Original Article

Monte Carlo Calculation of the Energy Spectrum of a 6 MeV Electron Beam using PENetration and Energy Loss of Positrons and Electrons Code

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Abstract

Background: The limited bibliographic existence of research works on the use of Monte Carlo simulation to determine the energy spectra of electron beams compared to the information available regarding photon beams is a scientific task that should be resolved. **Aims:** In this work, Monte Carlo simulation was performed through the PENELOPE code of the Sinergy Elekta accelerator head to obtain the spectrum of a 6 MeV electron beam and its characteristic dosimetric parameters. **Materials and Methods:** The central-axis energy spectrum and the percentage depth dose curve of a 6 MeV electron beam of an Elekta Synergy linear accelerator were obtained by using Monte Carlo PENELOPE code v2014. For this, the linear accelerator head geometry, electron applicators, and water phantom were simplified. Subsequently, the interaction process between the electron beam and head components was simulated in a time of $86.4x10^4$ s. **Results:** From this simulation, the energy spectrum at the linear accelerator exit window and the surface of the phantom was obtained, as well as the associated percentage depth dose curves. The validation of the Monte Carlo simulation was performed by comparing the simulated and the measured percentage depth dose curves via the gamma index criterion. Measured percentage depth- dose was determined by using a Markus electron ionization chamber, type T23343. Characteristic parameters of the beam related with the PDD curves such as the maximum dose depth (R_{100}), 90% dose depth (R_{90}), 90% dose depth or therapeutic range (R_{85}), half dose depth (R_{50}), practical range (R_p), maximum range (R_{max}), surface dose (D_s), normalized dose gradient (G_0) and photon contamination dose (D_x) were determined. Parameters related with the energy spectrum, namely, the most probable energy of electrons at the surface ($E_{p,0}$) and electron average energy ($\bar{E}_0$) were also determined. **Conclusion:** It was demonstrated that PENELOPE is an attractive and accurate tool for the obtaining of dosimetric parameters of a medical linear accelerator since it can reliably reproduce important clinical data such as the energy spectrum, depth dose, and dose profile.

Keywords: Dose profile, electron spectrum, Monte Carlo simulation, PENetration and Energy LOss of Positrons and Electrons, percentage depth-dose

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Introduction

Radiation therapy is one of the most used treatment modalities of cancer. Its objective is to maximize the dose delivered to cancer while minimizing the delivery in healthy tissues. The choice of the type of radiation (electrons, photons, protons, or heavy ions) and the availability of advanced tools for treatment are crucial to the success of radiotherapy.[1,2] Electron beams[3,4] are specially used for the treatment of superficial tumors because of the fast energy loss of the electrons in the first layers of the material.[5-7] Many efforts have been done both in order to achieve better planning and dosimetry in the electron treatments and to assess the risks and benefits of this procedure.[1,8,9] Computational simulations are one of the most common and effective ways used to bring us as close as possible to the conditions and characteristics of the clinical setting. Monte Carlo method (MMC) is a powerful tool to simulate the interaction of ionizing radiation with matter. It

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also allows to model radiation beams (electrons, photons, positrons, neutrons, and protons) produced in clinical linear accelerators.[10-14] With this, Monte Carlo simulation (MCS) can be used to obtain and analyze different clinical parameters such as energy spectrum, angular distribution, percentage depth dose (PDD), and other clinical parameters.[15]

The MCS validation is done by comparing the dose distribution obtained from the simulation with the experimental measurements. To perform this validation, the gamma-index can be used. Gamma-index is a mathematical parameter that evaluates the degree of agreement between two dose distributions considering spatial and dose distances under predefined tolerance limits.[16-19] The report 42 of the International Commission on Radiation Units and Measurements (ICRU)[20] states that, in order to have a high level of precision in the MCS of a beam, there should be no discrepancy between dose distributions >±2% or ± 2 mm.[21] In addition to the considerations given in the report 42, the accuracy of the simulation depends directly on the choice and how well the parameters or input information, the characteristics of the materials immersed in the constructed geometries, and the nominal energies can be represented.[15,21]

The choice of the Monte Carlo code for the simulation marks a differential in obtaining satisfactory results. Currently, there are several radiation transport simulation codes based on the MMC, some free and others sold. For example, there is the EGSnrc system which is a Monte Carlo code to simulate the transport of electrons and photons in various geometries,[12,22,23] and whose valid energy range is between 1 keV and 100 GeV. Geometry ANd Tracking (GEANT4) is a code that simulates the transport of all kinds of particles in the energy range between 250 eV and about 10 TeV.[24] It is mainly used in high-energy physics as well as in medical physics. FLUktuierendeKAskade is used in high-energy physics and medical physics. It is a general-purpose code that reproduces the interaction of ionizing radiation with the matter of up to 60 different particles at the same time, electrons and photons (from 1 keV to 1000 TeV), hadrons (up to 20 TeV), neutrons (including thermal), and heavy ions. Like GEANT4, it presents various applications in high-energy physics and medical physics.[25] Monte Carlo N-Particle is another general-purpose code for the transport of neutrons, photons, and electrons.[26-28] In this work, the PENetration and Energy LOss of Positrons and Electrons (PENELOPE) code is used. It has extensive information on various applications for radiotherapy and radiodiagnosis.[4,29-34] Since its first version launched in 1996, the MCS PENELOPE code has become a flexible and reliable tool to describe the coupled transport of photons and electrons in complex material structures,[35,36] presenting simplicity and versatility to be used in the two most used programming platforms such as Windows and Linux without the necessity of the usage of an intermediary interface. Moreover, the results obtained are presented in.*dat* extension which is easy to read in any code for statistical analysis such as Origin, Matlab, and Gnuplot.

The main motivation of this work is related to there are few research papers about the use of MCS to determine energy spectra of electron beams[21,31,37,38] and its characteristic dosimetric parameters in comparison to those existent for photon beam,[11,31,33,39-46] especially for linear accelerators still used in developing countries. Thus, in this work, an Elekta Synergy Platform linear accelerator was used as a reference, since the Synergy is still one of the most used accelerators in the Latin-American market and other developing regions of the world. The novelty of the present work consists of a complete description of how to simulate the Synergy Elekta linear accelerator head using PENELOPE. It was also demonstrated that PENELOPE is a cheap and powerful computational tool for the radiation external source modeling in radiotherapy since it reliably reproduced the relevant dosimetric data of the electron beam studied.

Materials and Methods

Monte Carlo simulation codes

MMC is any probabilistic method that is based on random sampling and provides numerical results. This method is widely applied for simulations in physics, biology, chemistry, and mathematics[12,22,36,47] since it can give numerical solutions of very complex functions. One of the many Monte Carlo versions utilized for studying the radiation transport in a material is the PENetration and Energy LOss of Positrons and Electrons code. Thus, PENELOPE is a general-purpose open code for the transport of electrons, photons, and positrons with a range of energies between 50 eV and 1 GeV. Because of this, its main fields of use are applications in medical physics, namely external radiotherapy, radiodiagnostic, nuclear medicine, and brachytherapy.

The several geometries used are constructed from quadratic surfaces, and variance reduction techniques are incorporated to have better adaptability and greater precision.[30,33,36,47,48] PENELOPE allows creating materials with a single component, alloys, or mixed materials that are present in the constitution of a clinical linear accelerator. All these help to make better reproductions and representations of experimental conditions. PENELOPE's stop simulation criteria depend on the real time of the simulation or the events/simulated shower number. In this work, the PENELOPE version 2014 was used.

Modeling of the electron radiation source using PENetration and Energy LOss of Positrons and Electrons

PENELOPE code was used to reproduce the physical, geometrical, and material characteristics that make up the head of an Elekta Synergy Platform linear accelerator. The technical detail of each of the mentioned characteristics is described in the phase spaces extracted from the manual provided by the manufacturer, and for commercial reasons, this information is omitted. Based on the geometric information and composition of the elements and components of the linear accelerator head provided in the manufacturer's manual, the virtual simulation was performed in PENELOPE. Both materials of the primary

and secondary collimators and those of the scattering foils used in the virtual geometry are composed of the same alloys and densities as the actual accelerator materials. The precision in the replication of these details allowed determining the characteristics of the energy spectrum of the electron beam both in the exit window after interacting with the head components as well as the spectrum on the surface of the phantom.

Figure 1 shows the virtual geometry of the Elekta linear accelerator built-in PENELOPE. To do this, three-dimensional gview software was used since it is the graphic display extension of PENELOPE. Figure 1a details the locations of the radiation source, the scattering foils, and the collimators inside the accelerator head. The geometry configuration shown in Figure 1b was used to simulate the interaction of the electron beam with the surface of the water phantom: gantry angle of 0°, nominal energy of 6 MeV, field size of 10 cm × 10 cm, 100 cm of source-skin distance (SSD), applicators of 10 cm × 10 cm, and a phantom water of 40 cm × 40 cm × 40 cm. The simulation time employed was 86.4×10^4 s, number of simulated showers of 3.5×10^9, and a confidence level of 99%. To carry out the simulations, the Educational Cluster of the University of São Paulo-Ribeirão Preto was used. All simulations were performed with respect to the central axis of the electron beam. For the experimental dosimetric measurements, the accelerator position was configured as follows: 0° gantry angle, 6 MeV nominal energy, 10 cm × 10 cm field size, 100 cm SSD with 10 cm × 10 cm applicators, and an automated tank, and a parallel flat ionization chamber was used Markus model with 3.05 mm detector radius. Throughout all the work, we will call the PENELOPE simulation as MCS.

Relationships between beam characteristics and depth-dose distribution

There are several dosimetric parameters to fully characterize an electron beam from the PDD curve recommended by ICRU. These parameters are: maximum dose depth (R_{100}), 90% dose depth (R_{90}), 85% dose depth (R_{85}), 50% dose depth (R_{50}), practical range (R_p), maximum range (R_{max}), the most probable energy of electrons on the surface ($E_{p,0}$), average energy of electrons ($\bar{E}_0$) on the surface, the dose gradient (G_0), percentage of doses of contaminating photons (D_x), and percentage of surface dose (D_s). In the Technical Report Series No. 381 reports of IAEA[49] and the report 32 of the AAPM,[6] empirical relationships between the parameters and the PDD curve are shown. The two best known relationships between E_0 and R_{50} are:

$$\bar{E}_0 = 0.656 + 2.059R_{50} + 0.022R_{50}^2 \quad (1)$$

$$\bar{E}_0 = 2.33R_{50} \quad (2)$$

Eq. (1) is recommended in the technical report 381 of the IAEA (1997)[49] while Eq. (2) is recommended in report 32 of the AAPM.[6] Both allow calculating the average energy of the electrons from R_{50}.

A very useful relationship is $E_{p,0}$ and R_p, which has the same form of Eq. (1) but with different constants and in relation to R_p.[6,49]

$$E_{p,0} = 0.22 + 1.98R_p + 0.0025R_p^2 \quad (3)$$

Another characteristic parameter that can be calculated is the standardized dose gradient (G_0), which describes the slope of

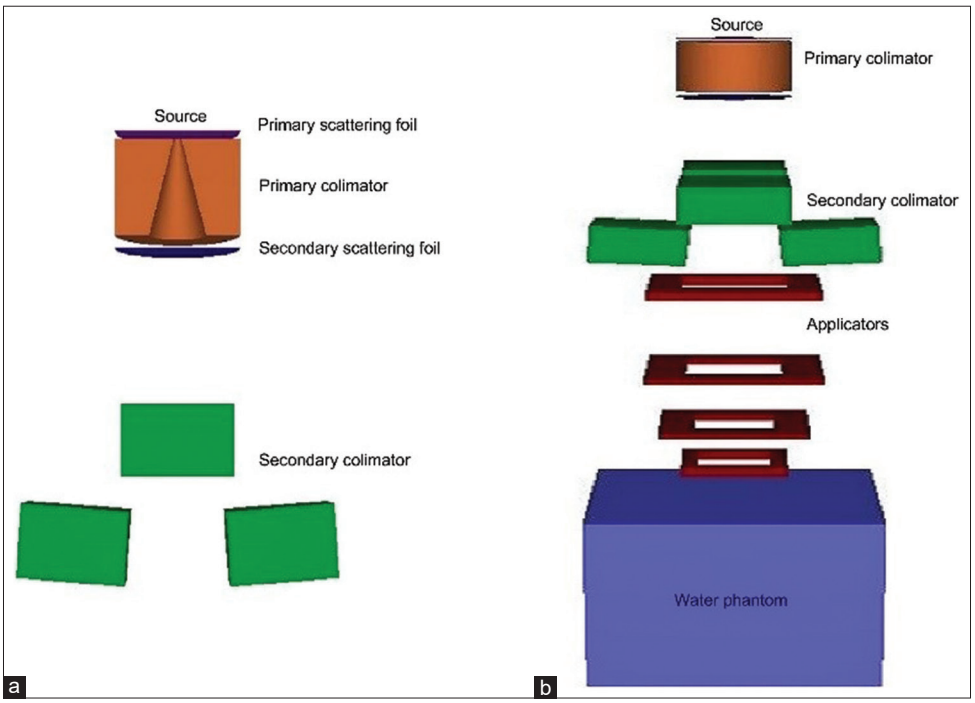

Figure 1: Representation of the virtual geometry simulated of the linear accelerator used to simulate the electron beam. Simulation of the accelerator head geometry (a) and the complete geometry of the linear accelerator (b)

the fall region of the PDD curve. This gradient is related to R_q and R_p,

$$G_0 = \frac{R_p}{R_p - R_q} \quad (4)$$

All parameters R_{100}, R_{90}, R_{85}, R_{50}, R_q, R_p, R_{max}, $E_{p,0}$, $\bar{E}_0$ and G_0 were obtained for the measured depth-dose distribution curve and also for the one generated by simulation with PENELOPE code, in order to validate the simulation and have a comparison between both curves.

In order to validate the PDD curve obtained from the simulation, it is compared to the measured PDD which was previously determined by employing an ionization chamber. The comparing method utilized was the gamma-index since it is widely known and used criterion in radiotherapy. The gamma-index (Γ) is determined by:

$$\Gamma(\vec{r}_c, \vec{r}_m) = \sqrt{\frac{|\vec{r}_s - \vec{r}_m|^2}{DTA^2} + \frac{|D_{\vec{r}_s} - D_{\vec{r}_m}|^2}{DD^2}} \quad (5)$$

where $|\vec{r}_s - \vec{r}_m|$ is the distance between the analyzed points, being $\vec{r}_s$ the obtained from simulation and $\vec{r}_m$ the experimentally measured, and $|D_{\vec{r}_s} - D_{\vec{r}_m}|$ represents the dose difference (DD) between the simulated and measured PDD curves at $\vec{r}_s$ and $\vec{r}_m$ respectively. The distance-to-agreement and DD values are scale values that adjust the gamma-index to the acceptance level required, i.e., they are the predefined tolerance values.[16,18]

Results and Discussions

Electron energy spectrum derived from Monte Carlo simulation

The simulated energy spectra at the linear accelerator exit window and at the water phantom surface are shown in Figure 2. The spectrum at the exit window was measured after the second scattering foil. The spectra were normalized to its most probable maximum energy value.

Figure 2a is observed the energy spectrum at the exit window with a narrow central peak and the presence of an additional small peak to its left. The narrowness of the central peak is because the electron beam has not interacted with most of the accelerator head structures and the entire air column. The small peak is generated as the beam passing through the first linear accelerator head metal structures (collimator and scattering foils) and interacting with them for producing this secondary radiation. Figure 2b shows the energy spectrum at phantom surface whose shape resembles a slightly asymmetric Gaussian distribution and with a width central peak. There is also observed a small peak to the left of the central peak in the energy range of 0–0.250 MeV which may be due to the contaminating photons that reach the water phantom surface. From Figure 2, two important spectral parameters can be obtained: the most probable energy, E_0, and the full width at half maximum (FWHM) of the central peak, γ_0. Not to be confused E_0 with $E_{p,0}$, since while both mean the same, E_0 is the most probable energy obtained from the analysis of the spectrum, while $E_{p,0}$ represents the most probable energy from R_{50} in the PDD curve.

Table 1 shows the values of E_0 and γ_0 for the spectra at the exit window and at the phantom surface. The value of γ_0, as well as its value respect to E_0, is shown as well. From Table 1 data, it is noted that as the beam approaches, the surface of the water phantom decreases the most probable energy and increases the FWHM of the spectrum. This is because of the low-energy electrons, generated by the interaction among the beam and the accelerator structures and air, reduce the hardness of the beam and they are more easily scattered.[21]

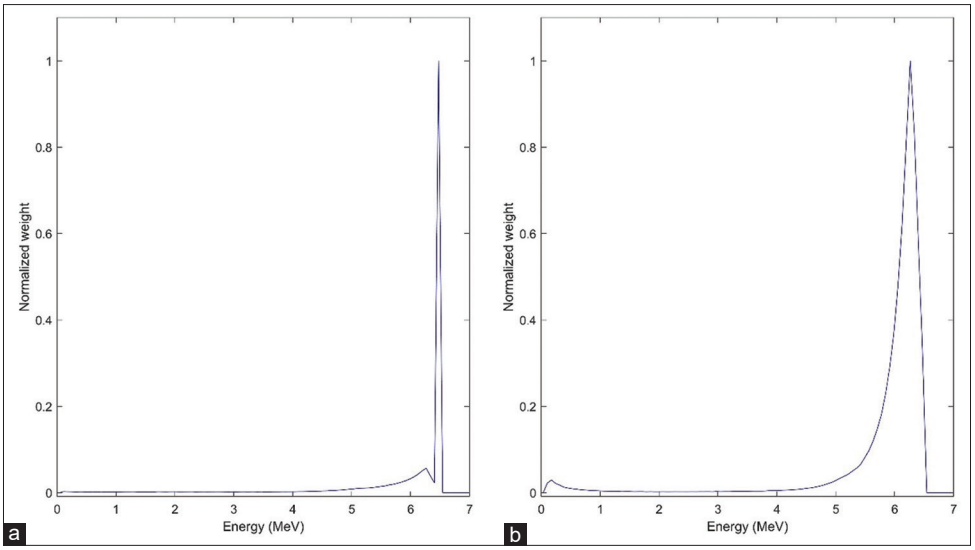

Figure 2: Energy spectra of the electron beam of 6 MeV at the exit window (a) and the phantom surface (b) obtained by PENetration and Energy LOss of Positrons and Electrons

Comparison of depth-dose distribution curves and dose profiles

Figure 3 shows the simulated and measured PDD curves for the electron beam of 6 MeV nominal energy. Vertical open circle lines are the values of the gamma-index in each depth.

At the build-up region (0–1 cm depth), a noticeable discrepancy in terms of DD is observed. The contribution of contamination photons is noted at the final part of PDD curves, specifically, from the 3.2 cm depth. Contamination photons are generated by the deflection of primary and secondary electrons passing through accelerator structures.[50] It was found that the contribution of contamination photon dose in the measured PDD curve is greater than the simulated one because of the inefficiency of the simulation to calculate the contamination photons amount. It is possible that such inefficiency obeys to the discrepancies in the constitution of the alloys of the accelerator materials simulated in PENELOPE and those of the real accelerator. ICRU recommendation is that the differences between the treatment (measured) and planning (simulated) PDD curves were within ± 2%/±2 mm.[21] Keeping this in mind, the DDs between the measured and simulated PDD curves were analyzed using the gamma-index. The largest differences are found at the shallow region of the water phantom. In fact, the DD between the PDD curves reached up to 3% in that region, while for the rest, it was not >1%. The acceptance percentage of the simulated PDD curve was 100% and 98% according to the gamma-index criterion of >95% of simulated curve within 2%/2 mm and 1%/1 mm, respectively.

Figure 4a displays the measured and simulated PDD curves in the build-up region. In this region, DDs are ranged from 1% to 3%. The largest difference occurs in the depth of the surface dose. This indicates that the simulated spectrum could not reproduce the dose data in this region with high accuracy. However, this is a really hard task since the experimental measurements of the dose at the build-up region are highly probabilistic due to here occur the first interaction of beam electrons with the water surface.

In Figure 4b, the measured and simulated dose profiles are compared. Dose profiles allow detailing the off-axis DDs between the dose profiles at a reference depth. The reference depth was stated in 1.3 cm. Moreover, from Figure 4b, A good agreement between measured and simulated dose profiles is observed, except in the field edge region. In the edge region, the differences are higher than the other regions of dose profiles because the incident electrons possess a greater angular spread.

Table 1: Relevant dosimetric parameters of the spectrum according to its registration location

Spectrum registration location	E_0 (MeV)	γ_0 (MeV)	γ_0/E_0 (%)
Exit window	6.46	0.04	0.62
Phantom surface	6.26	0.40	6.39

FWHM: Full width at half maximum, E_0: Most probable energy, γ_0: FWHM of the spectrum central peak

Beam characteristics derived from the percentage depth-dose curves

An additional way to evaluate the accuracy of the simulated electron energy spectrum is comparing the values of dosimetric parameters obtained from the measured and simulated PDD curves. The values of dosimetric parameters found are shown in Table 2.

From Table 2, a good approximation between the values of the measured and simulated characteristic parameter is observed. The highest deviations were found for G_0 and D_X.

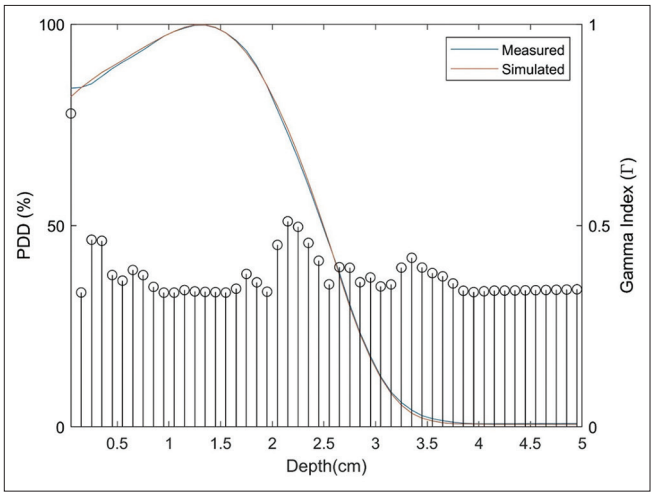

Figure 3: Comparison between the measured and simulated percentage depth-dose curves. Vertical lines (open circles) are the values of the gamma-index in each depth of percentage depth-dose curves. It can be observed that all gamma-index values are lower than 1, which indicates that the simulated percentage depth-dose curve meets with the imposed criterion of >95% of its points being within a 2%/2 mm radius with respect to the measured percentage depth-dose curve

Table 2: Values of the dosimetric parameters found from the measured and simulated percentage depth-dose curves

PDD curve	R_{100}	R_{90}	R_{85}	R_{50}	R_p	R_{max}	G_0	$E_{p,0}$	$\bar{E}_0$	D_s	D_x
Measured	1.30	1.84	1.94	2.48	3.20	3.78	0.45	6.58	5.78	84.10	0.58
Simulated	1.31	1.82	1.93	2.48	3.17	3.75	0.43	6.52	5.79	82.29	0.51
Deviation	0.76	1.1	0.52	0	0.95	0.79	4.4	0.91	0.17	2.2	12

Deviation is the percentage relative error between the measured and calculated data. R_{100}: Maximum dose depth, R_{90}: 90% dose depth, R_{85}: 85% dose depth or therapeutic range, R_{50}: Half-dose depth, R_p: Practical range, Rmax: Maximum range, D_s: surface dose, G_0: Normalized dose gradient, Dx: Photon contamination dose, PDD: Percentage depth dose

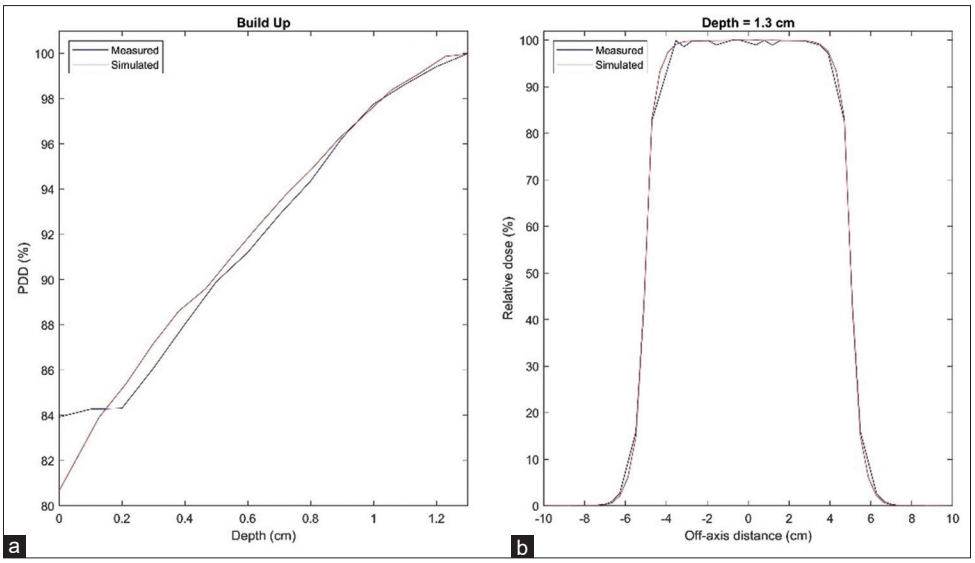

Figure 4: Comparison between the measured and simulated percentage depth-dose curves at the build-up region (a) and between the measured and simulated dose profiles at the reference depth of 1.3 cm (b)

Conclusions

Monte Carlo PENELOPE code represents a powerful tool to study the effects and characteristics of a medical electron beam. A good agreement between the measured and simulated depth-dose distributions was observed according to the gamma passing rate criterion. It was also seen a good agreement between the measured and simulated dose profiles excepting the field edge region. The small discrepancies found are related to the limited representation of the geometrical and the composition of accelerator head structures as well as the behavior of the simulated energy beam as it traverses such structures and the air. Most of the characteristic parameters of the simulated PDD relative are in accordance with those of the measured PDD. The dose gradient and the photon contamination dose were the characteristic parameters of PDD curves with the highest discrepancies. Therefore, it can be concluded that PENELOPE v2014 is an accurate tool to obtain the electron energy spectrum and other important dosimetric characteristics of an electron beam.

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Conflicts of interest

There are no conflicts of interest.

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