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Establishment of a calibration curve for an isocentric cobalt unit using Monte Carlo simulation

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Abstract Measurement of dose distribution in patients during radiotherapy is impossible. The Monte Carlo simulation is an alternative method for dose calculations. In routine radiotherapy, the source-to-surface distance (SSD) method is not practical for an isocentric unit because it requires numerous values of tissue–air ratios and inverse square law. Therefore, this method is time consuming. In this paper, the curves of relative depth doses were obtained for three different SSDs using the MCNP4C Monte Carlo simulation and approximated with a single curve called calibration curve. This curve was compared to the curve obtained by published data, differing in approximately 5% in the worst case. It was also observed that the obtained results were more accurate for distances between −5 and 10 cm from source-to-axis distance.

Keywords Radiotherapy · Source-to-surface distance (SSD) · Source-to-axis distance (SAD) · Calibration curve · Isocentric unit · Depth dose

1 Introduction

Radiotherapy is a cancer treatment with the main goal of producing a high dose of radiation to the tumor and a dose as low as possible to skin and surrounding healthy organs [1]. Dosimetry is highly important in radiation treatment planning because a successful treatment requires an accurate dose to be delivered to the target volume [2].

^{60}Co beam is a widespread radiotherapy source because of its proper energy, relatively long half-life, and high specific activity. ^{60}Co units are still available because of their reliability compared to modern linear accelerators (LINACs). ^{60}Co decays to ^{60}Ni by the emission of a beta particle. The activated nickel nucleus emits two gamma photons with energies of 1.17 and 1.33 MeV [3–5].

Dose calculation is practically impossible during radiotherapy. Therefore, two methods are used: experiment using a phantom and simulation with MNCP code [6, 7]. Several functions are used to relate the absorbed doses to tissue and air. Percent depth dose (PDD) and tissue–air ratio (TAR) are the main functions used for dosimetry.

Treatment techniques and calibration practices are varied in radiotherapy. There are two techniques for treating patients: SSD technique and SAD or isocentric technique. For dosimetric calculations, SSD and SAD techniques rely on PDD distributions and TARs, respectively.

^{60}Co units have isocentric mounts. In isocentric machines, the tumor is positioned on the isocenter. Therefore, the SSD and field size at the surface are varied during therapy [7].

Several authors have studied on dose measurement and calculation for ^{60}Co beams [8–12]. In previous studies, ^{60}Co therapy units were simulated using EGS and MCNP codes and the PDD distributions were calculated in a water phantom. A good agreement between the results and measurements was achieved [13–16]. The PDD distributions in water phantom were evaluated and the obtained results were compared with experiment, showing a good agreement [2]. In 2011, a ^{60}Co radiotherapy unit was simulated using GEANT4 for different beam sizes and a

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good agreement between the obtained results and the published data was observed [17, 18]. In 2013, dosimetric consistency of a ^{60}Co teletherapy unit was investigated for 10 years by the SSD and SAD techniques [3].

In routine radiotherapy, it is not practical to use direct method with PDDs for an isocentric unit because it is time consuming and numerous dosimetric tables are required. Another approach is to calculate the dose for each point using two TARs and the value of inverse square law and divide the results by the reference dose to obtain relative depth dose. As an alternative, the curves can be obtained for different SSDs and approximated with a single curve, called a calibration curve, which might be used for further dose calculations [7].

In this paper, curves of relative depth doses were obtained for three different SSDs using the MCNP4C Monte Carlo simulation, and a calibration curve was obtained for the first time. The values of this curve were compared to published data. Although Monte Carlo simulations and measurements were done for a ^{60}Co source, the isocentric technique and the approach have not been simulated using MCNP4C previously. The advantages of this study are simplicity, capability to use for complex geometries, and quick response.

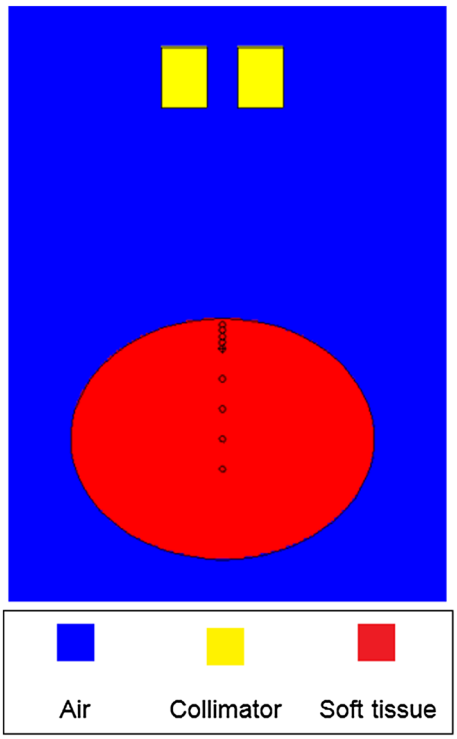

Fig. 1 (Color online) Sketch of simulated geometry: soft tissue phantom, collimator, and spherical cells as tally regions

2 Method

An ellipsoid phantom with radii of 25, 25, and 20 cm was modeled as a soft tissue using MCNP4C, as shown in Fig. 1. An isotropic point source of ^{60}Co beam was simulated simultaneously with two different gamma energies (1.17 and 1.33 MeV) and equal possibilities using SI (Source Information) and SP (Source Probabilities) cards. The source was positioned in an infinite air sphere. The photon weight factor was 1 in all cells and zero outside the sphere. The photon transport was considered (mode *p*) in simulation. Three different SSDs were considered in simulation: 75, 70, and 65 cm. The field size of 10 × 10 cm^2 at SAD of 80 cm (isocenter of machine) was defined using a collimator made of lead cuboid with an outer/inner side of 20 cm/5 cm. The values of dose were calculated in spherical cells with a radius of 0.5 cm. The deposited energy was determined by tally F6. The number of histories was 10^7. The cutoff energy for photon mode was set at 0.1 MeV.

Ten statistical tests were performed by the MCNP to assure the reliability of results. These tests are: (1) The mean must exhibit only random fluctuations as N increases, (2) relative error (R) must be less than 0.1, (3) R must monotonically decrease with N, (4) R must decrease as $1/\sqrt{N}$, (5) the magnitude of the variance of the variance (VOV) must be less than 0.1, (6) VOV must monotonically decrease, (7) VOV must decrease as $1/N$, (8) figure of merit (FOM) must remain statistically constant, (9) FOM must exhibit no monotonic up or down trends, and (10) the slope determined from the 201 largest scoring events must be greater than 3 [19].

3 Results and discussion

The aim of this study was to obtain curves of depth dose for different SSDs and derive a calibration curve, which can be used in isocentric technique. This was accomplished by using the MCNP4C simulation code. The problem was properly simulated because the tally passed all 10 statistical tests. The R and VOV were monotonically decreasing, the FOM was relatively constant, and the slope had a perfect value of 10. As a result, the R calculated by MCNP code, was always less than 1%.

Relative depth dose is the ratio of dose at a point on the central axis to the isocenter dose. For each SSD, the tally was calculated at distances −15 to 20 cm from SAD. Different curves of relative depth dose were obtained for different SSDs using MCNP4C, as shown in Fig. 2. The dose buildup region observed for each curve is defined as

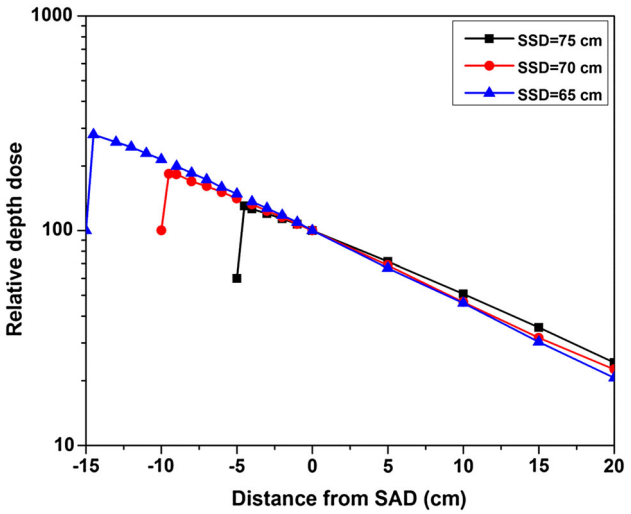

Fig. 2 (Color online) Curves of relative depth dose for three different SSDs. The errors are lower than 1% and therefore not visible

the region between the surface and depth of maximum dose. This happened because energetic secondary charged particles that are initially released in the patient by photon interactions have such a relatively long range where they can deposit their kinetic energy. Therefore, the relative depth dose curve increases for the first few mm, reaches a maximum at 0.5 cm, and decreases with increasing depth. Nominal value for depth of maximum dose is 0.5 cm for ^{60}Co, and this proved that the simulation was properly undertaken. The outlier of curves is accordingly related to the build up region [1, 7]. This behavior was also seen in the simulated curves.

The curves were approximated with a single curve, as illustrated in Fig. 3. In this approach, the outliers were not considered, as has been done in Ref. [7]. Otherwise, the accuracy would be lost. The function used to fit the data, parameters, their errors, and R^2 are shown in this figure. It is not scientific motivation to use the obtained function exactly because some approximations were taken into account. The parameters of the function depend on the geometry of the problem and composition of the materials used in simulation.

In Fig. 4, the fitted curve was compared to the curve obtained by published data [7], differing in approximately 5% in the worst case. The differences are due to geometry and composition of the materials. The accuracy of dose calculations is highly important in radiation therapy and overall a dose error less than 5% should be delivered to patients [20]. Since the difference in accuracy was obtained less than 5% in this study, the approach can be simulated by MNCP4C.

From Fig. 4, the obtained results were more accurate for distances between −5 and 10 cm from SAD and within 5% of the published curve. Moreover, the dose was always overestimated for points nearer to the surface than the reference point and slightly underestimated for points below it. This behavior was also obvious in Ref. [7]. This study can be extended for more than three SSDs to cover more depths in phantom. The precision can be increased by using smaller steps of SSD.

Run time is the limitation of MCNP to calculate routine dose. In this study, required time for achieving statistically acceptable results ranged between 6 and 12 min. The required time for direct method and hand calculation depends on the calculating process. For example, the simulation can be faster by a factor of 4, approximately. If a high degree of accuracy is needed, more run time is required. In these circumstances, some techniques such as variance reduction methods are useful.

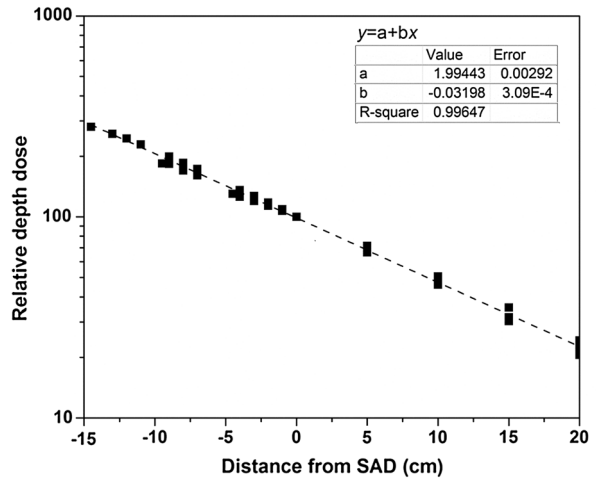

Fig. 3 Fitting of the curves obtained by MCNP4C. The errors are lower than 1% and therefore not visible

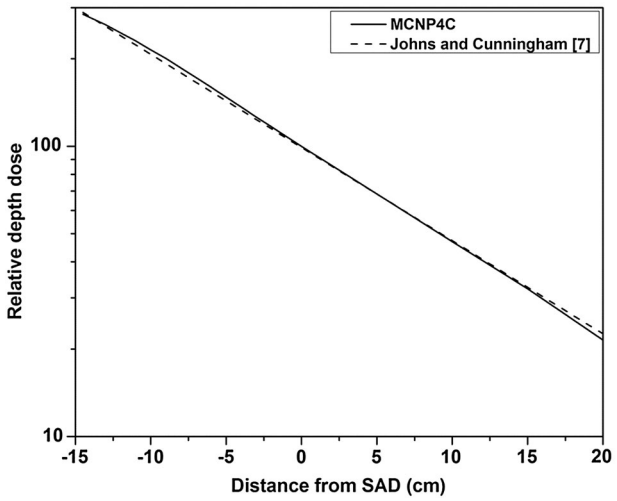

Fig. 4 Comparison of the calibration curve with the curve obtained by published data

4 Conclusion

All of the obtained results showed that the MCNP4C was successful in the calculation of the depth dose values. It is an alternative method when dose calculations are time consuming. The results serve as a starting point for better understanding the discrepancies between depth dose values of the published data and MCNP simulation. It is suggested that a similar procedure for a phantom including inhomogeneity should be repeated and the obtained results should be supported by experimental data for a satisfactory conclusion.

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