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Monte Carlo Modeling and Verification of 6 MV Linear Accelerator

Shixiong Lu[1], Haijun Deng[2]

[1]College of Nuclear Technology and Automation Engineering, Chengdu University of Technology, Chengdu, China
[2]Department of Oncology, Sichuan Mianyang 404 Hospital, Mianyang, China
Email: 864456327@qq.com

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Abstract

Purpose: To model the ELEKTA COMPACT accelerator head by using EGSnrc/BEAMnrc/DOSXYZnrc and to validate the simulation according to the depth-dose and lateral profiles of different radiation fields measured by the water phantom. **Methods:** IBA Blue Water Phantom2 and CC13 Ionization Chamber were used to measure the depth-dose curves at 10 cm × 10 cm field and profile curves at 10 cm depth underwater. In BEAMnrc, the main components of accelerator head and the initial electron beam are established based on the specifications file, and the phase space file containing the photon beam information is generated. In DOXYZnrc, phase space files were used to irradiate a homogeneous water phantom of the same size as the IBA water phantom, and the simulated percentage depth dose curves and lateral profiles were outputted. The accuracy of the model was evaluated by mean square error (MSE) compared with the measured data. PDD curves are used to determine the energy of the initial electron beam. Dose profile curves are used to adjust the flattening filter. The penumbra on lateral profiles is used to adjust the full-width half-maximum (FWHM) of the electron source. **Result:** The electron energy of 5.8 MeV was considered the best match after comparing the PDD curves of 5.6 - 6.2 MeV electron beams. The flattening filter can only be adjusted by trial. In the final result, the maximum fluctuation of profile curve within 80% of the maximum field size is less than 3%, which meets the requirements of field flatness. The optimum FWHM for different fields is not consistent due to the Transmission penumbra. But a match can be approached by adjusting the FWHM every 10 cm field size.

Keywords

EGSnrc/BEAMnrc/DOSXYZnrc, Linear Accelerator, Initial Electron Beam, PDD, Lateral Profiles

1. Introduction

Intensity modulated radiotherapy usually generates beams by using linear accelerator. Manufactures often provide an adaptive TPS planning system for planning and review. Some planning systems, such as MONACO, have been able to use Monte Carlo algorithm to perform more accurate calculation in the calculation of dose distribution for planning, and Monte Carlo method has been identified as the gold standard for dose calculation [1]. However, commercial TPS system mainly serves for clinical use. In the face of scientific research needs, especially the research on accelerator and beam itself, there is usually a lack of means and functions as well as difficulties in data extraction. This has led to the use of other Monte Carlo programs to model accelerators for research. However, it is a difficult and tedious process to accurately match the beam properties obtained from the model with the actual reference accelerator. The geometric parameters of components, materials and initial electron source parameters in the model all affect the final beam output. Different types of accelerators will have different beam properties due to component design and material differences. Even for the same type of accelerator, the adjustment during field installation will also affect the final beam properties. Based on the above reasons, this paper aimed to discuss the process of establishing Monte Carlo model of accelerator. The aim of this work is to establish a 6 MV ELECTA COMPACT accelerator head model based on the Monte Carlo program EGSnrc/BEAMnrc/DOSXYZnrc. The Electron Gamma Shower (EGS) software package originally developed at the Stanford Linear Accelerator Center (SLAC), and was completely overhauled by National Research Council of Canada, so called EGSnrc. BEAMnrc and DOSXYZnrc are built on the EGSnrc Code System for modelling radiotherapy sources and calculating dose distributions responsibility [2]. The consistency between the model beam and the actual beam was verified according to percentage depth dose [3] (PDD) and lateral dose profile. A new process for adjusting the energy and full-width half-maximum (FWHM) of incident electron beam and flattening filter to fit the percentage depth dose curve as well as the beam profiles was proposed.

2. Materials and Methods

2.1. Measurement Data

Two kinds of information are usually required to describe the X-ray beam properties of linear accelerator. One is the percentage depth dose curve, which is used to reflect the quality of rays [4]; another is off-axis profile curves, which is used to reflect the dose distribution rule in the radial direction of the radiation field [5]. The simulated accelerator model referred to the 6 MV ELECTA COMPACT IMRT (step & shot) accelerator in The Department of Oncology, Sichuan Mianyang 404 Hospital. Measurement data were performed by IBA Blue Water Phantom and IBA CC13 ionization chambers (IBA, Dosimetry, Schwarzenbruck, Germany). The percentage depth dose curves were measured at a SSD of

100 cm with 10 × 10 cm^2 field size. The profile curves of 10 × 10, 20 × 20, 40 × 40 cm^2 underwater at a depth of 10 cm were measured.

2.2. Components of Linac Head

The MC model were made in BEAMnrc according to the specifications file, as shown in **Figure 1**, including target, primary collimator, flattening filter, ionization chamber, mirror and 2 pairs of jaws. Cross section data (pegs 4 file) is 700 ICRU, means the minimum electron energy applicable to cross section data is 700 KeV (including the rest electron mass of 521 KeV). Other global Settings (including EGSnrc Parameters) use the default Settings.

2.3. Global Parameters

Global parameters were chosen in "main input parameters". "AIR700ICRU" was chosen for medium. Global cut of energy of electron and photon are 0.7 MeV and 0.01 MeV respectively. Chose "direction" for Bremsstrahlung Splitting [6]. Directional Bremsstrahlung Splitting is a variance reduction technique which can improve calculation efficiency. Photons aimed into a field of interest (encompassing the treatment field) are split at the time of creation while those aimed away from the field are not. In this way the phase space file contains a sufficient number of photons while the calculation time is greatly shortened. "source to surface distance" is 100 cm, "splitting field radius" is determined by the size of fields for different simulation purposes, Generally it's slightly larger than the diagonal of the field. "splitting number" is 5000, no e−/e+ splitting.

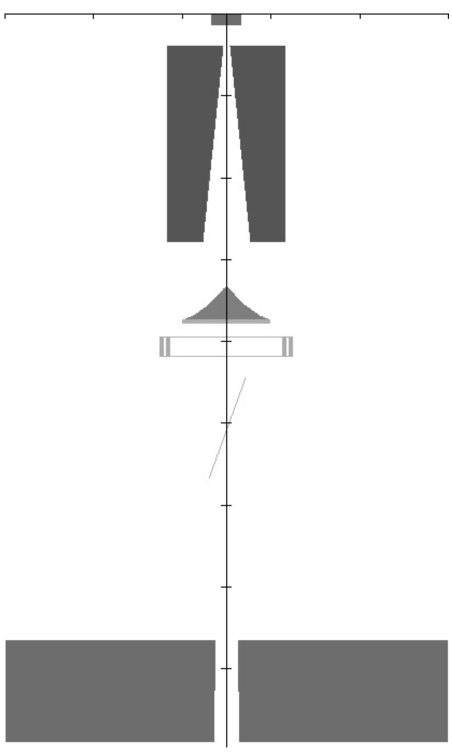

Figure 1. Model of linac head. Jaws in the other direction is not shown in the figure.

2.4. Determine the Incident Electron Energy by PDD Curves

Studies have shown that the flux of initial electron source has a Gaussian Distribution. Meanwhile the energy distribution is so concentrated that it can be considered a single energy source. PDD is almost unaffected by the radial distribution of the electron source, but sensitive to the energy of the electron source [7] [8] [9]. The actual kinetic energy of electron beam may differ from the nominal energy of 6 MeV. The energy of the electron source plays a decisive role in the effect of the photons quality, meanwhile the photons quality can be reflected by the relative dose deposition of the beam at different depths of the homogeneous phantom. Therefore, energy adjustments can be made according to the percentile depth dose curve. Based on the above, no.19 electron source was chosen, and the initial value of full-width half-maximum (FWHM) in X and Y directions is 0.1 cm. In order to find the most appropriate electron energy, PDD with energy of 5.6 - 6.4 MeV was calculated every 0.2 MeV at a $10 \times 10\ cm^2$ square field, and normalized at the maximum dose depth, was compared with the measured data. The scoring plane is set at 100 cm away from the target incident surface, which can record the momentum and position information of particles finally arriving there and generate a phase space file. The phase space file can represent the beam output of accelerator.

The phase space file was used as the source to irradiate a water phantom of $48 \times 48 \times 41\ cm^3$ with the voxel size of $0.5 \times 0.5 \times 0.5\ cm^3$ in DOSXYZnrc, and the dose deposited at the voxel at the central axis of the beam was output in sequence. After normalization, Percentage Depth Dose (PDD) curves were obtained.

2.5. Finish the Flattening Filter According to the Beam Profiles

The dose output deposited at the voxels on the same horizontal plane from the central axis to the edge of the water phantom is the dose profile curves. The beam profiles show the flatness and symmetry of the dose deposited on the same plane, and is highly related to the initial electron source parameters and the flattening filter. The energy fluence of photon beam from the metal target has a certain distribution, and the dose rate is higher as the voxel in the water phantom is closer to the central axis of the beam. As shown in the **Figure 2**, the dose profile at the depth of 10 cm with and without a flattening filter is shown when the field size is 40 cm × 40 cm (x-positive half-axis). For comparison, the beam profile with flattening filter is normalized at x = 0 cm, while the profile without flattening filter (flattening filter free, FFF) was normalized at x = 10 cm. It is obvious that the dose in the FFF mode is highest in the middle, and decreases with the increase of off-axis distance, and rapidly decreases at the edge of the field.

The dose flat region of the radiation field is mainly affected by the flattening filter. The flattening filter is a cone of quasi rotating Gaussian distribution, and the dose rate at the central axis of the field is decreased by the photon beam transmitted through the flattening filter and increased by the scattering and

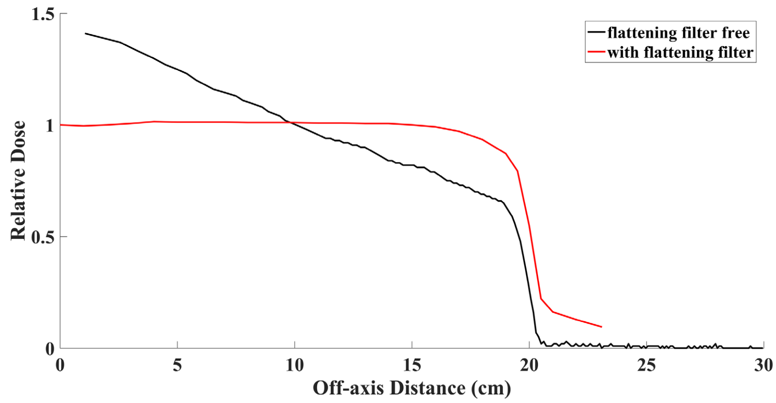

Figure 2. Dose profile at the depth of 10 cm with and without a flattening filter.

absorption of the beam, so as to flatten the dose distribution at the central axis of the radiation field. To finish the specific shape of the flattening filter, it can be cut into cylinders with different radii around the central axis, and the height of the cylinder can be continuously adjusted according to the distribution of dose profile.

2.6. Determine the FWHM of the Incident Electron Source Based on the Penumbra Dose

Source No. 19 in BEAMnrc is an electron source whose radial distribution is Gaussian, so the full width at half maximum of the electron source also needs to be determined. The FWHM of the electron source has little effect on the percent depth dose and the dose profiles at the flat area, but has a greater effect on the dose gradient in the penumbra area at the edge of the field. When the FWHM of the incident electron source becomes wider, the radius of the X-ray point source generated on the metal target will increase accordingly, resulting in an increase in the geometric penumbra and a decrease in the dose gradient in the penumbra area. **Figure 3** shows the energy fluence vs position of beams with different FWHM values. It can be seen that there is almost no difference in the flat area (off-axis distance ≤ 4), while separation occurred in the penumbra area. The gradient of the curve decreases as FWHM increases. Similar changes were observed in dose profile curves. Therefore, after the flattening filter is finalized, the matching degree of the penumbra area and the measured data can be adjusted by the FWHM parameter.

2.7. Comparison Method between Simulation Results and Measured Data

When running DOSXYZnrc, set the voxel size to 0.5 cm, which can take into account the simulation accuracy and match the measurement step size, to ensure that the position of the simulated data points and the measured data points are kept in a corresponding. After normalizing the curve to the maximum dose, use the mean squared error (MSE) to compare the degree of fit of the data, namely:

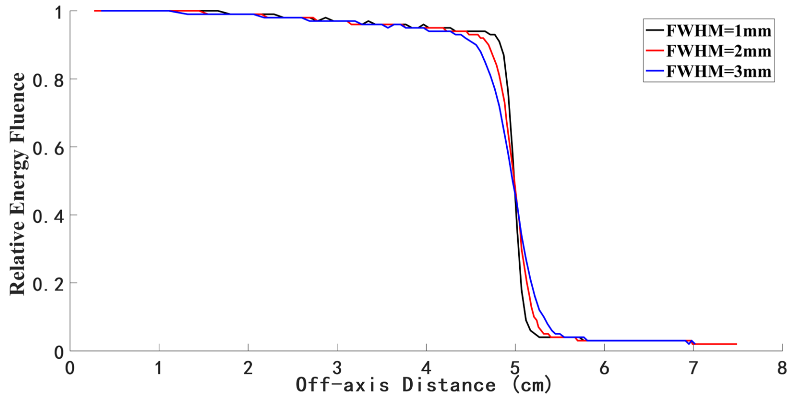

Figure 3. The energy fluence vs position of beams with different FWHM.

$$\mathrm{MSE} = \frac{1}{n}\sum_{i=1}^{n}\left[d_{i,MC} - d_{i,measure}\right]^2 \tag{1}$$

$d_{i,MC}$ is the calculated value of the i-th dose point, $d_{i,measure}$ is the measured value of the i-th dose point, and n is the number of compared dose points. Obviously, the smaller the MSE value is, the closer the MC PDD curve is to the measurement.

3. Result

3.1. Source Energy

Percentage depth dose curves of measurement and MC simulation with different incident electron energies are shown in the **Figure 4**. **Table 1** lists the mean square errors between the simulated curves and the measured curves.

The results show that the PDD curves are very close due to the very small difference in the investigated energies, and only the dose curves in the attenuation region are separated. This is because when the average energy of the beam becomes higher, first, the ionization ability of the rays is enhanced; second, the penetration is also improved, the attenuation index of the rays is reduced, and a higher flux can be maintained at the same depth. At the same time, the three main modes of action between photons and matter: photoelectric effect, Compton effects, and electron pair effect. When the photon energy increases, the scattering direction of the secondary electrons is more toward the photon incident direction, reducing the scattering loss. The mean square error results show that the percent depth dose curve obtained by the electron source of 5.8 MeV is most consistent with the measured data.

3.2. Field Flat Area and Flattening Filter

According to the International Electron Commission (IEC) regulations on the flatness of the field: within 80% of the width of the maximum field L, the relative percentage of the maximum and minimum doses deviating from the central axis dose at an equivalent water depth of 10 cm below the incident surface, and this percentage should be less than 3%. The result is shown in the **Figure 5**. After

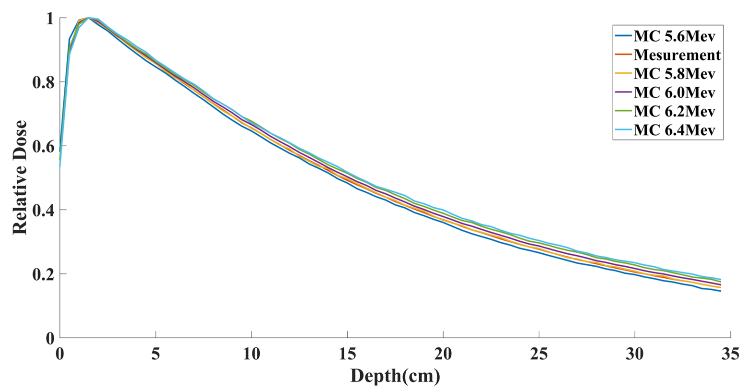

Figure 4. Percentage depth dose curves of measurement and MC simulation.

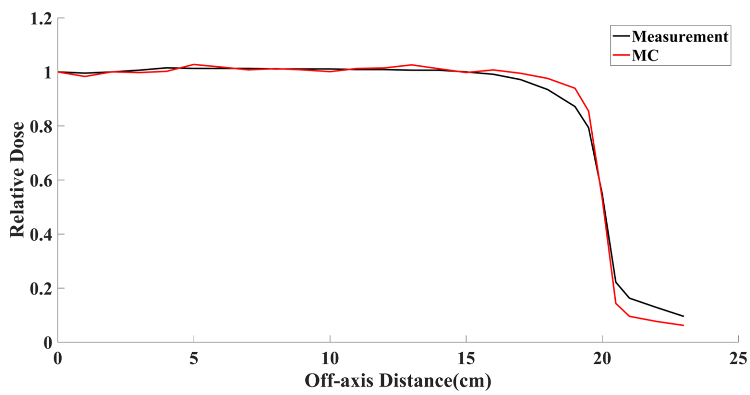

Figure 5. The dose profile curves of MC and measurement after adjusting the flattening filter.

Table 1. The best matching FWHM values for each field size.

Electron Mean Energy/MeV	5.6	5.8	6.0	6.2	6.4
MSE ($\times 10^{-4}$)	1.42	0.0648	0.823	3.29	5.28

normalizing the data to x = 0, the maximum error in the dose of $0 \le x \le 16$ cm is 2.7%, and it can be considered that the simulated results are in good agreement with the measured data in the flat area of the field.

3.3. Determination of FWHM and Penumbra Fitting

After the flat area of the field is adjusted, it can be found that the dose gradient at the edge of the field, that is, the penumbra area, is too large. Therefore, it is necessary to adjust the FWHM parameter of the electron source to expand the width of the penumbra area and slow down the dose gradient. However, during the adjustment process, it was found that the optimal electron source FWHM of the different sized fields were not consistent. The penumbra region has three components: the geometric penumbra caused by the radial distribution of the electron source, the penetrating penumbra caused by the edge of the jaws, and the scattering penumbra caused by the scattering of rays in the phantom. It is speculated that the reason for the inconsistency of the full width at half maximum of the electron source corresponding to different size fields is the error caused by the penetration penumbra: due to the fixed shape of the actual jaws' end face, the penetration of X-rays at the edge is not consistent when the size of the field is different. So the penetration penumbra will be different depending on the field size. In the simulation, the size of the open field is automatically calculated by the program, the end face of the jaws is variable, and it will automatically adapt to the incoming direction of X-rays to keep the penetration penumbra to a minimum.

Based on the above, if the research in different field sizes requires higher simulation accuracy of the penumbra area, different FWHM values can be used to generate phase space files respectively. Due to the limitation of processing power, the change of the dose profile ratio in the penumbra caused by the change of the FWHM value within 0.05 cm is less than the calculation uncertainty. Therefore, every 0.05 cm within 0.05 cm - 0.35 cm was used to find the best FWHM under different field sizes. Figure 6 shows the MSE of the relative dose in the penumbra area with different FWHM under the field sizes of 5 cm × 5 cm, 10 cm × 10 cm, 15 cm × 15 cm, 20 cm × 20 cm, 30 cm × 30 cm, and 40 cm × 40 cm. The penumbra area is within the range of 80% - 120% of the size of the field. Table 2 lists the best matching FWHM values for each field size. It can be seen that, with the increase of the field, in order to obtain a matching penumbra, the full width at half maximum of the initial electron source needs to be continuously increased. But under the precision of 0.05 cm in FWHM, the best width at half maximum value of the field side length of 5 cm and 10 cm, 15 cm and 20 cm cannot be distinguished, indicating that their penumbra properties are relatively close. In the case of limited computing power or low requirements for the accuracy of the penumbra, they can be considered to have the same penumbra properties.

Figure 7 is a comparison of the measured and simulated dose profile of the 10 cm × 10 cm, 20 cm × 20 cm, 30 cm × 30 cm, and 40 cm × 40 cm fields after adjustment. So far, the dose profile between the simulated beam and the actual beam has been basically agreed.

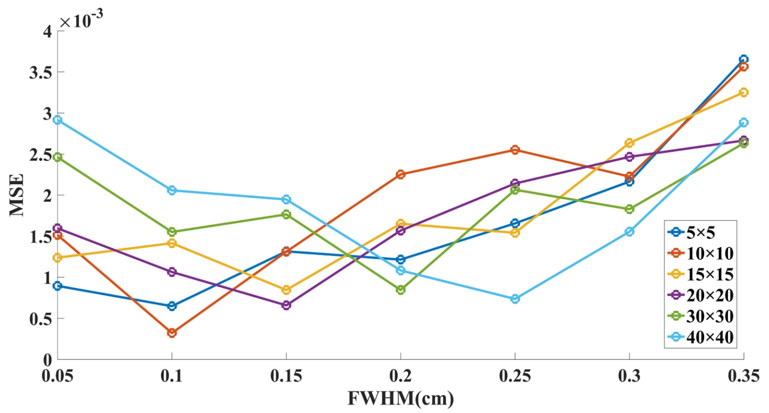

Figure 6. MSE of the relative dose in the penumbra area with different FWHM under the field sizes of 5 cm × 5 cm, 10 cm × 10 cm, 15 cm × 15 cm, 20 cm × 20 cm, 30 cm × 30 cm, and 40 cm × 40 cm.

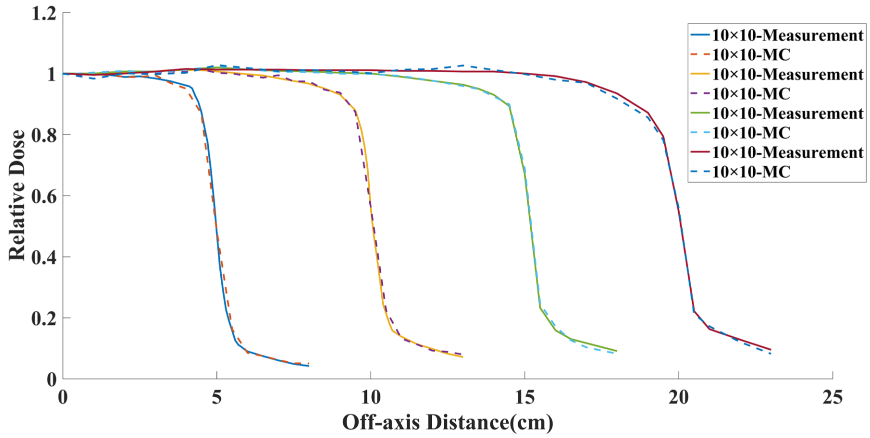

Figure 7. Comparison of measured and simulated dose profiles at 10 cm × 10 cm, 20 cm × 20 cm, 30 cm × 30 cm and 40 cm × 40 cm fields size after adjusting FWHM.

Table 2. The best matching FWHM values for each field size.

Field Size (cm)	5 × 5	10 × 10	15 × 15	20 × 20	30 × 30	40 × 40
Best Matching FWHM	0.1	0.1	0.15	0.15	0.2	0.25

4. Discussion

This work uses the BEAMnrc to build the Monte Carlo model of the linear accelerator. By comparison with the measurement results of the water phantom, it shows that the phase space files are in good agreement with the properties of the actual photon beam, which can provide treatment beam models for other studies of linacs.

The percent depth dose curve is mainly affected by the energy of the electron source, less affected by the shape of the flattening filter and the FWHM of the electron source, while the dose off-axis profile is more sensitive to the latter [10]. The flat area of the field is mainly controlled by the shape of the flattening filter, while the penumbra area is mainly controlled by the FWHM of the electron source. Based on the influence of each parameter on the results, a set of model building process is proposed in this study:

1) Set the target, primary collimator and other components according to the specification file, and define relevant global parameters.

2) Find energy of the incident electron source according to the percent depth dose curve.

3) Trim the shape of the flattening filter according to the flat region of the field

4) Fit the FWHM parameters according to the penumbra area.

Theoretically, the PDDs of the electron sources with different energies should be separated at the surface and the maximum dose depth. However, the PDDs of the initial electron sources with different energies in this paper only appear to be different at the end of the decay region. It is presumed that the size of the voxel used in this paper is larger, resulting in almost the same deposition dose of 5.6 -

6.4 MeV electron source on the 0.5 cm surface of the water phantom, and the maximum dose depth is also close. Reducing the voxel size increases the uncertainty of dose deposition. Although the curves are close, the dose in the decay region shows some difference, which brings the simulation accuracy of the incident electron source energy reach 0.2 MeV. The nature of the Monte Carlo method determines that it can only measure relative doses, which should be normalized to facilitate the comparison of different PDD curves, usually at D_{max}. The flat area of the field is mainly affected by the shape of the flattening filter, but the shape of the flattening filter is difficult to fix precisely. It may not get the ideal flattened dose profiles even using the parameters of the specifications file provided by the manufacturer and can only be ameliorated through trial and error. The FWHM of the electron source has the greatest influence on the edge of the field, especially the penumbra area, same with Chang's study [11]. But it has little effect on the percent depth dose curve and the flat area of the field, so it is appropriate to adjust the FWHM lastly. In the study, it was found that a single FWHM could not completely match the penumbra of all fields, which is presumed to be caused by the inconsistency of penetration penumbra under different size fields. Due to the sharp reduction of particles numbers, the uncertainty of the penumbra area will increase, and the accuracy of the final FWHM value is defined as 0.05 cm. Thus, the optimal FWHM values with field sides from 5 × 5 cm to 40 × 40 cm vary from 0.1 cm to 0.25 cm.

5. Conclusion

The verification and adjustment of Monte Carlo model for accelerator head are often a tedious process, especially when it comes to the energy and FWHM parameters of incident electron source. In this study, a model process of the accelerator head is performed for 6MV ELECTA COMPACT IMRT (step & shot) accelerator as an example. The obtained beam model is in good agreement with the measured data from percentage depth dose to dose profile curves. This model can be used in dosimetry research in the future.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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