Original Article

The Effect of Algorithms on Dose Distribution in Inhomogeneous Phantom: Monaco Treatment Planning System versus Monte Carlo Simulation

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Abstract

Background: The aim of this study is to evaluate the dose calculation algorithms commonly used in TPS by using MC simulation in the highly different inhomogeneous region and in the small fields and to provide the following uniquely new information in the study of correction algorithm. **Materials and Methods:** We compared the dose distribution obtained by Monaco TPS for small fields. **Results:** When we examine lung medium, for four different fields, we can see that the algorithms begin to differ. In both the lung and bone environment, the percentage differences decrease as the field size increases. In areas less than or equal to 3x3 cm2, there are serious differences between the algorithms. The CC algorithm calculates a low dose value as the photon passes from the lung environment to water environment. We can also see that this algorithm measures a low dose value in voxel as the photon passes from the water medium to the bone medium. In the transition from the water environment to the bone environment or from the bone environment to the water environment, the results of the CC algorithm are not close to MC simulation. **Conclusion:** The effect of the algorithms used in TPS on dose distribution is very strong, especially in environment with high electron density variation and in applications such as Stereotactic Body Radiotherapy and Intensity Modulated Radiotherapy where small fields are used.

Keywords: Collapse cone, EGSnrc, inhomogeneous phantom, monaco treatment planning system, monte carlo simulation

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Introduction

Treatment planning systems (TPSs) constitute the most important part of the radiation oncology department.[1,2] The use of reliable TPS contributes to the accuracy of the dose given to the patient. A relative accuracy of ≤5% should be acquired through the radiation implementation process.[3] The algorithms play a crucial role for dose accuracy, especially in small fields and the presence of inhomogeneous. Various TPS comprise pencil beam (PB) algorithm and Collapse Cone (CC) algorithm. The Monaco TPS also includes Monte Carlo (MC) algorithm.

In the PB algorithm, the dose is estimated by kernel energy that defines the dose accumulation around the main photon.[4] In the environment of heterogeneous, the PB algorithm applies correction factor. However, the PB algorithm has serious lack in the presence of inhomogeneous because the one uses one-dimensional density correction. The use of 1-dimensional density correction prevents to dose accuracy within large density variations and small fields because it does not model accurately the distribution of secondary electrons.[5-7]

The CC algorithm is one of the convolution-superposition algorithms. The CC algorithm also includes contributions of primer photon contaminating photon and electron, unlike the PB algorithm. Each contribution is related to the accumulation and fluency of the scatter kernel energy. Using electron density (ρe), the kernel energies having lateral scattering are calculated. The CC algorithm can calculate the final dose containing the total energy deposited. The predicted dose using convolution-superposition algorithms is very close to

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the correct dose occurring in the medium.[8-11] The reason why the CC algorithm overestimates the dose in low-density areas (especially for small fields) is because the algorithm models electron transport in a simple way.[12-14]

The MC simulation exhibits accuracy very close to reality on scattering and dose absorption, especially at inhomogeneous medium. The MC algorithm predicts interaction possibilities for various physical processes. This algorithm uses random numbers to solve the problem. The MC algorithm accomplishes excellent dose distribution as it uses reliable distribution functions that control each interaction of photons and electrons in air and matter.[15] The MC simulation programs, such as EGSnrc, take into account photon and electron interactions starting from the collision of the electron with the target. However, the MC algorithm in Monaco TPS, which uses XVMC++ based MC algorithm, calculates photon and electron interactions only in the medium.

The maximum lateral spacing of the secondary electrons is smaller than the field size when the small field size is used. This constitutes a less in the charged particle equilibrium. In addition, in small field-size applications, in the measuring zones, the target is partially obstructed by the collimator part. This problem causes a sharp reduction in output and overlapping the penumbra of the two opposing jaws.[16-18] In the low-density inhomogeneous environment, the range that the electron can reach increases and the charged particle balance decreases.[4,16-18] The effect of electron transport increases when the ρ_e of the medium decreases, especially for small field sizes. For this reason, It would be useful to examine the effect of ρ_e on dose calculation algorithms.

The importance of the algorithms used in TPS becomes more pronounced when radiotherapy planning is implemented in very different density environments with small radiation fields.[19,20] Because of this importance, the aim of this study is to evaluate the dose calculation algorithms commonly used in TPS by using MC simulation in the highly different inhomogeneous regions and in the small fields and to provide the following uniquely new information in the study of the correction algorithm. Studies involving algorithm comparisons in a nonhomogeneous environment are limited, especially about Monaco TPS. This reason prompted us to carry out the present work. PB algorithm was not included in this study, as there were enough studies on PB algorithm in the literature.

Materials and Methods

Monte carlo simulation

BEAMnrc and DOSXYZnrc, based on the EGSnrc MC method which is under license to the National Research Council of Canada, were utilized to model linac head and measure, respectively.[21,22] First, linac head geometry was simulated using BEAMnrc. Second, doses formed on the phantom were measured in DOSXYZnrc.[23] In this study, Siemens Artiste Linac with 6 MV photon beam and 160 multi-leaf collimator (MLC) with 2 cm × 2 cm, 3 cm × 3 cm, 4 cm × 4 cm, 5 cm × 5 cm, and 10 cm × 10 cm field sizes were simulated using the MC method. The linac head components comprises the exit window, target, primary collimator, flattening filter, monitor chamber, Y jaws and X MLC. PEGS4 (EGSnrc preprocessor) cross-section data for specific materials in the accelerator were obtained from 700icru.pegs4 data file. Physical density values such as mass density, atomic number, and ρ_e for all the different materials used in the accelerator, and cross-section data for particles are available in the PEGS4 file.[22,24-26]

In BEAMnrc, the number of histories of MC calculation was 6×10^8 particles. In all simulations, the electron cut-off energy (ECUT) and the photon cut-off energy (PCUT) were defined 0.7 MeV and 0.01 MeV, respectively. For photon beam simulation, ISOURC 19 (Elliptical Beam with Gaussian Distribution in X and Y) was used. The monoenergetic beam value was 6.3 MeV and the full width of half-maximum value was 0.3 cm. These values were used by making use of previous publications.[24] Directional bremsstrahlung splitting was used as the variance reduction parameters.

The output of the simulation is a file called phase space file that has all the information of the particles leaving the linac head. The phase space file is utilized to acquire dose distribution in DOSXYZnrc.[22] The file, which was used in DOSXYZnrc, is at 100 cm distance from the target. The voxel size is 0.2 cm × 0.2 cm × 0.2 cm in DOSXYZnrc for phantom. 6×10^8 histories were run in the simulation. Statistical uncertainty of <0.4% was achieved. The Percent Depth Dose (PDD) curves were computed along the central axis and all PDD curves were normalized to the maximum dose. The PDD result obtained from DOSXYZnrc were compared with algorithms data.

Inhomogeneous phantom

The inhomogeneous phantom sizes are 10 cm × 10 cm × 10 cm. The phantom comprises water materials (ρ_e = 1 g/cm^3) from depths of 0 cm–2 cm, lung materials (ρ_e = 0.3 g/cm^3) from depths of 2 cm–4 cm, water materials (ρ_e = 1 g/cm^3) from depths of 4 cm–6 cm, bone materials (ρ_e = 1.85 g/cm^3) from depths of 6 cm–8 cm and water materials (ρ_e = 1 g/cm^3) from depths of 8 cm to 10 cm. Figure 1 represents inhomogeneous phantom. This inhomogeneous phantom was generated on two different platforms, i.e. Monaco TPS (v. 5.10.04) and DOSXYZnrc. It was important to ensure the same ρ_e values on TPS and DOSXYZnrc. The PDD was calculated along the phantom centerline.

Dose calculate in DOSXYZnrc and monaco treatment planning system

In DOSXYZnrc, the voxel size is 0.2 cm × 0.2 cm × 0.2 cm. The inhomogeneous virtual phantom was identified by three different materials on inputs. The density of voxels for water, lung and bone were created as 1 g/cm^3, 0.3 g/cm^3, and 1.85 g/cm^3, respectively. For 2 cm × 2 cm, 3 cm × 3 cm, 4 cm × 4 cm, and 5 cm × 5 cm field sizes, the four different phase-space files were used in DOZSYZnrc. 6×10^8 histories were run for each calculation. ECUT and PCUT parameters

are set to 0.7 MeV–0.01 MeV, respectively. Absorbed dose as PDD was calculated using voxel of 0.2 cm^3.

The Monaco TPS allows you to use PB, CC, and MC algorithms. The CC and MC algorithms were used to achieve relative absorbed dose curves in a virtual inhomogeneous phantom with 10 cm × 10 cm × 10 cm. The five different contours with 2 cm thickness starting from the surface were drawn in Monaco TPS. The ρ_e for these contours were assigned as 1 g/cm^3, 0.3 g/cm^3, 1 g/cm^3, 1.85 g/cm^3, and 1 g/cm^3, respectively. The PDDs were obtained using CC and MC algorithms at 2 cm × 2 cm, 3 cm × 3 cm, 4 cm × 4 cm, and 5 cm × 5 cm field sizes.

Measurement data for validation

The measurement data of PDD and lateral dose profile were achieved in water by a farmer ion chamber (PTW, Freiburg Germany) at 10 cm × 10 cm. The lateral dose profile was taken at the depth of the maximum dose (d_{max}). These measurement data were used to ensure validation of MC simulation.

Results

Validation of monte carlo simulation

For validation, the measurement data obtaining by ion chamber for 6 MV photon was compared with experimental data calculating by DOSXYZnrc in a homogeneous environment and are presented in Figures 2 and 3. It seems that the comparison demonstrated good conformity between measurement data and MC simulation. For PDD, $TPR_{20}/_{10}$ and d_{max} were examined for conformity. $TPR_{20}/_{10}$ was obtained from the formula.[15,27]

$$TPR_{20,10} = 1.2661\frac{D20}{D10} - 0.0595, (1)$$

where D_{20} is the dose at a depth of 20 cm and D_{10} is the dose at a depth of 10 cm.[15,27]

The $TPR_{20}/_{10}$ values obtained from D_{20}/D_{10} values (D_{20} = dose at a depth of 20 cm, D_{10} = the dose at a depth of 10 cm) were 0.6683 for measurement and 0.6681 for MC simulation. The quality index ($TPR_{20}/_{10}$) was found compatible. In addition, when the lateral dose profiles were compared using gamma index, we observed appropriate similarity under the gamma parameters of 1 mm for the position and 1% for the calculated dose. These results proved that the MC simulation was accurately modeled, especially the target and flattening filter, which have a major influence on PDD and lateral dose profile.

Dose distribution in the inhomogeneous phantom

Figure 4 demonstrates PDD curves for the inhomogeneous phantom with water, lung, and bone materials calculated by MC simulation in comparison with TPS algorithms. It is easily understood that the algorithms behave differently in different parts of the phantom. In addition, the dose distribution varies according to field size in the inhomogeneous environment. All algorithms were found to be compatible with MC simulation from surface to 2 cm depth. When we examine the environment between 2 cm and 4 cm, which is lung medium, for four different fields, we can see that the algorithms begin to differ. In both the lung and bone environment, the percentage differences decrease as the field size increases. In areas ≤3 cm × 3 cm, there are serious differences between the algorithms. In fields

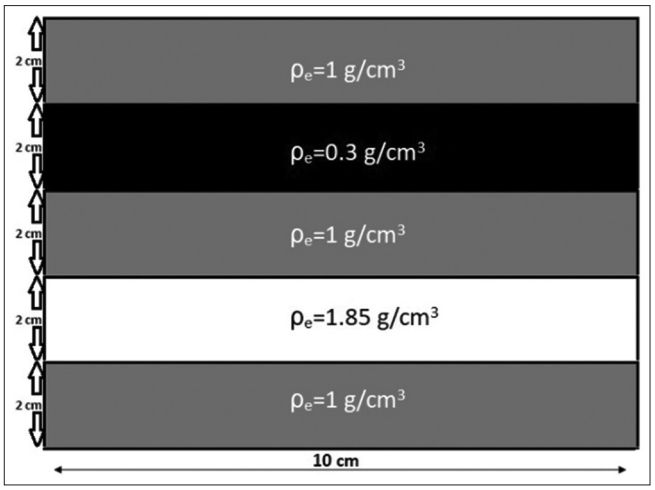

Figure 1: Inhomogeneous phantom structure

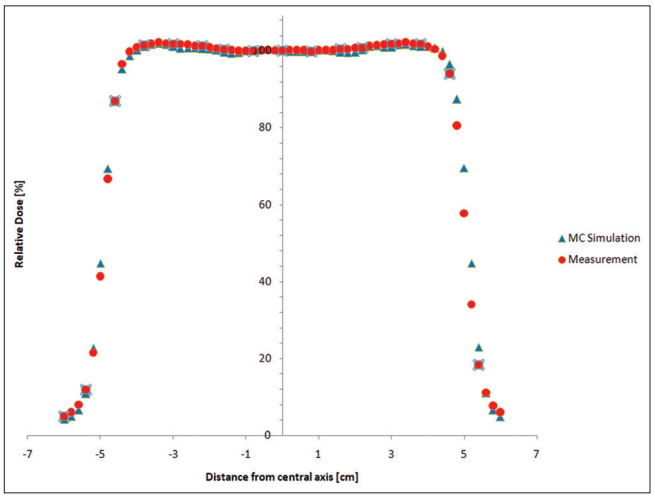

Figure 2: Comparison of lateral dose profiles obtained from Monte Carlo simulation and water phantom for verification

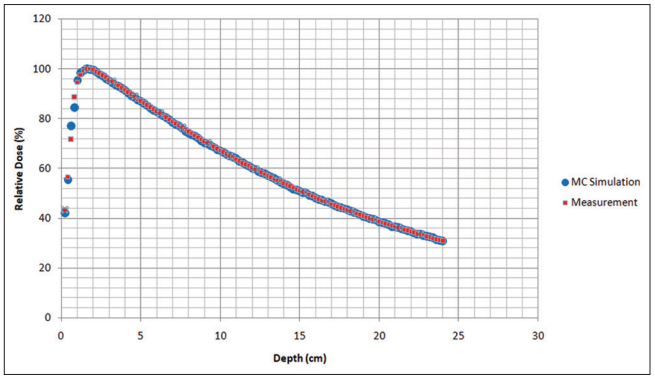

Figure 3: Comparison of percent depth doses obtained from Monte Carlo simulation and water phantom for verification

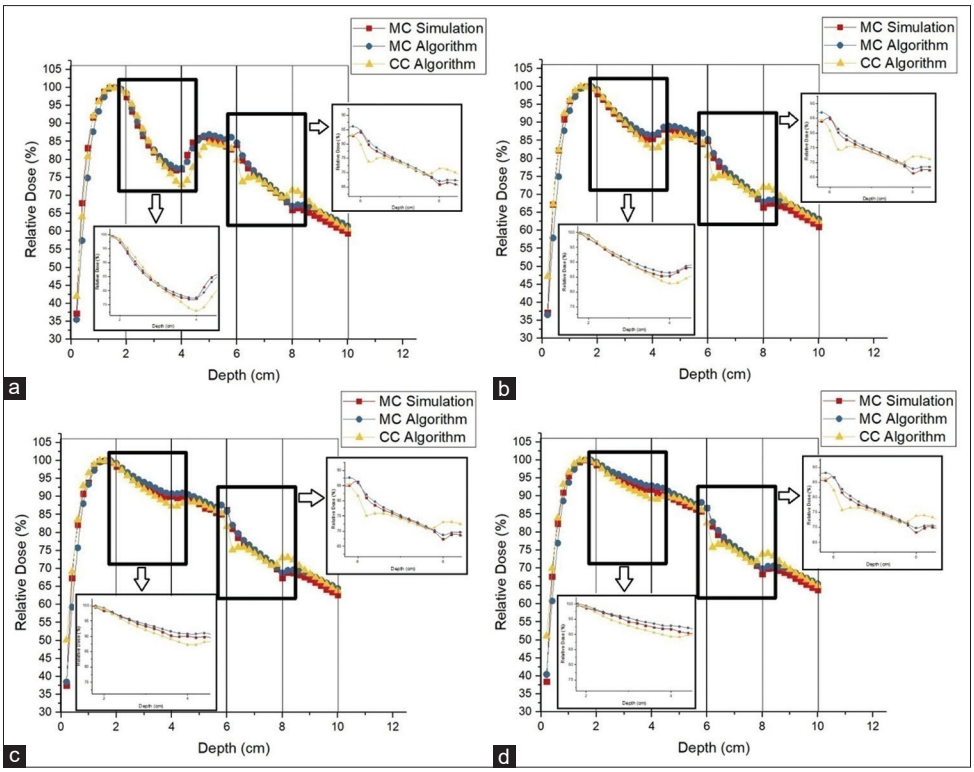

Figure 4: Percent depth dose curves for the inhomogeneous phantom. (a) 2 cm × 2 cm, (b) 3 cm × 3 cm, (c) 4 cm × 4 cm, (d) 5 cm × 5 cm

where electronic equilibrium is insured, the reduction in the cross-section of interaction is greater than the transfer rate in the lung medium. This clarifies the overdose prediction by algorithms that do not model the reduction of the interaction coefficient and take into account the higher conduction of radiation in low-density medium.[11] In small fields, the main reason for nonoverlapping dose curves compared with MC simulation is that the loss of lateral electronic equilibrium is not taken into account by the algorithms. This impression is further apparent in low-density materials such as the lung, due to Compton electrons procreating a characteristic reduction in the PDD.[11]

Discussion

When we look at the results of the CC algorithm in an inhomogeneous environment, we see that the PDD curves give a similar result to MC simulation. However, we can see from Figure 4 that the CC algorithm calculates a low dose value as the photon passes from the lung environment to the water environment. We can also see that this algorithm measures a low dose value in voxel as the photon passes from the water medium to the bone medium. As expected, the CC algorithm overestimated the dose in the entry areas of the lung environment. The excess in the dose was calculated as 2.1% at 2.2 cm depth and 2.74% at 2.4 cm depth. For bone environment, the dose values calculated by the CC algorithm are in agreement with the values given by the MC simulation. However, in the transition from the water environment to the bone environment or from the bone environment to the water environment, the results of the CC algorithm are not close to MC simulation. We observe a low dose as the photon passes from water environment to the bone environment and a high dose when passing from the bone environment to water environment. When the percentage differences are considered, the max percentage differences for lung and bone environment are 5.7% (at 4 cm deep for 2 cm × 2 cm) and 8.3% (at 8 cm deep for 2 cm × 2 cm), respectively. Aarup *et al*. reported that the percentage difference for the CC algorithm was 8% compared with MC simulation.[28] In addition, the results obtained are consistent with those reported by the authors.[10,12,29-31]

When we analyzed the experimental results obtained from MC simulation with the results obtained from the MC algorithm in Monaco TPS, we acquired near-perfect results both in lung and bone environment, even in the transitions between densities. MC simulation predicts photon and electron interactions using the MC algorithm from the time the electron hits the target. The MC algorithm in Monaco TPS uses the MC method after the radiation affects the environment. This contributes to a faster dose calculation of the MC algorithm in TPS than MC simulation. Nevertheless, the data obtained from the TPS were in perfect agreement with the MC simulation. For the MC algorithm in Monaco TPS, the max percentage differences for both lung and bone environment were 1.56% (at 3.8 cm deep for 3 cm × 3 cm) and 1.64% (at 8 cm deep for 2 cm × 2 cm), respectively.

Studies comparing the MC algorithm in Monaco TPS and MC simulation have not been found in the literature. Therefore, the results obtained are of great importance.

Conclusion

The fact that the dose distribution values achieved in TPS are similar to the actual dose distribution values is of great importance for the correct implementation of radiotherapy. The effect of the algorithms used in TPS on dose distribution is very strong, especially in environment with high ρ_e variation and in applications such as stereotactic body radiotherapy and intensity-modulated radiotherapy where small fields are used. The algorithm accuracy in TPS should not be neglected, especially for complex treatments.

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Conflicts of interest

There are no conflicts of interest.

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