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Original research article

Monte Carlo simulation using PRIMO code as a tool for checking the credibility of commissioning and quality assurance of 6 MV TrueBeam STx varian LINAC☆

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ABSTRACT

Aim: To validate and implement Monte Carlo simulation using PRIMO code as a tool for checking the credibility of measurements in LINAC initial commissioning and routine Quality Assurance (QA). Relative and absolute doses of 6 MV photon beam from TrueBeam STx Varian Linear Accelerator (LINAC) were simulated and validated with experimental measurement, Analytical Anisotropic Algorithm (AAA) calculation, and golden beam.

Methods and Materials: Varian phase-space files were imported to the PRIMO code and four blocks of jaws were simulated to determine the field size of the photon beam. Water phantom was modeled in the PRIMO code with water equivalent density. Golden beam data, experimental measurement, and AAA calculation results were imported to PRIMO code for gamma comparison.

Results: PRIMO simulations of Percentage Depth Dose (PDD) and in-plane beam profiles had good agreement with experimental measurements, AAA calculations and golden beam. However, PRIMO simulations of cross-plane beam profiles have a better agreement with AAA calculation and golden beam than the experimental measurement. Furthermore, PRIMO simulations of absolute dose agreed well with experimental results with ±0.8% uncertainty.

Conclusion: The PRIMO code has good accuracy and is appropriate for use as a tool to check the credibility of beam scanning and output measurement in initial commissioning and routine QA.

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1. Introduction

Accuracy of dose delivered to the patient is directly related to the beam data commissioning used in a Treatment Planning System (TPS). These data are verified periodically in the Quality Assurance (QA) of LINAC beam performance by a medical physicist.[1] Lack of standards and need for precision are challenges to the medical physicist, in the credibility of measurements in initial commissioning and routine QA. The TG-106 report of the American Association of Physicists in Medicine (AAPM)[2] gives two recommendations to verify initial commissioning results. The first recommendation is to use golden beam data for checking the quality of the beam scanning. Varian provides golden beam data, which is a reference dosimetric dataset. It could be used to evaluate the beam reproducibility of LINAC. The golden beam dataset is available at www.myvarian.com with the name "TrueBeam Representative Beam Data for Eclipse". Another recommendation is to verify beam scanning with Monte Carlo (MC) simulation. However, experimental measurements or golden beam are still needed to validate such MC simulation.

MC simulation is the most powerful tool for dose calculations in radiotherapy. MC simulation is implemented in several available codes, e.g. MCNP,[3] Geant,[4] PENELOPE,[5] FLUKA[6] for general applications; and PEREGRINE,[7] EGSnrc,[8] DPM,[9] VMC++,[10] ORANGE,[11] PRIMO[12] for medical applications. The availability of MC simulation tools has led to clinics using it in clinical radiation oncology.[13,14] Nevertheless, the selection of a suitable and practical MC simulation code, and accurate validation of the simulation parameters, are necessary.

PRIMO is a MC code specific for radiotherapy. The computation engine of PRIMO is based on the PENELOPE general MC code. It can use parallel processors and variance reduction techniques to make the simulation quicker in real time. PRIMO simulates medical LINAC

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and estimates absorbed dose distributions in a water phantom or in Computed Tomography (CT) data. PRIMO can simulate almost all Varian and Elekta LINAC, with their electron applicators and MLC.[12]

There are two ways to characterize the source of radiation for an MC simulation, to inform about particle type, energy, position, direction of movement, etc.[15] The first is by using phase-space files,[16] and the second is by providing detailed geometry of the LINAC head that should be modelled.[17] Phase space files of TrueBeam 6 MV photon beam have been made available by Constantin and co-workers at www.myvarian.com/montecarlo. The phase-space files are formatted according to practices of the International Atomic Energy Agency (IAEA). Simulations were divided into two parts, (1) accelerator part using the Parmela code, (2) LINAC head using the Geant4 V4.9.2.p01 MC code. The first phase space result was used as input for the second simulation.[18]

Percentage Depth Dose (PDD) and beam profiles (cross-plane and in-plane) are two important concerns affecting the accuracy of MC modeling in a relative dose measurement. PDD is used as a beam quality parameter, and beam profiles are used for radiation dose reliability assessment.[19–21] Aside from the relative dose, also the absolute dose is an important dosimetry aspect pursued by initial commissioning and routine QA. Experiments on absolute dose are also called output measurements.[22]

Belosi and co-workers simulated 6 and 10 MV FFF TrueBeam using Varian phase-space files. Seven experimental measurements and golden beam dataset were used to validate the MC results.[23] Our previous work has published 6 MV FFF photon beam simulation of TrueBeam using the PRIMO code. In this publication authors generate phase space files with 10^9 histories. The results were in a better than 84% agreement with experimental measurements, using 1% 1 mm gamma criteria.[24]

In most clinical practice QA of beam performance is done by matching the flatness and symmetry with commissioning data, although this is still a rough approach. Verification of all points in PDD and beam profiles would be needed for a precise QA of beam performance. Toutaoui et al. verified photon dose calculation by multi-grid superposition in a commercial TPS (CMS Xio, Elekta) using MC EGSnrc code.[25] Another study concerned the electron mode.[26] MC EGS4/BEAM code was used to commission the electron beam of Varian Clinac 2100C. However, the MC code used was not well suited for regular use as a verification tool in initial commissioning and routine QA. Moreover, the precise, reliable, and standard model of MC simulation is important if it is used as a verification tool of experimental measurements.

The goal of this work was to validate and implement MC simulation using the PRIMO code for 6 MV photon beam of TrueBeam STx Varian LINAC as a tool to verify the initial commissioning and routine QA. PRIMO simulation results are compared with results from experimental measurements, AAA calculations, and golden beam. TrueBeam STx Varian LINAC Radiotherapy facility at Songklanagarind Hospital, Prince of Songkla University, will be utilized in experimental measurements with the AAA Eclipse treatment planning system.

2. Materials and methods

2.1. Varian phase-space files

The phase-space files of 6 MV photon beam of TrueBeam STx as provided by Varian are available at www.myvarian.com/montecarlo.[18] These serve as the first phase-space files in Fig. 1. The phase-space files can be used to describe the radiation source for dose estimation by MC simulation. Photon beam 6 MV of TrueBeam phase-space files contains 4.95×10^{10} histories and in total 1.79×10^9 particles.

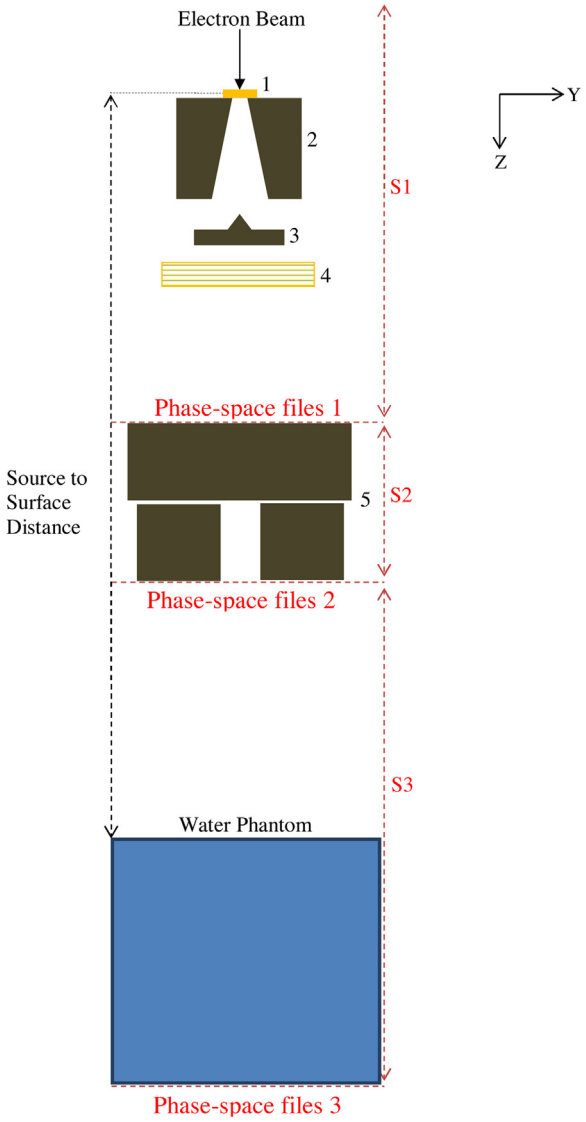

Fig. 1. Sketch of Geometry of TrueBeam STx Varian LINAC head and water phantom in relation to simulation stages S1, S2, and S3.

2.2. Monte Carlo simulation using the PRIMO code

Simulation processes in the PRIMO code were divided into 3 parts. The first segment is called S1, which models from the electron beam to the ion chamber. The second segment called S2 has four blocks of jaws that can be adjusted to determine the field size of the radiation beam. The third segment is S3, which can be a water phantom or a patient's Digital Imaging and Communications in Medicine (DICOM) data. TrueBeam Varian phase-space files for the 6 MV photon beam were imported in the S1 part and simulated in the S2 and S3 parts using the PRIMO code, as shown in Fig. 1. Head of LINAC parts and estimated materials in each component are summarized in Table 1. The voxel size $3 \times 3 \times 3$ mm^3 was used to simulate the water phantom.

2.3. AAA calculation

The Analytical Anisotropic Algorithm (AAA) is used in the Eclipse treatment planning system. It was developed by Waldemar Ulmer and Wolfgang Kaissl, in the publication "A Triple Gaussian Pencil beam Model for Photon beam Treatment Planning", in 1995.[27] Photon dose in the water phantom was calculated using AAA in Eclipse

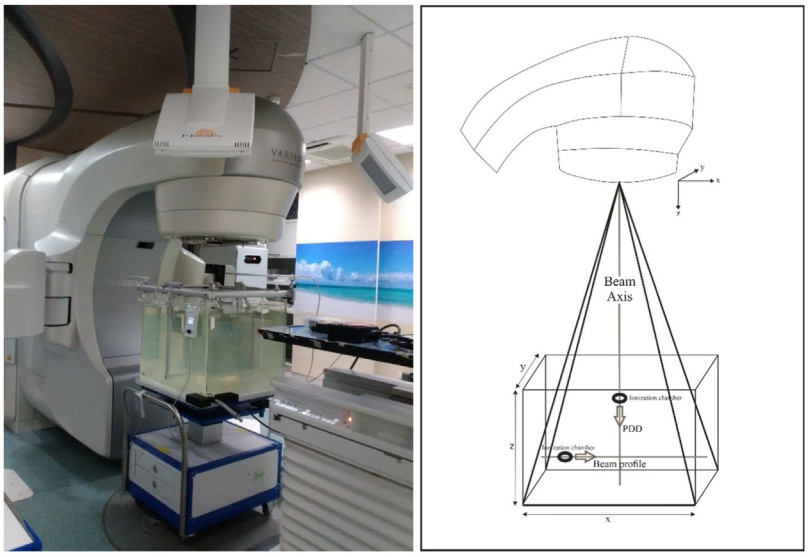

Fig. 2. Experimental set-up (a) in a photograph and (b) in a schematic drawing.[21]

Table 1
Head of TrueBeam STx Varian LINAC parts and estimated materials.

No	Component	Composition	Symbol
1	Target	Tungsten, Tungsten-Copper	W, W-Cu
2	Primary collimator	Tungsten	W
3	Flattening filter	Lead-Steel-Copper	Pb-Fe-Cu
4	Ion chamber	Copper	Cu
5	Secondary collimator (Jaws)	Tungsten	W

software. PDD, cross-plane beam, and in-plane beam profiles were calculated along each axis. The AAA calculation in Eclipse software generated $0.25 \times 0.25 \times 0.25\ mm^3$ voxels.

2.4. Experiment setup

2.4.1. Relative dose measurement

TrueBeam STx Varian LINAC facility at Songklanagarind Hospital, Prince of Songkla University, was used in this experiment. Fig. 2a shows the 6 MV photon beam irradiating a water phantom. IBA blue phantom was used in the relative dose measurement by using IBA cc13. The ionization chamber scanned along each axis, as shown in Fig. 2b. When scanning along the Z, X, and Y axes, the PDD, cross-plane and in-plane beam profiles were obtained. The ionization chamber was set to move in 1 mm steps along each axis.

2.4.2. Absolute dose measurement

Experimental measurements of the absolute dose followed the IAEA Technical Report Series No. 398.[28] In this work, the Source to Surface Distance (SSD) of water phantom was 100 cm. However, all LINACs in Songklanagarind Hospital calibrate to 1 Gy at Dmax by using the Source Axis Distance (SAD) technique. A comparison between SAD and SSD techniques is shown in Fig. 3. IBA FC65-G with 0.65 cm^3 cavity volume, an ionization chamber, was used to measure the output radiation along the central axis at depths of 1.5, 5, 10, and 20 cm.

2.5. Relative dose comparisons

Experimental measurement, AAA calculation, and golden beam data in ASCII format were imported to the PRIMO software. Comparisons between PRIMO simulation results and experimental

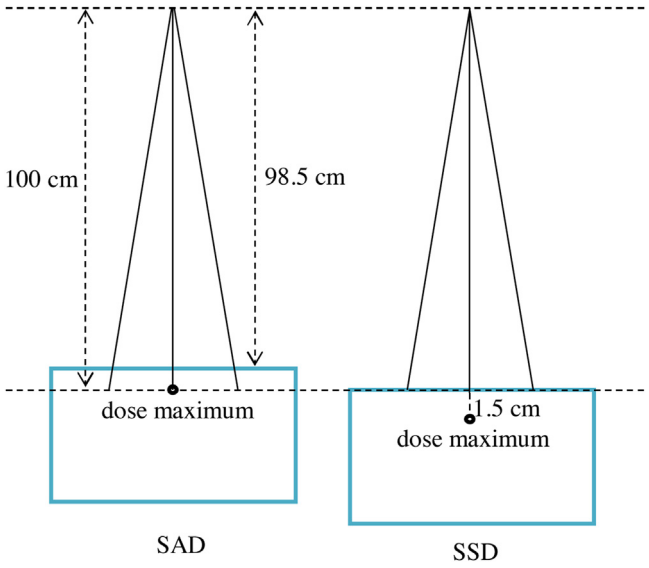

Fig. 3. Comparison of SAD and SSD techniques.

measurement, AAA calculation, and golden beam were performed using gamma analysis as proposed by Low et al.[29] Experimental measurement, AAA calculation, and golden beam were used as reference data and PRIMO simulation results as evaluation data. Gamma index (Γ) for reference point (p) and the dose at that point $d_e(p)$ are calculated based on Eq. (1).

$$\Gamma = min\left\{\sqrt{\left(\frac{\Delta d_i}{\Delta D}\right)^2 + \left(\frac{\Delta s_i}{\Delta S}\right)^2}\right\} \quad (1)$$

where:

ΔD = acceptance criteria for the dose difference,

ΔS = acceptance criteria for the distance to agreement,

Δd_i = the difference between $d_e(p)$ and the PRIMO simulated dose at a certain point p_i,

Δs_i = the distance between p and p_i.

In this work, the lowest acceptance criteria of 1% for the dose difference (ΔD) and 1 mm for the distance to agreement (ΔS) were

Table 2
PDD compared between PRIMO simulation and experimental measurement.

Field Size (cm^2)	Average Gamma Index		Percentage Passing Criteria (%)
	Build up Region	Equilibrium Region	
4×4	0.80	0.20	98.60
10×10	0.82	0.19	98.33
20×20	0.87	0.30	98.13
30×30	0.72	0.57	97.19
40×40	1.32	0.78	82.11

Table 3
PDD compared between PRIMO simulation and AAA calculation.

Field Size (cm^2)	Average Gamma Index		Percentage Passing Criteria (%)
	Build up Region	Equilibrium Region	
4×4	1.59	0.18	98.89
10×10	1.37	0.21	98.44
20×20	1.00	0.15	99.28
30×30	0.87	0.16	98.89
40×40	1.14	0.55	97.19

used. Based on Belosi et al.,[23] gamma passing criteria of 1%, 1 mm will show higher sensitivity than 2%, 2 mm.

2.6. Absolute dose comparisons

Absolute dose from the PRIMO simulation was compared with experimental measurements in field sizes 4×4, 10×10, and $20 \times 20\,cm^2$ with and without MLC, and the field size $40 \times 40\,cm^2$ was without MLC. Eq. 2 proposed by Zavgorodni et al.[30] was used to convert the absolute dose of PRIMO simulation from eV/g to Gy units.

$$D_{xyz,abs} = D_{xyz}.S_b.\frac{D^{cal}_{xyz,abs}}{D^{cal}_{xyz}} \quad (2)$$

where:

- $D_{xyz,abs}$ is the absolute dose of MC simulation in Gy after conversion,
- D_{xyz} is the normalized dose of MC simulation in eV/g,
- S_b is the monitor backscatter factors,
- $D^{cal}_{xyz,abs}$ is the absolute dose of experimental measurement in Gy at a reference point,
- D^{cal}_{xyz} is the normalized dose of MC simulation at a reference point.

3. Results

3.1. Percentage depth dose

PRIMO simulation of PDD gave a good agreement with experimental measurements, AAA calculations, and golden beam for field sizes up to $40 \times 40\,cm^2$ as shown in Fig. 4a–e. Details of gamma agreement between the PRIMO simulation with experimental results, AAA calculations, and golden beam are presented in Tables 2–4, respectively.

3.2. Cross-plane beam profile

Beam profiles were determined with field size $10 \times 10\,cm^2$ inside the water phantom at depths of 1.5, 5, 10, and 20 cm. Fig. 5a–d shows the comparison between the PRIMO simulation with experiment, AAA calculation, and golden beam. The PRIMO simulation of the cross-plane beam profile has the poorest agreement with the experimental measurements, which only pass 68–71% gamma agreement as shown in Table 5, while the PRIMO simulation results compared with AAA calculation and golden beam give a better than 77% passing gamma agreement, as shown in Tables 6 and 7.

Table 4
PDD compared between PRIMO simulation and Golden Beam.

Field Size (cm^2)	Average Gamma Index		Percentage Passing Criteria (%)
	Build up Region	Equilibrium Region	
4×4	1.47	0.16	98.85
10×10	1.16	0.17	98.99
20×20	1.01	0.24	98.56
30×30	1.28	0.24	98.16
40×40	1.33	0.22	96.55

Table 5
Cross-plane beam profile compared between PRIMO simulation and experimental measurement for field size $10 \times 10\,cm^2$.

Depth (cm)	Average Gamma Index			Percentage Passing Criteria (%)
	Inside field	Penumbra	Outside field	
1.5	0.59	1.82	0.99	68.96
5	0.66	1.77	0.94	70.55
10	0.70	1.36	0.95	68.90
20	0.61	1.16	0.94	71.02

Table 6
Cross-plane beam profile compared between PRIMO simulation and AAA calculation for field size $10 \times 10\,cm^2$.

Depth (cm)	Average Gamma Index			Percentage Passing Criteria (%)
	Inside field	Penumbra	Outside field	
1.5	0.43	1.10	0.32	98.40
5	0.49	0.86	0.43	98.10
10	0.57	0.87	0.53	96.53
20	0.51	0.66	0.61	87.21

Table 7
Cross-plane beam profile compared between PRIMO simulation and Golden Beam for field size $10 \times 10\,cm^2$.

Depth (cm)	Average Gamma Index			Percentage Passing Criteria (%)
	Inside field	Penumbra	Outside field	
1.5	0.93	1.91	0.38	77.32
5	0.65	1.55	0.30	88.15
10	0.65	1.26	0.28	92.51
20	0.46	0.71	0.30	95.62

Table 8
In-plane beam profile compared between PRIMO simulation and experimental measurement for field size $10 \times 10\,cm^2$.

Depth (cm)	Average Gamma Index			Percentage Passing Criteria (%)
	Inside field	Penumbra	Outside field	
1.5	0.59	1.99	0.46	92.33
5	0.53	1.31	0.40	92.81
10	0.56	0.71	0.28	92.37
20	0.43	0.50	0.18	95.22

3.3. In-plane beam profile

The PRIMO simulation of the in-plane beam profile had good agreement with experimental results and AAA calculations, as shown in Fig. 6a–d. It had a better than 92% agreement with the experimental measurements and over 71% agreement with the AAA calculations, as shown in Tables 8 and 9.

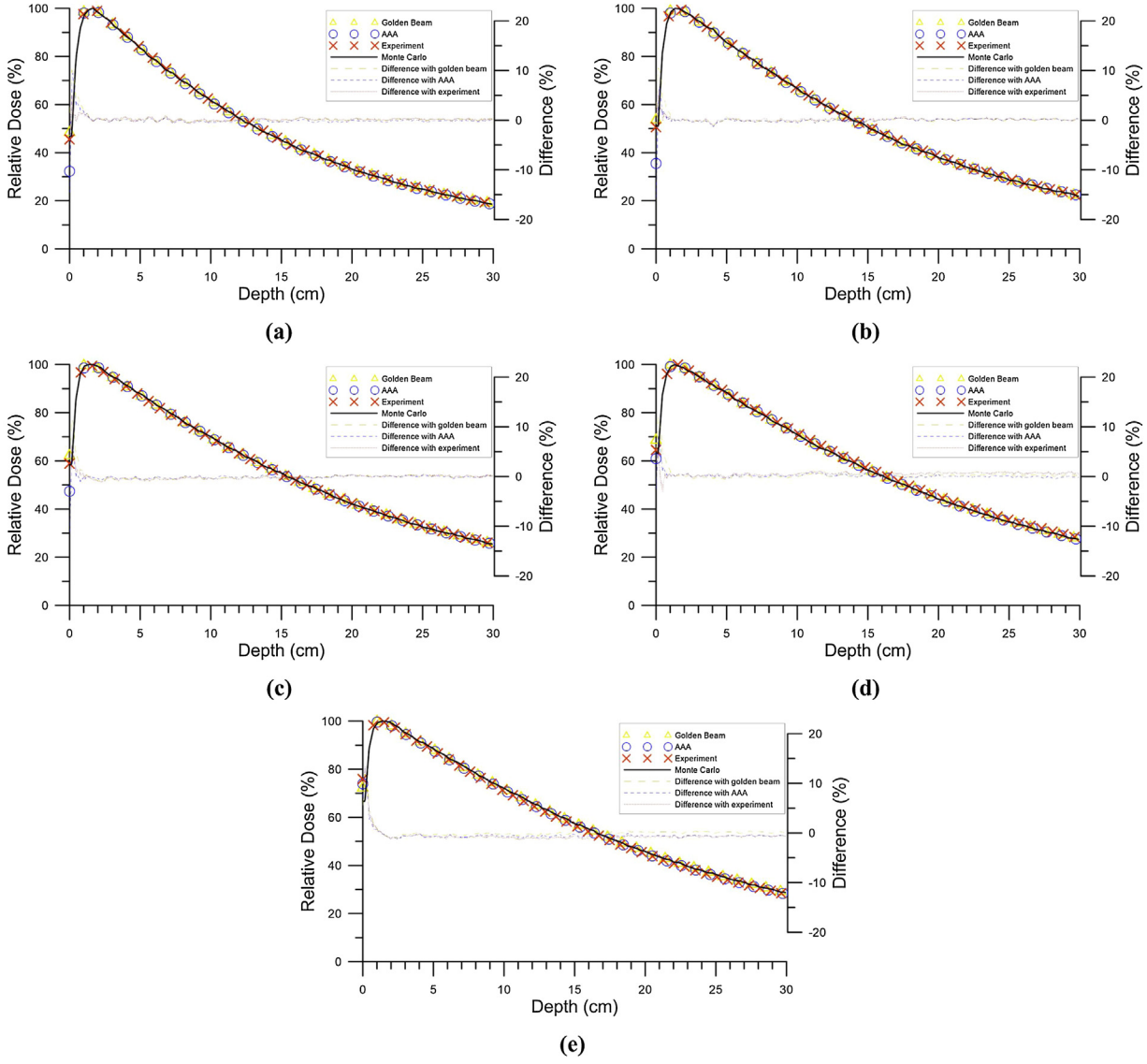

Fig. 4. PDD compared for field sizes: (a) $4 \times 4\,cm^2$; (b) $10 \times 10\,cm^2$; (c) $20 \times 20\,cm^2$; (d) $30 \times 30\,cm^2$; and (e) $40 \times 40\,cm^2$.

Table 9
In-plane beam profile compared between PRIMO simulation and AAA calculation for field size $10 \times 10\,cm^2$.

Depth (cm)	Average Gamma Index			Percentage Passing Criteria (%)
	Inside field	Penumbra	Outside field	
1.5	0.36	0.81	0.76	80.82
5	0.51	1.38	0.82	78.37
10	0.58	1.14	0.82	87.57
20	0.47	0.87	0.96	71.36

Table 10
Absolute dose compared for field size $4 \times 4\,cm^2$.

Depth (cm)	Non MLC			MLC		
	Simulation (Gy)		Experiment (Gy)	Simulation (Gy)		Experiment (Gy)
	Dose	2 σ	Dose	Dose	2 σ	Dose
1.5	0.9005	0.0065	0.9014	0.9020	0.0066	0.9029
5	0.7466	0.0055	0.7549	0.7508	0.0055	0.7638
10	0.5523	0.0044	0.5565	0.5513	0.0044	0.5621
20	0.2980	0.0033	0.3008	0.2981	0.0033	0.3034

3.4. Absolute dose

PRIMO simulations of the absolute dose with about ±0.8% uncertainty agreed well with the experimental results. The comparisons between the PRIMO simulation and experimental results are shown in Tables 10–13 for the respective field sizes.

4. Discussion

TrueBeam STx Varian LINAC has been simulated using the PRIMO code. Varian phase-space files of 6 MV photon beam were imported into the S1 part. PRIMO code begin simulated the 6 MV photon beam of TrueBeam STx Varian LINAC from four block of jaws and water phantom in the S2 and S3 parts. PRIMO code appears suitable for use in small field dosimetry.[31]

However, Geometry of the TrueBeam STx Varian LINAC is still not distributed freely, instead the Varian Medical Systems provide the phase space files. Accuracy of MC simulations will depend on these phase-space files.

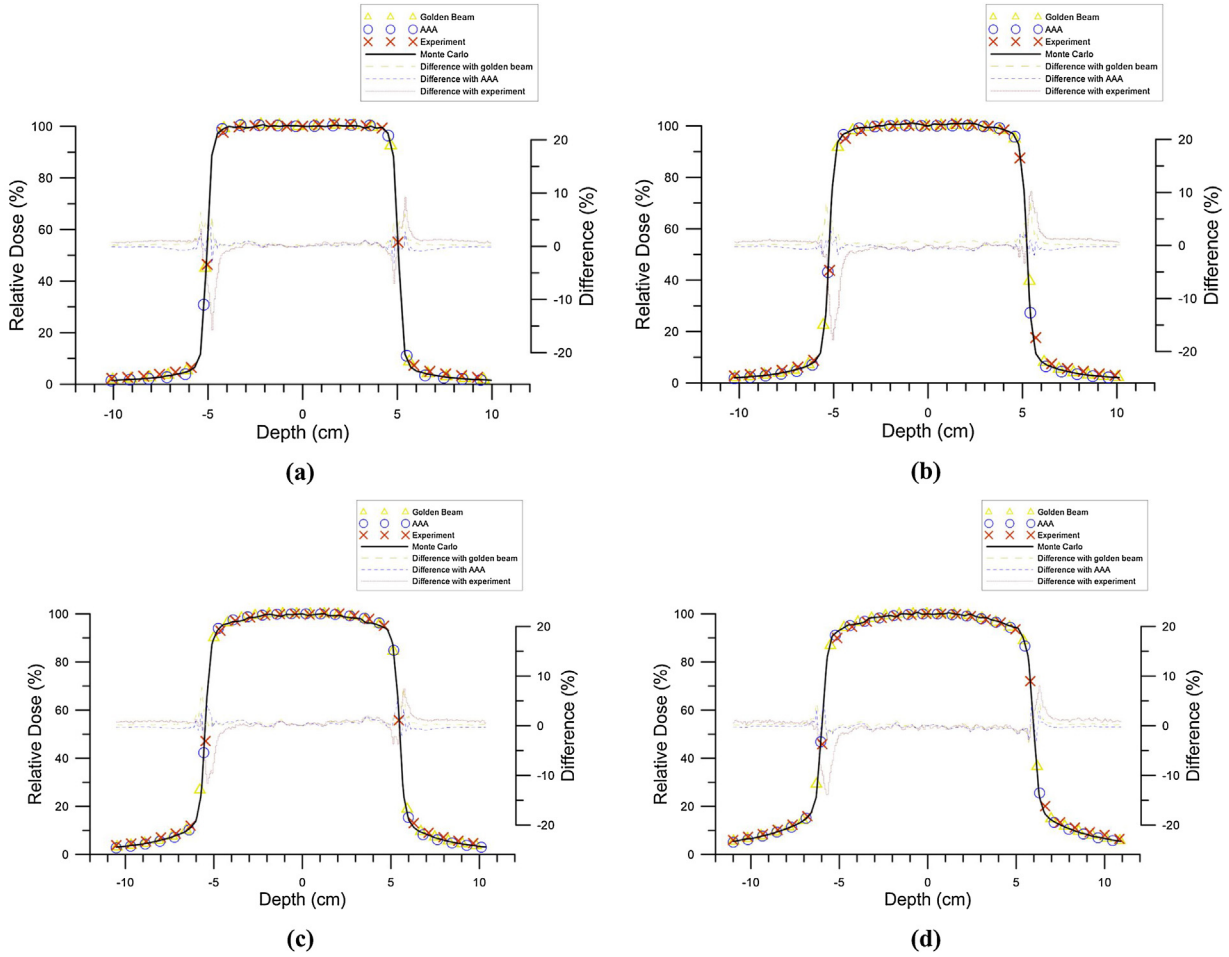

Fig. 5. Cross-plane beam profile compared for the field size $10 \times 10\,cm^2$ at the depths: (a) 1.5 cm; (b) 5 cm; (c) 10 cm; and (d) 20 cm.

Table 11
Absolute dose compared for field size $10 \times 10\,cm^2$.

Depth (cm)	Non MLC			MLC		
	Simulation (Gy)		Experiment (Gy)	Simulation (Gy)		Experiment (Gy)
	Dose	2 σ	Dose	Dose	2 σ	Dose
1.5	0.9692	0.0066	0.9692	0.9714	0.0066	0.9714
5	0.8284	0.0055	0.8373	0.8334	0.0055	0.8386
10	0.6403	0.0055	0.6464	0.6424	0.0055	0.6464
20	0.3663	0.0033	0.3701	0.3687	0.0033	0.3736

Table 12
Absolute dose compared for field size $20 \times 20\,cm^2$.

Depth (cm)	Non MLC			MLC		
	Simulation (Gy)		Experiment (Gy)	Simulation (Gy)		Experiment (Gy)
	Dose	2 σ	Dose	Dose	2 σ	Dose
1.5	0.9938	0.0065	0.9928	1.0252	0.0067	1.0242
5	0.8657	0.0054	0.8691	0.8919	0.0056	0.8954
10	0.6880	0.0054	0.6943	0.7087	0.0056	0.7133
20	0.4178	0.0043	0.4226	0.4299	0.0044	0.4342

4.1. Relative dose

The PDD curve is divided into two parts. The first part is from the surface of water to the depth of dose maximum, called the build-up region. The other part is the equilibrium region, which are the depths after dose maximum. The PDD was determined up to 30 cm under the surface of water phantom. Fig. 4 shows that the differences are bigger in the build-up region than in the equilibrium region. This is because in the build-up region there are free electrons interacting with Compton scattering, photoelectric effect, and pair production. High energy electrons will be ejected when a high energy photon interacts with water. These electrons will deposit their energy to the water, as explained in our previous article.[24]

PRIMO simulation of PDD agreed well with the experiment, AAA calculation, and golden beam with over 96.55% passing the gamma criteria, except for in comparison with the experiment at the field size $40 \times 40\,cm^2$. The poorer gamma agreement with the field size $40 \times 40\,cm^2$ was probably caused by the length limitation of IBA blue phantom, making it not appropriate for scanning beam profiles up to 40 cm.

There are two kinds of beam profiles, a cross-plane beam profile in the X axis direction and an in-plane beam profile in the Y

Table 13
Absolute dose compared for field size $40 \times 40\,cm^2$.

Depth (cm)	Non MLC		
	Simulation (Gy)		Experiment (Gy)
	Dose	2 σ	Dose
1.5	1.0196	0.0064	1.0166
5	0.8996	0.0054	0.8972
10	0.7312	0.0054	0.7263
20	0.4632	0.0043	0.4588

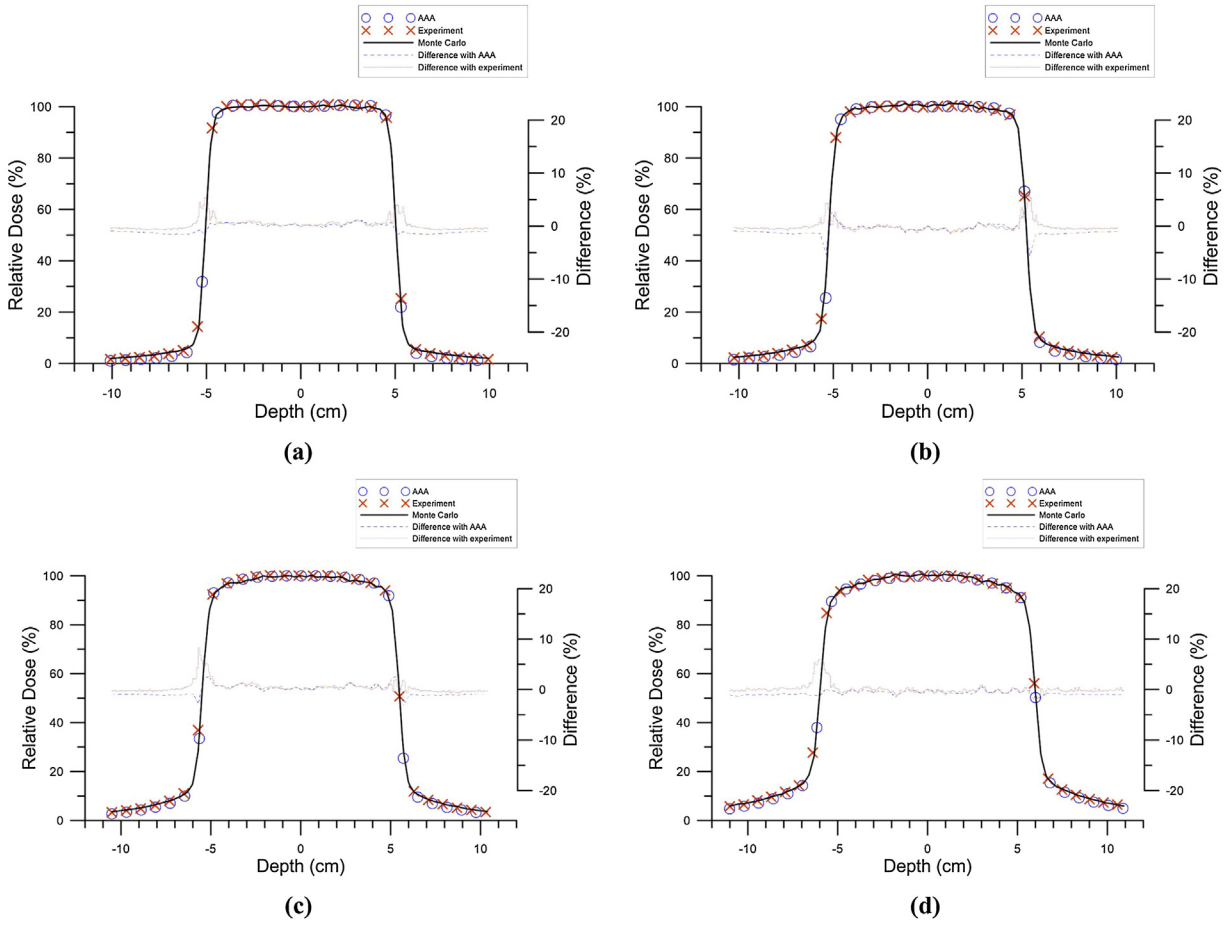

Fig. 6. In-plane beam profiles compared for field size $10 \times 10\,cm^2$ at the depths: (a) 1.5 cm; (b) 5 cm; (c) 10 cm; and (d) 20 cm.

axis direction. The beam profile curve is further divided into three regions, namely the inside field region, the penumbra region where the dose falls rapidly towards the beam edge, and the outside field region out of the field. Dose difference is higher in the penumbra region than in the inside field and the outside field regions, as shown in Figs. 5 and 6. This is probably so because a lower number of simulated particles will be found in the penumbra region, and this will cause large stochastic fluctuations in the MC simulation and influence the gamma index.[32,33]

The PRIMO simulations of the cross-plane beam profiles had a better agreement with AAA calculations than with experimental measurements. The PRIMO simulations of the cross-plane beam profiles had the poorest agreement with experimental measurements, which in turn had a good agreement with AAA calculations and golden beam of the cross-plane beam profiles. PRIMO simulation had a better than 87% agreement (i.e., passing the gamma criteria) with AAA calculations, as shown in Table 6.

Experimental measurement of the cross-plane beam profiles deviate from the ideal profiles. These beam profiles should be examined further, as they may contribute to inaccurate measurements of the LINAC configuration itself. Inaccurate beam profiles cause discrepancies with commissioning beam reference data, which is ultimately used by TPS. It will cause dosimetric characteristics of TPS not compatible with the real dose distribution received by patients.

4.2. Absolute dose

PRIMO simulation produces the absolute dose in electron-volts per gram (eV/g), and conversion to Gray (Gy) units is possible using the monitor backscatter factor.[30] Absolute dose at 1.5 cm depth in field size $10 \times 10\,cm^2$ was determined using the SSD technique as 0.9692 Gy for both simulation and experimental measurement, while it is 1 Gy using the SAD technique. This is because the different positions of ionization chamber, as shown in Fig. 3, as the dose in the SSD technique decreases by the inverse-square law. The absolute dose was higher with Multi-leaf Collimator (MLC) than without it. This is because the MLC scattered radiation. In bigger field sizes the differences were much larger.

The good agreement in this work between the PRIMO simulations and experimental measurements of absolute dose with MLC show that the MLC model in the PRIMO code is precise and appropriate for use as a patient-specific QA of IMRT and VMAT plan. Moreover, the PRIMO code could be more practical than that in a recent publication.[34]

5. Conclusions

PRIMO simulations were in a good agreement with experimental measurements, AAA calculations, and golden beam in PDD and in-plane beam profiles. However, the PRIMO simulations had the poorest agreement with experiments in the cross-plane beam profiles. This probably indicates that the cross-plane beam profiles in experimental measurements deviate from the ideal profiles.

PRIMO simulation of the absolute dose (±0.8% uncertainty) was in a good agreement with the experimental measurements. The TrueBeam STx Varian LINAC with MLC had more scattered radiation than without the MLC and gave higher absorbed dose in the ionization chamber or scoring region. This study indicates that the

PRIMO code can be used as a tool for checking the credibility of measurements in initial commissioning and routine QA (beam scanning and output). Moreover, superior to golden beam data, PRIMO simulation results provide dose distribution in three dimensions.

Financial disclosure

None declared.

Conflict of interest

None declared.

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