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Technical Note

Evaluation of the usefulness of the electron Monte Carlo algorithm for planning radiotherapy with the use of electron beams

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Abstract

The aim of the study was to verify the accuracy of calculations of dose distributions for electron beams performed using the electron Monte Carlo (eMC) v.10.0.28 algorithm implemented in the Eclipse treatment planning system (Varian Medical Systems). Implementation of the objective of the study was carried out in two stages. In the first stage the influence of several parameters defined by the user on the calculation accuracy was assessed. After selecting a set of parameters for which the best results were obtained a series of tests were carried. The tests were carried out in accordance with the recommendations of the Polish Society of Medical Physics (PSMP). The calculation and measurement of dose rate under reference conditions for semi quadratic and shaped fields were compared by individual cut-outs. We compared the calculated and measured percent depth doses, profiles and output factors for beams with an energy of 6, 9, 12, 15 and 18 MeV, for semi quadratic fields and for three different SSDs 100, 110, and 120 cm. All tests were carried out for beams generated in the Varian 2300CD Clinac linear accelerator. The results obtained during the first stage of the study demonstrated that the highest compliance between the calculations and measurements were obtained for the mean statistical uncertainty equal to 1, and the parameter responsible for smoothing the statistical noise defined as medium. Comparisons were made showing similar compliance calculations and measurements for the calculation grid of 0.1 cm and 0.25 cm and therefore the remaining part of the study was carried out for these two grids. In stage 2 it was demonstrated that the use of calculation grid of 0.1 cm allows for greater compliance of calculations and measurements. For energy 12, 15 and 18 MeV discrepancies between calculations and measurements, in most cases, did not exceed the PSMP action levels. The biggest differences between measurements and calculations were obtained for 6 MeV energy, for smallest fields and large SSD distances. Despite these discrepancies between calculations the model was adopted for clinical use.

Key words: radiotherapy; electron beam; Monte Carlo; dose calculation algorithm; TPS control.

Introduction

The basic algorithm used to calculate the dose distributions of the electron beam has for many years been the Pencil Beam algorithm proposed by Hogstrom [1]. In real clinical situations, in case of heterogeneity, large absorbent curvatures and, in the case of a change of SSD, from a distance for which the input data was measured, and at greater distances the Hogstrom algorithm did not provide satisfactory accuracy [2-4]. The increasing power of computers and the development of algorithms allowed to implement the Monte Carlo method in the treatment planning systems for electron beams [5-7]. This method has been used in the Varian Eclipse treatment planning system [8]. The transport of electron in the absorbent medium is simulated with the Monte Carlo algorithm. Every act of electron interaction with matter is modelled independently by drawing the angle of dispersion and particle energy "emitted". The simulated measure of the impact leads to energy absorption. Due to the high complexity of modeling particle transport, the implementation of the Monte Carlo code has always had some simplification, in particular, when this calculation method is used in applications whereby a reasonable period of completion time of the calculation plays an important role. In the case of planning treatment such a situation exists. Before commissioning the treatment planning system for clinical applications, it is necessary to verify the accuracy of calculations. The scope and method of the control system for planning treatment is defined in the recommendations prepared by different organizations [9-14]. The results of the comparison calculations performed using the Monte Carlo algorithm were implemented in the Varian Eclipse treatment planning system, carried out in accordance with the recommendations published by the Polish Society of Medical Physics [13].

Materials and Methods

The implemented Monte Carlo method allows the user to perform calculations for several different values of calculation parameters referred to by the English terms: "accuracy", "smoothing levels" and "calculation grid size" [8]. According to the information provided in the instruction manual, the user can select specific, discrete parameter values:

- Accuracy - the average statistical uncertainty in all voxels within the contour of the body where the dose of > 50% of maximum dose D_{max}:
  - available options: 1, 2, 3;
  - selected by default: 1.

  The average statistical uncertainty depends on the number of analyzed history – the higher the number, the smaller statistical error but longer calculation time
- Smoothing levels - Smoothing determines the strength of the statistical noise in the dose distribution (without smoothing the distribution is discontinuous):
  - available options: low, medium, strong;
  - selected by default: medium.
- Calculation Grid Size - This is the resolution of the calculation grid; the smaller the calculation grid, the longer the calculation time in assuming greater accuracy:
  - available options: 0.1 cm, 0.15 cm, 0.2 cm, 0.25 cm, 0.50 cm;
  - selected by default: 0.25 cm.

That is the reason that the work was carried out in two stages. A preliminary qualitative assessment of the accuracy of calculations was carried out. In the first stage, depending on the selected parameter calculation values. For this purpose a calculation of the percentage depth dose (PDD) for a beam energy of 12 MeV, the quadratic fields having a side of 6, 10, 15, 20, 25 cm. The calculated PDD was compared visually with those measured.

After selecting the parameters that provided the best visual consistency between calculations and measurements, the results of calculations and dose rate measurements of PDD and profiles were compared quantitatively. We compared also the output factors. These comparisons were carried out for:

- the electron energies of 6, 9, 12, 15, 18 [MeV];
- quadratic fields of side: 6, 10, 15, 20, 25 [cm];
- SSD distances: 100, 110, 120 [cm].

Dosimetric measurements

The dose distributions were measured with a Clinac 2300CD using the PTW MP3 3D radiation analyzer field system controlled by Mephysto computer software. The PDD were measured from the surface of the phantom to a depth determined by the practical extent (increased by 4 cm) in steps of 0.1 cm, using a Marcus parallel-plane type ionization chamber. Profile measurements were made in steps of 0.2 cm at a depths of 1 cm (beam energy 6 MeV), 2 cm (for beams with energies of 9, 12, 15 MeV) and 3 cm (beam energy of 18 MeV) for the field enlarged by 2 cm, using a PTW 31010, 0.125 cc semiflex chamber. Each profile was normalized to a maximum at the central axis of the beam and expressed as a percentage.

The dose rate was measured at a depth of maximum dose in a PTW solid water phantom using a Marcus chamber and PTW UNIDOS dosimeter. The value of the dose rate is always adjusted to the current dose rate for the field reference. The dose rate was determined in accordance with the recommendations of the IAEA 398 Report [12].

Computer calculations

Parameters of the calculation algorithm are shown in **Table 1**. In order to compare the measured and calculated dose rate in the treatment planning system, the number of monitor units (MU) necessary to deliver 100 cGy to maximum were calculated. For this number of MU the maximum doses were measured. The measurement results were always corrected for the actual output factor for field of 10 cm x 10 cm. All calculations were performed in the water phantom generated in TPS Eclipse ver. 10.0 with dimensions of 50 x 50 x 50 [cm], CT Value: 0 HU (relative electron density: 1, mass density: 1 g/cm^3) in steps of 0.5 cm.

Table 1. Eclipse electron Monte Carlo calculation parameters used in this study.

Parameter	Size
Accuracy	1
Accuracy Limit	3
Calculation Grid Size	**0.25 0.10**
Random generator seed number	39916801
Number of particie histories	0
Smothing method	3-D_Gaussian
Smothing level	Medium

Table 2. Action levels for tests according to the PSMP and the IAEA.

REGION	Homogeneous medium, a simple geometry	Complex geometry (wedges, field symmetrical, blocks, MLC)
1 – the central axis– outside the build-up; small dose gradient (limit - δ_1)	2%	3%
2 – outside the central axis of the beam - high dose, small dose gradient (limit - δ_3)	3%	3%
3 – increase the dose in the central axis of the beam, penumbra - high dose, high dose gradient (limit - δ_2)	10% or 2 mm	15% or 3 mm
4 – outside the limit of the beam – low dose, small dose gradient (limit - δ_4)	3%	4%

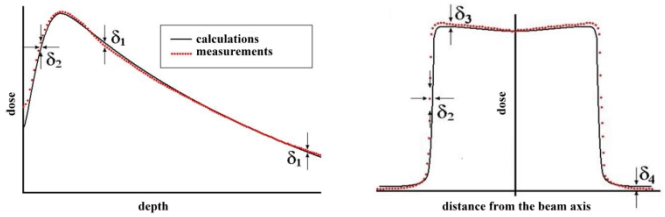

Figure 1. Regions of high and low dose gradients and criteria of measured and calculated dose distribution comparison (Fig.4ab PSMP [13]).

Evaluation of the results obtained

The differences between the calculations and measurements were assessed using the criteria proposed by PSMP [13]. In these recommendations, it is proposed to apply different criteria for areas in which there is a high and low dose gradient. **Table 2** shows the criteria proposed by PSMP. **Figure 1** schematically presents the areas of small and large dose gradients, and noted the importance of designations used in **Table 2**. In areas of low dose gradient the differences were expressed in terms of δ_1, δ_3, δ_4 defined with **Equation 1**. In areas of high dose gradient the measure of the discrepancies δ_2 were calculated which is the so called distance to agreement (DTA). It defines the distance to the nearest measured point A_{meas}, where the dose is closest to the dose calculated at the point of A_{calc}.

$$\delta(\%) = 100 * \left(\frac{D_{calc}}{D_{meas}^{corr}} - 1\right) \quad \text{Eq. 1}$$

where: D_{calc} – calculated dose, and D_{meas}^{corr} – adjusted dose measured at the current value of the dose rate for field reference, i.e. field 10 cm x 10 cm.

PSMP recommendations state that the maximum acceptable discrepancy between the calculations and performance measurements for fields carried out in reference conditions (depth d_{max}, field 10 cm x 10 cm, SSD = 100 cm) amounts to ±1,5%. For the remaining fields, the maximum acceptable discrepancy is 3%.

Results and discussions

Quantitative evaluation of the accuracy of calculations

The quantitative results showed that little better agreement between the calculations and measurements for the grid size of 0.1 cm were obtained. Reducing the default resolution setting on the calculation grid reduces slightly the differences between the calculated and measured PDD curves. This improvement has been found particularly in the area of the build-up of the dose. Due to the fact that improving the accuracy of calculation was small, it was decided to carry out a test on two calculation grids of the value of 0.25 cm and 0.10 cm during stage 2.

Quantitative comparison of calculations and measurements

In **Figures 2a, 2b and 2c** the differences between the measured and the calculated output factors are presented for a number of radiation energy of a few different fields and for the SSD = 100, 110, 120 cm distances carried with grid size of 0.1 cm. This comparison was also carried out for a grid of 0.25 cm. Greater compatibility was measured and calculated performance achieved for grid size of 0.1 cm. For grid of 0.25 cm the number of fields for which the discrepancy between measurements and calculations exceeded 3% (the level of acceptance of PSMP recommendations) was 10 (for a total comparisons made for 75 fields). For grid of 0.10 cm such a divergence was obtained for 6 fields. The SSD distance has a significant impact on compliance calculations and measurements. With the increase in SSD, the deviation between the measured and the calculated doses increases. Calculations performed for SSD of 100 cm with grid size of 0.1 cm never exceeded 1.5%. For grid size of 0.25 cm for 12 fields the discrepancies exceeded 1.5%. The biggest discrepancies are between the measured and the calculated for the largest SSD = 120 cm and the smallest energy i.e. 6 MeV. It should be noted, however, that due to the construction of the collimating system for the electron beam, therapy is carried out substantially less at a distance of 100 cm than at a distance of 110, and 120 cm. For the electron beams with 6 MeV and 9 MeV energies and small-sized fields, discrepancies between the calculated and measured yields are higher for the smaller Calculation Grid Size. In other cases, a reduction in the calculation grid will improve the accuracy of the calculations. For the 6 and 9 MeV energy, the 0.10 cm grid allows for narrowing of the gaps for the larger field sizes.

Figures 3a and 3b, presents the comparison of the measured (dots - measurements) and calculated PDD (solid line - calculations) electron beams with energies in the field of 6-18 MeV, 25 cm x 25 cm fields, SSD 110 cm, calculated using Calculation Grid Size 0.25 cm and 0.1 cm. At depths greater than 1 cm compatibility between the measured and calculated PDD was little better for Calculation Grid Size 0.25 cm than for 0.1 cm. The mean difference for 0.25 cm grid size was 0.78%, while for the smaller grid it was 1.07%. Such good compatibility has not been achieved in the area of build-up of the dose. In **Figures 4a and 4b** a comparison is presented of the measured (dots) and calculated PDD (solid lines) in the area of build-up dose for energy 6, 9, 12, 15 and 18 MeV respectively for the 0.25 cm and 0.1 cm calculation grid. Discrepancies between measured and calculated PDD are greatest for depths less than 1cm. For a depth of less than 3mm the calculations underestimate the PDD very much. In this region the difference exceeds doses of up to 5% for the 0.25 cm grid and 2% for the 0.10 cm grid. The calculated dose at the surface is lower than the measured one by several tens of percent.

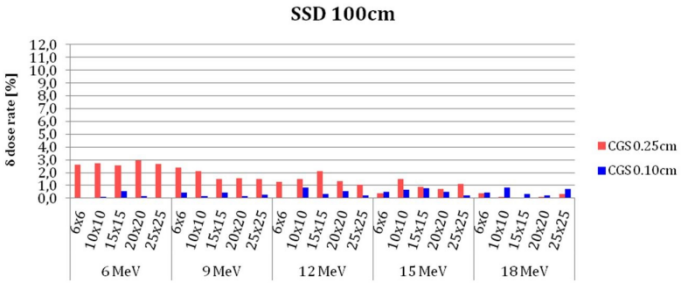

Figure 2a. Differences between measured and calculated dose rates for electron beams of energies 6, 9, 12, and 15 MeV and for SSD = 100 cm.

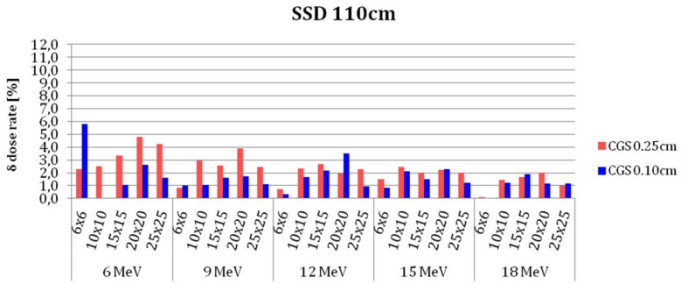

Figure 2b. Differences between measured and calculated dose rates for electron beams of energies 6, 9, 12, and 15 MeV and for SSD = 110 cm.

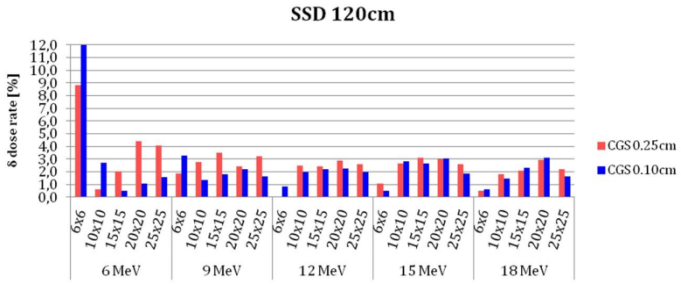

Figure 2c. Differences between measured and calculated dose rates for electron beams of energies 6, 9, 12, and 15 MeV and for SSD = 120 cm.

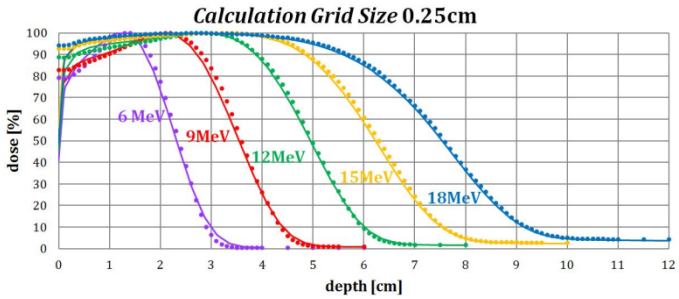

Figure 3a. Measured and calculated percentage depth doses for electron beams of energies 6, 9, 12, 15, 18 MeV, for SSD 110 cm (dots - measurements, solid lines - calculations). Calculations were performed with grid size of 0.25cm.

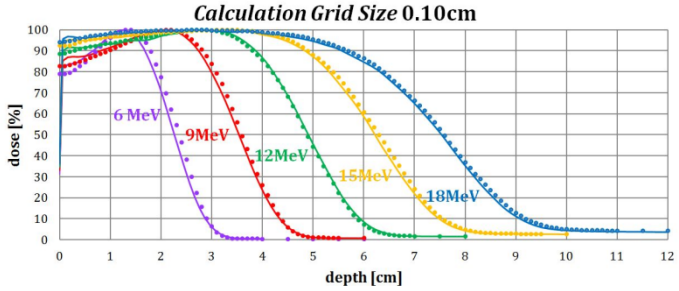

Figure 3b. Measured and calculated percentage depth doses for electron beams of energies 6, 9, 12, 15, 18 MeV, for SSD 110 cm (dots - measurements, solid lines - calculations). Calculations were performed with grid size of 0.1cm.

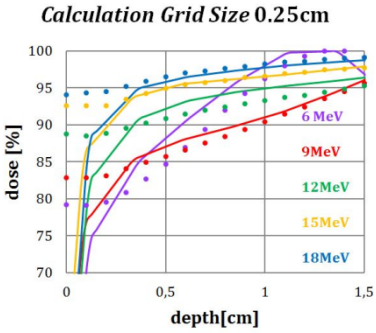

Figure 4a. Measured and calculated percentage depth doses for electron beams of energies 6, 9, 12, 15, 18 MeV, for SSD 110 cm in the build-up region (dots - measurements, solid lines - calculations). Calculations were performed with grid size of 0.25 cm.

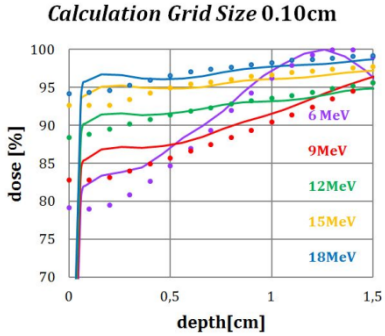

Figure 4b. Measured and calculated percentage depth doses for electron beams of energies 6, 9, 12, 15, 18 MeV, for SSD 110 cm in the build-up region (dots - measurements, solid lines - calculations). Calculations were performed with grid size of 0.1 cm.

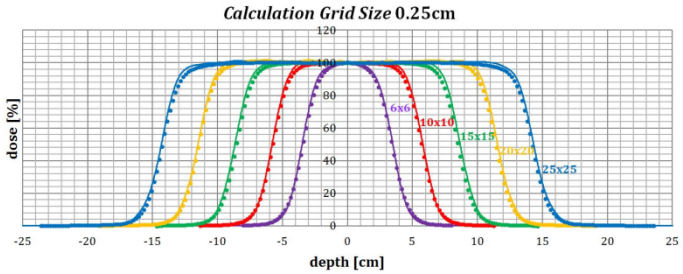

Figure 5a. Measured and calculated profiles for electron beams with energy of 9 MeV, at depth of 2 cm, for square fields 6, 10, 15, and 25 cm, for SSD 110 cm (dots - measurements, solid lines - calculations). Calculations were performed with grid size of 0.25 cm.

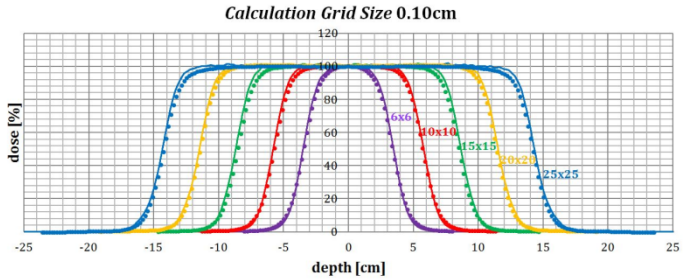

Figure 5b. Measured and calculated profiles for electron beams of 9 MeV energy, at depth of 2cm, for square fields 6, 10, 15, and 25 cm, for SSD 110 cm (dots - measurements, solid lines - calculations). Calculations were performed with grid size of 0.1 cm.

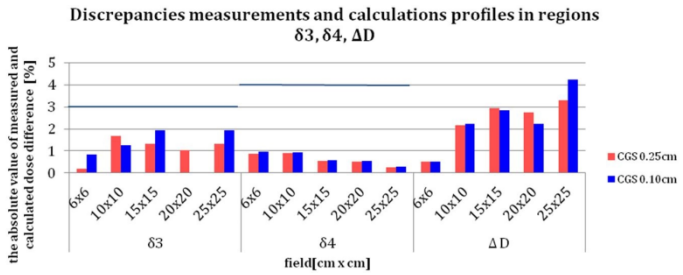

Figure 6a. Measured and calculated dose differences of profiles for energy 9 MeV for = SSD 110cm. Results are given in terms of δ_3, δ_4, ΔD regions. Calculations were performed for two grid sizes 0.25 cm, 0.10 cm

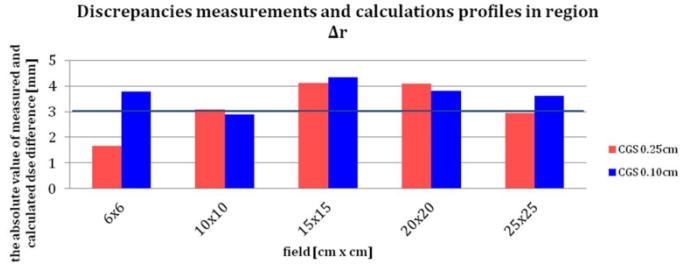

Figure 6b. Comparison of measured and calculated dose difference profiles results in terms of Δr for energy 9 MeV for SSD=110cm, for two grid sizes 0.25 cm, 0.10 cm

Figures 5a and 5b, presents the comparison of the measured (dots - measurements) and calculated profiles (solid lines - calculations) electron beams with energies in the field of 9 MeV (at a depth of 2 cm), 6-25 cm quadratic fields, SSD 110 cm, calculated using Calculation Grid Size 0.25 cm and 0.1 cm. The results obtained showed a good agreement between calculations and measurements. Minor differences were observed in the area between high doses of close to 100% and of the penumbra area. PSMP recommendations (Table 2 and Figure 1) allow the incompatibility of δ_3 = 3%, δ_4 = 4%, i ΔD = 15% and Δr = 3 mm. **Figures 6a and 6b** shows the results for the beam with an energy of 9 MeV for a number of fields for SSD = 110 cm and two calculation grids. The action levels recommended by PSMP are exceeded. Similar results were obtained for the remaining energy of the electron beams. Results for the two calculation grids do not differ significantly from each other.

According to the best knowledge of the authors of this study, so far one paper was published analyzing the accuracy of calculations of dose distributions for electron beams carried out in Eclipse Monte Carlo [15]. In this study, Xu assess the accuracy of the calculations for small fields, it is for the quadratic fields with sides not larger than 5 cm. In the majority Xu compared the results of measurements and calculations for the SSD distance = 100 cm. For this SSD distance, Xu obtained a good compatibility between the measurements and calculations. Xu also made the comparison for the SSD distance = 105 and 110 cm to a limited extent. The results are consistent with the results obtained in our study. For larger SSD and small 6 MeV and 9 MeV energy, Xu received a large discrepancy between measurements and calculations.

Summary

In most of the analyzed geometries a satisfactory agreement between calculations and measurements was achieved. But it must also be noted that in the Eclipse treatment planning system implemented, the Monte Carlo algorithm cannot cope well with the lowest 6 MeV energy, especially when the SSD is larger than 100 cm. Unsatisfactory results were obtained for small 6 MeV beams and the distance of 120 cm. In this case, calculating the number of monitor units should be carried out by an independent method. The Monte Carlo method implemented in the Eclipse treatment planning system has been approved for clinical use.

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