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Monte Carlo Simulation of Electron Beams for Radiotherapy - EGS4, MCNP4b and GEANT3 Intercomparison

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Abstract

In medical radiation physics, an increasing number of Monte Carlo codes are being used, which requires intercomparison between them to evaluated the accuracy of the simulated results against benchmark experiments. The Monte Carlo code EGS4, commonly used to simulate electron beams from medical linear accelerators, was compared with GEANT3 and MCNP4b. Intercomparison of electron energy spectra, angular and spatial distribution were carried out for the Siemens KD2 linear accelerator, at beam energies of 10 and 15 MeV for a field size of 10×10 cm^2. Indirect validation was performed against electron depth doses curves and beam profiles measured in a MP3-PTW water phantom using a Markus planar chamber. Monte Carlo isodose lines were reconstructed and compared to those from commercial treatment planning systems (TPS's) and with experimental data.

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1 Introduction

Monte Carlo (MC) simulation is regarded as a precise technique for radiotherapy and radiation dosimetry. In this field, Monte Carlo codes can be use to characterize electron or photon beams produced by clinical linear accelerators. While photon beams are used to deep-seated radiation therapy, electron beams are used for superficial pathologies due to their dose deposition characteristics.

EGS [1] is the most used MC code for electron beam simulation, and the results it provides are well established against experimental data. MCNP4b [2], due to the enhanced electron physics, is also currently used for electron beam simulation. In the present work, EGS4 has been compared with MCNP4b and GEANT3 [3]. This code, although used for hadron-therapy, has been less benchmarked for conventional radiotherapy. It was found that electron transport simulations are sensible to fine details of accelerator geometry and to different electron transport algorithms [4]. This motivates the intercomparison between different codes. For this purpose, two different intercomparison stages have been considered. First stage comprehended spatial and angular distribution simulations for electrons and contaminant photons along the accelerator head. In the second stage, indirect validation of these results have been performed against experimental central axis depth dose curves and profiles measured in water. However, the information provided by the simulation of the central depth dose curves is not sufficient to fully characterize the spatial radiation distribution produced by the beam. In clinical practice, calculation of radiation dose distributions is performed by treatment planning systems (TPS's) through the display of isodose lines, so a two dimensional method of representation was required for more accurate results. Reconstructed isodose lines from the simulation results of EGS4, MCNC4b and GEANT3 have been compared with commercially available TPS's, and experimental results.

2 Materials and Methods

A Siemens KD2 in electron mode with a square applicator of $10{\times}10$ cm^2 for 10 and 15 MeV nominal energies was simulated. Detail technical construction data was kindly provided by Siemens AG Medical Engineering. During preliminary simulations, energy tuning was performed for the incident electron beam. Identical values were then use in all MC codes and electron sources were assumed to be point-like and monoenergetic. Along the beam line, phase space distributions were obtained at pre-determined planes, stored into data *Ntuples* and intercompared using PAW software package [5]. Energy values for photons and electrons cut-offs were the same for all codes, respectively 10 and 700 keV (total energy) in the accelerator head, and 10 keV and 521 keV in the water phantom.

The experimental data, depth doses and profiles, were obtained in a MP3-PTW water phantom using a Markus planar chamber.

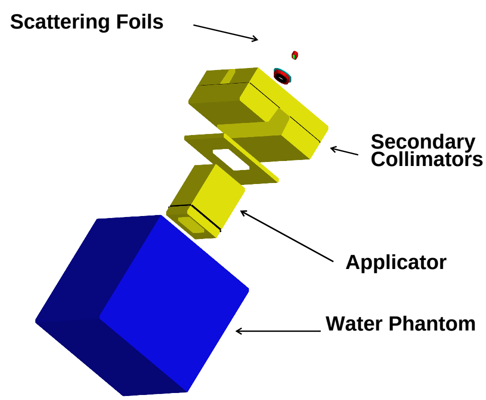


Figure 1: Siemens KD2 displayed in GEANT 3.21

2.1 GEANT3 Code

Originally designed for detector simulation in High Energy Physics, GEANT3 features cross-sections for physical processes spanning a wide energy range. In simulations, user selection of tracking parameters were used. Maximum fractional energy loss due to continuous processes in an electron step, DEEMAX, was chosen to be a material-dependent parameter. After preliminary runs DEEMAX was set to 0.3% – 0.5% (high-Z materials) and 1% (low-Z materials). Built-in variance reduction techniques, such as electron range rejection, were switched off for this set of results. By default, GEANT3 simulates hadron-photon-lepton coupled transport. In order to decrease total CPU time only relevant electromagnetic process to low energy photon-electron simulation were included: photoeletric effect, Compton scattering, pair production, positron annihilation and bremstralhung photon production. Energy loss straggling for charged particles was accounted by explicit generation of δ-rays. Below the threshold for charged secondaries particle production, continuous energy fluctuations were sampled from a restricted Landau distribution. In GEANT3 an interactive graphics interface, capable of displaying 3D geometrical setup (see figure 1) and particle transport on real-time is also available.

2.2 EGS4 User Code

The accelerator head was modeled with an EGS4 User Code, using a general purpose geometry package previously developed [6]. This User Code contains also several auxiliary subroutines used for I/O operations, histogram booking and scoring.

The PRESTA electron transport algorithm was switched off. Maximum fractional energy loss due to continuous processes, ESTEPE, was set to 0.5%

in the accelerator and 1% in the water phantom. Since EGS4 does not account for continuous energy loss straggling, lower thresholds were used for secondary particle production (AE and AP). This option is required to account for the correct energy distribution on the final electron beam. Thresholds values were set to 521 keV (total energy) for electrons (AE) and 10 keV for photons (AP). For dose calculations, in the water phantom, AE was set to 512 keV [7].

2.3 MCNP4b Code

Concerning this work the enhanced electron physics, to the level of ITS-3, is the most important aspect of the MCNP4b. It takes into account collision energy loss straggling (Landau), angular distributions with partial sub-step to boundary, forward scattering and energy indexing. The tabular region is increased in resolution and an analytic asymptotic form of treatment is used for large energy losses. Material and energy dependent cut-offs are applied to obtain the correct mean energy loss; the Gaussian width is empirically corrected following Seltzer [8]. To obtain the dose values that allowed to draw the isodose curves the water phantom was divided into small cells using the lattice capacities of MCNP. Due to the very small dimensions of the scoring cells, particularly along the beam axis, special attention has been put on the number of the electron sub-steps. For this purpose, ESTEP parameter was set at 15 and 25 for electron source energy of 10 MeV and 15 MeV, respectively.

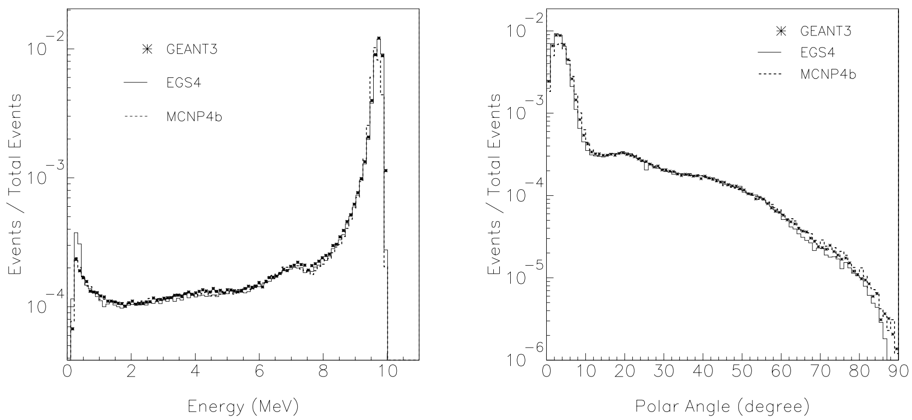
3 Results and Discussion

3.1 Accelerator simulation

Phase space distributions were obtained at the end of scattering foils, secondary collimator and electron applicator. Intercomparison has focused electron and photon energy spectra and polar angular distributions. Plots were normalized to total number of simulated events. Overall agreement is good at the different planes. Electron energy and polar angular distribution at the phantom surface are present in figure 2.

3.2 Phantom Simulation

Although the agreement between EGS4, MCNP4b and GEANT3 was achieved in a great extent along the beam line, final validation was performed in water. Central axis depth doses and profiles at several depths have been simulated and compared with experimental data. Scoring volumes were chosen with dimensions similar to the Markus planar chamber. In figure 3, 10 and 15 MeV depth dose curves are shown. Each curve was normalized at maximum dose on the central axis. Agreement in depth dose curves achieved by EGS4 and GEANT3, for the two energies, were at the 1% level. It was found that MCNP4b slightly underestimates dose deposition at larger depths, demonstrating an adjustment to experimental points identical to the one obtained by Jeraj *et al* [9]. For isodose reconstruction, dose values were scored on a 3D cross-plane grid, filled

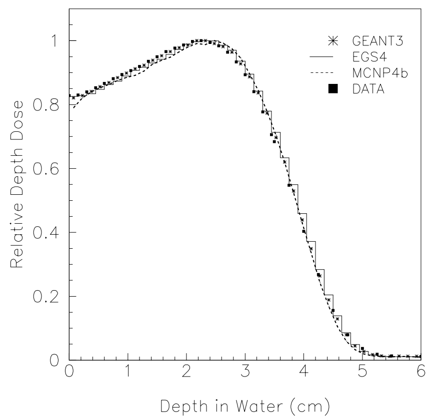


(a) (b)

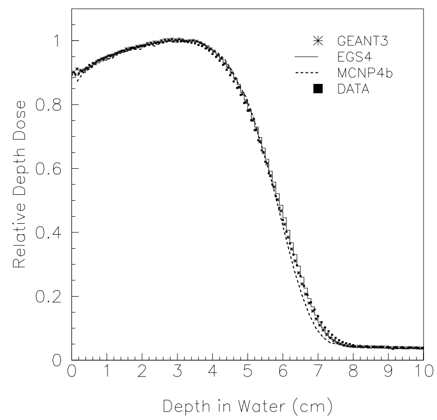
Figure 2: (**a**) Electron energy spectra and (**b**) polar angular distribution at phantom surface, for a 10×10 cm^2 square field at 10 MeV nominal energy

with voxels. Using a linear interpolation algorithm available in PAW, points with equal dose were join. The curves were normalized to 100% at depth of maximum dose on the central axis. Monte Carlo isodose lines were then compared with experimental data. From figure 4(a), EGS4 and GEANT3 were found to be in close agreement with each other and the experimental points. Disagreement for MCNP4b at the 10% isodose line is related with differences shown in the simulated central axis depth dose curve. For all MC codes lateral adjustment is less than 1 mm, denoting a good agreement with experimental beam profiles and a clearly definition of the field edges.

Data for 10 and 15 MeV isodose lines were calculated with two current commercial TPS, PLATO (version 2.2.15 from Nucletron) and TMS (version 5.0A from HELAX). These lines were then reconstructed with PAW algorithm. Isodose curves from PLATO and TMS were compared with GEANT3. The good agreement at the central axis seen in figure 4(b), indicates that electron depth dose curves are usually very well calculated by TPS's. However, a quite different behavior is demonstrated at the field edges, namely concerning one of the systems and mainly for the lower level isodose curves (below 50%). Indeed, for the PLATO system, the process of commissioning and validation includes, after the input of the basic data (depth dose curves and output factors for each field size), the adjustment of the initial angular spread parameter. This parameter has been adjusted for each energy, in order that the best fit corresponds to the higher level isodose curves - calculated isodose widths at the maximum dose depth, should coincide as much as possible with the experimental and simulated ones (arrows) downgrading the adjustment for lower isodose lines.



(a)

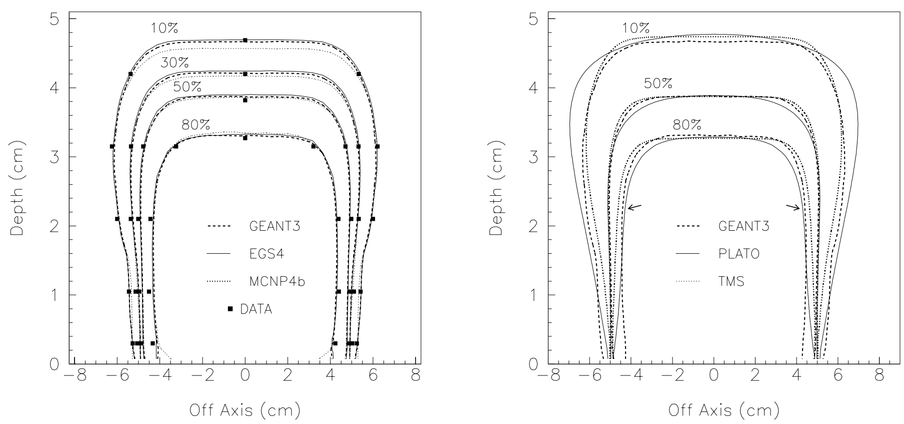


(b)

Figure 3: Comparison between experimental and simulated central axis depth doses for 10 MeV (**a**) and 15 MeV (**b**) nominal energy

4 Conclusions

From the comparison with the Monte Carlo code EGS4, it was found that GEANT3 is a reliable system with excellent capabilities for clinical electron beam simulations. Unclarified differences in depth dose curves calculated with MCNP4b affect the adjustment of lower isodose lines. However, comparisons along the accelerator head at different levels reveals a good agreement with GEANT3 and EGS4. This kind of study is very important for the therapeutic use of electron beams. Indeed, quite frequently in clinical practice, several electron fields are used together covering extended regions of the patient skin (for instance along a scar). For decision on field separation, a good dosimetric description at the beam edges and shallow depths is crucial in order to determine the homogeneous dose distribution. The isodose configuration calculated in superficial depths by treatment planning systems, would predict an erroneous overdosage for two adjacent beams at the skin level. On the other hand, both experimental and MC results show an isodose configuration at the beam edges enabling the adjacency of two fields without overdosage in depth.



(a) (b)

Figure 4: (**a**) 10 MeV Monte Carlo reconstructed isodose curves compared with experimental data. (**b**) Isodose curves from PLATO and TMS compared with GEANT3

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