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Validation of the 6 MV TrueBeam linear accelerator model for out-of-field radiation dose calculation using PHITS Monte Carlo code

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ABSTRACT

Background: Radiotherapy treatment planning usually concerns in-field radiation dose to produce a high therapeutic ratio with high dose to the target and minimum normal tissue complication. However, out-of-field radiation dose should also be considered because it causes additional radiation exposure to the patient, resulting in an increased risk for developing secondary cancer in the patient and health consequences in the fetus if the patient is pregnant. Monte Carlo simulation is useful for estimating out-of-field dose. The American Association of Physicists in Medicine Task Group 158 (AAPM TG 158) recommends that Monte Carlo simulation for calculation of out-of-field radiation dose should be validated in terms of percentage depth dose, lateral beam profile, dose near the phantom surface and peripheral dose.

Objectives: To validate the 6 MV TrueBeam linear accelerator model developed using Particle and Heavy Ion Transport code System (PHITS) Monte Carlo code for out-of-field dose calculation for the field sizes of 10x10, 10x20 and 40x40 cm^2.

Materials and methods: The Monte Carlo simulation was validated against experimental data at the same conditions. Percentage depth dose, lateral beam profile and dose near the phantom surface were measured at 10x10, 10x20, and 40x40 cm^2 field sizes, while peripheral doses were measured using 10x10 cm^2 field size at 0, 5, 10 and 15 cm distances from the field edge and at 5 and 10 cm depths in a water phantom. The 6 MV radiation fields were delivered using Varian TrueBeam linear accelerator. For the Monte Carlo simulation, phase space data above the jaws were provided by the vendor. PHITS code version 3.20 was used for modeling the treatment head downstream of the phase space surface and the measurement set-up. The gamma evaluation method was used to compare between the calculation and the measurement.

Results: The experimental data and the Monte Carlo simulation were in good agreement. The gamma passing rates with 3%/3mm criteria were 100% for percentage depth dose, 95% for lateral beam profile, 50% for dose near the phantom surface and 81% for peripheral dose.

Conclusion: The 6 MV TrueBeam linear accelerator model developed using PHITS Monte Carlo code was validated according to the AAPM TG 158's recommendation. The simulation results showed good agreement with the experimental data. Therefore, this Monte Carlo model can be used for out-of-field dose calculation.

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Introduction

Radiotherapy treatment planning systems focus on in-field radiation dose for determination of treatment plans. The aim is to have a high therapeutic ratio with high dose to the target and minimum dose to healthy tissues to minimize any normal tissue complications. However, out-of-field radiation dose should also be considered because it may cause unwanted radiation exposure to the patient, increasing risk for developing secondary cancer and health consequences in the fetus of a pregnant patient. Therefore, accurate determination of out-of-field dose is important for assessment of secondary cancer risks as well as fetal dose and its consequences.[1-3]

Out-of-field dose in radiotherapy using linear accelerators arises from head leakage, collimator scatter and patient scatter. Out-of-field dose was found to be dependent on the distance from the central axis and the field size, but nearly independent on the depth. Similarly, dose near the surface of the patient is dependent on the field size and also on the photon energy.[4] The contributions from patient scatter and collimator scatter give rise to the dependence of out-of-filed dose on the field size and the distance near the field edge, while head leakage affects out-of-field dose at distances far away from the field edge.[5-10]

Out-of-field dose cannot be estimated using treatment planning systems. A comparison of measured doses with those calculated by a treatment planning system showed that the difference of dose could exceed 30% even at 3 cm distance from the field edge and the discrepancy increases with increased distance from the field edge.[4]

Measurement of out-of-field dose is subject to large errors if the detector was calibrated for in-field measurement because of different energy spectra between in-field and out-of-field radiations. The average energy of scattered photons contributed to out-of-field dose was found to be lower than in-field photon energy, being 0.2 and 1.5 MeV for a 6 MV photon beam, respectively.[4] The difference in energy spectra will cause different detector responses.[4] To overcome the limitation in the measurement, Monte Carlo simulation is another method of choice for out-of-field dose determination.[4]

Monte Carlo simulations have been used for determination of out-of-field dose for various treatment techniques and linear accelerator models.[4, 11] Testing accuracy of radiation dose calculated by a Monte Carlo simulation should be done by comparing experimental data obtained from reliable measurements with simulated results from the Monte Carlo simulation. For in-field dose calculations, calculated percentage depth dose (beyond the depth of the maximum dose, D_{max}) and lateral beam profile should be validated against their corresponding measurements. In addition, for out-of-field dose calculations, the American Association of Physicists in Medicine Task Group 158 (AAPM TG 158) recommends that Monte Carlo Simulation should also be validated in terms of dose near the phantom surface and peripheral dose. Dose near the phantom surface (in the build-up region) corresponds to dose at depths shallower than the depth of the maximum dose (D_{max}), taking into account electron dose near the surface that might affect the accuracy of out-of-field dose calculation. Peripheral dose is dose outside the field edge, directly representing out-of-field radiation dose.

In this work, the 6 MV TrueBeam linear accelerator (Varian Medical System. Inc., Palo Alto, CA, USA) was modeled using the Particle and Heavy Ion Transport code System (PHITS) Monte Carlo code for the purpose of out-of-field dose calculation to be used in the evaluation of fetal dose during breast cancer radiotherapy. The field sizes of interest included 10x10, 10x20 and 40x40 cm^2. Percentage depth dose, lateral beam profile, dose near the phantom surface and peripheral dose calculated by the Monte Carlo simulation were validated against the measurements at the same conditions.

Materials and methods

Measurement set-up

Percentage depth dose, lateral beam profile and peripheral dose were measured in Wellhofer Scanditronix Blue water phantom (IBA Dosimetry, Schwarzenbruck, Germany). Dose near the phantom surface was measured in WP1D water phantom (IBA Dosimetry, Schwarzenbruck, Germany) with 100 MU. Irradiation of 6 MV X-rays was achieved using Varian TrueBeam linear accelerator at 100 cm source-surface distance (SSD) and dose rate of 400 MU/min. The measured data were analyzed with Omni-pro program (IBA Dosimetry, Schwarzenbruck, Germany) and presented in term of dose relative to D_{max} for percentage depth dose (PDD) and dose near the phantom surface (DNS) as shown in equation 1, as well as dose relative to the central axis dose for lateral beam profile (LP) and peripheral dose (PD) as shown in equation 2.

$$\text{PDD and DNS} = D(z)/D_{max} \times 100 \quad (1)$$

$$\text{LP and PD} = D(r)/D(0) \times 100 \quad (2)$$

where D is dose at a specified depth z or lateral distance r (in-plane or cross-plane), D_{max} is the maximum dose of the depth dose curve and D(0) is dose at the central axis.

CC13 ionization chamber (IBA dosimetry, Schwarzenbruck, Germany) was used for measuring percentage depth dose, lateral beam profile and peripheral dose. However, for the measurement of dose near the phantom surface, which needed a higher spatial resolution, PP05 parallel plate ionization chamber (IBA dosimetry, Schwarzenbruck, Germany) was used instead. CC13 has the active volume of 0.13 cm^3 with the inner diameter of the outer electrode of 6.0 mm, while PP05 has the active volume of 0.05 cm^3 and the small collecting volume of 0.6 mm plate spacing. Therefore, PP05 offers a higher spatial resolution of dose measurement and is a more suitable detector than CC13 for dose determination in the region with high dose gradient such as that near the phantom surface.

Most of the measurements were done for the field sizes of 10x10, 10x20 and 40x40 cm^2, except for the measurement of the peripheral dose that was done only for 10x10 cm^2 field size. Percentage depth dose was measured in 1 mm step from 0.09 to 27.49 cm depth. Dose near the phantom surface was measured also in 1 mm step from 0.00 to 19.50 cm depth. The measurement of lateral beam profile was done at 5 and 10 cm depths with a step of 1 mm. Peripheral dose was measured at the distances of 0, 5, 10, 15 cm from the field edge (10x10 cm^2 field size), corresponding to ±5, ±10, ±15, and ±20 cm distances from the central axis, respectively.

Monte Carlo simulation

Monte Carlo simulation required the information of the treatment head in terms of dimension, elemental composition and density. To model the treatment head, TrueBeam Monte Carlo Data Package was used.[12] This data package provides phase space files of photons and electrons just above the movable upper jaws at the distance of 73.3 cm from the isocenter with 100 cm SSD as well as the detailed information (dimension, material type and material density) of the treatment head components downstream of the phase space surface. Twenty-five phase space files were converted with PSFC4PHITS to dump files readable by PHITS[13], corresponding to the number of converted particles of about $1.2×10^9$. The lower part of the treatment head was simulated in detail, consisting of X and Y Jaws with the characteristics as described in the TrueBeam Monte Carlo Data Package and shown in Figure 1.

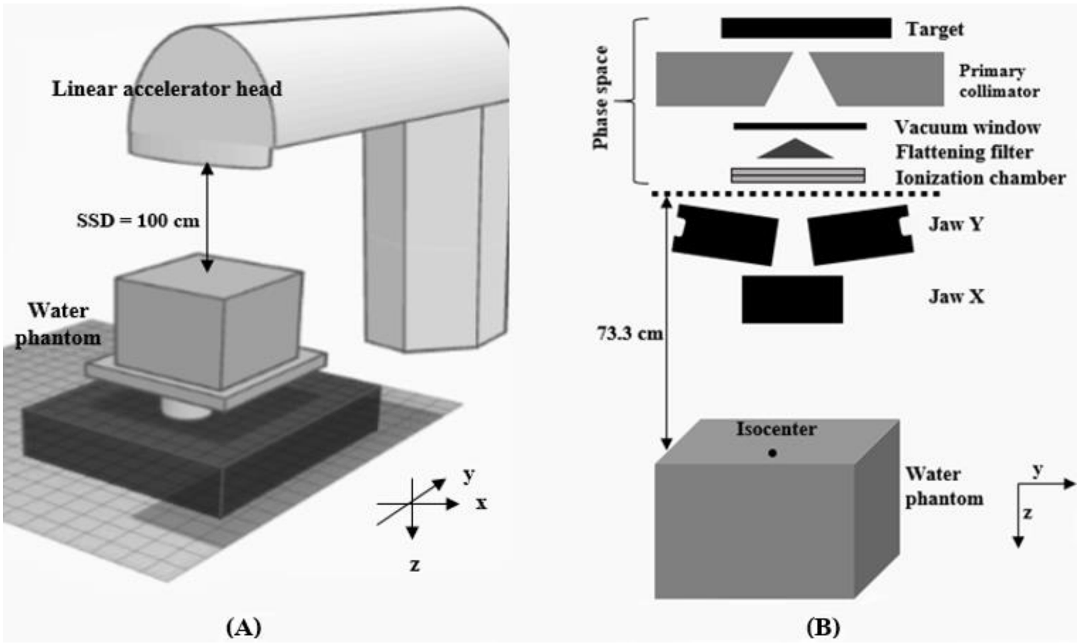


Figure 1. *Set-up of the TrueBeam linear accelerator and the water phantom: (A) Measurement set-up and (B) Monte Carlo model. Dashed line in figure (B) indicates the phase space surface for the Monte Carlo simulation.*

PHITS (Particle and Heavy Ion Transport code System) is a general purpose Monte Carlo particle transport simulation code that can simulate all particles and electromagnetic radiation over wide energy ranges. PHITS can be used to study a variety of topics, for example, accelerator technology, radiation protection and radiotherapy.[14] PHITS version 3.20 was used in this work for modeling the treatment head and for calculation of radiation dose. EGS5 mode of PHITS was used for electron and photon transport. The number of simulated particles at the phase space surface was in the range of 10^9 to produce reasonable standard deviations of the simulated results. The dose was calculated in the water phantom (50 cm x 50 cm x 50 cm) for 100 cm SSD.

Percentage depth dose and dose near the phantom surface was calculated in cylindrical voxels with 0.5 cm radius and 0.1 cm step ranging from 0.05 to 27.50 cm depth in the water phantom. Standard deviations of the results were not exceeding 3.3%. For the calculation of lateral beam profile and peripheral dose, dose was tallied in rectangular voxels with the dimensions of 2x0.1x2 cm^3 and 0.1x2x2 cm^3 for in-plane and cross-plane dose, respectively. The standard deviations of the calculated lateral beam profiles were less than 1.2% at the central region. The simulations were done on a high-performance computing (HPC) server using 16 cores of Intel Xeon E5-2600 v4 at 3.2 GHz with the simulation time of about 5.5 h for each simulated field size.

Comparison between the experimental data and the Monte Carlo simulation of percentage depth dose, lateral beam profile, dose near the phantom surface and peripheral dose was done using gamma evaluation method[15] with 3% dose difference at 3 mm distance-to-agreement (3%/3mm). In addition, for the lateral beam profile, point-by-point comparison of dose was done at the central region (plateau region) and the comparison of penumbra width (80%-20%) was done at the penumbra region. In this study, the central regions were defined between ±4.9 cm, ±9.9 cm and ±19.9 cm distances from the central axis for the field sizes of 10x10 cm^2, 10x20 cm^2 (in-plane or cross-plane) and 40x40 cm^2, respectively. In this work, the Monte Carlo simulated results for lateral beam profile and peripheral dose are presented as dose relative to average dose at the central regions.

Results

The experimental data and the Monte Carlo simulated results of percentage depth dose are shown in Figure 2A, Figure 3A and Figure 4A for the field sizes of 10x10 cm^2, 10x20 cm^2 and 40x40 cm^2, respectively. The experimental data and the Monte Carlo simulated results of dose near the phantom surface are shown in Figure 2B, Figure 3B and Figure 4B for the respective field sizes. D_{max} in the measured percentage depth dose curves were 1.55, 1.55 and 1.35 cm, while D_{max} in the measured doses near the phantom surface were 1.45, 1.45 and 1.15 cm, for the respective field sizes. In comparison, D_{max} obtained from the Monte Carlo simulation were 1.65, 1.45 and 1.55 cm, respectively. The maximum standard deviations of the measured doses near the phantom surface were 0.3%, 0.2% and 0.3% for the respective field sizes, and the maximum standard deviations of the Monte Carlo simulated results were 3.3%, 3.1% and 2.6%, respectively. For percentage depth dose and dose near the phantom surface, the average differences between the calculated and measured doses for all investigated field sizes were 2.7% and 8.6%, respectively. Moreover, the gamma passing rates (3%/3mm) of percentage depth dose and dose near the phantom surface were at least 100% and 50%, respectively, as shown in Table 1.

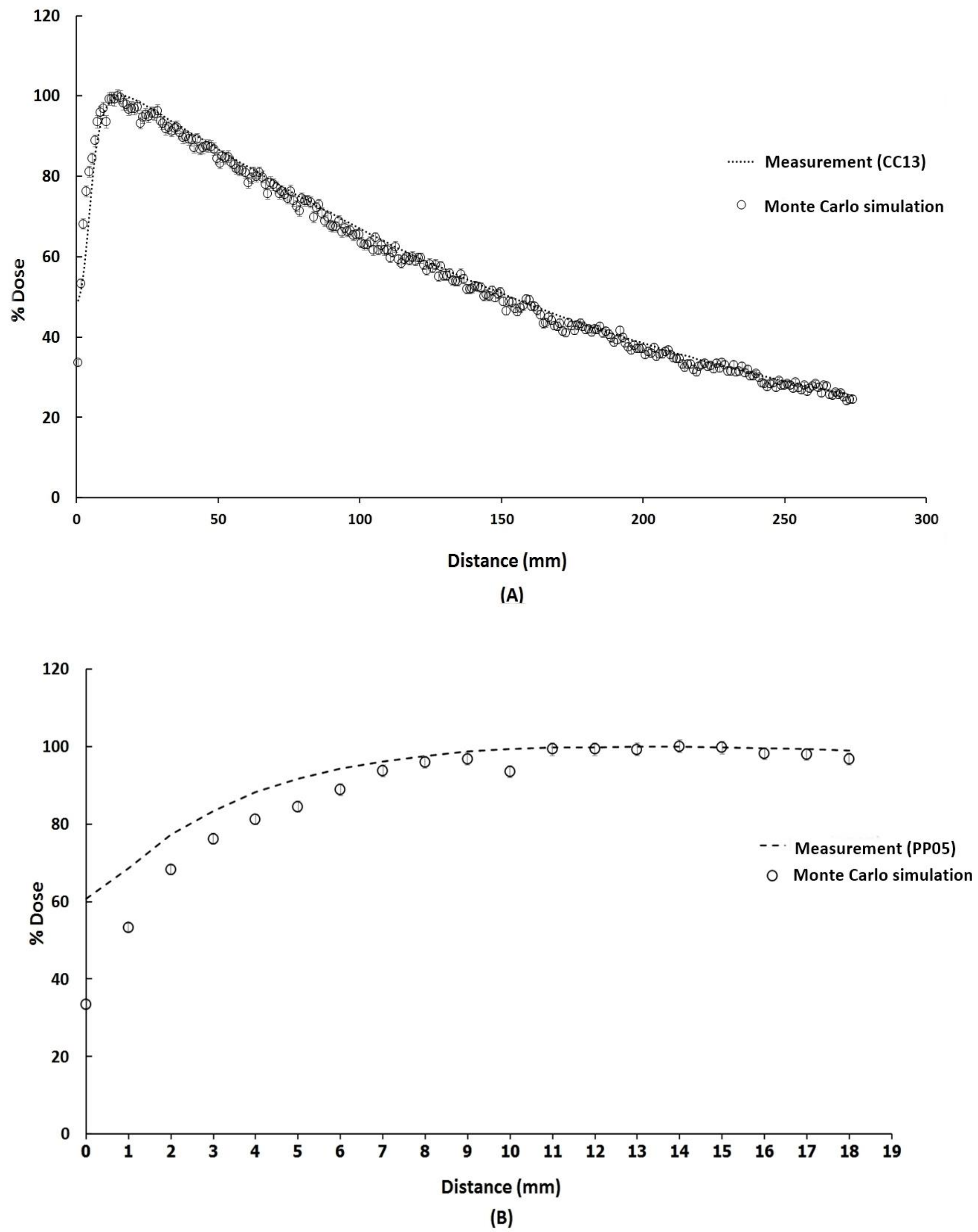
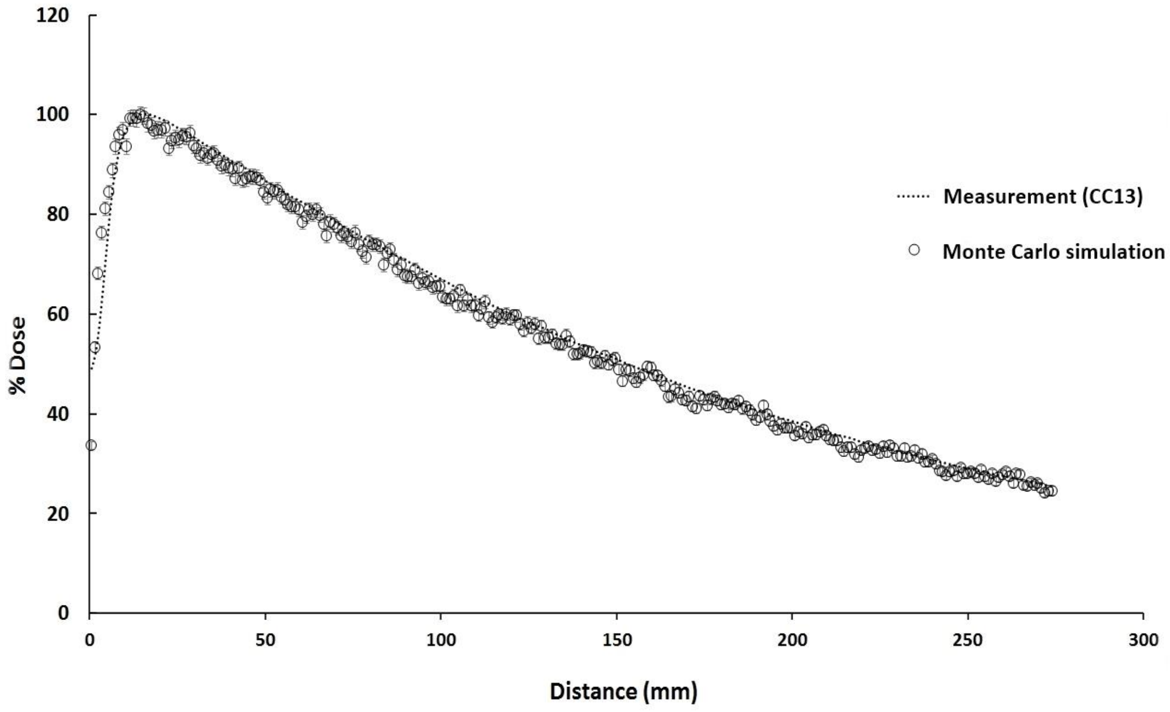
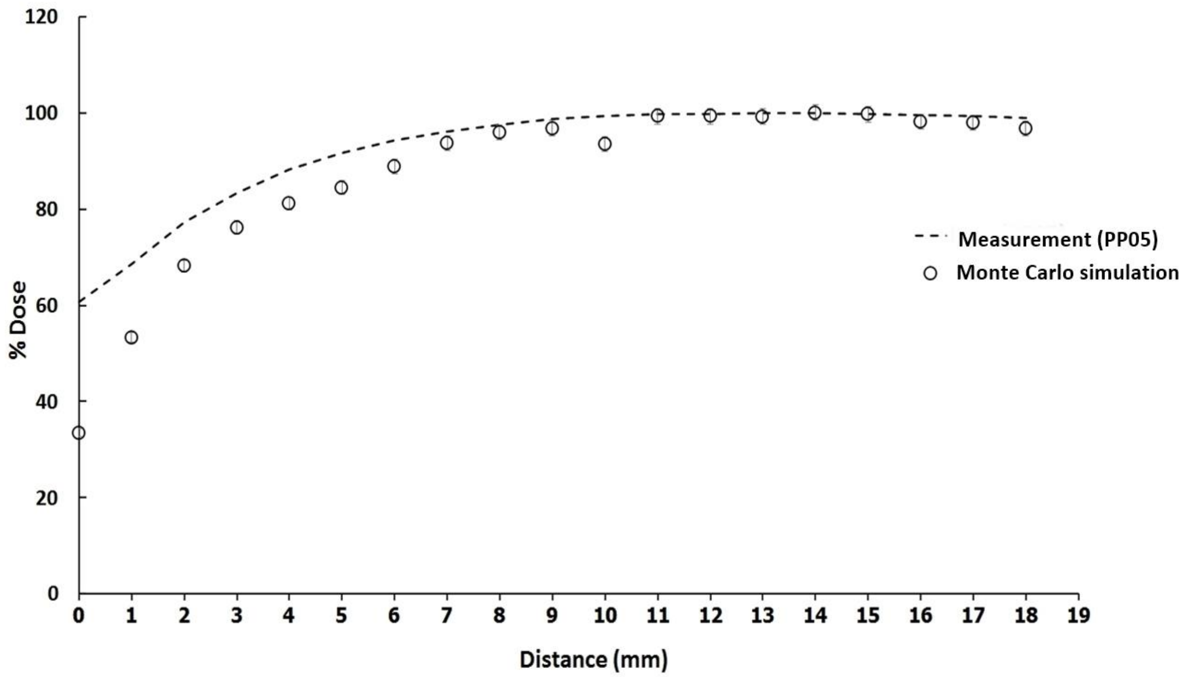


Figure 2. *Percentage depth dose and dose near the phantom surface for 10x10 cm^2 field size. A: percentage depth dose, B: dose near the phantom surface, symbols are Monte Carlo simulated results and lines are experimental data.*



(A)



(B)

Figure 3. *Percentage depth dose and dose near the phantom surface for 10x20 cm² field size. A: percentage depth dose, B: dose near the phantom surface, symbols are Monte Carlo simulated results and lines are experimental data.*

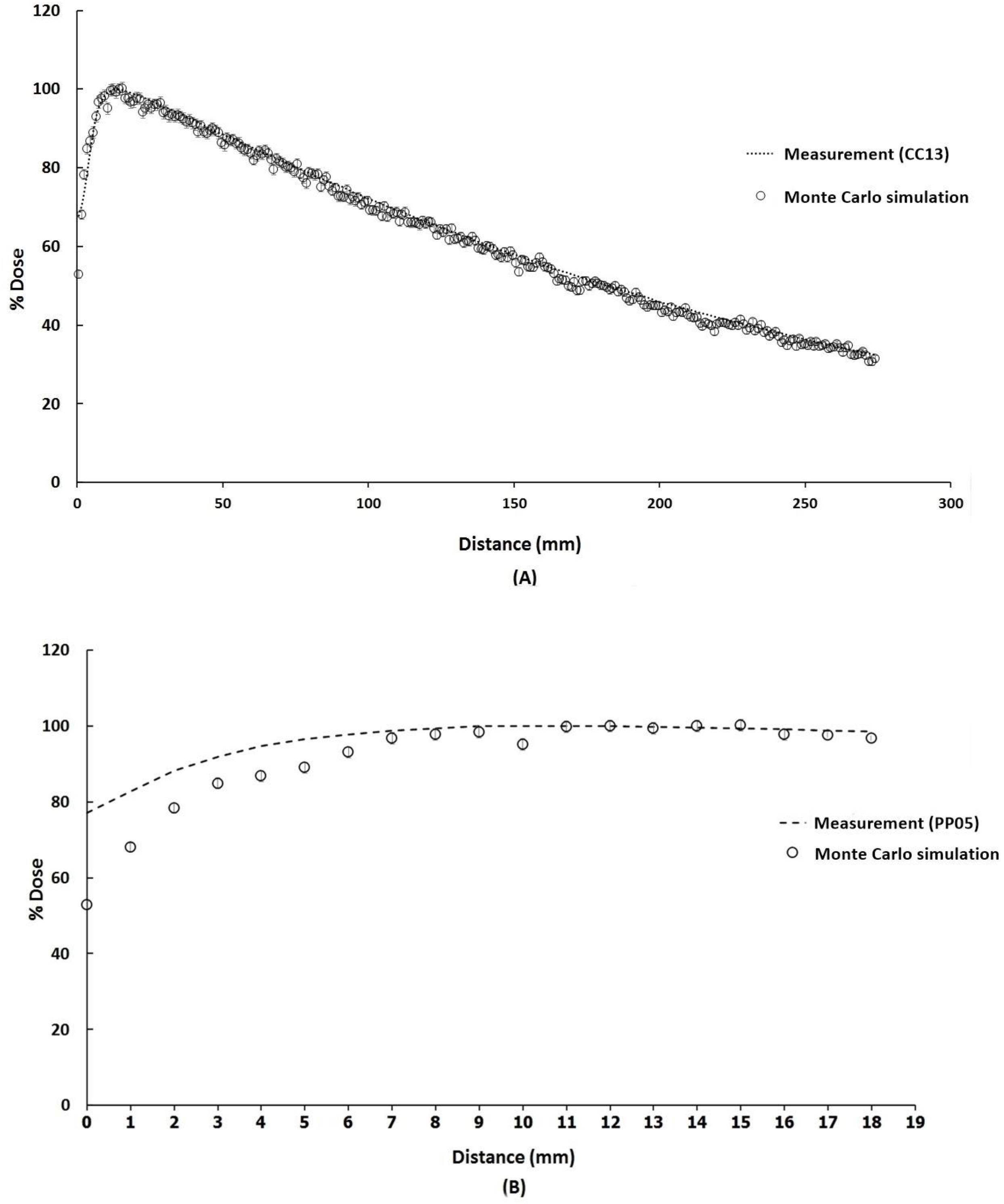
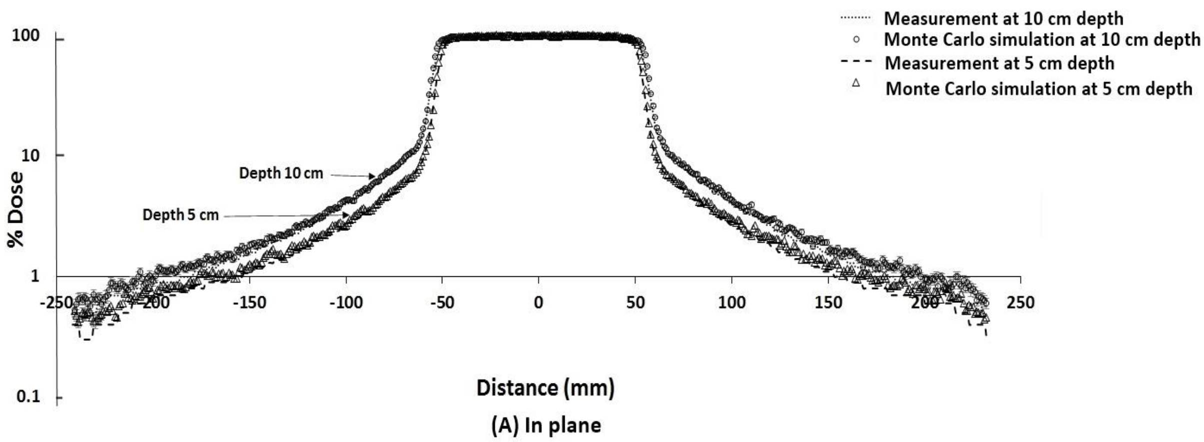


Figure 4. *Percentage depth dose and dose near the phantom surface for 40x40 cm^2 field size: A: percentage depth dose, B: dose near the phantom surface, symbols are Monte Carlo simulated results and lines are experimental data.*

Table 1 Summary of gamma passing rates with 3%/3mm criteria of percentage depth dose and dose near the phantom surface.

Field size	Gamma passing rates (%)	
	Percentage depth dose	Dose near the phantom surface
10x10 cm^2	100.0	75.0
10x20 cm^2	100.0	73.3
40x40 cm^2	100.0	50.0

The experimental data and Monte Carlo simulated results of lateral beam profile, including in-plane and cross-plane doses, at 5 and 10 cm depths are shown in Figure 5, Figure 6 and Figure 7 for the field sizes of 10x10, 10x20 and 40x40 cm^2, respectively. The maximum standard deviations of the Monte Carlo simulated results were 1.2%, 1.1% and 0.9%, for the respective field sizes. The differences of the simulated and measured doses at the central regions did not exceed 3% and the differences of the penumbra widths were at maximum 3 mm for all investigated field sizes.



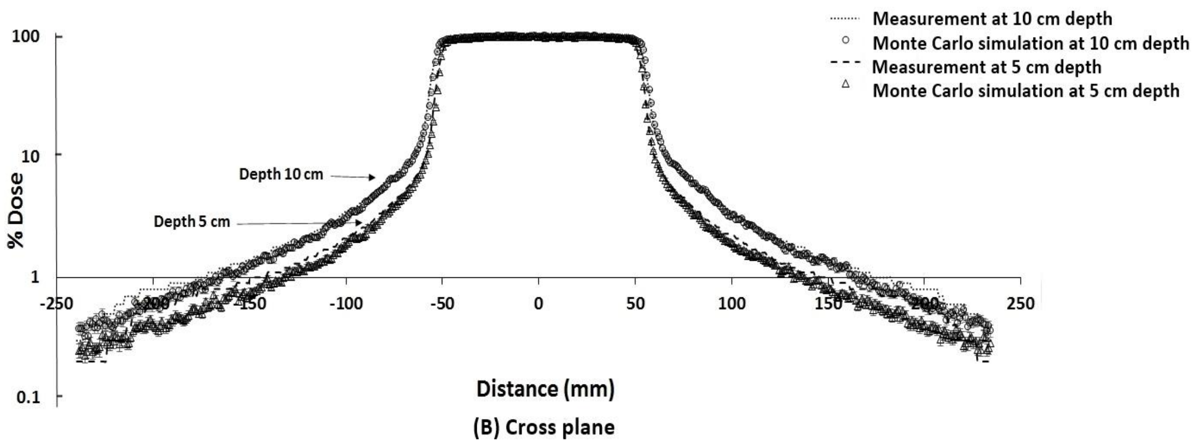


Figure 5. *Lateral beam profiles for the field sizes of 10x10 cm^2 at 5 and 10 cm depth. A: in-plane, B: cross-plane doses, symbols are Monte Carlo simulated results and lines are experimental data.*

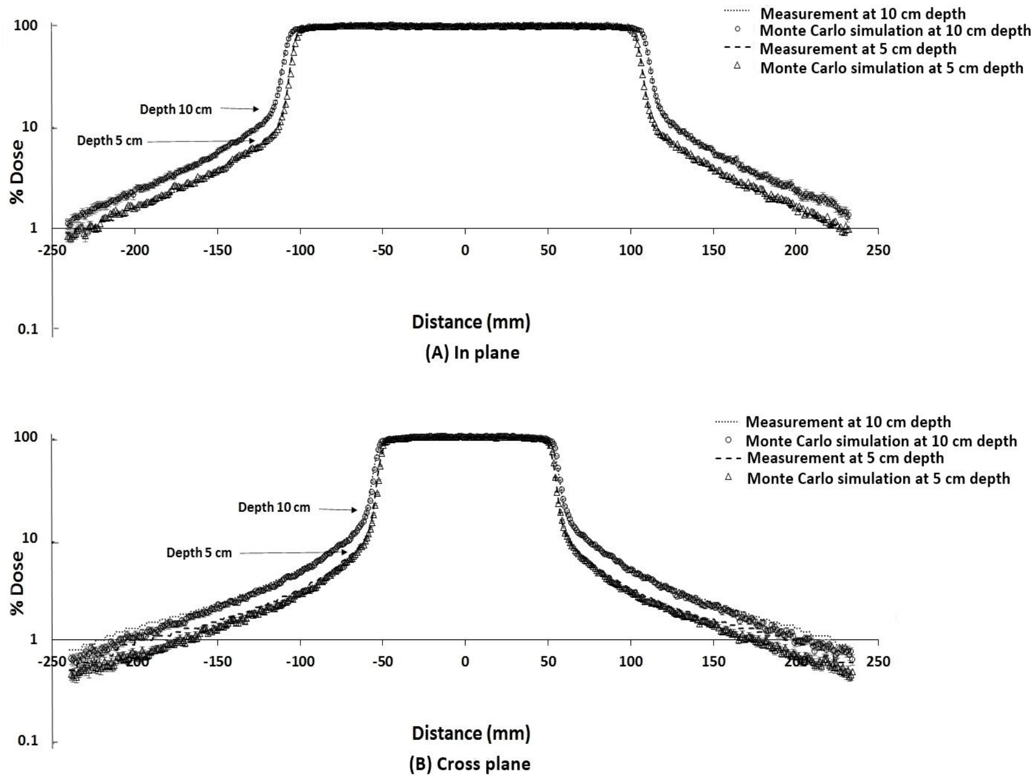


Figure 6. *Lateral beam profiles for the field sizes of 10x20 cm² at 5 and 10 cm depth. A: in-plane, B: cross-plane doses, symbols are Monte Carlo simulated results and lines are experimental data.*

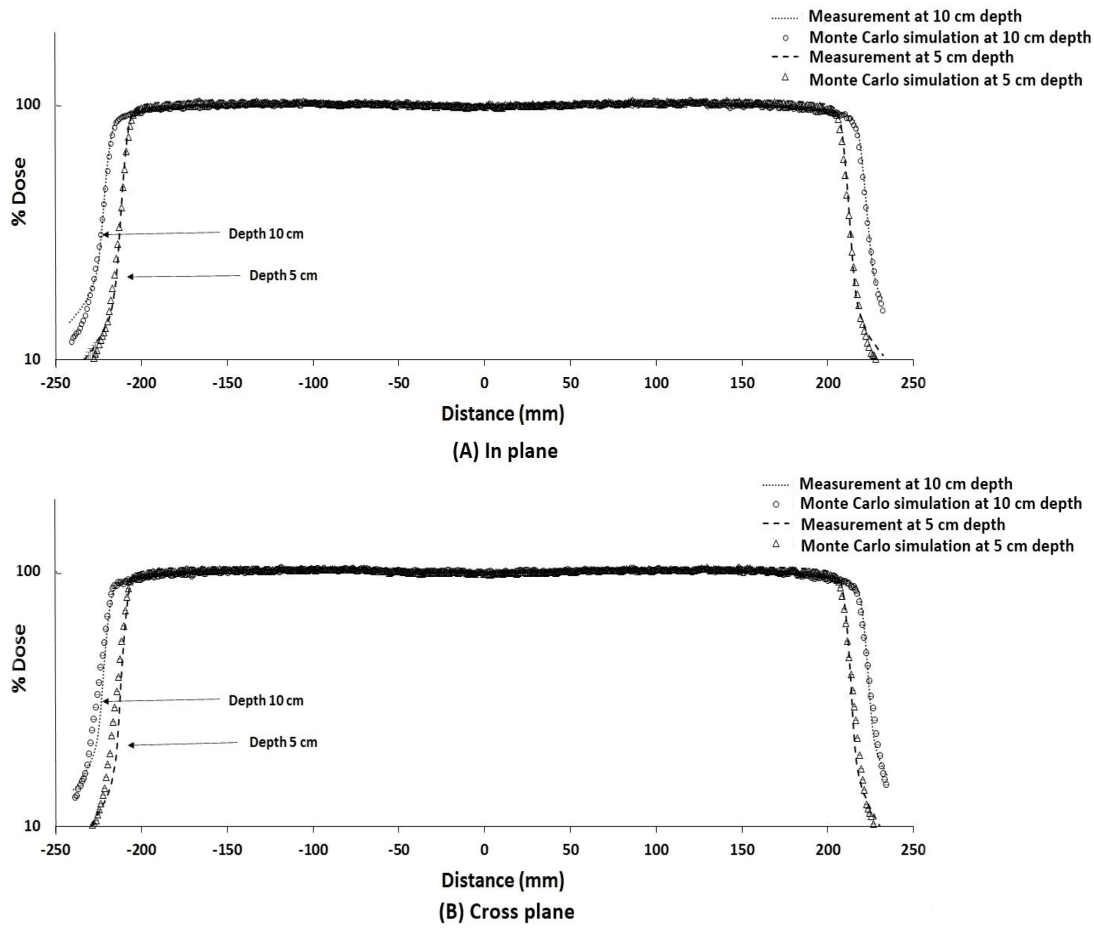


Figure 7. *Lateral beam profiles for the field sizes of 40x40 cm² at 5 and 10 cm depth. A: in-plane, B: cross-plane doses, symbols are Monte Carlo simulated results and lines are experimental data.*

Table 2 Summary of gamma passing rates with 3%/3mm criteria of lateral beam profile.

Field size	Lateral beam profile at 5 cm depth						Lateral beam profile at 10 cm depth					
	central region		Penumbra region		All regions		central region		Penumbra region		All regions	
	In plane	Cross plane	In plane	Cross plane	In plane	Cross plane	In plane	Cross plane	In plane	Cross plane	In plane	Cross plane
10x10 cm^2	95.0	96.9	100.0	100.0	95.0	95.8	97.0	97.9	100.0	100.0	96.3	96.2
10x20 cm^2	99.4	96.0	100.0	100.0	95.1	95.1	100.0	97.9	100.0	100.0	97.6	95.1
40x40 cm^2	95.0	97.0	100.0	100.0	96.2	96.3	96.0	98.0	100.0	100.0	98.9	98.7

Table 3 Summary of peripheral doses.

Distance from the central axis (cm)	Peripheral dose at 5 cm depth				Peripheral dose at 10 cm depth			
	In plane		Cross plane		In plane		Cross plane	
	Exp	MC	Exp	MC	Exp	MC	Exp	MC
-20 cm	0.70	0.67±0.10	0.60	0.40±0.09	0.90	0.90±0.09	0.80	0.60±0.07
-15 cm	1.10	1.21±0.07	0.95	0.73±0.07	1.60	1.76±0.06	1.40	1.25±0.05
-10 cm	2.68	2.63±0.04	2.10	1.86±0.05	3.98	4.22±0.03	3.55	3.10±0.04
-5 cm	73.10	84.73±0.01	73.80	76.18±0.01	85.60	93.40±0.01	89.60	90.70±0.01
5 cm	80.00	90.00±0.01	84.80	90.79±0.01	89.60	92.40±0.01	90.60	93.99±0.01
10 cm	2.70	3.20±0.04	2.30	1.93±0.04	4.00	4.38±0.03	3.55	3.24±0.03
15 cm	1.10	1.20±0.06	1.00	0.80±0.06	1.50	1.60±0.05	1.40	1.35±0.06
20 cm	0.60	0.78±0.09	0.60	0.40±0.08	0.80	0.94±0.08	0.80	0.57±0.07
Gamma passing rate	83.0%		84.0%		85.0%		81.0%	

Note: *Exp: experimental data, MC: Monte Carlo simulation, % relative to average dose in the central region and gamma passing rates with 3%/3mm criteria.*

Discussion

In this study, the 6 MV TrueBeam linear accelerator model for out-of-field dose calculation was developed using PHITS Monte Carlo code for the field sizes of 10x10, 10x20 and 40x40 cm^2. The Monte Carlo model was validated against experimental data according to the recommendation of AAPM TG 158.[4]

In terms of percentage depth dose and dose near the phantom surface, the comparisons of the calculated and measured doses gave the gamma passing rates (3%/3mm) of 100% and at least 50% for all investigated field sizes, respectively. In general, the gamma passing rates of dose near the phantom surface is expected to be lower than those of percentage depth dose due to a steep dose gradient near the phantom surface. As recommended by a previous study[16], the comparison of experimental data and Monte Carlo calculated doses near the phantom surface should not exceed 15%. When analyzing the present results following that recommendation, it was found that all parts of doses near the phantom surface passed this criterion except at the surface. As shown in previous studies, differences of doses at the phantom surface obtained from measurements and Monte Carlo simulations were as large as 40%.[10,17,18] In term of field size dependence, the calculated doses near the phantom surface obtained in this work exhibited a field size dependence, in accordance with previous studies.[9,10,19] The larger field size was associated with the larger dose due to a higher degree of electron contamination.[10,19]

For the validation of lateral beam profile, the gamma passing rates were at least 95% for all investigated field sizes and depths. The point-by-point differences of doses at the central region did not exceed 3% and the differences of the penumbra widths were less than 3 mm for all investigated field sizes and depths. The differences of doses at the central region and penumbra widths should not exceed 3% and 3 mm, respectively.[16] Thus, the simulation and the measurement carried out in this work were considered to be in good agreement.

For the validation of peripheral dose, the gamma passing rates were larger than 81% for all investigated depths. In this work, the measured peripheral doses were in relatively good agreement with the Monte Carlo simulated results at close distances from the field edge. However, the differences of the calculated and measured doses at 15 cm distance from the field edge (20 cm distance from the central axis) were as large as 33%. Such large discrepancies have also been observed in the previous studies,[5,6,20] which may arise from statistical uncertainties of the simulation (up to 10% in this work) and the uncertainty of dose measurement[4].

It should be mentioned that using phase space files obtained from the vendor allowed fewer opportunities to improve the Monte Carlo model. For example, the treatment head model upstream from the jaws needed to be treated as a black box that could not be adjusted to give a better agreement to the experimental data. Nevertheless, from the validation carried out in this work, the agreement between the measured and calculated doses suggested that the developed Monte Carlo model of the 6 MV TrueBeam linear accelerator can be used for out-of-field dose calculation.

Conclusion

In this work, the 6 MV TrueBeam linear accelerator model developed using PHITS Monte Carlo code for out-of-field dose calculation was validated against experimental data based on the recommendation of AAPM TG 158. The field sizes of interest included 10x10, 10x20 and 40x40 cm^2. Percentage depth dose, lateral beam profile, dose near the phantom surface and peripheral dose calculated by the Monte Carlo simulation were validated against the measurements at the same conditions. The comparison showed good agreement between the experimental data and the Monte Carlo simulation for all investigated field sizes with the gamma passing rates (3%/3mm) of at least 100% for percentage depth dose, 95% for lateral beam profile, 50% for dose near the phantom surface and 81% for peripheral dose at 5 and 10 cm depth. The results suggested that the developed Monte Carlo model can be used for calculation of out-of-field dose, for example, for determination fetal dose during radiotherapy for a pregnant patient.

Conflict of interest

The authors declare that there is no conflict of interest.

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