



Original paper

An EGS Monte Carlo model for Varian TrueBEAM treatment units: Commissioning and experimental validation of source parameters



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ABSTRACT

In this work we have created and commissioned a Monte Carlo model of 6FFF Varian TrueBeam linear accelerator using BEAMnrc. For this purpose we have experimentally measured the focal spot size and shape of three Varian TrueBeam treatment units in 6FFF modality with a slit collimator and several depth dose and lateral beam profiles in a water phantom. The Monte Carlo model of a 6FFF TrueBeam machine was implemented with a primary electron source commissioned as a 2D Gaussian with Full Width Half Maximum selected by comparison of simulated and measured narrow beam profiles. The energy of the primary electron beam was optimized through a simultaneous fit to the measured beam depth dose profiles. Special attention was paid to evaluation of uncertainties of the selected Monte Carlo source parameters. These uncertainties were calculated by analysing the sensitivity of the commissioning process to changes in both primary beam size and energy.

Both experimental and Monte Carlo commissioned focus size values were compared and found to be in excellent agreement. The commissioned Monte Carlo model reproduces within 1% accuracy the dose distributions of radiation field size from 3 cm × 3 cm to 15 cm × 15 cm.

1. Introduction

Monte Carlo simulation is a very useful tool to calculate radiation transport and absorbed dose delivered by radiotherapy beams. It has been employed to pre-calculate dose deposition kernels used in dose calculation algorithms of these software tools. It has also been employed to produce tabulated data used in dosimetry, such as stopping power ratios [1,2] or correction factors [3]. Finally, it has been extensively employed in clinical and physical dosimetry research mostly in cases where classical dosimetry formalisms, based on assumption of charged particle equilibrium, fail; such as build up regions, media interfaces and notably narrow beams. Recently it has been employed for obtaining correction factors in IAEA dosimetry protocol about small field dosimetry [3].

Accurate Monte Carlo simulations of dose distributions delivered by a treatment unit demand LINAC geometry to be defined with as much detail as possible and to perform an appropriate comparison with an experimental data set.

Although Flattening Filter Free (FFF) beams have been being installed extensively in clinics worldwide in the last 5 years many of the aspects on their dosimetry are being studied. One of the main tools to analyse the dosimetry of these beams is Monte Carlo simulation. The proprietary condition of the detailed technical information of these treatment units has increased the difficulty to provide accurate models.

For instance, Varian Medical Systems (Palo Alto, California, USA) has published phase space files for their TrueBEAM treatment unit above jaws [4] and even a virtual tool for creating phase spaces, based in Geant 4 code [5], but does not provide detailed information about target or filtering elements if they do exist [6]. This model has been tested yielding limited accuracy [7]. Some authors have overcome this limit and lack of information by creating different Monte Carlo models [8–10], validated by comparing beam transversal profiles and percentage depth doses.

In this work, we have defined a Monte Carlo geometry model of a Varian TrueBeam generic treatment unit and we have chosen a dual approach for the description of the primary electron source geometric

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parameters. We have performed direct measurements with a slit collimator [11] of primary radiation focus distribution and compared them with the optimum value from Monte Carlo by tuning it with dose distribution measurements carried out in three different treatment units installed between years 2015 and 2017. Through this optimization process we have obtained altogether the energy of the primary electron beam and compared the results with wide beam profiles and depth dose profiles. We have additionally studied the sensitivity of this commissioning process to changes in its two free parameters (mean energy and spatial distribution of initial electrons impinging on target) and estimated their uncertainty.

The present model, and methodology employed to commission and validate it, might be used as a benchmark for producing reliable Monte Carlo results, especially whenever focal spot is of critical importance, such as in small and/or non-reference correction factors. Therefore has interest for different groups working in this topic [12–15].

2. Methods

2.1. Measurement of electron source focal spot

To perform a direct measurement of the LINAC focal spot we employed two 20 cm thick parallel lead collimator blocks, separated as to form a 0.13 mm width slit. These blocks were mounted on a linear stage with the slit arranged perpendicularly to the direction of the linear stage movement and this stage placed on top of a rotating plate [11]. A photon dosimetry shielded diode (PTW TM60008) was placed inside a tungsten block attached to the bottom part of the lead blocks with its reference point aligned with the slit air gap and within an aperture in the tungsten block. Therefore, at any measuring point along the linear stage movement direction, the detector integrates the projection of the slit in the primary source plane. By scanning in several directions around the radiation axis, and by a reconstruction method (see below), the size and shape of the primary electron radiation source, or focal spot, can be determined. Slit width was chosen as a compromise between high signal to noise ratio in the diode measurements and good spatial resolution. A drawing of this Beam Scanning Device (BSD), which has been used in a previous work [11], is shown in Fig. 1.

Field size was set to 5 cm × 5 cm during measurements, as that is

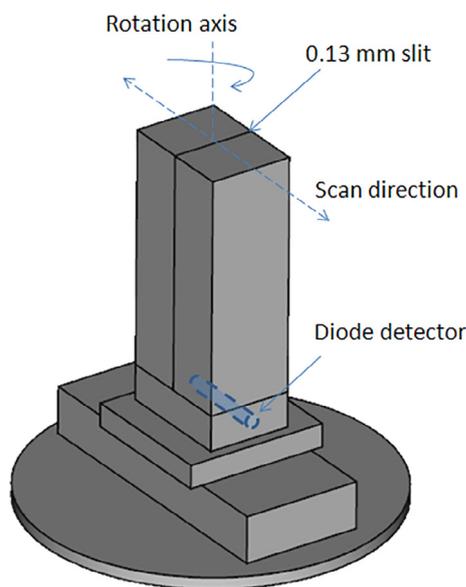


Fig. 1. Beam scanning device: A 0.13 mm aperture slit collimator on top of a motorized linear stage which is on top of a rotating plate. For the measurements a diode is placed within the collimator with its sensitive volume aligned with the slit.

the approximate cross section of the collimator.

We expected a small increase in the width of the scanned intensity profiles with increasing source-detector distance caused by the non null width of the slit. For this reason, several source to detector distances were considered in the experimental set up.

Focal spot reconstruction algorithm, that finds the radiation source distribution from measurements, was developed using MATLAB® (MathWorks, Natick, MA, USA) software. This algorithm is based on a geometric model that considers a two dimensional gaussian distribution for the focal spot. The length and width of the slit as well as the source-detector distance are taken into account in the calculation.

After revision of experimental results we found that an axially symmetric 2D Gaussian could reproduce accurately the data. Consequently we adopted a single Full Width at Half Maximum (FWHM) parameter to describe the focus size. This FWHM is varied, and for each FWHM, the algorithm calculates the fluence projected in each point of the scanning line to generate a slit profile. The algorithm iteratively searches a solution that minimizes the root mean square of the differences between the calculated and measured slit profile widths, for all source-detector distances.

It should be emphasized that the narrow slit and the thickness of the collimator allows only the detection of most forward peaked (highest energy) Bremsstrahlung photons. These correspond to high energy electrons interacting very close to the top surface of the target and thus are assumed to be an appropriate surrogate for the electron focal spot size.

2.2. Monte Carlo simulation of phase space and dose distributions

In the present work EGSnrc version 4 Monte Carlo [16] code was employed in all the simulations. BEAMnrc code (Rev1.78 version) [17] was used to produce phase space files scored at a plane at 100 cm distance from the source. These phase spaces were used as source to calculating dose distributions (percentage depth doses and beam lateral profiles) within a water tank with `egs_chamber` code [18]. In all dose simulations, the dose scoring geometry employed was a model of the detector employed in the corresponding measurement which we wanted to reproduce, instead of a water voxel, as this will produce a more accurate result, especially in the penumbra of small field profiles.

2.2.1. Phase spaces: Varian TrueBeam model

This work was focused in reproducing 6FFF modality delivered dose distributions. Our TrueBeam LINAC model was constructed from the classical VARIAN CLINAC 2100 geometry (as described in the Monte Carlo data package provided by Varian through Non-Disclosure Agreement) with some modifications. Namely, the 6FFF target model consisted of a 2.54 mm thick and 6.5 mm radius tungsten disk embedded in a copper frame (having 5.55 mm thickness below the tungsten disk), both sandwiched between 0.254 mm beryllium windows in order to preserve vacuum while the flattening filter was accordingly removed.

Monitor chambers were considered to be the same as in a Varian CLINAC treatment unit.

All fields in this work were collimated by Jaws.

Primary electron source in phase space simulations was considered to have two-dimensional Gaussian shape. This distribution is characterized in our work by a single FWHM for both dimensions based on the experimental evidence of LINAC electron focal spot symmetry [11].

Electrons impinging the target had no angular spread (parallel to beam axis) and were considered as monoenergetic in the simulation.

Different phase space files were simulated, for several field sizes and for different combination of primary radiation source parameters. The choice of phase space files is described in Section 2.3.

Directive Bremsstrahlung Splitting was employed with a splitting factor of 1500 and a radius defined by the square root of the square field side to be simulated plus a margin of 0.5 cm.

Global electron and photon energy transport cut offs were set to 0.700 and 0.010 MeV respectively. Local electron energy transport cut off was reduced to 0.521 MeV in regions with air. Other simulation transport parameters were set as the default recommended values. The number of initial electrons was adjusted to produce approximately a million particles per square centimetre at the scoring plane.

2.2.2. Dose distributions

IC detectors employed in measurements were modelled in MC and their air cavities set as scoring regions. A detailed model of the chambers was introduced in the input files using combinatory geometry functions contained in egs++ package. The different chambers employed are described in Section 2.3. Code version 1.21 was used.

Each dose point was simulated 3 times by recycling the corresponding phase space, changing each of the 3 times the initial random seeds.

Photon Cross Section Enhancement (XCSE) and Range Rejection (RR) were used. For XCSE, chamber geometries were set inside a cylinder 1 cm larger than the chamber radius and 2 cm longer than the chamber length. Enhancement factor was set to 176 in all chamber regions. For RR, a survival probability of 1/175 was set to electrons outside from the cavity if their range in water was shorter than the distance from interaction point to the closest frontier of the cavity. E_save was set to 1 MeV. These Variance Reduction parameter values were previously optimized by running several simulations in which parameters were varied in order to maximize simulation efficiency while not producing result biases.

Global electron and photon energy transport cut offs were set to 0.512 and 0.001 MeV respectively. Other simulation transport parameters were set as the default recommended values.

In these conditions simulated dose type A relative uncertainties ranged between 0.1% and 0.5% depending on location within the water tank.

2.3. Commissioning and validation

Commissioning of the model was applied to three Varian TrueBeam treatment units and performed through the selection of primary electron beam parameters, namely: electron beam size at target (FWHM) and energy (E). The methodology followed was analogous to that of a previous work [19]. This method compares simulated percentage depth dose (PDD) and lateral beam profiles of different radiation field sizes and different combinations of FWHM and E with the corresponding experimental curves. The commissioning method yields a value of the incident electron Energy at target and electron beam FWHM which reproduces optimally the experimental results. The agreement is quantified by a figure of merit function which takes into account dose differences in several points within one or several curves. Therefore the parameter selection is obtained through minimization of these objective functions (see below).

Percentage depth dose distributions are more sensitive to the incident electron beam energy (E) than to their impact spatial distribution on the target (FWHM). The dependence of PDD on FWHM decreases as field size increases. For this reason, for the selection of E we consider first a PDD of a 10 cm × 10 cm field for a fixed FWHM.

Electron beam FWHM has a greater impact on simulated penumbræ in fields smaller than 3 cm × 3 cm. Therefore for selection of this parameter, 3 cm × 3 cm beam profile simulations of various FWHM are compared with the corresponding measured profile curves.

We perform simulations with different electron energies for a selected beam FWHM covering broad set of field sizes. In those simulations we considered monoenergetic electron sources and through the use of an objective function, we search for an overall agreement in the electron beam parameters.

All experimental curves were obtained at 100 cm Source to Surface Distance. Dose rate was 400 MU/min in order to remove recombination

effects but keeping an appropriate noise to signal ratio. A PTW 31,010 Semiflex and 31,022 Pinpoint chambers were used for PDD and profile measurements respectively, with a 0.6 times their radius displacement toward source of their reference points.

The commissioning process sequence is detailed in the following sub-sections:

2.3.1. Coarse selection of E

For a fixed focal spot FWHM equal to that measured as described in Section 2.2, phase space files of 10 cm x10 cm field were simulated for energies ranging from 5.8 to 6.4 MeV, in steps of 0.2 MeV (4 phase space), and their PDDs compared to experimental ones. A PTW TM31010 Semiflex (PTW Freiburg) chamber was employed in measurements and thus its geometry used in the simulation to define the scoring region.

The best fit is selected by minimizing the function Gamma Sum Value (GSV):

$$GSV(E) = \sum_{i=1}^N \gamma(0.5\text{mm}, 0.5\%)_{z_i} \quad (1)$$

where $\gamma(0.5\text{mm}, 0.5\%)_{z_i}$ is the 0.5% dose, 0.5 mm global gamma value [20] at depth z_i . Doses are normalized for each field size at 10 cm depth. Eleven depths were considered ranging from 1.4 cm to 25 cm.

2.3.2. Selection of focal spot FWHM:

For the coarsely selected energy best reproducing the set of four PDDs, phase space files of 3 cm × 3 cm radiation field were simulated for FWHM values of 1.2, 1.3, 1.4, 1.5, 1.55, 1.6, 1.65, 1.7, 1.8 and 1.9 mm (10 phase spaces), and their lateral profiles at a depth of 5 cm compared to experimental ones. A PTW TM31022 Pinpoint (PTW Freiburg) chamber was employed in measurements and therefore its geometry used in the simulation to define the scoring region.

The best fit is selected by minimizing the function Mean Square Deviation (MSD):

$$MSD(FWHM) = \frac{1}{M} \sum_{j=1}^M (D_{MC}(x_j) - D_{exp}(x_j))^2 \quad (2)$$

where $D_{MC}(x_j)$ is relative dose simulated by Monte Carlo at off-axis point x_j and $D_{exp}(x_j)$ is the measured value at the same point. The off-axis positions x_j were set at fixed off-axis distances of 1.3, 1.4, 1.7 and 1.8 cm corresponding approximately to penumbræ values of 13, 22, 73 and 85% in the experimental curve respectively. Use of MSD function for selection of focal spot makes commissioning procedure more sensitive to Monte Carlo FWHM changes than GSV function.

2.3.3. Fine tuning of electron beam energy:

For the FWHM best reproducing lateral profiles, a fine selection of energy was carried out by simulating phase spaces of 3 × 3, 5 × 5, 10 × 10 and 15 cm × 15 cm for energies ranging from 5.8 to 6.4 MeV in steps of 0.1 MeV (4 field sizes times 7 energies for a total of 28 phase spaces) and comparing their simulated PDDs with the corresponding experimental ones. Again a PTW TM31010 (PTW Freiburg) chamber was employed in measurements and thus its geometry used in the simulation to define the scoring region.

The best fit is selected by minimizing the function:

$$GSV(E) = \sum_{\substack{i=1 \dots N \\ k=1 \dots P}} \gamma(0.5\text{mm}, 0.5\%)_{z_i, FS_k} \quad (3)$$

where $\gamma(0.5\text{mm}, 0.5\%)_{z_i, FS_k}$ is the 0.5%, 0.5 mm global gamma value [20] at depth z_i and for field size FS_k . Eleven depths were considered ranging from 1.4 cm to 25 cm.

Uncertainties were assigned to both parameters by considering B type and A type uncertainty in the same way as in a previous work [19]. B type uncertainties were calculated as the typical uncertainty from a

square distribution whose width was taken to be the sampling intervals of the model parameters considered in phase space simulations (0.2 mm for FWHM and 0.2 MeV for energy). Type A uncertainties were calculated by smearing each dose point within every experimental curve 2000 times, according to a random Gaussian distribution with a FWHM equal to experimental uncertainties (0.2%). The commissioning process was repeated using the resulting smeared curves, each time producing a different best value of Energy and a best value of FWHM. The resulting 2000 best values of Energy and 2000 values of FWHM were represented as histograms and adjusted to Gaussian distributions. Type A uncertainties ($k = 1$) for E and FWHM were taken as their respective standard deviation.

The accuracy of the model was further evaluated by simulating additional 5×5 , 10×10 , $15 \text{ cm} \times 15 \text{ cm}$ lateral profiles at 5 cm depth. Thus, all the curves in the selected field size range were measured and simulated. Additionally, $10 \text{ cm} \times 10 \text{ cm}$ lateral profile at 20 cm depth and off axis (4 cm displacement in X and Y axis) percentage depth dose were also simulated and compared with measurements.

3. Results & discussion

3.1. Electron focal spot

Direct measurement of focal spot size was performed through the analysis of the experimental signal slit profiles following the procedure described in Section 2.1. To illustrate this method, Fig. 2 shows the scans made in one of the treatment units considered in this work. Slit profile curves in all measured directions have the same FWHM, which confirms the assumption of focal spot axial symmetry.

With respect to the slit profiles measured at several source to detector distances, a 0.06% increase in slit profile measured width with increasing distance was observed, in agreement to what was expected.

The slit profile data was used to feed the algorithm developed in Matlab to search for an optimal FWHM of the radiation source distribution considering a two-dimensional Gaussian model. The values yielded by the iterative algorithm were 1.55, 1.57 and 1.56 mm for the three treatment units considered in this study, which implies that treatment unit focal spot sizes could be considered identical within the 0.01 mm method resolution.

Uncertainty was estimated by considering two components: repeatability of the measured values under the same conditions and reproducibility of the measurement with varying field size and SDD.

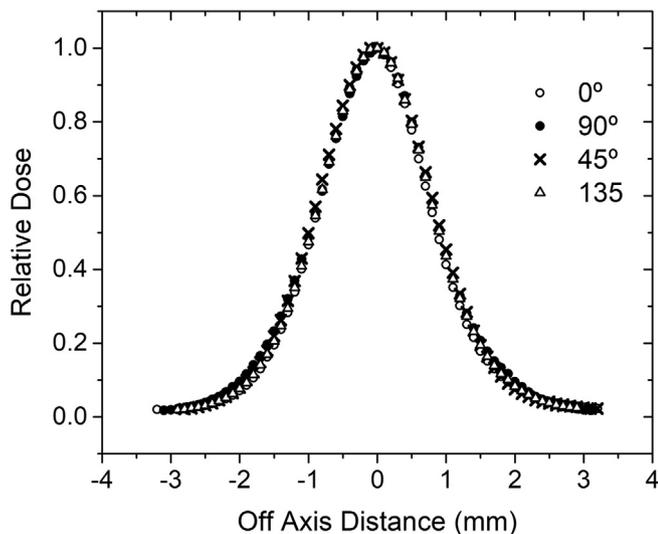


Fig. 2. Source slit scan profiles for several directions (angles indicated in the figure) in a plane perpendicular to the beam axis, for one of the machines, at Source to Detector Distance of 100 cm.

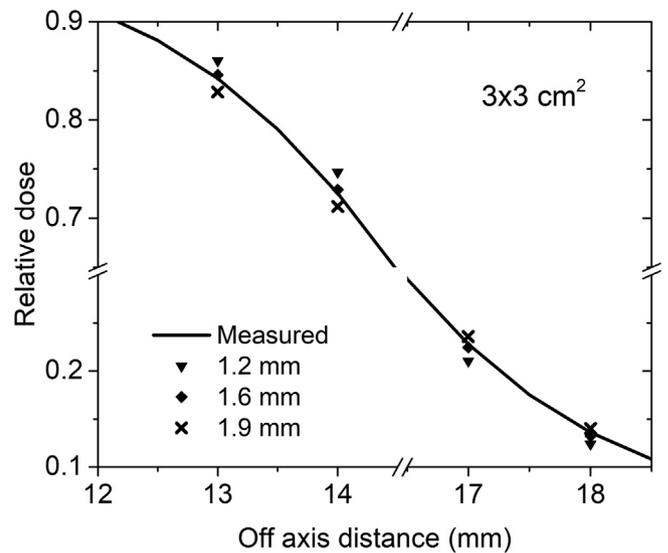


Fig. 3. Detail of simulated dose to 31,022 chamber cavity within field penumbra of $3 \text{ cm} \times 3 \text{ cm}$ field for different electron focal spot FWHM (markers) and beam profile measured with a 31,022 chamber (continuous line).

Assigned combined uncertainty was therefore 0.02 mm.

Focal spot size values in present work are consistent with the range of 1.1 to 2.5 mm stated in previous work [21] of 2013, which employed two methods, different from our approach, for the measurement of this parameter in early TrueBeam treatment units. Nevertheless our measurements yielded to symmetrical distribution results rather than the asymmetrical result of aforementioned work.

3.2. Monte Carlo commissioning

Focal spot size can also be estimated through the Monte Carlo approach (Section 2.3). To illustrate the commissioning method, the simulated penumbra of a $3 \text{ cm} \times 3 \text{ cm}$ field profiles for the minimum and maximum electron beam FWHM considered, where the scoring region is the active volume of a 31,022 Pinpoint chamber, together with the corresponding experimental curve for one of the treatment units are shown in Fig. 3. The experimental profile for the three treatment units modelled proved to be nearly identical with local relative dose differences below 0.3%.

From Fig. 3 it can be seen clearly, that one of the FWHM produces the best fit of the measured values. This indicates that the detector and field size employed in the commissioning process are sensitive to changes in FWHM at least equal to the sampling interval chosen between FWHMs, which is 0.1 mm. This sensitivity can be expressed in terms of penumbra percentage variation divided by FWHM difference, and for this combination of field size and detector amounts to 3.9% per mm.

Primary electron beam energy was also tuned through Monte Carlo simulation through comparison with experimental depth dose profiles (Section 2.3.2). Values of the function Gamma Sum Value as a function of electron energy for a fixed electron spatial FWHM of 1.6 mm are shown in Fig. 4, for one of the treatment units. The optimum energy of the MC commissioning for the three treatment units had the same value of 6.1 MeV.

According to the method described in Section 2.3 we computed the Mean Square Difference as a function of FWHM for fixed electron energy of 6.1 MeV. The results are shown in Fig. 5, for one of the treatment units. The optimal value for the three treatment units was 1.6 mm. Vertical uncertainties shown in the figure represent the uncertainty of the MSD objective function. Our commissioning process exhibits sensitivity to changes in Energy, due to the associated uncertainty, of twice

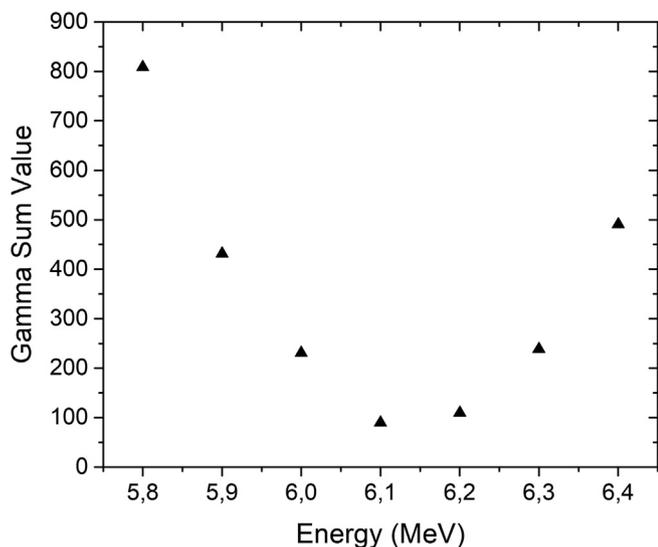


Fig. 4. Gamma Sum Value as a function of simulation source initial electron energy for a fixed electron spatial FWHM of 1.6 mm.

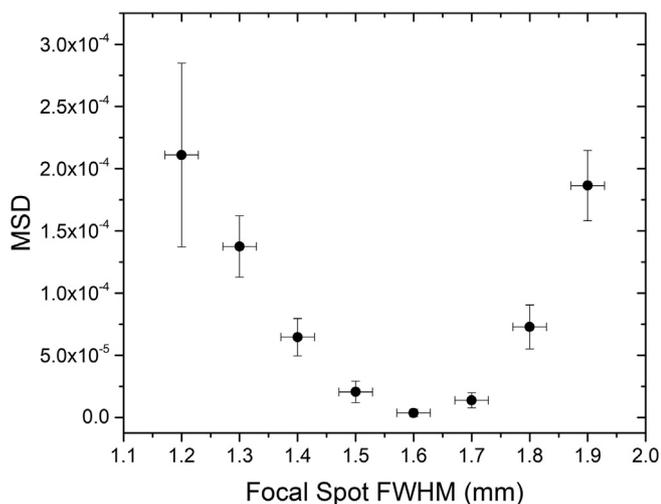


Fig. 5. Mean Square Difference as a function of simulation source electron spatial FWHM for fixed electron energy of 6.1 MeV.

the sampling interval, this means 0.2 MeV. This sensitivity can be quantified in terms of PDD local differences at 25 cm depth of 4.7% per MeV.

Histogram used for evaluating uncertainties of type A for both parameters electron energy and spatial FWHM are shown in Fig. 6 for one of the treatment units. Corresponding typical uncertainty is evaluated as type A ($k = 1$) and amount to 0.06 MeV for the energy histogram and 0.033 mm for the Focal Spot FWHM histogram.

Table 1 summarizes the results of the commissioning for the three treatment units. It shows also the corresponding measured FWHM for the focal spot.

Monte Carlo primary electron FWHM values obtained through this commissioning process match with high accuracy those found experimentally (within 0.05 mm). This shows the consistency of our method for focal spot measurement. The resultant energy value is equal to that obtained in an alternative Monte Carlo model implemented in EGSnrc [9], although in that work the focal spot considered was smaller than ours by a factor of 2.13. A possible cause is that in that work a figure of merit based on gamma analysis with 1%, 1 mm tolerances was used. This will limit the sensitivity of the commissioning method for selecting source FWHM, since points within the penumbra will probably agree

due to the very high gradient involved in 1 mm lateral distance. Actually authors in such reference, state that agreement below $4 \text{ cm} \times 4 \text{ cm}$ is poorer than for larger fields. In that same work, the authors included a thin brass foil instead of the flattening filter while we did not. The effect of the filter in energy is therefore negligible, as predicted in Section 2.2.1, since commissioned energy is equal whether the filter is employed or not. In a different work which employed also an EGSnrc model [10], energy of 5.9 MeV and FWHM of 1.3 mm were used as source parameters. However, in this case, fields larger than $5 \text{ cm} \times 5 \text{ cm}$ were employed to select FWHM, again limiting the sensitivity of the commissioning process to focal spot size. In this approach, the energy was tuned employed the $5 \text{ cm} \times 5 \text{ cm}$ field, which is better reproduced with lower energies than larger fields.

Our FWHM value is consistent within 0.05 mm with that from simulations using Varian phase space files with code Geant4 [10], while their energy (5.9 MeV) is lower than ours. A work comparing Varian phase space files and BEAMnrc approach suggested that this energy should be increased in order to improve the agreement with measurements which in turn could improve consistency with our best energy [10].

Penelope based models such as [8] employ higher energy (6.3 MeV) than our model. This difference with our lower energy could be attributed to the artificial filter included in that work which is employed in order to improve lateral profile agreement, which will produce an extra attenuation that should be compensated by increasing the energy.

3.3. Validation of Monte Carlo model

Monte Carlo results for the best fitting parameters are shown in this section. Percentage depth dose and lateral beam profiles at 5 cm depth for field sizes ranging between $3 \text{ cm} \times 3 \text{ cm}$ and $15 \text{ cm} \times 15 \text{ cm}$ are shown in Figs. 7 and 8 respectively. Fig. 9 shows lateral profile of a $10 \text{ cm} \times 10 \text{ cm}$ field at 20 cm depth and an off-axis percentage depth dose where the scan axis is set 4 cm away from central axis in both directions. Experimental and simulation results are normalized to their correspondent values for a $10 \text{ cm} \times 10 \text{ cm}$ field at 5 cm depth.

All percentage depth dose profiles evaluated reproduce measurements with accuracy (in terms of relative local difference) better than 1%. At depths below 15 cm, for field sizes of $5 \text{ cm} \times 5 \text{ cm}$ and especially for $3 \text{ cm} \times 3 \text{ cm}$, Monte Carlo results are systematically higher than measurements. At the same time, for the $15 \times 15 \text{ cm}$ field the opposite happens as Monte Carlo results tend to be lower than measurements. Simulated Off axis PDD shows an agreement better than 1%.

Within the previous interval of field sizes, dose profiles will be reproduced with a high accuracy with our model primary source parameters. For smaller fields, focal spot plays the main influence and therefore our model with a fine tuned primary beam FWHM may reproduce results (for example output factors) down to $2 \text{ cm} \times 2 \text{ cm}$ or even less. Above $15 \text{ cm} \times 15 \text{ cm}$ the influence of energy is dominant and the geometry model may not reproduce experimental results, especially at depths below 15 cm, due to poor scattering reproduction in head elements for large area fields compared to that of small fields.

Simulated off-axis doses, for all field sizes, present a relative difference respect to measurements below 2%. For the $3 \text{ cm} \times 3 \text{ cm}$ field, differences do not exceed 1% since the jaws in simulations were adjusted to fit exactly the field width (2.92 cm). In the rest of profiles, this fine adjustment was not considered in simulations and therefore points in the 20–80% penumbra region show differences up to 2% due to the difference between actual jaw settings and simulated ones.

The agreement is in general similar or better than that obtained by previous works [8] and better than that obtained by using manufacturer phase space files [7–10]. For the off axis PDD there is no published data, but the agreement with experimental data is similar to all obtained in the present work.

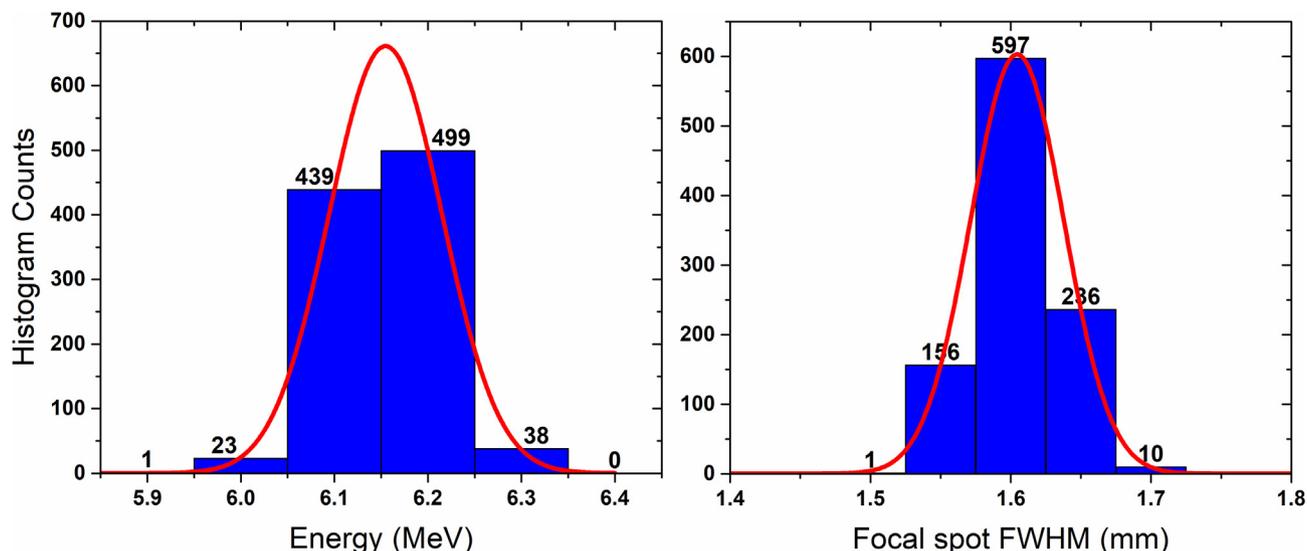


Fig. 6. Left: Histogram used for obtaining uncertainties of type A for parameter electron energy. Fit of data to normal distribution, whose FWHM represents type A uncertainty ($k = 1$) is also shown. Right: Histogram used for obtaining uncertainties of type A for parameter electron spatial FWHM. Fit of data to normal distribution, whose FWHM represents type A uncertainty ($k = 1$) is also shown.

Table 1

Monte Carlo commissioning results of the three treatment units studied and corresponding experimental focal spot size from slit measurements (third column).

Treatment unit	MC Best Energy (MeV)	MC Best FWHM (mm)	Focal spot FWHM (mm)
#1 – installed 2015	6.1 ± 0.1	1.60 ± 0.05	1.55 ± 0.02
#2 – installed 2017	6.1 ± 0.1	1.60 ± 0.05	1.57 ± 0.02
#3 – installed 2016	6.1 ± 0.1	1.60 ± 0.05	1.56 ± 0.02

4. Conclusions

In this work we have created an alternative EGSnrc base Monte Carlo model of the 6 MV Flattening Filter Free modality of a TrueBeam LINAC, and commissioned three different treatment units with high accuracy. For this scope, experimental procedures included direct measurement of focal spot size altogether with depth dose and transversal dose profiles in a water phantom. The main difference with other TrueBeam models was the effort in careful modelling of the target for which there is no detailed information easily provided by the manufacturer. We have paid especial attention in describing the methodology

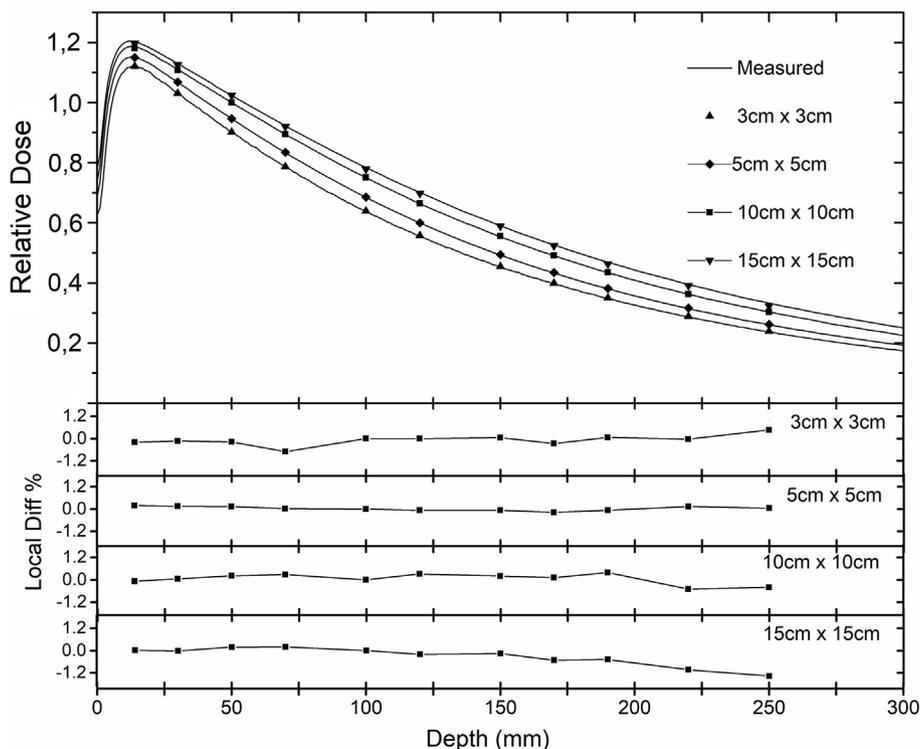


Fig. 7. Depth Dose Profiles obtained from the commissioned simulation compared to experimental data for fields $3\text{ cm} \times 3\text{ cm}$, $5\text{ cm} \times 5\text{ cm}$, $10\text{ cm} \times 10\text{ cm}$ and $15\text{ cm} \times 15\text{ cm}$. All curves are normalized to dose at 5 cm depth of the $10\text{ cm} \times 10\text{ cm}$ field. Simulation uncertainties range between 0.1 and 0.5%.

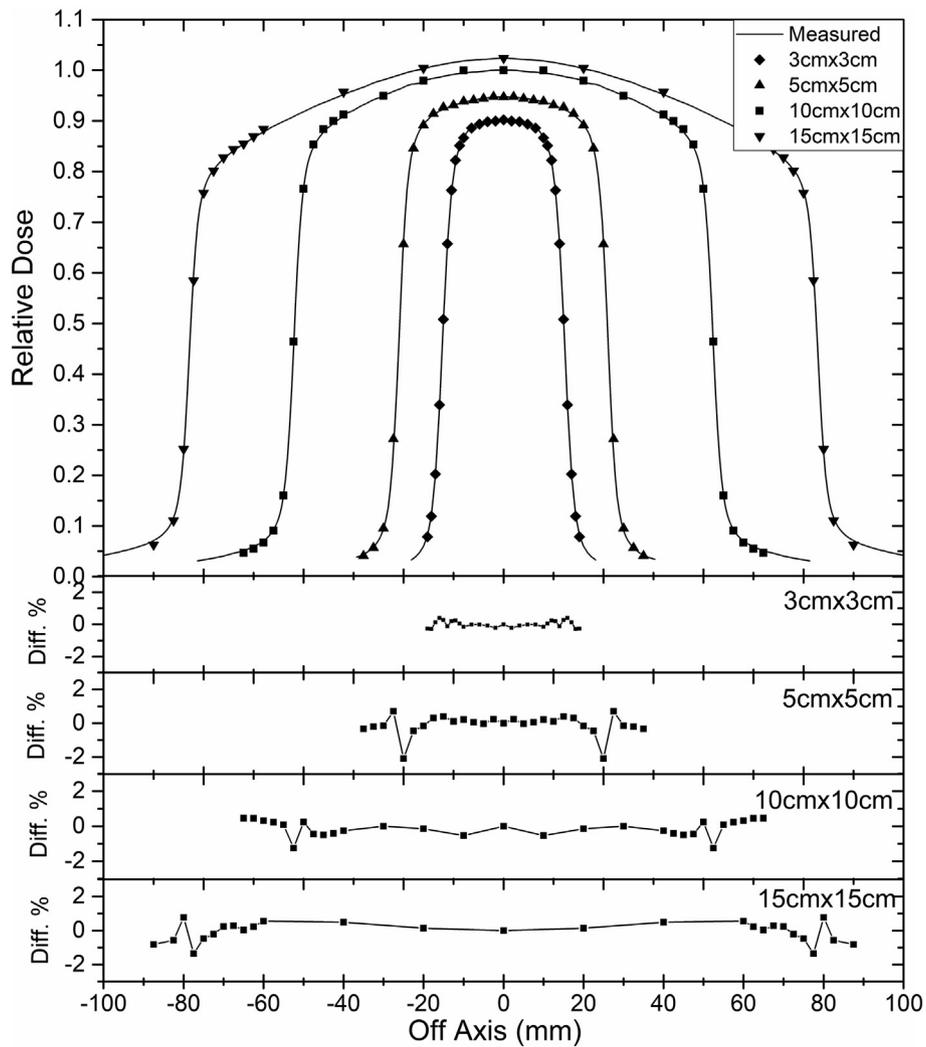


Fig. 8. Transversal dose profiles obtained from the simulation compared to experimental data (continuous line) for field sizes $3 \times 3 \text{ cm}^2$, $5 \times 5 \text{ cm}^2$, $10 \times 10 \text{ cm}^2$ and $15 \times 15 \text{ cm}^2$ at 5 cm depth. Simulation uncertainties range between 0.1 and 0.5%.

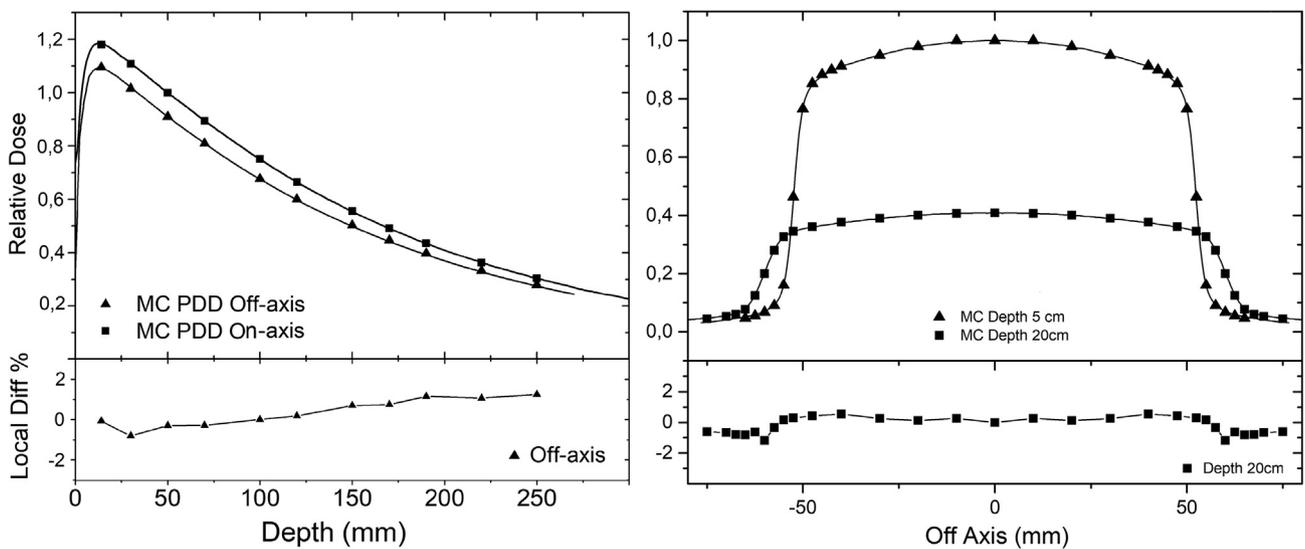


Fig. 9. Left: Off axis (4 cm in both directions) Depth Dose Profiles obtained from the commissioned simulation compared to experimental data for $10 \text{ cm} \times 10 \text{ cm}$ field. On axis Depth dose profile is also shown for comparison. Simulation uncertainties range between 0.1 and 0.5%. Right: Transversal dose profiles obtained from the simulation compared to experimental data (continuous line) for $10 \text{ cm} \times 10 \text{ cm}$ at 20 cm depth. 5 cm depth profile is also shown for comparison. Simulation uncertainties range between 0.1 and 0.5%.

employed in order to help the reader, reproducing it.

We found that in order to produce a better agreement between measurements and simulations it is of critical importance to consider the same scoring geometry (tuned exactly to the specific Ion Chamber model chosen in the experimental work) in the simulation that the one used in the measurements. This obvious conclusion is not always taken into account in clinical practice, for example when commissioning of TPS is performed, or in small field correction factors calculation by Monte Carlo simulation.

We have used small field profiles like the 3 cm × 3 cm profile to tune the primary electron beam size FWHM. This field size, in combination with a pinpoint type chamber, yields commissioning process sensitivity to focal spot size high enough to reproduce lateral profile penumbræ down to 0.1%. The results of the Monte Carlo beam size estimate have been independently compared to the experimental measurements with differences below 0.01 mm and falling in the middle of the experimental range obtained in 2013 in another work [21].

Uncertainties of the commissioning process to Monte Carlo source parameters amounts to 0.1 mm for electron spatial FWHM and 0.2 MeV for electron energy.

Our commissioned model reproduces experimental dose distributions in water of three treatment units within 1% accuracy for all fields, even the off axis percentage depth dose. This particular agreement indicates the robustness of our model, as this type of test is considered in TPS validation protocols such as IAEA tecdoc 1540 [22], therefore confirming the accuracy of the target model developed.

Finally, we have found a remarkable reproducibility between all TrueBeam treatment units studied (installed between 2015 and 2017).

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