



A Comparison between Electron Gamma Shower, National Research Council/Easy Particle Propagation (EGSnrc/Epp) and Monte Carlo N-Particle Transport Code (MCNP) in Simulation of the INTRABEAM® System with Spherical Applicators

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ABSTRACT

Background: Online Monte Carlo (MC) treatment planning is very crucial to increase the precision of intraoperative radiotherapy (IORT). However, the performance of MC methods depends on the geometries and energies used for the problem under study.

Objective: This study aimed to compare the performance of MC N-Particle Transport Code version 4c (MCNP4c) and Electron Gamma Shower, National Research Council/easy particle propagation (EGSnrc/Epp) MC codes using similar geometry of an INTRABEAM® system.

Material and Methods: This simulation study was done by increasing the number of particles and compared the performance of MCNP4c and EGSnrc/Epp simulations using an INTRABEAM® system with 1.5 and 5 cm diameter spherical applicators. A comparison of these two codes was done using simulation time, statistical uncertainty, and relative depth-dose values obtained after doing the simulation by each MC code.

Results: The statistical uncertainties for the MCNP4c and EGSnrc/Epp MC codes were below 2% and 0.5%, respectively. $1e9$ particles were simulated in 117.89 hours using MCNP4c but a much greater number of particles ($5e10$ particles) were simulated in a shorter time of 90.26 hours using EGSnrc/Epp MC code. No significant deviations were found in the calculated relative depth-dose values for both in the presence and absence of an air gap between MCNP4c and EGSnrc/Epp MC codes. Nevertheless, the EGSnrc/Epp MC code was found to be speedier and more efficient to achieve accurate statistical precision than MCNP4c.

Conclusion: Therefore, in all comparisons criteria used, EGSnrc/Epp MC code is much better than MCNP4c MC code for simulating an INTRABEAM® system.

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Keywords

INTRABEAM® System; Simulation; Spherical Applicators; Monte Carlo N-Particle Transport; Statistical Uncertainty; MCNP4c; EGSnrc/Epp, Radiotherapy; Monte Carlo Method; Computer Simulation

Introduction

A Monte Carlo (MC) approach was used to design the atomic weapons for the first time. Progressively, many different areas of applications, such as applications of medical physics have

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evolved [1] and there are numerical solutions to a problem based on random statistical trials [2]. The use of MC methods to study researching problems in the field of radiotherapy (RT) dosimetry has increased almost exponentially in the last decades [3, 4]. MC applications are ranged from the fundamental dosimetric quantity calculation to the RT treatment planning simulations [3]. It is also noted that, for photon and electron dose calculations in RT, MC simulation is a good benchmarking tool [1, 5, 6]. The particle transport is reliant on the energy and the materials interacting with it and is a complicated process. Thus, the accuracy of the MC codes depends on their inner accuracy in particle transport and the precision of the user utilizing the code [7]. The MC codes are inherently time-consuming methods and it is their major weakness. However, concerning the variance reduction techniques and the development of computer technology, the MC method is becoming a practical approach in dose calculations in different techniques of RT [8, 9]. Several general-purpose MC codes available for radiation transport in the matter are GEometry ANd Tracking (GEANT4), Monte Carlo N-Particle Transport Code (MCNP), Penetration and ENergy LOss of Positrons and Electrons (Penelope), and Electron Gamma Shower, National Research Council (EGSnrc). Performance comparisons of different versions of EGSnrc MC codes with different MC codes were done for RT applications. The performance of EGSnrc/BEAMnrc MC code was compared with MCNP to model Gamma Knife 4C [10] and a 6 MV medical linear accelerator (LINAC) [11]. EGSnrc of different versions such as EGSnrc/easy particle propagation (Epp) and EGSnrc/DOSXYZnrc were also compared using X-ray imaging [12]. Intraoperative radiotherapy (IORT) has been hand and eye guided without treatment planning. However, online MC treatment planning is used to increase the precision of the application and the precise documentation of the location and the depos-

ited dose in the tissue with the help of image guidance [13]. Additionally, MC methods help IORT specify its electron beam quality [14]. MCNP4c, written in a FORTRAN programming language, is a general-purpose MC code developed by Los Alamos National Laboratory that can be used for electron, photon, and coupled photon-electron transport [6]. The EGSnrc MC Simulation type Epp is written in a C++ programming language and is based on the EGSnrc C++ class library (egspp) initially developed by the Canadian National Research Council [12]. EGSnrc/Epp models the propagation of particles with kinetic energies between 1 keV and 10 GeV whereas MCNP4c models it between 1 KeV and 1000 MeV. Low energy phenomena, such as characteristic x-ray and Auger electrons, can be accurately modeled using both MCNP4c and EGSnrc/Epp [15].

After breast-conserving surgery, a low-kV energy (50 kV) INTRABEAM[®] system (Carl ZEISS Surgical GmbH, Oberkochen, Germany) using spherical applicators allows for direct local radiation dose delivery to the tumor bed and decreases exposure to the healthy tissues and adjacent organs [16]. Therefore, the main aim of this study was to compare MCNP4c and EGSnrc/Epp MC codes based on the depth dose values, simulation time, and statistical uncertainty in the simulated INTRABEAM[®] system. Additionally, this study compares MCNP4c and EGSnrc/Epp MC codes in the presence of an air gap between the surface of spherical applicators and the tumor bed. Accordingly, the gap is present because, the spherical applicators do not fit into the surgical cavity (tumor bed) due to inappropriate choice of applicators sizes.

Material and Methods

Description of the INTRABEAM[®] device

This simulation study was to compare the performance of MCNP4c and EGSnrc/Epp

MC codes using an INTRABEAM® system. In this study, a type of an IORT, INTRABEAM® system with spherical applicators was chosen for the first time to compare the performance of EGSnrc/Epp and MCNP4c MC codes implemented in particle transport. MCNP4c and EGSnrc/Epp released in 1999 and 2018 respectively were used in this study. In our previous study (Tegaw et al. 2020) [17], the INTRABEAM® device (Carl ZEISS Surgical GmbH, Oberkochen, Germany) with all the sizes of applicators were described. Additionally, the depth dose values measured by the utilization of an ionization chamber type PTW 34013 on water phantom were used to validate the Geant4 MC simulation. Similarly, those measured depth-dose values without any change were used to validate the simulations of this study, MCNP4c and EGSnrc/Epp MC Simulations. In this study, the smallest (a 1.5-cm-diameter) and the largest (a 5-cm-diameter) applicator sizes were considered.

MC simulation

MCNP4c input files are structured into three major sections: cell cards (This section divides complex geometries into several cells to make it simpler), surface cards (This section describes either geometries or cells or positions), and data cards (This section consists of materials, sources, and tallies (to monitor results)). By the use of Tutor7pp as a base, the

code was modified to allow for photoelectric interactions, atomic relaxations resulting in Auger electrons, and Compton interactions. After modifying Tutor7pp, the input syntax in this study consisted of input/output control, run control, MC transport parameters, geometry, media, source, view control, AUSGAB OBJECTS (dose scoring object definition), and track scoring object definition. For MC transport parameters, the EGSnrc/Epp defaults were used with the exceptions bound for Compton scattering, Rayleigh scattering, and electron impact ionization turned on and pair angular sampling turned off. To score the dose at different depths, dose scoring volumes of 0.0053 cm^3 equivalent to the sensitive volume of the ionization chamber type PTW 34013 utilized in our previous study [17] to measure the doses for validation of the simulation, were used. In this case, tally F6 was defined in the data card section of MCNP4c code to score the dose, however, in the application of EGSnrc/Epp, the setting of the region dose was assigned as yes and the dose scoring volume was defined in the AUSGAB OBJECTS (Dose scoring object definition) section of EGSnrc/Epp. A photon transport cut-off energy of 1 keV [18] was used for both MCNP4c and EGSnrc/Epp. In this study, Figure 1 was used to compare the MCNP4c and EGSnrc/Epp codes using their number of particle histories, simulation time, and statistical uncer-

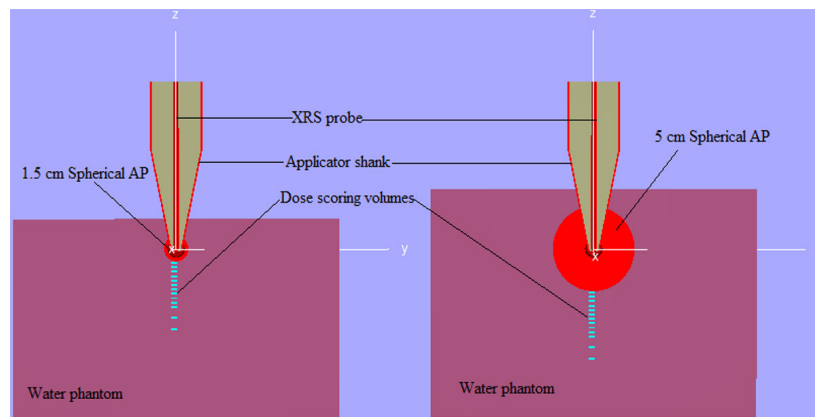


Figure 1: A model of simulation set-up similar to the measurement of depth-doses for the purpose of simulation validation. These sketches are not drawn to show the corresponding scales.

tainty. In this study, two desktop computers with Intel(R) Core™ i7-4790 CPU @ 3.60 GHz, RAM of 8 GB, and 64-bit operating system were used. For each MC code, the simulation was done by using six parallel processes. Modeling medical physics problems using MC codes are approximations of the true values and varies from one MC code to another. Thus, because of the statistical nature of MC codes, each calculated parameter always implies statistical uncertainties. Statistical uncertainties of the MC codes can be lowered using two techniques: use of an increasing number of particles histories and use of variance reduction techniques in the simulations [19, 20]. In this study, an increasing number of particles histories was applied to both MCNP4c and EGSnrc/Epp codes. Though an increasing number of particle histories is time-consuming, it can limit the statistical error and result in more statistical accuracy (below 2%). In both MCNP4c and EGSnrc/Epp codes, simulations were continued with an increasing number of primary particles until acceptable statistical uncertainties were obtained. Validation of both MCNP4c and EGSnrc/Epp codes utilizing previously measured depth-dose values [17] was done using Figure 1 set-up.

Presence of an air gap

The applicator is inserted into the surgical cavity with the tumor bed surrounding it.

Since these AP shapes are uniform spheres, they may not fit into the tissues completely (due to the non-uniformity of the tissues). This gap between the surface of the applicator and the tumor bed may also be induced due to human errors. The air gap causes dose fall-offs before delivering radiation to the tumor bed. As it can be seen in the setup shown in Figure 2, a 2 mm air gap was considered between the surface of the spherical applicators and the tumor bed to estimate the dose fall offs for the two MC codes, MCNP4c and EGSnrc/Epp.

The relative dose delivery difference due to the 2 mm air gap for both MCNP4c and EGSnrc/Epp codes was calculated using the following equation:

$$\text{Relative dose difference (\%)} = \left(\frac{D_{\text{without air gap}} - D_{\text{with air gap}}}{D_{\text{without air gap}}} \right) \times 100 \quad (1)$$

Where $D_{\text{with air gap}}$ is the dose when a 2 mm air gap is present between the surface of each applicator size and the tumor bed, while $D_{\text{without air gap}}$ is the dose when there is no air gap between the surface of each applicator size and the tumor bed.

Results

Validation of MC simulation

Validation results of the simulations are presented in Figure 3.

Table 1 presents the results of the number of

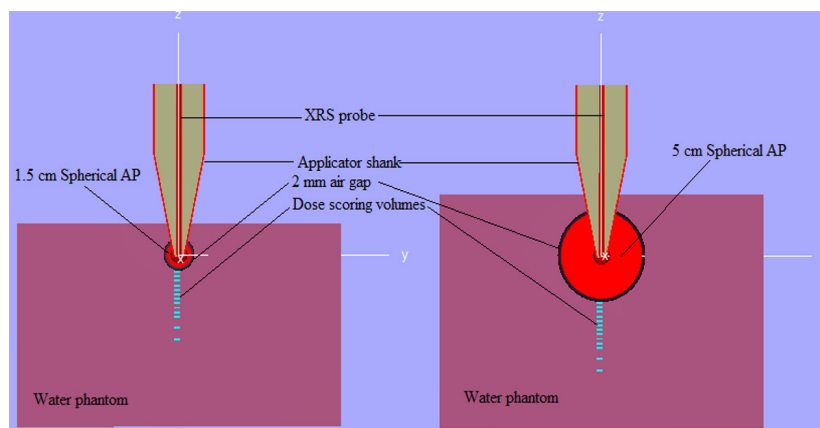


Figure 2: A model of simulation set-up in the presence of a 2 mm air gap between the spherical applicators and tumor bed. These sketches are not drawn to show the corresponding scales.

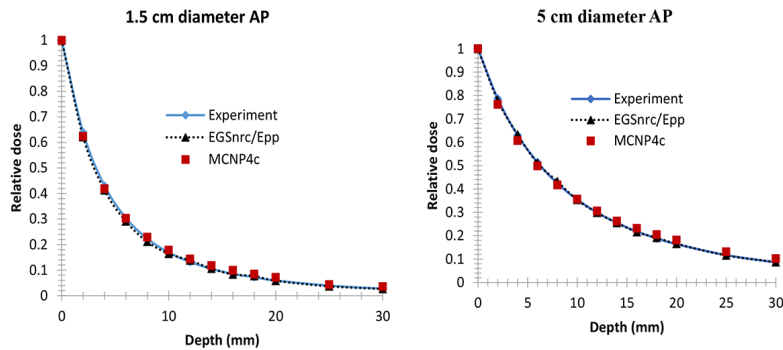


Figure 3: Monte Carlo N-Particle Transport Code version 4c (MCNP4c) and Electron Gamma Shower, National Research Council/Easy particle propagation (EGSnrc/Epp) was validated based on the measured depth-dose profile data using both 1.5- and 5-cm-diameter applicators. Depth is measured from the applicator surface (depth=0 corresponds to applicator surfaces)

Table 1: Simulation parameters of Monte Carlo N-Particle Transport Code version 4c (MCNP4c) and Electron Gamma Shower, National Research Council/Easy particle propagation (EGSnrc/Epp)

Parameter	EGSnrc/Epp	MCNP4c
Number of histories (particles)	5e10	1e9
Simulation time (hours)	90.26	117.89
Statistical uncertainty (%)	Less than 0.5	Less than 2

EGSnrc/Epp: Electron Gamma Shower, National Research Council/Easy particle propagation, MCNP4c: Monte Carlo N-Particle Transport Code version 4c

particles histories, simulation time, and statistical uncertainty for both MCNP4c and EGSnrc/Epp using the set-up presented in Figure 1.

Presence of an air gap

The results of Figure 4 were obtained from the simulation set-up shown in Figure 2 in the presence and absence of a 2 mm air gap between the surface of the 1.5- and 5-cm-diameter spherical applicators and the tumor bed for both Monte Carlo N-Particle Transport Code version 4c (MCNP4c) and Electron Gamma Shower, National Research Council/Easy particle propagation (EGSnrc/Epp) codes.

At depth 0 (applicator surface), the relative dose difference in the presence of a 2 mm air gap was calculated using equation 1. Thus, for MCNP4c, the relative dose differences were 40.8% and 21.6% for the 1.5- and 5-cm-

diameter applicators, respectively. Similarly, for EGSnrc/Epp, the relative dose differences were 40.7% and 21.4% for the 1.5- and 5-cm-diameter applicators, respectively.

Discussion

In this study, the depth-dose values that were measured using an ionization chamber type PTW 34013 on water phantom from our previous study [17] were utilized without any change to validate the simulation procedure used in the present study, by comparing the simulated profiles with the measured depth-dose profiles shown in Figure 3. Because of the low kV energy (50 kV) used in this study, the relative depth-dose values shown in Figure 3 drop rapidly for both MCNP4c and EGSnrc/Epp MC codes. The statistical uncertainties

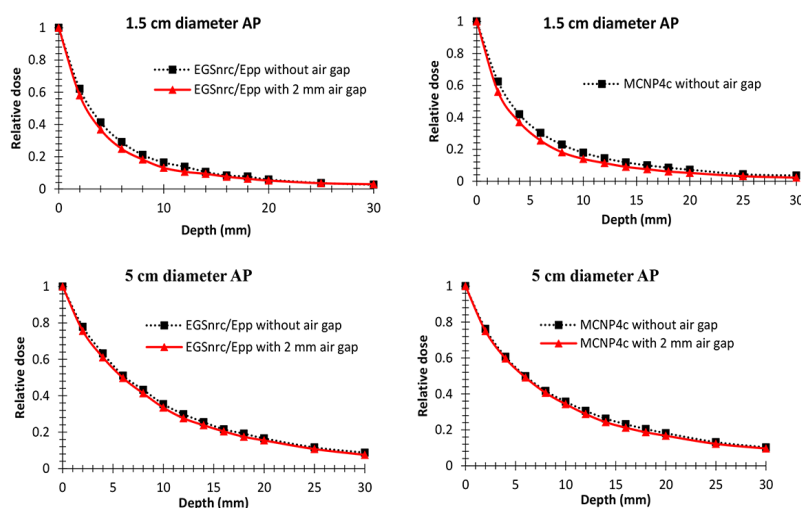


Figure 4: Depth-dose profiles without and with a 2-mm air gap, for 1.5- and 5-cm-diameter applicators for both Monte Carlo N-Particle Transport Code version 4c (MCNP4c) and Electron Gamma Shower, National Research Council/Easy particle propagation (EGSnrc/Epp) codes. Depth is measured from the applicator surface (depth = 0, corresponds to the applicator surfaces)

for MCNP4c and EGSnrc/Epp MC codes were acceptable and below 2% and 0.5%, respectively. Because of the approximation differences in MC codes and the differences in transport algorithms, EGSnrc/Epp MC codes were found to be more proficient than MCNP4c MC codes to achieve statistical precision. Table 1 also presents the number of particle histories, simulation time, and statistical uncertainties of the two codes. The simulation time in EGSnrc/Epp MC codes (553,955,240 particles/hour) was also faster than MCNP4c MC codes (8,482,484 particles/hour) to simulate particles. Yani *et al.*, have also compared EGSnrc using a phase space scoring plane with MCNPX for X-ray target in 6 MV photon beam using statistical uncertainty and simulation time. According to his study, EGSnrc MC codes were faster and more efficient than MCNPX MC codes in simulation time and statistical uncertainty [11]. In another study, EGSnrc/Epp MC codes were at least two times faster than DOSXYZnrc (slightly modified from the official version for saving phase space information of the photons leaving the geometry)

[12].

Figure 4 presents the depth-dose values of Monte Carlo N-Particle Transport Code version 4c (MCNP4c) and Electron Gamma Shower, National Research Council/Easy particle propagation (EGSnrc/Epp) codes in the presence or absence of a 2 mm air gap between the surface of applicators and the tumor bed to estimate the dose fall-offs. Practically, there will be an air gap due to the non-uniformity of the tumor bed and the uniform shape of the surface of the spherical applicators or by any other technical errors. During the INTRA-BEAM[®] irradiation of the tumor bed in the presence of a 2 mm air gap, the dose fall-offs using a 1.5-cm-diameter applicator was higher than that of a 5-cm-diameter applicator. However, the dose fall-offs using MCNP4c and EGSnrc/Epp were found to be approximately similar because these codes were validated based on the measured dose values equally.

Conclusion

We concluded that EGSnrc/Epp MC codes were more efficient in reducing statistical un-

certainties than MCNP4c MC codes for both 1.5- and 5-cm-diameter applicators in an INTRABEAM® system simulation. Additionally, EGSnrc/Epp MC codes have faster simulation time compared to MCNP4c MC codes. However, EGSnrc/Epp and MCNP4c MC codes were approximately equivalent in depth-dose profiles in the presence and absence of an air gap between the surface of applicators and the tumor bed. The dose fall-off due to an air gap between the surface of the applicators and the tumor bed using the smallest size of AP was higher than the largest size of applicator for both EGSnrc/Epp and MCNP4c MC codes. Finally, we potentially recommend that EGSnrc/Epp is much better than MCNP to be used for an online treatment planning and beam quality specification for the treatment of breast cancer patients using an INTRABEAM® system after breast-conserving surgery.

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Conflict of Interest

None

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