Case Study

Monte Carlo Model Validation of 6MV Beam of OMID, the First Iranian Linear Accelerator

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Abstract

Monte Carlo (MC) techniques are regarded as an accurate method to simulate the dose calculation in radiotherapy for many years. The present paper aims to validate the simulated model of the 6-MV beam of OMID linear accelerator (BEHYAAR Company) by EGSnrc codes system and also investigate the effects of initial electron beam parameters (energy, radial full width at half maximum, and mean angular spread) on dose distributions. For this purpose, the comparison between the calculated and measured percentage depth dose (PDD) and lateral dose profiles was done by gamma index (GI) with 1%-1 mm acceptance criteria. MC model validating was done for 3 cm × 3 cm, 5 cm × 5 cm, 8 cm × 8 cm, 10 cm × 10 cm, and 20 cm × 20 cm field sizes. To study the sensitivity of model to beam parameters, the field size was selected as 10 cm × 10 cm and 30 cm × 30 cm. All lateral dose profiles were obtained at 10 cm. Excellent agreement was achieved with a 99.2% GI passing percentage for PDD curves and at least 93.8% GI for lateral dose profiles for investigated field sizes. Our investigation confirmed that the lateral dose profile severely depends on the considered source parameters in this study. PDD only considerably depends on the initial electron beam energy. Therefore, source parameters should not be specified independently. These results indicate that the current model of OMID 6-MV Linac is well established, and the accuracy of the simulation is high enough to be used in various applications.

Keywords: *Benchmarking, dose distribution, EGSnrc, gamma analysis, Monte Carlo simulation*

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Introduction

Radiotherapy (RT) is an effective way of cancer treatment that uses ionization radiation to destroy tumor cells. External RT is often carried out by medical linear accelerators (Linacs) because Linacs are so flexible and reliable in delivering doses to the cancerous tissues.

In the past 50 years, Monte Carlo (MC) is regarded as the "gold standard" in RT applications because of its accuracy in calculating dose distribution.[1-3] Despite several MC codes that have been created and developed so far, EGSnrc[4] is the most widely used in RT.

Input data for MC modeling of each Linac included geometry, size, and materials of Linac head components, and source parameters were provided by the manufacturers. Although electron source characteristics are usually provided, they need to be specified precisely. There are discrepancies between MC simulations and measurements for large field sizes, especially in the build-up region.[5-7]

Many authors simulated Linac head by MC method and investigated the influence of energy and radial distribution of initial electron beam on dose distribution (depth dose and lateral dose profiles).[8-15] Some of these studies investigated other source parameters such as energy spread,[8,10] angular spread,[8,14,15] or the effect of Linac components such as target density[9] and flattening filter material and density.[8]

Aljarrah *et al*.[12] studied some different ways to compare measured and simulated dose distributions, and the analysis methods included Chi-square, mean absolute error, DD at the penumbra edge point, the slope of the DD of the lateral dose profile, and κ_α factor. Low *et al*.[16] proposed gamma index (GI), which is a quantitative analytic way.

Some recent studies used the GI aiming to tune source parameters of specific linear

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accelerator model and investigated the effects of the primary electron energy, full width at half maximum (FWHM) of radial mean angular spread on the results.[17-20]

Most of the investigations mentioned so far worked with the well-known medical linear accelerator manufacturer (Varian, Elekta, and Siemens). Our aim is using the EGSnrc package for MC modeling of OMID 6-MV medical Linac (Behyaar Sanaat Sepahan, Isfahan, Iran) for the first time. In the present study, using GI, we compare MC simulation results with measurement ones to tune electron source parameters. Then, simulations in various field sizes are carried out with this tuned source to analyze the precision of these source parameters.

Materials and Methods

In the present paper, the EGSnrc code systems were used for modeling 6-MV beam of OMID linear accelerator. The Linac head was simulated by BEAMnrc code,[21] and the phase space files for each open field size were generated at the top of the water phantom, perpendicular to the beam axis (+Z direction). Phase space files contained detailed information such as energy, direction, and position of all particles that cross the scoring plane.

To calculate dose distribution in a water phantom along depth and lateral directions, the DOSXYZnrc code[22] was applied.

A supercomputer consisted of 24 processing cores with 2.93 GHz CPU, and 24 gigabytes of physical memory were used for MC simulations. The manufacturer (Behyaar Sanaat Sepahan, Isfahan, Iran) provided the measured data and the Linac head geometry and material. The measured data were collected in a 50 cm × 50 cm × 50 cm homogeneous water phantom and placed at source-to-surface distance (SSD) of 100 cm.

The electron source parameters (energy, FWHM of intensity distribution, and mean angular spread) were tuned by analyzing the comparison between MC simulation and measurement of percentage depth dose (PDD) curves and lateral dose profiles. For this purpose, GI which is a quantitative test with acceptance criteria of 1%-1 mm (dose difference [DD %]- Distance to agreement [DTA mm]) was used. For primary electron energy, the field size of 10 cm × 10 cm and for radial FWHM and mean angular spread, the field size of 30 cm × 30 cm was considered. All lateral dose profile data were obtained at the depth of 10 cm. The measured PDD curve and lateral dose profile in various square field sizes usually were applied for benchmarking. Moreover, the influences of each source parameter on dose distribution were discussed. When the MC model of OMID 6-MV Linac is validated, other field sizes (20 cm × 20 cm, 10 cm × 10 cm, 8 cm × 8 cm, 5 cm × 5 cm, and 3 cm × 3 cm) were simulated and compared to corresponding measured data and were analyzed using GI test.

Linac head simulation

The BEAMnrc was used to model 6-MV OMID Linac head components (target, primary collimator, flattening filter, ion chamber, and X and Y jaws). Figure 1 shows all information of Linac head components provided by the manufacturer, represented by the BEAMnrc GUI. The number of history was varied from 35 × 10^6 to 10^8, depending on the studied field sizes led to 4–6 h of simulation time. The smaller fields require more processing time. In this study, the directional bremsstrahlung splitting (DBS) was turned on and set DBS = 1000 for all simulations, and photon cutoff energy (PCUT) and electron cutoff energy (ECUT) were set to 0.7 MeV and 0.01 MeV, respectively. The range rejection and Russian roulette were not considered. The cross-sectional data were obtained from 700icru.pegs4, and all EGSnrc parameters were set as default. The best approximation for electron spatial distribution in X and Y directions was Gaussian distribution.[13,23] Hence, the electron source was assumed as ISOURCE = 19 (elliptical beam with Gaussian distributions in X and Y directions). The output of BEAMnrc simulations is a massive phase-space file (.egsphsp).

Dose calculations

For dose calculation, a homogeneous water phantom with dimensions of 50 cm × 50 cm × 50 cm and SSD of 100 cm was simulated by DOSXYZnrc. The generated phase-space files by BEAMnrc were used as a source in DOSXYZnrc. To calculate PDD curves, the voxel size was considered 0.25 cm × 1 cm × 1 cm along the depth, in-plane, and cross-plane directions, respectively. To calculate PDD and lateral dose profile in the field size of 30 cm × 30 cm, the voxels size were 0.5 cm × 0.5 cm × 0.5 cm, and for other studied field sizes were 0.25 cm × 0.5 cm × 0.5 cm. Due to the insensitivity of lateral dose profiles to the electron contamination, all of the lateral dose profiles in this study were obtained at a depth of 10 cm.[10] To keep statistical uncertainty <1% in all simulations, the NRCYCLE

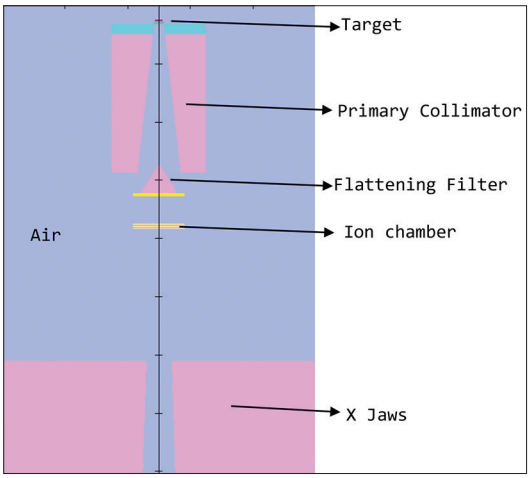

Figure 1: Schematic representation of OMID 6-MV Linac head with various component modules previewed by BEAMnrc GUI

parameter was 25 and 50 for calculating depth dose and lateral dose profile, respectively, PCUT was 0.7 MeV, and ECUT was 0.01 MeV, and the other parameters were set as default. In this kind of DOSXYZnrc simulation, the result is a. 3ddose file. The statistical uncertainties of the calculated dose for all voxels were <1%, mostly 0.5%.

Dose measurements

To evaluate the accuracy of the MC dose calculations of the Linac head, the measured data were required for comparison. The data were taken from the IBA ion chamber dosimeter in a Scanditronix-Wellhofer, RFA-300 water phantom with dimensions of 50 cm × 50 cm × 50 cm placed under the Linac head at SSD of 100 cm, and the PDD curve and lateral dose profiles were obtained for various open fields.

Gamma index

To tune the electron source, the comparison between measurements and MC simulations must be accomplished to find the optimum value for each source parameter. In this study, the GI was employed to evaluate the source parameters quantitatively. The dose difference (DD [%]) passing criterion was 1%, and the distance to agreement (DTA [mm]) passing criterion was 1 mm. A MATLAB® (R2016b; Mathworks, Natick, MA, USA) script was written for GI calculation. This script was created according to ScanDoseMatch, an open-source software, parameters value.[24] If the calculated gamma value for each point was ≤1, the calculation passed; otherwise, it failed.[16]

Results and Discussion

The main concern of the paper is to adjust the electron source parameters and to investigate their effects on the PDD curve and lateral dose profile in a water phantom.

Primary electron energy

In this part, the primary electron energies varied from 5.5 to 6.2 MeV (with 0.1 MeV interval); radial FWHM and mean angular spread were constant and equal to 0.2 cm, 0°, respectively. For these parameters, depth dose and lateral dose distribution were calculated and illustrated in Figure 2. The data were not normalized to demonstrate that the effect of electron energy on the dose distribution is remarkable.

The GI values corresponding to each electron energy are represented in Table 1. Accordingly, the best GI passing percentage specifies the optimum primary electron energy. Figure 3 indicates the lateral dose profile (Figure 3a) and PDD curve (Figure 3a) of the best match. In the build-up region of the PDD curve, the dose distribution gradient is too much and it causes significant differences, particularly in the surface dose, as it is obvious in Figure 3b. It may be referred to as the small size of the ionization chamber.[25]

According to Figure 2a, the increment of electron energy increases the deposited energy along the off-axis. The influence of electron energy on the shape of the lateral dose profile is shown in Figure 4. For better representation, the lateral dose profile correspond to two values were shown. Electron energy affects the shape of the lateral dose profile mostly by decreasing the horns of profiles. We found that the penumbra and umbra regions were less influenced by electron energy, qualitatively. These results were consistent with some previous investigations.[8-10,14]

Table 1: Gamma index passing percentages with acceptance criteria of 1%-1 mm correspond to each electron energy

Primary electrons energy (MeV)	GI passing percentage	
	Profile	PDD
5.5	96.6	96.0
5.6	96.6	97.6
5.7	98.3	99.2
5.8	91.5	99.2
5.9	88.1	96.8
6	64.4	96.0
6.1	76.2	92.9
6.2	64.4	86.7

Radial FWHM and mean angular spread of the electron source were fixed to 0.2 cm and 0°, respectively. PDD – Percentage depth dose; GI – Gamma index; FWHM – Full width at half maximum

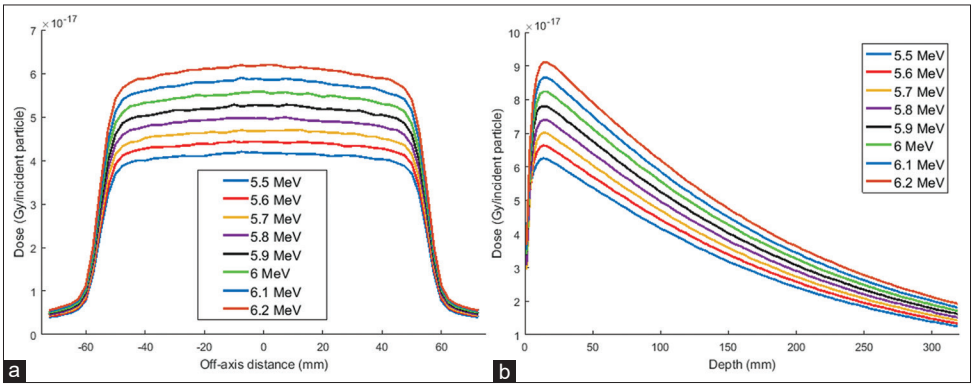

Figure 2: (a) Lateral dose profiles and (b) Depth dose curves for the field size of 10×10 cm² for the different values of primary electron energy. The normalization has not been applied to the curves

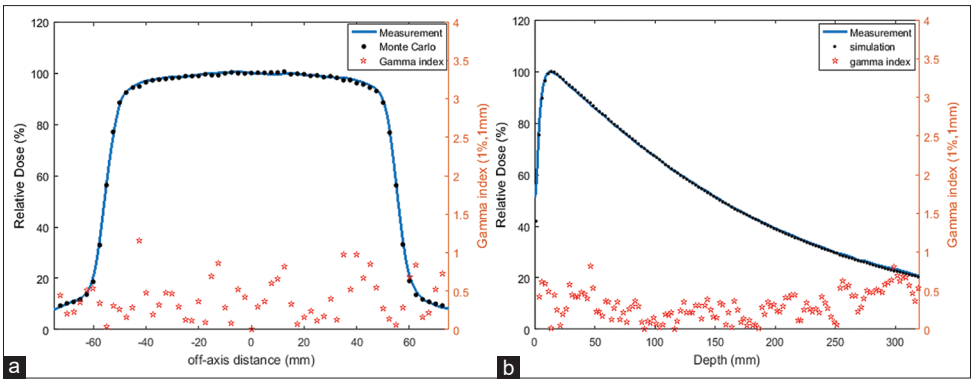

Figure 3: (a) Lateral dose profile and (b) percentage depth dose curve for the field size of 10 cm × 10 cm with gamma index values, when primary electron energy is optimum (5.7 MeV). The radial full width at half maximum and mean angular spread were constant and assumed 0.2 cm and 0°, respectively

Table 1 illustrates that electron energy has a slight effect on PDD curves and Figure 2b shows that the deposited energy at each depth increases along the central axis with increasing electron energy. These results are in agreement with previous studies.[8,9,11,15,26] Table 1 also indicates that the electron energy has an effect on depth dose curves and even lateral dose profiles.[10,14] We can conclude from Table 1 that the sensitivity of lateral dose profiles to electron energy is more than PDD curves.[10,20]

Radial full width at half maximum and mean angular spread determination

In this study, we determined radial FWHM and mean angular spread together. Many simulations were done with combinations of radial FWHM/mean angular spread. GI passing percentage with acceptance criteria of 1%-1 mm was calculated to analyze the comparison between measurement data against simulation corresponding to each combination of radial FWHM/mean angular spread [Figure 5].

Among many cases, the highest GI value corresponded to the best source parameter. Therefore, the optimum value of radial FWHM and mean angular spread was 0.25 cm/2°.

In this section, we considered large field size to determine the optimum value of the radial FWHM and mean angular spread parameter. It was reported that the sensitivity of dose distributions in large field sizes to the variation of radial FWHM and mean angular spread parameter was more than in small field sizes (i.e., 10 cm × 10 cm).[10,11,19,20,25] Hence, in this section, lateral dose profiles and PDD curves were obtained for a field size of 30 cm × 30 cm. The influences of each parameter (radial FWHM and mean angular spread) on dose distribution were discussed in the following.

The impact of radial FWHM variation on the dose distribution is shown in Figure 6. The radial FWHM varied in the range of 0.15–0.3 cm. These results were obtained when electron energy and mean angular spread were constant and equal to 5.7 MeV and 2°, respectively.

Figure 6a illustrates the impact of radial FWHM on lateral dose profile. The increment of the radial FWHM leads to

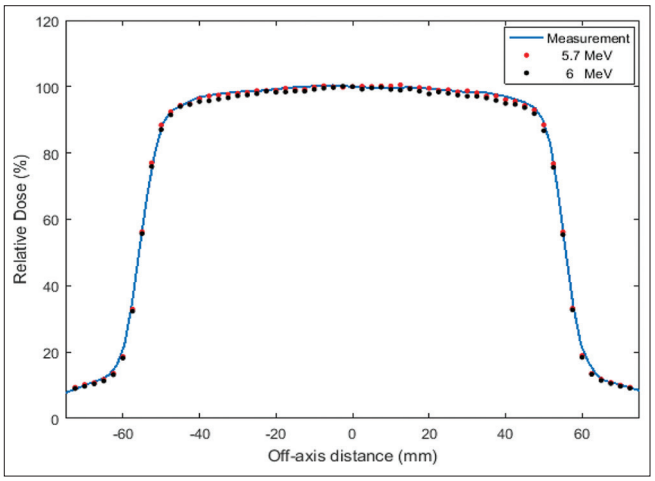

Figure 4: Influence of electron energy on the shape of lateral dose profile for the field size of 10 cm × 10 cm

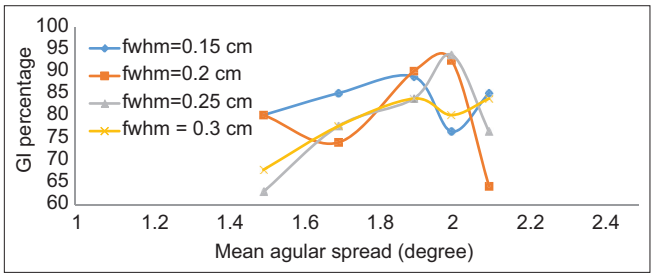

Figure 5: Gamma index passing percentage in terms of mean angular spread for different full width at half maximum values on 30 cm × 30 cm lateral dose profile at a depth of 10 cm

decreasing the horn of dose profiles.[9,10,14] Unlike the lateral dose profiles, the depth dose curves are not affected by the variation of radial FWHM [Figure 6b]. This result is consistent with previous studies.[8,10]

GI passing percentage values are also demonstrated in Table 2. It can be concluded that the optimum value for radial FWHM can be determined by lateral dose profiles, which is considerably sensitive to radial FWHM variation.

The effect of mean angular spread variation on lateral dose profiles and PDD curves is represented in Figure 7.

These results were obtained when electron energy and radial FWHM were determined and were held constant equal to 5.7 MeV and 0.25 cm, respectively. According to Mohammed *et al*.,[18] the dependency of lateral dose profile shape to mean angular spread is affected by the distance between the source of electrons and the surface of the target. In this study, the distance is 1 cm.

Regarding Figure 7 and Table 3, the lateral dose profile is much more sensitive to mean angular spread compared to the PDD curve, which is consistent with the results of some previous studies.[18-20]

Increasing the mean angular spread enhances the shoulders and flat region of lateral dose profiles [Figure 7a]. This result is also consistent with Chibani *et al*.[14] and Najafzadeh *et al*.[20] Based on Figure 7b, the variation of mean angular spread has slight effects on PDD curves which are more significant at the larger depths.[18]

Figure 8 demonstrates the lateral dose profile and PDD curve with GI values with acceptance criteria of 1%-1 mm for the field size of 30 cm × 30 cm, achieved from optimum source parameters as follows: primary electron energy 5.7 MeV, radial FWHM 0.25 cm, and mean angular spread 2°.

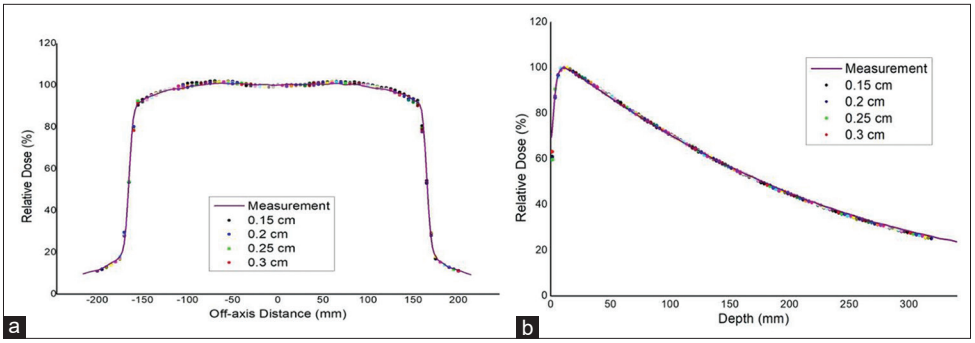

Figure 6: Comparison between Monte Carlo simulations with various radial full width at half maximum and measurement in (a) lateral dose profile and (b) percentage depth dose curve for the field size of 30 cm × 30 cm, whereas electron energy and mean angular spread were fixed to 5.7 MeV and 2°, respectively

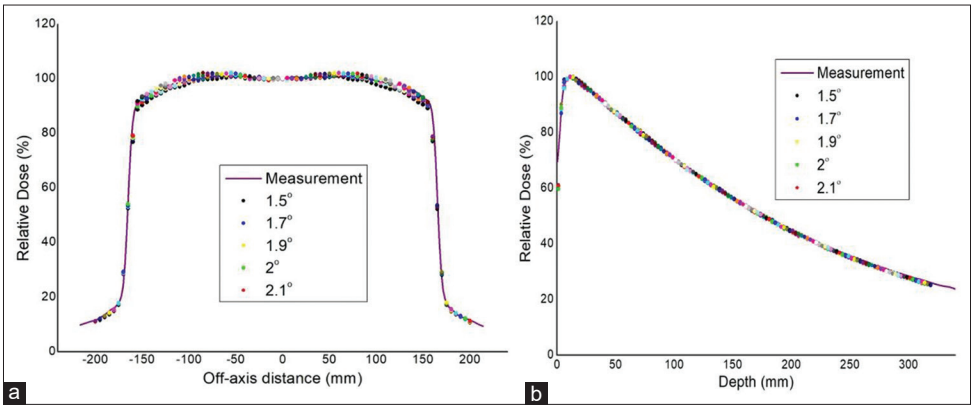

Figure 7: Comparison between Monte Carlo simulations with various mean angular spreads and measurement in (a) lateral dose profile and (b) percentage depth dose curve for the field size of 30 cm × 30 cm, whereas electron energy and radial full width at half maximum were fixed to 5.7 MeV and 0.25 cm, respectively

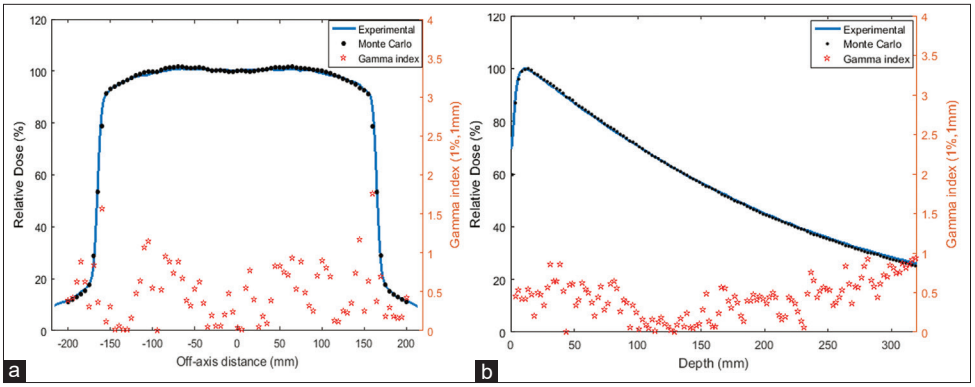

Figure 8: (a) Lateral dose profile and (b) percentage depth dose curve for the field size of 30 cm × 30 cm, achieved from optimum source parameters (primary electron energy = 5.7 MeV, radial full width at half maximum = 0.25 cm, and mean angular spread = 2°)

Benchmarking various field sizes

The optimum value of source parameters was determined in the previous sections, and the MC model of OMID 6-MV Linac was validated. In Figure 9a-e, PDD curve and lateral dose profile for different field sizes (20 cm × 20 cm, 10 cm × 10 cm, 8 cm × 8 cm, 5 cm × 5 cm, and 3 cm × 3 cm) are illustrated, whereas MC simulations were applied with validated model.

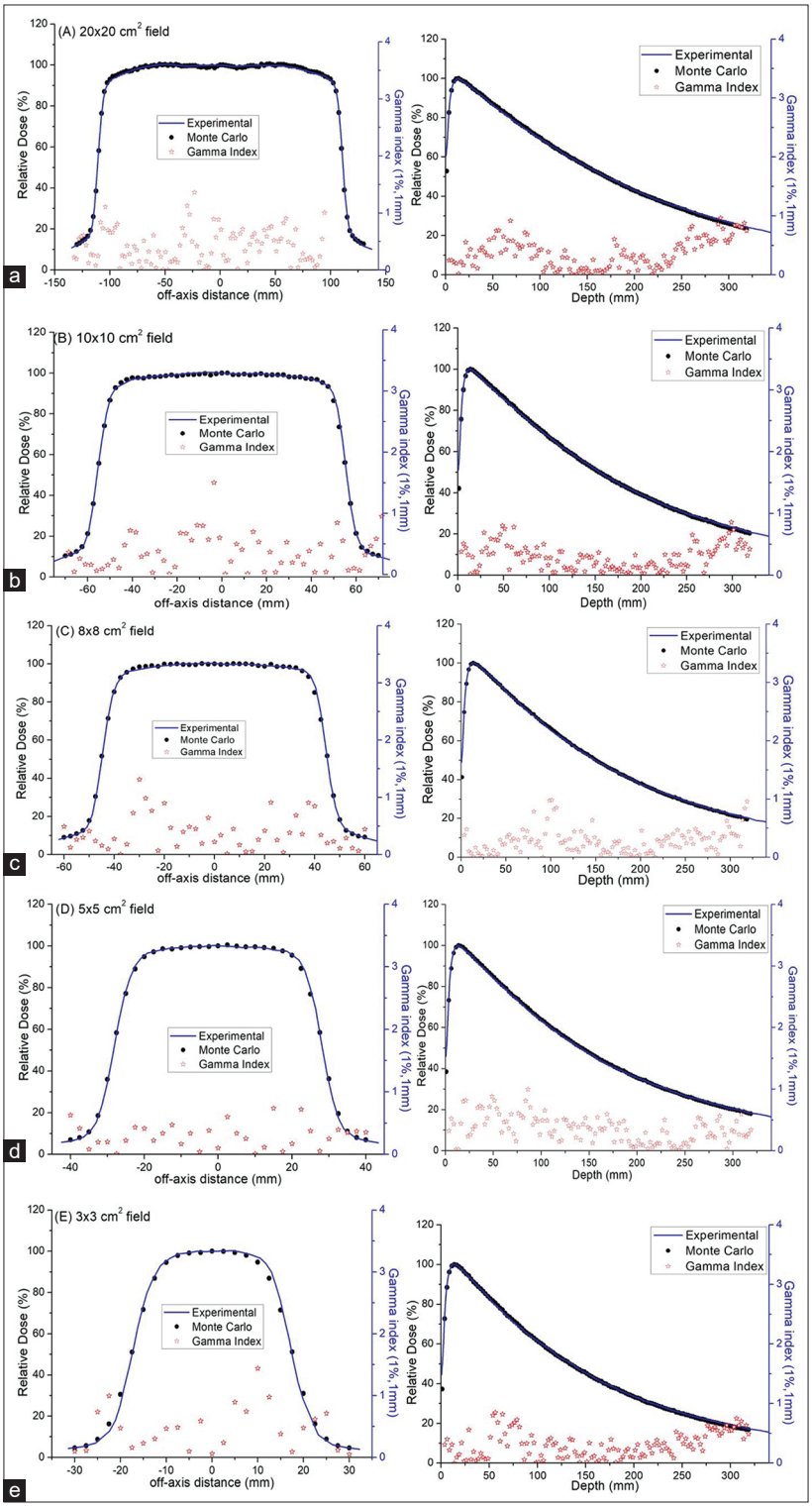

Figure 9: The lateral dose profile (left) percentage depth dose curve (right) for various field sizes (a) 20 cm × 20 cm, (b) 10 cm × 10 cm, (c) 8 cm × 8 cm, (d) 5 cm × 5 cm, and (e) 3 cm × 3 cm, with gamma index value with acceptance criteria 1%-1 mm. These results are obtained from the optimum source parameters (primary electron energy = 5.7 MeV, radial full width at half maximum = 0.25 cm, and mean angular spread = 2°)

Table 4 indicates the GI passing percentage of the lateral dose profile and PDD curve for each field size. As it can be concluded, there is a good agreement between simulations and measurements for all field sizes.

Conclusion

The MC simulation of OMID 6-MV Linac showed that the optimal values for primary electron energy, radial FWHM, and mean angular spread were 5.7 MeV, 0.25 cm, and 2°, respectively.

Good agreement between simulated and measured dose distribution was found for the field sizes of 3 cm × 3 cm, 5 cm × 5 cm, 8 cm × 8 cm, 10 cm × 10 cm, 20 cm × 20 cm, and 30 cm × 30 cm using the optimum source parameters.

Table 2: Gamma index passing percentage with acceptance criteria of 1%-1 mm corresponds to each radial full width at half maximum, whereas electron energy and mean angular spread of the electron source were fixed to 5.7 MeV and 2°, respectively

Radial FWHM (cm)	GI passing percentage	
	Profile	PDD
0.15	74.5	98.4
0.2	92.5	99.2
0.25	93.8	99.2
0.3	87.6	98.4

PDD – Percentage depth dose; GI – Gamma index; FWHM – Full width at half maximum

Table 3: Gamma index passing percentage with acceptance criteria of 1%-1 mm corresponds to each mean angular spread, whereas electron energy and radial full width at half maximum were fixed to 5.7 MeV and 0.25 cm, respectively

Mean angular spread (°)	GI passing percentage	
	Profile	PDD
1.5	61.4	98.4
1.7	79.0	96.8
1.9	90.1	95.3
2	93.8	99.2
2.1	67.9	99.2

PDD – Percentage depth dose; GI – Gamma index; FWHM – Full width at half maximum

Table 4: Gamma index passing percentage with acceptance criteria of 1%-1 mm of various field sizes

Field size (cm^2)	GI passing percentage	
	Profile	PDD
3×3	96.9	99.2
5×5	100	99.2
8×8	97.9	99.2
10×10	98.3	99.2
20×20	96.1	99.2

PDD – Percentage depth dose; GI – Gamma index

For all field sizes, the GI passing percentage values for lateral dose profiles were above 93.8% and for PDD were 99.2% and only for the voxel of the surface was out of the agreement.

It was found that lateral dose profile is more sensitive to the variation of all discussed source parameters. Radial FWHM and mean angular spread have a low effect on PDD curves; however, primary energy has more effect.

The lateral dose profile shape severely depends on energy, radial FWHM, and mean angular spread of the electron source. Increasing electron energy and radial FWHM result in decreasing the horn of lateral dose profiles, whereas increasing mean angular spread enhances the horns of lateral dose profiles. Furthermore, we recommend that the radial FWHM and mean angular spread should be determined together, because they have only influences on the lateral dose profile and their effects are rather on the contrary. Tuning source parameters of Linac head by comparing MC simulations against measurements of dose distribution on large field size will lead to great results and agreement for very small field sizes one.

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Conflicts of interest

There are no conflicts of interest.

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