator

the present study. In this simulation, Z-axis is taken along the beam axis, and the origin is taken at the front face of the target.

In the Monte Carlo simulations, a mono-energetic electron beam of kinetic energy 6.2 MeV with a Gaussian distribution of full width half maximum 0.1 cm was incident on the target. This optimized energy of 6.2 MeV was selected from the previous research of Subhalaxmi *et al.*^[13] Phase space data were scored at a distance of 100 cm SSD for all the treatment field sizes ranging from 5 cm × 5 cm to 25 cm × 25 cm in an increment of 5 cm². The phase space file contains information about the simulated particles (energy, position, and direction). The electron transport cutoff (ECUT) and photon transport cutoff (PCUT) energy were set to 0.7 and 0.01 MeV, respectively. No photon interaction forcing was used. As described in the published literature,^[17] range rejection was turned on with ESAVE value of 0.7 MeV in the target and 2 MeV in the other part of the linear accelerator geometries as they do not contribute significantly and this helps in optimizing the computational time. The PEGS4 data set needed for the simulations was based on the state-of-art XCOM compilation.^[28] The number of particles histories simulated in the Monte Carlo calculation was 6×10^9 .

Monte Carlo Simulation using DOSXYZnrc code

The phase space data from the aforementioned simulations served as the source for the simulation using the DOSXYZnrc user-code of EGSnrc code system. DOSXYZnrc is capable of 3D absorbed dose calculations in Cartesian coordinates

in the water phantom. In DOSXYZnrc, the water phantom size was $50\text{ cm} \times 50\text{ cm} \times 50\text{ cm}$ and the phase space source position was on the water surface, i.e., at $Z = 100\text{ cm}$. The phantom was divided into a number of voxels. The voxel dimensions were different in different dose gradient regions of the water phantom. The voxel dimensions were adapted to be small in regions of high dose gradients and vice versa. For central axis PDD simulation, up to a depth of 2 cm , absorbed dose was scored in voxel dimension of $1.0\text{ cm} \times 1.0\text{ cm} \times 0.05\text{ cm}$ and for depths from 2 cm to 25 cm , voxel dimension of $1.0\text{ cm} \times 1.0\text{ cm} \times 0.1\text{ cm}$ was considered. The beam profiles (both X and Y directions) were calculated at three different depths such as depth of maximum dose (1.5 cm), 5 cm , and 10 cm . For beam profile simulations, different voxel dimensions were chosen for the shoulder, penumbra, and unflat regions. For example, for dose profile simulation in X-direction for a field size of $10\text{ cm} \times 10\text{ cm}$, voxel dimensions of $0.1\text{ cm} \times 1.0\text{ cm} \times 0.1\text{ cm}$ (from -4.0 to $+4.0$) for unflat region and $0.05\text{ cm} \times 1.0\text{ cm} \times 0.1\text{ cm}$ for shoulder and penumbra regions (from -7.5 to -4.0 to $+7.5$ to $+4.0$) were used. The PEGS4 data set needed for the simulations was based on the state-of-art XCOM compilation.^[28] The parameters set for DOSXYZnrc simulation were, $\text{ECUT} = \text{AE} = 0.521\text{ MeV}$, and $\text{PCUT} = \text{AP} = 0.01\text{ MeV}$. PRESTA-II electron-step algorithm was used in all simulations. The total number of histories set in the calculation was 6×10^9 . The 1σ statistical uncertainty on the dose estimates were $<0.8\%$.

Measurement of photon beam dosimetric parameters

PDD and beam profile measurements were carried out in the service mode of the linac (as FFF beam is under investigation before its clinical implementation) using PTW, Germany, make RFA dosimetric system (water tank MP3-M and 0.125 cm^3 ion chamber). The measurements were performed with 1 mm resolution for PDD curves, beam profiles, and TPR 20/10. Field sizes considered were from $5\text{ cm} \times 5\text{ cm}$ to $30\text{ cm} \times 30\text{ cm}$ at 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.

RESULTS AND DISCUSSION

Analysis of spectra

The BEAMDP code was used to analyze the phase-space files, extract the various types of spectra of all particles reaching the plane at SSD 100 cm and to determine the photon fluence spectra, mean energy distribution, and electron contamination fluence spectra.

Photon fluence spectra

Photons emerging from the target passes through the primary collimator and other components of the collimating system on their way to the scoring plane at SSD 100 cm . Figure 2 shows on-axis photon fluence spectra calculated at the scoring plane for different field sizes. Scoring plane is an annular region of 2.5 cm radius around the central axis.

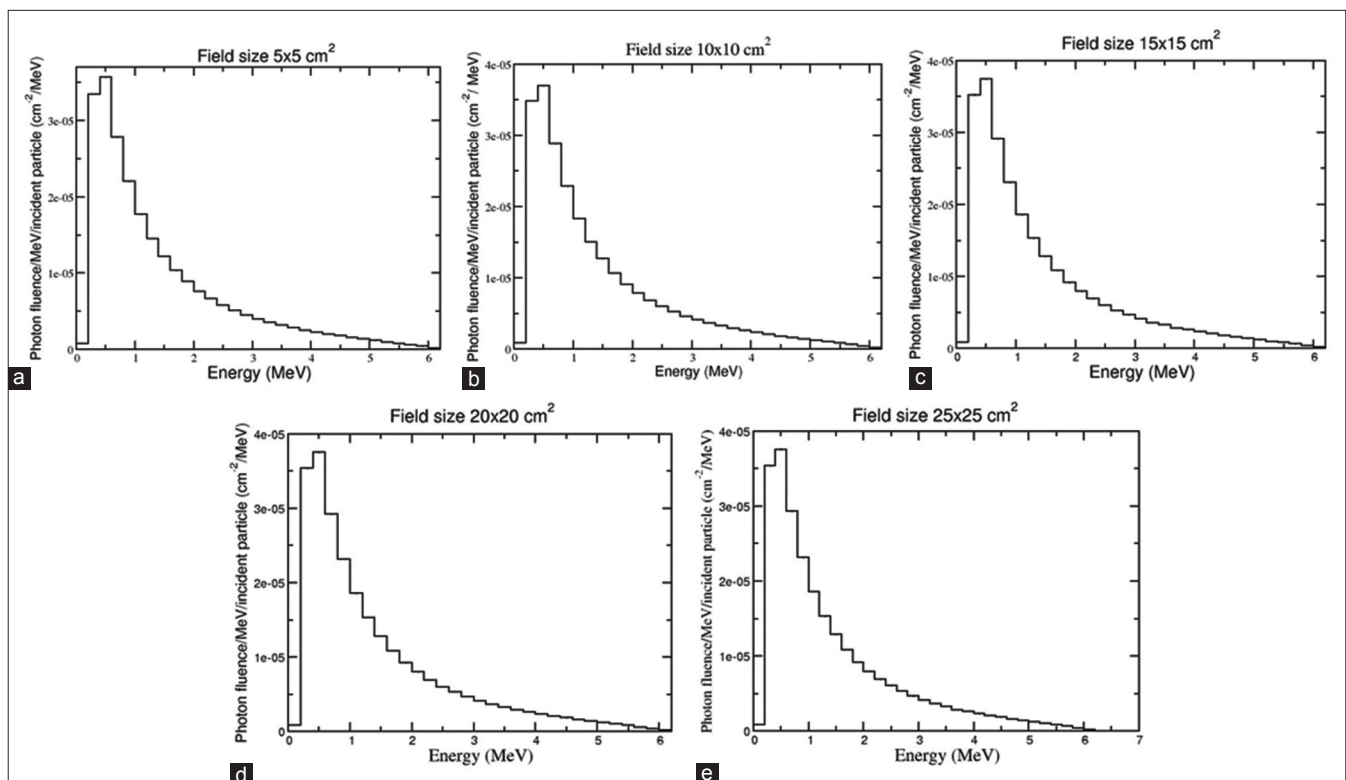


Figure 2: Monte Carlo calculated photon fluence spectrum for field sizes (a) $5\text{ cm} \times 5\text{ cm}$ (b) $10\text{ cm} \times 10\text{ cm}$ (c) $15\text{ cm} \times 15\text{ cm}$ (d) $20\text{ cm} \times 20\text{ cm}$ (e) $25\text{ cm} \times 25\text{ cm}$

Contaminant electron fluence spectra

Secondary electrons generated from different components of the linac head and also by the primary photons inside the phantom are the sources of contaminant electrons. Figure 3 shows the calculated contaminant electron fluence spectra along the central axis for all the investigated field sizes. The contaminant electron fluence spectra were scored in an annular region of radius 2.5 cm around the central axis. It is observed that the number of electrons reaching the phantom surface strongly depends on the field size and increases with increase in field size. The mean electron fluence for field size 20 cm × 20 cm was found to be 1.8 times higher than that for 10 cm × 10 cm and 3.6 times for 5 cm × 5 cm field size.

Mean energy

The fluence-weighted mean energies were calculated for field sizes of 5 cm × 5 cm, 10 cm × 10 cm, 15 cm × 15 cm, 20 cm × 20 cm, 25 cm × 25 cm and summarized in Table 1. The

Table 1: Variation of mean energy and surface dose with field size for flattening filter-free indigenous linear accelerator of photon energy 6 MV

Field size (cm ²)	Mean energy (MeV)	Surface dose (%)
5 × 5	1.29	55.7
10 × 10	1.27	59
15 × 15	1.21	61.5
20 × 20	1.17	62.9
25 × 25	1.14	64.2

mean energy of photon decreases with the increasing field size due to the increased contribution of more low-energy scattered photons from the linac head.

Percentage depth-dose characteristics

PDDs were calculated for depths from 0 cm to 25 cm for the field sizes 5 cm × 5 cm, 10 cm × 10 cm, 15 cm × 15 cm, 20 cm × 20 cm, and 25 cm × 25 cm. Both the calculated and measured central axis depth-dose curves were normalized to the value of maximum dose for the respective field size on the central axis and then compared. Figure 4 shows the comparison between the calculated and measured PDDs for all the field sizes studied in this work. The dose difference between the calculated and measured PDD values was under 1% for all the investigated field sizes. 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.

The measured d_{max} occurred at 1.4 cm for all the investigated sizes except 5 cm × 5 cm for which it occurred at 1.6 cm. The Monte Carlo calculated d_{max} occurred at about 1.5 cm for all the investigated field sizes. D_{max} was mostly constant with increase in field size for FFF beams. The measured and calculated PDD value at a depth of 10 cm for a field size of 10 cm × 10 cm is about 64% which is comparable to the literature quoted value of 63.4% by Vassiliev *et al.*^[2] and Ankit *et al.*^[18] for an FFF 6 MV Varian Clinac 21EX.

TPR 20/10

An energy parameter value for comparison purposes was obtained using a TPR 20/10 ratio. The TPR 20/10 value

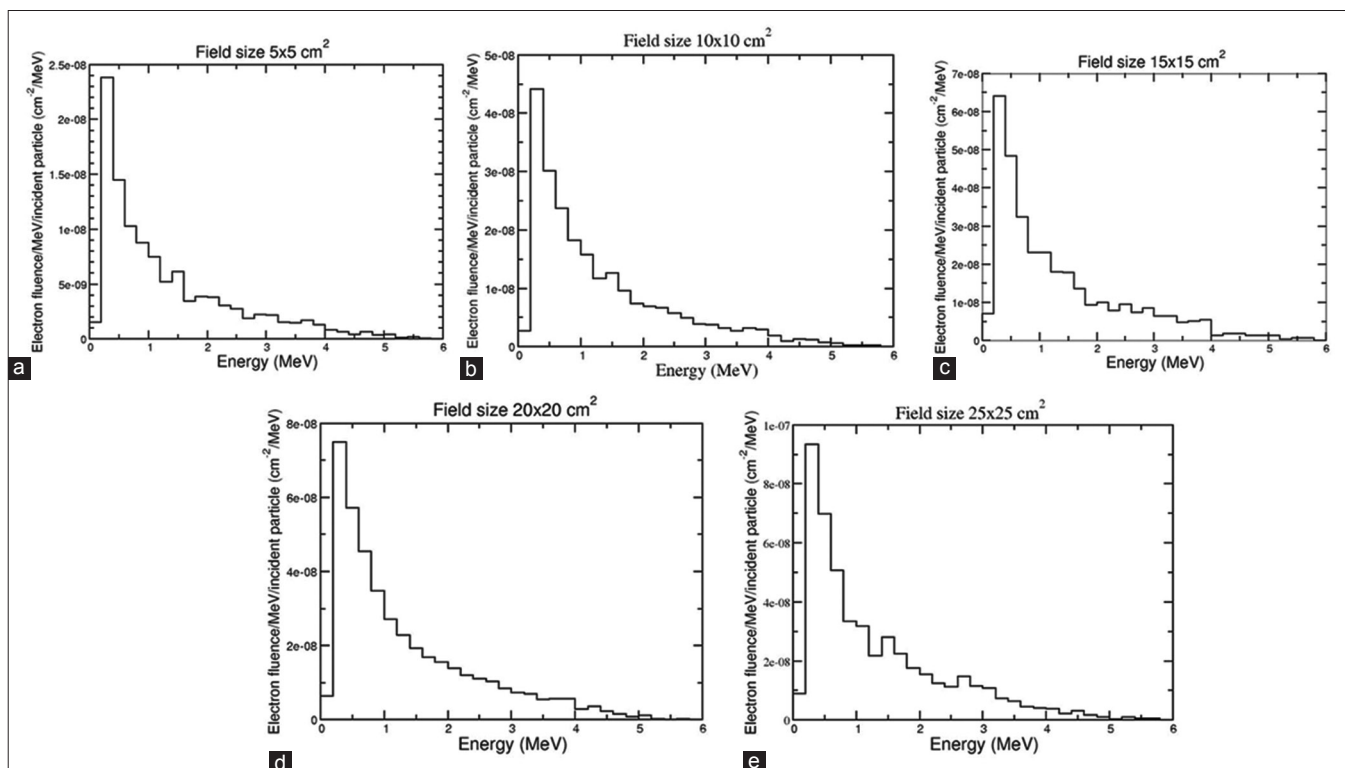


Figure 3: Monte Carlo calculated contaminant electron fluence spectrum for field sizes (a) 5 cm × 5 cm (b) 10 cm × 10 cm (c) 15 cm × 15 cm (d) 20 cm × 20 cm (e) 25 cm × 25 cm

was determined from the calculated PDD values at 20 cm and 10 cm using an empirical approximation relation^[29] ($\text{TPR } 20/10 = 1.2661 \text{ PDD } 20/10 - 0.0595$), where $\text{PDD } 20/10$ is the ratio of PDD at 20 cm to the PDD at 10 cm depth. The calculated $\text{TPR } 20/10$ value was found to be 0.638 which is in close agreement with the measured $\text{TPR } 20/10$ value of 0.634.

Surface dose and build up dose

Surface dose or skin dose is the dose calculated at the entrance of the phantom. The surface dose for any field size is defined as the dose measured at the surface for that field size divided by the dose at d_{max} for a 10 cm \times 10 cm field size. The region between the surface and the point of maximum dose is called the build-up dose region. Both surface dose and build-up region doses are affected by variation in field size. Surface dose increases with increase in field size. Table 1 shows the variation of Monte Carlo calculated surface dose with field size. For the first 10 mm build-up depths, the dose increased from 55.7% to 95.1%, 59% to 98.3%, 61.5% to

98.4%, 62.9% to 98% and 64.2% to 98% for the field sizes 5 cm \times 5 cm, 10 cm \times 10 cm, 15 cm \times 15 cm, 20 cm \times 20 cm, and 25 cm \times 25 cm, respectively. The maximum difference was observed for smaller field size, and the difference reduced with increase in field size. The surface dose for a field size of 10 cm \times 10 cm is 59% which is comparable to the literature quoted value of 56.2% by Ankit *et al.*^[18]

Beam profiles

The 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. All the beam profiles were normalized to their central axis value. As there is symmetry between X and Y profiles, only X profile is presented. Figure 5 shows the comparison of Monte Carlo calculated and measured beam profiles obtained at 100 cm SSD for the investigated field sizes at depths of d_{max} and 10 cm inside the water phantom in X direction. The agreement between calculated and measured dose values was within 1%, except for the penumbra region where the maximum deviation was about 2.6%. At the d_{max} , the agreement between the calculations and measurements is about 2% in the unflat region and about 3% in the penumbra region.

CONCLUSIONS

In this study, a Monte Carlo model of indigenous FFF linac (6 MV) has been developed using the Monte Carlo-based BEAMnrc user-code of the EGSnrc Monte Carlo code system. The dosimetric parameters such as PDD and beam profile were calculated using DOSXYZnrc user-code. This Monte Carlo model was benchmarked against the measured data. The differences between calculated and measured PDD values were <1% in the tail region and <0.5% in the superficial depth region for all the investigated field sizes. The d_{max} occurred at 1.5 cm and mostly remained constant with field size. Surface dose and build-up region doses vary with field size. Surface doses increased with increase in field size.

Results indicate good agreement between Monte Carlo calculated and measured lateral beam profiles (X and Y) obtained at SSD = 100 cm for all the investigated field sizes at depths of d_{max} , 5 cm and 10 cm. The difference between calculated and measured dose values were <1%, except for

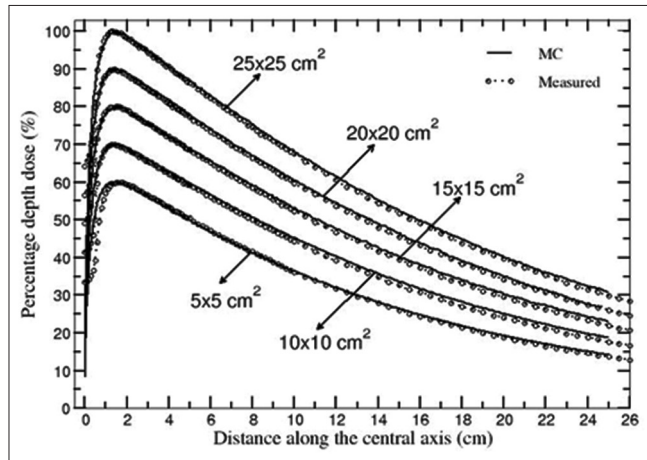


Figure 4: Comparison of Monte Carlo calculated and measured percentage depth dose curves of 6 MV flattening filter-free photon beam (at source to surface distance = 100 cm) for 25 cm \times 25 cm, 20 cm \times 20 cm, 15 cm \times 15 cm, 10 cm \times 10 cm, and 5 cm \times 5 cm field sizes. Depth dose profiles for 20 cm \times 20 cm, 15 cm \times 15 cm, 10 cm \times 10 cm and 5 cm \times 5 cm field sizes are scaled by 0.9, 0.8, 0.7, and 0.6, respectively, for inclusion on the same graph, and all profiles are normalized at their respective value of depth of maximum dose and expressed as percentage

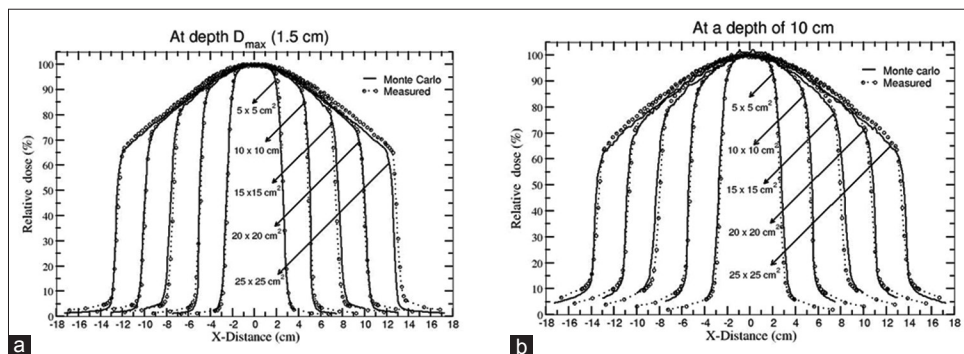


Figure 5: Comparison of Monte Carlo calculated and measured X-profiles of all the investigated field sizes. All profiles are normalized to the central axis dose and expressed as percentage. (a) At depth of maximum dose (1.5 cm) depth (b) at 10 cm depth

the penumbra region where the maximum deviation between calculated and measured dose values were found to be around 3% (at depth d_{max}). Phase space files were analyzed using BEAMDP user-code of EGSnrc code system.

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Nil.

Conflicts of interest

There are no conflicts of interest.

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