e-ISSN 2083–4640
ISSN 1507–1367

RESEARCH PAPER

Reports of Practical Oncology and Radiotherapy
2023, Volume 28, Number 5, pages: 592–600
DOI: 10.5603/rpor.96865
Submitted: 01.03.2023
Accepted: 28.07.2023

Using PRIMO to determine the initial beam parameters of Elekta Synergy linac for electron beam energies of 6, 9, 12, and 15 MeV

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ABSTRACT

Background: The purpose of this research was to establish the primary electron beam characteristics for an Elekta Synergy linear accelerator. In this task, we take advantage of the PRIMO Monte Carlo software, where the model developed contains the majority of the component materials of the Linac.

Materials and methods: For all energies, the Elekta Linac electron mode and 14 × 14 cm^2 applicator were chosen. To obtain percentage depth dose (PDD) curves, a homogeneous water phantom was voxelized in a 1 × 1 × 0.1 cm^3 grid along the central axis. At the reference depth, the dose profile was recorded in 0.1 × 1 × 1 cm^3 voxels. Iterative changes were made to the initial beams mean energy and full width at half maximum (FWHM) of energy in order to keep the conformity of the simulated and measured dose curves within. To confirm simulation results, the Gamma analysis was performed with acceptance criteria of 2 mm — 2%. From the validated calculation, the parameters of the PDD and profile curve (R100, R50, Rp, and field size) were collected.

Results: Initial mean energies of 7.3, 9.85, 12.9, and 15.7 MeV were obtained for nominal energies of 6, 9, 12, and 15, respectively. The PRIMO Monte Carlo model for Elekta Synergy was precisely validated.

Conclusions: PRIMO is an easy-to-use software program that can calculate dose distribution in water phantoms.

Key words: PRIMO Code; Elekta Synergy; Monte Carlo simulation; linac; electron beam

Rep Pract Oncol Radiother 2023;28(5):592–600

Introduction

Radiotherapy is a common treatment for superficial cancers, with electrons being a preferred choice because of their ability to produce a uniform dose within therapeutic limits and abrupt declines that reduce exposure to the underlying healthy tissues [1]. However, it can be difficult to accurately predict the deposited dose in heterogeneous situations, especially with conventional algorithms [2–4]. Monte Carlo (MC) codes have been developed to calculate dose distributions with great accuracy [5]. A limitation of the use of MC codes is the need for accurate input data, such as geometry, component composition and initial beam characteristics. Unfortunately, manufacturers do not always clearly disclose this information, which makes it difficult to accurately predict the dose deposited. As well as the beam parameters, in particular the size of the spot, the energy and its spectrum which are crucial for the accurate prediction of radiation dose [6].

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PRIMO is a PENELOPE-based MC software that includes pre-programmed structural details for certain types of linear accelerators (linacs) [7]. It offers an easy-to-use graphic interface for simulating beams of electrons and photons in any size field and computes dose distributions in computer tomography or water phantoms. However, despite its versatility, there is a lack of research on the use of PRIMO for determining initial beam parameters for Elekta Synergy linac electron beams. Previous studies have investigated the use of PRIMO for simulating photon beams from various linac models. For example, Mohammad Javad Khosravanipour et al. [8] used PRIMO to simulate a Varian 600c and Varian 80L MLC, and found that the software was able to accurately predict the MLC motion using checkpoints obtained from treatment planning software (TPS). Marcelino Hermida-López et al. [9] investigated the suitability of PRIMO's default beam settings to produce accurate dosimetric results for 6 MV photon beams from Varian Clinac 2100 linacs and 6 MV unfiltered beams from Varian TrueBeam linacs. A. Esposito et al. [10] studied the use of PRIMO for simulating a Varian Trilogy with a Millennium120 MLC and a Varian Novalis with a 120HD MLC, and found that the software was able to accurately predict the static MLC simulations. However, to the best of our knowledge, there have been no studies investigating the use of PRIMO for determining the initial beam parameters of Elekta Synergy linac electron beams.

The sensitivity of the dose distributions to the parameters of the initial beam has been the subject of numerous studies. Concerning electrons, the reference work on the influence of the different parameters has been carried out by Bjork et al. [11] on an Elekta linac. They studied the influence of the mean energy, the energy distribution, the spatial distribution, and the angular distribution of the primary electron beam on the dose distributions [percentage depth dose (PDD) and dose profiles]. The average energy of the primary electrons is the parameter with the greatest impact on the PDD. Indeed, a variation of 200 keV in the primary beam causes the practical path of the electrons in water to vary by 1 mm. On the other hand, the average energy has no influence on the dose profiles [11]. Concerning the energy distribution, many studies have shown that when the width at half height of the energy distribution is increased, the dose gradient of the electron yield becomes smaller [11–14]. The same authors have also shown that the increase of the width at mid-height of the energy distribution causes an increase of the dose at the surface. In contrast, the dose profiles are not influenced by the energy distribution. The work of Faddegon et al. [15] and Bjork et al. [8] showed that the spatial distribution of the primary electron beam and the angular distribution had no impact on the dose profiles and the depth performance. In conclusion, for electron beam the PDD are impacted by the average energy and by the dispersion of the primary electron beam, while the dose profiles are not impacted by any parameter. The determination of the primary electron beam parameters will begin with the adjustment of the average energy by matching the measured and simulated particular depth R_{50}, (50% dose range) of PDD. The FWHM dispersion energy (full width at half height) will then be further adjusted to minimize differences between measured and simulated PDD curves at different depths. The reference field for parameter determination is 14 × 14 cm².

The purpose of the present task is to fill the research gap of determining the initial parameters of the Elekta Synergy linac electron beams using PRIMO. The findings of this study will contribute to the field by providing accurate data on initial beam parameters for Elekta Synergy linac, which can be used to improve the accuracy of dose prediction in radiation therapy. This work will be important as it will provide the necessary information for accurate prediction of radiation therapy doses and will be a pioneer study of this type for Elekta Synergy linac electron beams.

Materials and methods

Experiment

Electron beams from the Elekta Synergy linear accelerator with nominal energies of 6, 9, 12 and 15 MeV were delivered to a scanning water phantom that is computer controlled (PTW BEAMSCAN). Measurements were made using a calibrated PPC40 parallel plate ion chamber and the MEPHYSTO analysis software. A 14 × 14 cm^2 applicator was used in all energies with a source-to-surface distance (SSD) of 100 cm (Fig. 1).

In this study, the main objective was to determine the primary beam parameters of the Elekta Synergy

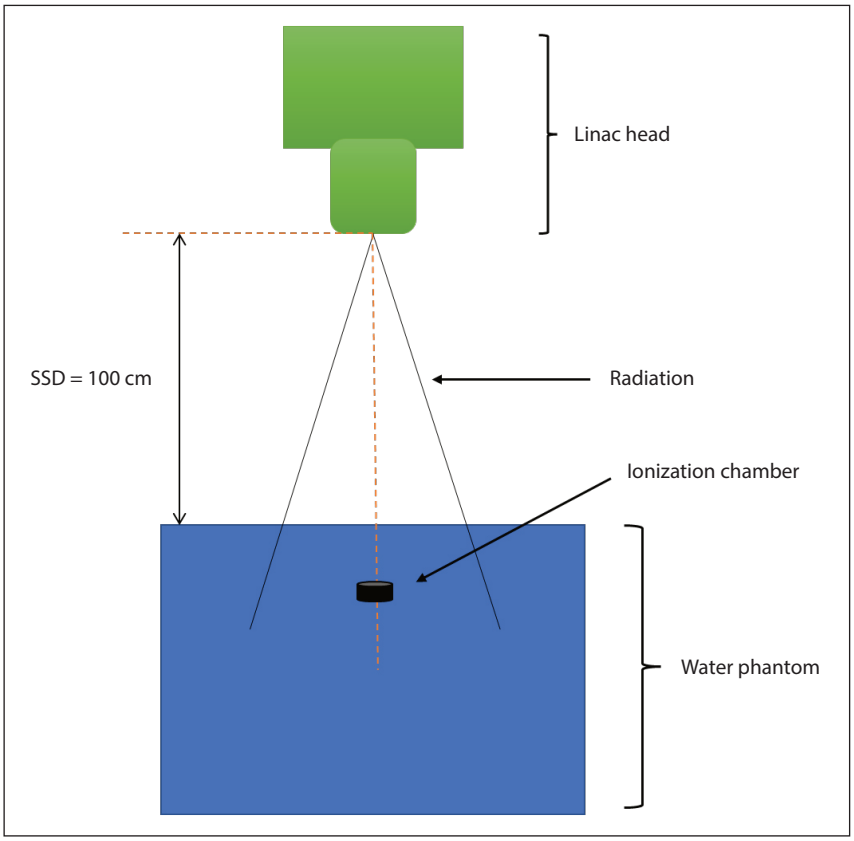

Figure 1. Schematic of the measurement equipment for the collection of percentage depth dose (PDD) and profiles

linear accelerator using the PRIMO code. The focus was specifically on the reference radiation field applicator 14 × 14 cm². This field was selected because it is recommended by the manufacturer for the calibration of the different electron beams.

The PTW water phantom system (BEAMSCAN) is intended for carrying out dosimetric measurements in the context of a radiation system. The device is intended to determine the radiation properties (beam data acquisition).

MEPHYSTO (Medical Physics Tool) is a software package for automatically recording and evaluating relative and absolute dose distributions of radiotherapy systems, using controlled PTW water phantoms by computer. MEPHYSTO allows data analysis according to international dosimetry protocols.

The percentage depth ionization (PDI) curves are measured at the center of the electron beam. PDIs were converted to percent depth dose (PDD) based on water/air mass stopping power ratios using the MEPHYSTO program [16].

Following that, the curves were used to extract the significant dose properties, such as the surface dose (D_s), maximal and 50% dosage ranges (R_{100} and R_{50}), practical range (R_p), and photon contamination dose (D_x). For each nominal energy, the dosage profile at the reference depth is measured.

Simulation setup

PRIMO (version 0.1.5.1202) was run on a server with 24 cores (Intel Xeon CPU E5-2690). For all energies, the electron mode of the Elekta Synergy linac and the 14 × 14 cm² applicator were chosen.

To make the simulation of medical linacs easier, Brualla, Rodriguez, and Sempau created the PRIMO program [7, 17]. It allows for the computation of dose distributions and Monte Carlo simulations of accelerators in a simple operational environment with a graphical user interface. This Program is founded on the Monte-Carlo PENELOPE calculation code (version 2011) and on the penEasy and penEasyLinac programs [18]. The penEasyLinac program serves as a supplementary tool for penEasy, enabling the creation of essential input files for simulating the majority of conventional accelerator models produced by Varian (Varian Medical System Inc., USA) and Elekta (ElektaAB, Sweden).

The graphical interface of PRIMO allows the user to define the configuration of the accelerator: photon or electron mode, radiation energy and jaw position and accessory configuration: positions of the MLC leaves or choice of applicator for electron mode. The software without user intervention automatically determines simulation-specific parameters (particle transport and variance reduction).

Variance reduction techniques aim to enhance the efficiency of computer calculations. Efficiency is represented by the equation $\eta = 1/(T.\sigma^2)$, where T denotes computation time and σ^2 corresponds to variance. To improve efficiency, either T or σ^2 should be reduced. In most Monte Carlo algorithms, T remains constant and can only be decreased by modifying the algorithm itself. Therefore, reducing σ^2 becomes the alternative approach, achievable through variance reduction techniques [19, 20].

PRIMO provides various methods for variance reduction. These techniques encompass the enforcement of bremsstrahlung interactions in the linac target, simple splitting in the water phantom or CT, as well as two specific techniques known as rotational splitting and splitting roulette. The latter method was used in our case.

The use of specific variance reduction techniques and the parallelization of calculations on several processors allow the calculation of doses in a few hours with uncertainty compatible with clinical objectives. PRIMO also includes various tools to represent and analyze the doses recorded during the simulation. In the software, it is possible to calculate doses in simple phantoms created by the user using homogeneous water block. The second option is to record doses in voxel geometries based on CT images of patients.

As previously stated, the electron beam parameters, including initial-energy, and FWHM of energy distribution, should be established for all nominal energies. The simulation was performed taking into account the developer's recommended default parameters for beginning energy.

PDD curves were obtained using a voxelized water phantom with a grid of $1 \times 1 \times 0.1$ cm^3 along the center axis. At reference depth, the dose profile was calculated in $0.1 \times 1 \times 1$ cm^3 voxels.

To achieve a dose uncertainty of less than 0.5%, the number of histories for PDD and profile calculation was set at 10^9.

To assess the simulation findings, the program's dose analysis component is used to compare each simulated PDD curve to the appropriate measured curve. The starting energy was modified iteratively, and the simulation was repeated until both PDD curves coincided at R_{50}. Following initial energy optimization, the energy FWHM was changed to reduce the differences between the measured and simulated PDD curves at the majority of depths.

The simulation findings were then validated using the Gamma analysis, which had acceptable requirements of 2 mm-2%. From a verified calculation, the main PDD and dose profile curve parameters (R_{100}, R_{50}, R_p, Ds, D_x, and field size) were collected.

Results

Initial energy values were set to defaults to begin the simulation. Despite the inventors' suggestion for a monoenergetic primary beam, simulated results did not match the data from measurements.

To determine the average energy, the simulations were carried out with an energy variation with an increment of 50 keV. In an iterative process, the initial energy was adjusted and the simulations were re-run until the calculated PDD curves matched the measured pdd curves at the specific depth R50, which represents 50% of the deposited dose. After the muzzle energy was optimized using this method, attention shifted to the full-width-half-height (FWHM) energy fit. The objective was to minimize the discrepancies between the simulated and measured PDD curves at different depths.

After numerous modifications to the initial parameters and execute simulations, the greatest agreement between the measured and calculated curves was achieved by using the values indicated in Table 1.

Table 1. Beam parameters for different nominal energies

Nominal energy [MeV]	Initial energy [MeV]	FWHM [MeV]
6	7.3	1.2
9	9.85	1.3
12	12.9	1.5
15	15.7	1.6

FWHM — full width at half maximum

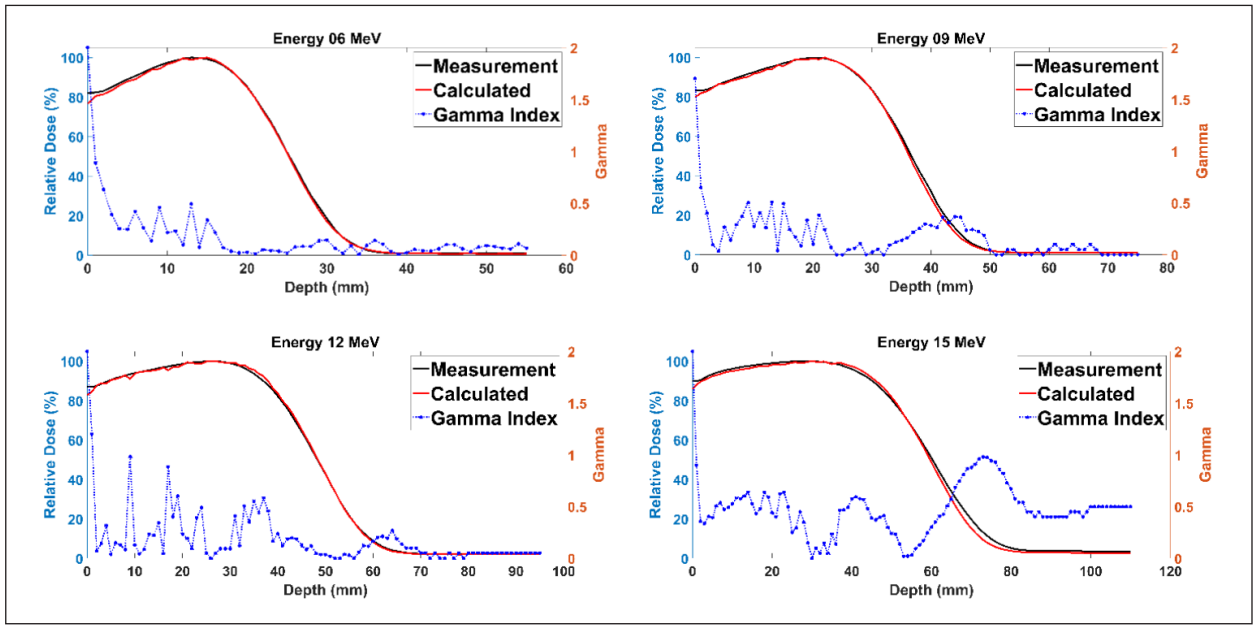

Figure 2. Comparison of simulated and measured percentage depth dose (PDD) curves for energies of 6, 9, 12, and 15 MeV

Table 2. Percentage depth dose (PDD) curve measured and calculated parameters and percentage of points that passed Gamma index with 2%/2 mm criteria

	D_s (%)		R_{100} [mm]		R_{50} [mm]		R_p [mm]		D_x (%)		Percentage of points that passed Gamma index criteria (2%/2 mm)
Energy (MeV)	Meas[a]	Cal[b]	Meas	Cal	Meas	Cal	Meas	Cal	Meas	Cal	
6	82.25	78.59	13.01	14	25.30	25.24	31.87	31.59	82.20	76.67	99
9	83.37	80.85	20.99	21	36.69	36.31	45.24	44.37	83.37	79.80	98.7
12	86.90	83.65	26.01	26.02	48.32	48.40	59.08	58.92	86.90	82.80	98
15	89.90	86.90	29.01	30.02	60.26	59.67	72.79	71.97	89.90	85.70	99.1

[a]measured; [b]calculated

Table 1 shows the beam parameters of the Elekta Synergy linear accelerator for different nominal energies. The initial energy and Full Width at Half Maximum (FWHM) of energy are reported for each energy level, with nominal energies of 6, 9, 12, and 15 MeV. The initial energy values are 7.3, 9.85, 12.9, and 15.7 MeV, respectively, while the FWHM values are 1.2, 1.3, 1.5, and 1.6 MeV, respectively.

PDD curves obtained with these parameters and associated measurements are shown in Figure 2. Gamma indices versus depth using 2%/2 mm criterion are also displayed.

Table 2 shows the measured and calculated parameters for the percentage depth dose (PDD) curve, as well as the percentage of points that passed the Gamma index with 2%/2 mm criteria for each energy level (6 MeV, 9 MeV, 12 MeV, and 15 MeV). The measured and calculated parameters include D_s (%), R_{100} (cm), R_{50} (cm), R_p (cm), and D_x (%), which represent the dose at surface (depth of 0.5 mm), the depth of 100% dose, the depth of 50% dose, the practical range, and the dose at a specific depth (0 mm), respectively. The table also shows the percentage of points that passed the Gamma index with 2%/2 mm criteria for each energy level.

Figure 3 displays measured and calculated dose profiles at reference depths. Gamma analysis findings using the 2%/2 mm criterion have shown that two profiles are in compliance with one another.

Table 3 presents the results of measuring and calculating the beam parameters for different nominal

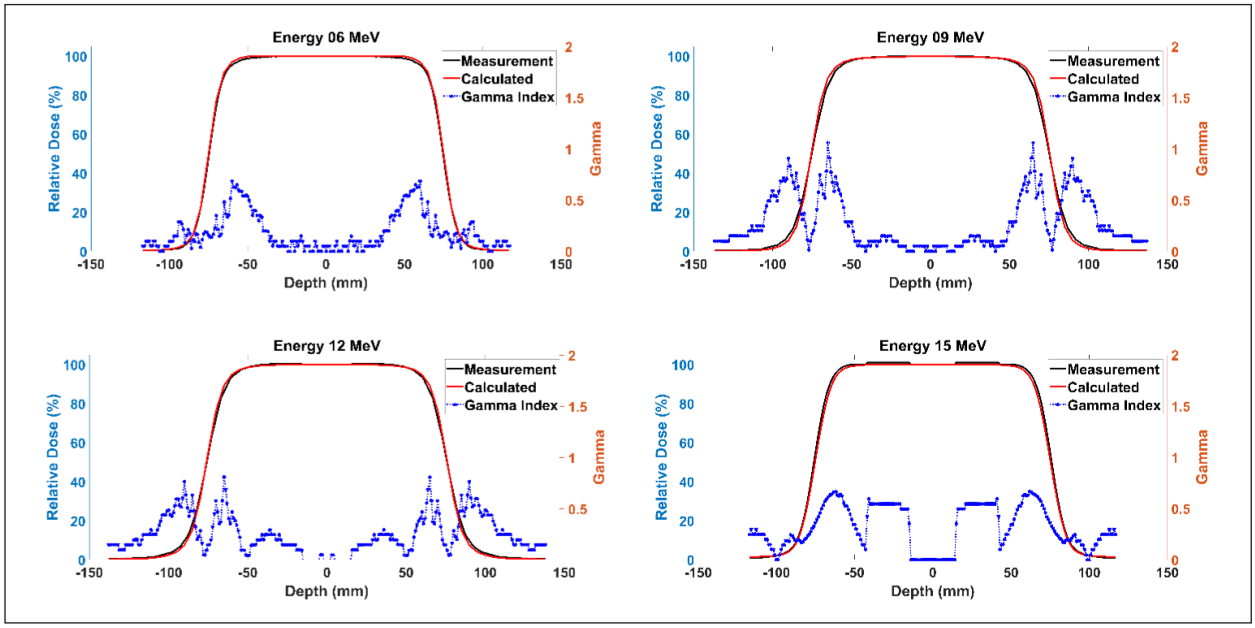

Figure 3. Comparison of simulation and measurement profiles at reference depths for 6, 9, 12, 15 MeV, respectively. Field size is 14 × 14 cm^2 for all cases

Table 3. Penumbra and field size obtained from profiles. Achievement percentages and mean gamma scores for various regions are also showed

Nominal energy (MeV)	Field width [cm]		Penumbra [cm]		Average Gamma inside field	Average Gamma in penumbra	Average Gamma outside field	Percentage of points that passed Gamma index criteria (2%/2 mm)
	Meas	Cal	Meas	Cal				
06	14.93	14.99	1.205	1.17	0.22	0.16	0.1	100
09	15.04	15.09	1.64	1.43	0.2	0.35	0.34	99.3
12	15.17	15.21	1.67	1.49	0.18	0.27	0.32	100
15	15.20	15.06	1.34	1.42	0.39	0.34	0.17	100

energies in terms of field width, penumbra, average Gamma values inside field, in the field, and outside the field, and the percentage of points that passed the 2%/2 mm gamma index criteria. The measured and calculated values for field width and penumbra are given in centimeters.

Discussion

Table 2 presents the comparison between the measured and calculated PDD curve parameters for different electron beam nominal energies (6, 9, 12, and 15 MeV). The table shows the percentage of points that passed the gamma test with 2%/2 mm criteria, which is an important parameter to assess the agreement between the measured and calculated data.

The table shows the percentage of points that passed the gamma test was high, ranging from 98% to 99.1%, indicating good agreement between the measured and calculated data. The differences were highest in the surface region, which may be due to dosimeter volume and measurement inaccuracy along the air/water boundary [21, 22].

The measured and calculated PDD curve parameters, including R_{100} (cm), R_{50} (cm), and R_p (cm), were in good agreement for all four energies. The differences between the measured and calculated values were generally small, with discrepancies ranging from 0.6 mm to 1 mm. These values do not exceed the recommendations given by AAPM [23].

The R50 matching is the initial phase of PDD verification, and the values' differences were lower than 0.6 mm. The following important element,

R_p, is adjusted within 0.9 mm, which indicates that the electron beam depth-dose distribution was well-modeled by the Primo code.

D_x (%) and D_s (%) parameters indicate the surface dose at depths of 0 mm and 0.5 mm, respectively. The disparities observed between the simulated and measured doses at the surface can likely be attributed to the volume of the ionization chamber employed in the measurements. The size of the ionization chamber can introduce errors in dose measurements at the surface within the water phantom, potentially resulting in the observed differences [22, 24].

In summary, Table 2 demonstrates good agreement between the measured and calculated PDD curve parameters for the four different electron beam nominal energies, indicating that the Primo accurately models the electron beam depth-dose distribution.

Table 3 presents the results of the penumbra and field size analysis, as well as the average gamma scores for different regions. The penumbra distance was defined as the area between the 20% and 80% isodoses. The achieved percentages and mean gamma scores for various regions are also reported.

The measured and calculated field widths for all nominal energies were in good agreement, with differences less than 0.15 cm.

The acceptability criteria recommended by the AAPM [24] for the penumbra region is 2 mm. Based on the data provided in Table 3, the differences between the calculated and measured penumbra values are 0.35 mm, 1.9 mm, and 0.8 mm for the energies of 6, 12, and 15 MeV, respectively. This suggests good agreement between the simulation results and the measurements for 6, 12, and 15 MeV energies.

However, for the energy of 9 MeV, the difference in penumbra width is 2.1 mm, which is still considered acceptable. Figure 2 illustrates that for this energy, there are points in the penumbra region where the gamma index is higher than 1. These points are located at the edge of the penumbra region and correspond to very low dose values. As a result, this leads to a high percentage difference between the calculated and measured dose. This observation aligns with a similar finding reported in reference [25].

The average gamma scores were below 0.4 in all regions, indicating good agreement between the measured and calculated profiles. The passed percentage for the 2%/2 mm gamma criterion was high for all energies, ranging from 99.3% to 100%.

Overall, the results of the penumbra and field size analysis, as well as the gamma evaluation, show good agreement between the measured and calculated profiles for all nominal energies.

Based on Table 1, electrons have initial energies over their nominal values. The nominal energy is an estimate of the electrons' most likely energy at the Phantom's surface. This difference results from the electrons' energy being attenuated during its path. The monoenergetic starting beam in the current simulation was unable to offer satisfactory agreement with data. These findings contrast with those of certain research that made use of monoenergetic electron beams. They employed simple monoenergetic rays because their research centered on other main goals, such as automatic initial parameter determination [26], heterogeneity impacts [27], and focal spot identification [28]. It should be noticed that they haven't explicitly revealed their validation criteria.

It is noted that, when the full width at half maximum (FWHM) of the energy distribution is increased, the dose gradient of the electron yield (percentage depth dose, PDD) becomes less steep. and there is an increase in the surface dose. This finding is consistent with previous studies mentioned in references [11–14].

Furthermore, it is found that the spatial distribution of the primary electron beam does not affect the dose profiles and the depth performance. This aligns with similar conclusions reported in references [8] and [15].

Conclusion

PRIMO was successfully used in this study to determine the initial parameter values for electron beams with different nominal energies. The matching of measured and simulated depth dose curves was used to determine the initial beam energy and energy FWHM while considering the acceptance criteria. The results obtained through PRIMO simulation were found to be in good agreement with the measurements, indicating that PRIMO is an effective and accurate tool for simulating the linear accelerator head and calculating the dos-

age distribution in homogeneous phantoms. Overall, the findings of this task highlight the potential of PRIMO for optimizing the beam parameters of electron beams in radiation therapy.

Ethical permission

Ethical approval was not necessary for the preparation of this article.

Conflict of interest

None declared.

Funding

This publication was prepared without any external source of funding.

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