Original Article

Validation of PRIMO Monte Carlo Model of Clinac®iX 6MV Photon Beam

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Abstract

Purpose: This study aims to model 6MV photon of Clinac®iX linear accelerator using PRIMO Monte Carlo (MC) code and to assess PRIMO as an independent MC-based dose verification and quality assurance tool. **Materials and Methods:** The modeling of Clinac®iX linear accelerator has been carried out by using PRIMO simulation software (Version 0.3.1.1681). The simulated beam parameters were compared against the measured beam data of the Clinac®iX machine. The PRIMO simulation model of Clinac®iX was also validated against Eclipse® Acuros XB dose calculations in the case of both homogenous and inhomogeneous mediums. The gamma analysis method with the acceptance criteria of 2%, 2 mm was used for the comparison of dose distributions. **Results:** Gamma analysis shows a minimum pass percentage of 99% for depth dose curves and 95.4% for beam profiles. The beam quality index and output factors and absolute point dose show good agreement with measurements. The validation of PRIMO dose calculations, in both homogeneous and inhomogeneous medium, against Acuros® XB shows a minimum gamma analysis pass rate of 99%. **Conclusions:** This study shows that the research software PRIMO can be used as a treatment planning system-independent quality assurance and dose verification tool in daily clinical practice. Further validation will be performed with different energies, complex multileaf collimators fields, and with dynamic treatment fields.

Keywords: Clinac iX, Monte Carlo simulation, PENELOPE, PRIMO

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Introduction

In the case of radiotherapy treatment planning, a continuing advancement is observed in mathematical and computational techniques which aim at highly accurate dose calculations.

The continuous evolution of dose calculation algorithms has led to significant improvement in accuracy in the presence of tissue inhomogeneity.[1] The AAPM TG-65 report[2] suggests that the accuracy in tissue inhomogeneity correction should reach a level of 2%, but it is difficult to achieve with many currently used algorithms,[3] particularly in heterogeneous patient tissues where the effects of electron transport cannot be accurately handled with conventional, deterministic dose algorithms.[4] In the case of treatment plan protocol development and multi-institutional quality assurance audits, it is very crucial to assess the dose calculation accuracy of the algorithm available as the accuracy of the dose reported affects the result of the study.

In order to increase the accuracy, Monte Carlo (MC)-based calculations have been tried for the simulation of radiation dose delivery since the 1980s.[5] Many studies conclude that MC simulation techniques are the gold standard for radiation-absorbed dose calculation.[6,7] MC techniques are capable of giving highly accurate results for the spatial distribution of absorbed dose in heterogeneous media and thus have been considered a benchmark for dose calculation accuracy.[5,7,8]

The main disadvantage of MC is its long calculation time required to achieve an acceptable statistical uncertainty in dose distribution.[8] However, after the development of fast MC codes such as Macro MC,[9] Voxel MC,[10] and dose planning method (DPM),[11] which use a lot of variance reduction techniques, the calculation becomes much faster compared

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to general-purpose MC codes such as EGSnrc. The recently introduced algorithm Acuros® XB (Varian Medical Systems, Palo Alto, CA, USA) is considered a fast and accurate alternative to MC for patient dose calculation.[12] The validation of Acuros® XB in heterogeneous medium against MC has been carried out by many researchers.[13,14]

PRIMO[15] is a software solution that allows performing the MC simulations of most of the medical linear accelerators. It is a program based on the codes PENELOPE,[16,17] PENEASY,[18] and PENEASYLINAC.[19] The program for fast MC simulation of coupled electron and photon transport called DPM is also incorporated in PRIMO. A graphical user interface encompasses all these components in a single user-friendly environment. PRIMO can be used for the full MC simulation of most Varian and Elekta linacs and the estimation of the dose distribution in water phantoms and computed tomography (CT). The linac geometries are part of the package, so the user need not input the details of the geometry and materials of the linac head. The user has to input the values of primary electron beam energy, energy Full Width at Half Maximum (FWHM), focal spot FWHM, and beam divergence to begin the simulation. The code suggests a set of default values for initial beam parameters which can be fine-tuned until the best match between simulated and physical measurements is achieved. It is possible to select the parameters of the treatment fields, such as number, size, presence or absence of multileaf collimators (MLC), type of MLC, and type of electron applicator. It is also possible to import a treatment plan from an external treatment planning system (TPS) into PRIMO.

The variance reduction techniques available in PRIMO help to reduce the simulation time and the statistical uncertainties associated with the simulation. There is an option to select appropriate variance reduction techniques,[20] such as movable skins technique, splitting roulette, rotational splitting, and fan splitting.[21,22] PRIMO allows the import of CT of a patient or a phantom. It is also possible to create a slab phantom with various materials provided by PRIMO.

A voxelized simulation geometry consisting of a set of material and mass density value pairs has to be generated prior to any simulation.[23] The volume segmentation is done by assigning a material to a CT number interval.[23] Up to ten materials, selected from a list of forty, can be assigned to a CT volume. Graphical and numerical tools for the analysis of both phase-space files and dose distributions are incorporated in PRIMO. The analysis tools include an option to analyze DVH and dose profiles and to compare experimental dose measurements with the MC-estimated dose distributions using the gamma index.[24]

Very few studies have been published on the validation of PRIMO MC code.[25-27] This study aims to model 6MV photon of Clinac®iX linear accelerator by fine-tuning the default initial beam parameters of PRIMO MC code.

Materials and Methods

PRIMO simulation software Version 0.3.1.1681 (https://www.primoproject.net) was used in this study. The full MC simulation of Clinac®iX (Varian Medical Systems, Palo Alto, USA) linear accelerator was carried out using PRIMO. The study was carried out in two stages. In the first stage, the simulated model of Varian Clinac®iX linear accelerator has been validated by comparing the simulated percentage depth dose (PDD) and beam profile curves against the measured data.

Simulation setup

In order to perform the simulations, the Varian Clinac 2300 model was selected from the list of linear accelerators available in PRIMO. A water phantom with dimensions of 40 cm × 40 cm × 30 cm (x, y, and z) defined in PRIMO was used to tally the dose. The simulation was started with the default set of parameters available in PRIMO for 6 MV photon beam. In PRIMO, the primary electrons hitting the target is defined as a Gaussian distribution. The default parameters of 6 MV photon beam for Clinac 2300 model in PRIMO consist of an electron beam with an initial energy of 5.4 MeV with an energy FWHM of 0.05 MeV, the focal spot size of 1 mm, and a beam divergence of 1°. The Source to Surface Distance (SSD) and field size were fixed at 100 cm and 10 cm × 10 cm, respectively. The initial energy of the electron beam was changed, and simulation was repeated in an iterative process till the simulated PDD curve coincided with the measured curve. After optimization of initial energy, the focal spot size, energy FWHM, and beam divergence values were adjusted to achieve the closest matching to measure the beam profile. The measured transverse beam profile for 10 cm × 10 cm field at 10 cm depth was used for analysis.

A total of 5×10^8 primary photons were simulated. PRIMO allows tallying a phase-space file at three positions. The first one at the lower end of the upper part of the linear accelerator above the jaws, identified in PRIMO as segment-1 (s1). Phase-space file can also be tallied at the downstream end of the linear accelerator which consists of sets of jaws and possibly a multileaf collimator. This region is identified as segment-2 (s2) in PRIMO. The s2 stage uses the phase-space file created at segment-1 (s1) as the radiation source. Both the s1 and s2 steps provide an International Atomic Energy Agency (IAEA)-formatted phase space file as the output. The geometric region corresponding to the patient or phantom, in which the absorbed dose is estimated, is called segment-3 (s3). The last stage, s3, uses the phase-space file created at segment-2 (s2) for the simulation of three-dimensional (3D) dose distribution. In the segment s3, a homogeneous water phantom with dimensions of 40 cm × 40 cm × 30 cm with a bin size of 2 mm × 2 mm × 1 mm was constructed to tally the dose. The different segments of the linac simulation are shown in Figure 1.

The maximum number of bins is limited to 10^8 in PRIMO simulations. The uncertainty associated with the mean dose per history and the time needed to achieve a given uncertainty depend on voxel size.[19] Voxel size and number of primary histories have to be optimized to obtain statistical

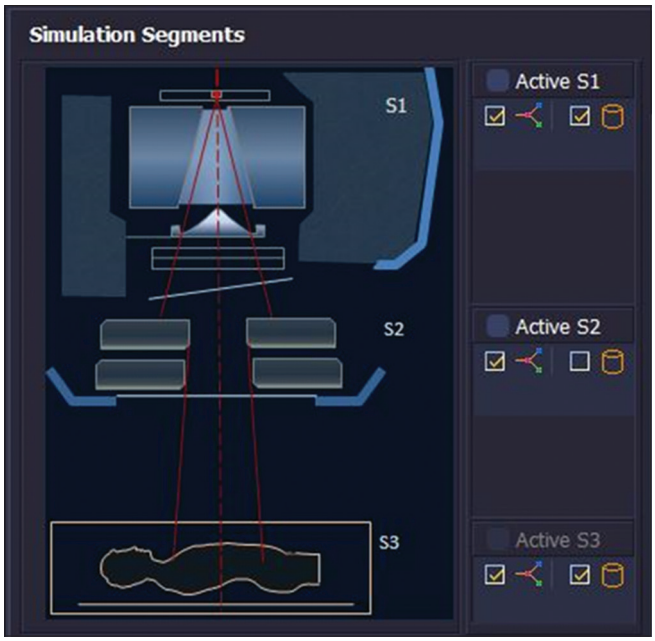

Figure 1: Different segments of PRIMO simulation

uncertainties below 2% in suitable calculation time. To get high spatial resolution in the dose build-up region when analyzing the PDD curve, a bin size of 1 mm was chosen in the Z direction. A bin size of 2 mm × 2 mm in the lateral directions was found adequate for evaluating the dose profiles in the penumbra region. PRIMO requires to define a set of simulation parameters called transport parameters.[23] In this work, the default values provided by PRIMO have been used for simulation. Transport parameters used in the simulations were as follows: C1 = C2 = 0.1, WCC = 200 KeV, and WCR = 200 KeV. C1 and C2 control the cutoff for elastic collisions; WCC and WCR are the cutoff values for inelastic and bremsstrahlung interactions, respectively. The cutoff energies for electrons, positrons, and photons are set to E_{abs} (e−) = E_{abs} (e+) = 200 KeV and E_{abs} (ph) = 50 KeV.

Variance reduction techniques and simulation efficiency

When simulating linac parts (s1 and s2), one can choose between splitting roulette, rotational splitting, or no splitting as a variance reduction technique.[28] According to the authors of the PRIMO code, splitting-roulette is recommended for nominal energies below 15 MV, and rotational splitting is usually more efficient for nominal energies above 15 MV.[20,23] Early work done by Rodriguez *et al*. reports that splitting-roulette improves the simulation efficiency by a factor of 45 for a simplified geometry of an Elekta linac and a water phantom.[20] The splitting-roulette technique used in this study is a combination of particle splitting and Russian roulette.[20] To analyze the contribution of variance reduction technique in simulation efficiency, the simulation of 10 cm × 10 cm field was repeated without choosing splitting-roulette and by keeping all other simulation parameters same. A comparison of PDD curves with and without splitting-roulette was made. A suitable combination of forcing of bremsstrahlung interactions in the linear accelerator target and simple splitting in the water phantom or the CT improves the simulation efficiency considerably.[23] In order to apply simple splitting in the water phantom or the CT, a splitting factor between 100 and 300 needs to be applied.[23] An optimum value of the splitting factor has to be found in an iterative process. Other variance reduction techniques used in PRIMO have been tuned up by the authors of the code and the user cannot make any change on them. The simulations were performed in a Dell Precision T5600 CPU with 32 GB of RAM, and 24 CPU cores with 2.0 GHz speed. The CPU time taken to simulate 5×10^8 primary photons was 8.57×10^5 s (≈10 days).

In PRIMO, the simulation efficiency ε is calculated using Equation (1) as follows:

$$\varepsilon = \frac{1}{\Delta^2 t} \quad \text{Eq. (1)}$$

where Δ is the average statistical uncertainty achieved in a simulation time of t seconds. PRIMO reports the average statistical uncertainty (at 2 standard deviations) of all voxels, accumulating more than 50% of the maximum absorbed dose.[23]

Absolute dose calibration in PRIMO

PRIMO reports dose in units of eV/g per primary particle. The PRIMO allows the conversion from eV/g to Gy. The dose (D) in Gy, for a single fraction of a given treatment plan, is given by the following expression:

$$D = \frac{D_{exp}^{ref}}{MU^{ref}} \frac{D_{MC}}{D_{MC}^{ref}} MU \quad \text{Eq. (2)}$$

where D_{exp}^{ref} is the dose in Gy measured in reference conditions (100 cm SSD, 10 × 10 cm² field size, 10 cm depth) in a water tank phantom. D_{MC}^{ref} is the dose estimated by a MC simulation (in eV/g per history) in reference conditions. MU^{ref} is the reference monitor units used to obtain the measured reference dose. D_{MC} is the simulated dose (in eV/g per history) for the treatment plan, and MU is the monitor units of the plan.

Simulation of percentage depth dose and profiles

The PDD curves were simulated in PRIMO for field sizes 4 cm × 4 cm, 6 cm × 6 cm, 8 cm × 8 cm, 10 cm × 10 cm, 15 cm × 15 cm, 20 cm × 20 cm, and 30 cm × 30 cm at 100-cm SSD. The transverse dose profiles at various depths (viz., d_{max}, 5.0 cm, 10.0 cm, and 20.0 cm) were simulated for the field size 10 cm × 10 cm at 100-cm SSD. The transverse dose profiles at a depth of 10 cm were simulated for field sizes 4 cm × 4 cm, 6 cm × 6 cm, 8 cm × 8 cm, 15 cm × 15 cm, 20 cm × 20 cm, and 30 cm × 30 cm at 100-cm SSD. The simulated curves were compared against the measured data using the gamma index evaluation tool available in PRIMO.

A water phantom with dimensions of 40 cm × 40 cm × 30 cm (x, y, and z) defined in the S3 segment of PRIMO was used to tally the dose. The phantom has a bin size of 0.2 cm × 0.2 cm × 0.1 cm (x, y, and z). The physical

measurement of PDD curves and beam profiles were carried using a computer-controlled three-dimensional (3D) water phantom (Blue Phantom®, IBA, Germany). PDD curves were measured at 100-cm SSD for field sizes of 4 cm × 4 cm, 6 cm × 6 cm, 8 cm × 8 cm, 10 cm × 10 cm, 15 cm × 15 cm, 20 cm × 20 cm, and 30 cm × 30 cm. Transverse dose profiles were measured at various depths (viz., d_{max}, 5.0 cm, 10.0 cm, and 20.0 cm) for field sizes of 4 cm × 4 cm, 6 cm × 6 cm, 8 cm × 8 cm, 10 cm × 10 cm, 15 cm × 15 cm, 20 cm × 20 cm, and 30 cm × 30 cm. Cylindrical ion chamber (CC-13, IBA Dosimetry, Germany) was used for PDD and profile measurements. All PDD and profile measurements were repeated twice to minimize systematic uncertainties due to the machine and phantom settings. The accuracy of measured data was verified against data acquired at the time of commissioning the machine. The measured curves were converted to ASCII format using Omnipro Accept® (IBA Dosimetry, Germany) software. The ASCII file was then converted to a *. dat text file composed of X, Y, and Z and dose information. The measured PDD and profiles in the *.dat format were then imported into PRIMO for numerical and gamma analysis. In order to quantify the level of agreement/disagreement between measured and simulated curves, gamma analysis method was chosen.[24] The percentage difference between measured and simulated PDD values was calculated using Equation (3). The CC-13 cylindrical ion chamber (IBA Dosimetry, Germany) with an active volume of 0.13 cc was used for absolute dose measurements.

$$\%Diff = \frac{\left(PDD_{\text{measured}} - PDD_{\text{Monte Carlo}}\right)}{PDD_{\text{measured}}} \times 100 \quad \text{Eq. (3)}$$

Beam quality verification

In order to verify the beam quality index,[29] tissue–phantom ratio in a water phantom at depths of 20 and 10 g/cm^2 was calculated from the PRIMO simulations and compared with measurements. A water phantom with dimension 30 cm × 30 cm × 30 cm created using PRIMO was used for simulation.

Simulated TPR was obtained using the following relation:[30]

$$TPR_{20}/_{10} = 1.2661 \times PDD_{20}/_{10} - 0.0595 \quad \text{Eq. (4)}$$

where $PDD_{20/10}$ is the ratio of ionization at depths of 20 cm and 10 cm, obtained from the simulated PDD for the field size 10 cm × 10 cm.

Output factor verification

An absolute dose calibration was obtained using Equation (2). In order to verify the absolute dose reported by PRIMO, output factors were calculated from the simulation results by taking the ratio of the dose of a given field size to the dose of the reference field size at 100-cm SSD, both at a depth of 5 cm along the central axis. Output factors were calculated for square field sizes ranging from 4 cm × 4 cm to 30 cm × 30 cm with field size 10 cm × 10 cm as reference. Cylindrical ion chamber (CC-13, IBA Dosimetry) was used to obtain the measured value of the output factor from the linac. An average of three measurements was taken in output dose measurements.

PRIMO simulation of a three-dimensional-conformal radiotherapy plan

After the analysis of simulated beam parameters against the measured data, the generated phase-space file was used as a valid model of the 6 MV beam produced by the linear accelerator unit Clinac®iX operating at our center. The model was used in all the subsequent PRIMO simulations performed in this work. In order to compare the simulated model against TPS, a conformal radiotherapy plan was simulated using PRIMO. The water-equivalent I'mRT® verification phantom (IBA Dosimetry, Germany) was used in this study. A CC-13 ionization chamber was placed at the center of the phantom. The CT images of the I'mRT® verification phantom with a slice thickness of 2.5 mm were obtained with a GE Optima®580 CT scanner (GE Healthcare, USA). The CT data set was imported into Eclipse® TPS (Varian Medical System, Palo Alto, CA, USA). Circle-shaped PTV structure was drawn in the axial CT images of the phantom around the CC-13 chamber, with a diameter of 8 cm and length of 10 cm. A four-field 3D-conformal plan was created, with CC-13 chamber at isocenter, for 6 MV beam of Clinac®iX machine. The dose calculations were performed in Eclipse® TPS for a fixed monitor units of 100 from each beam. Acuros®XB (Varian Medical System, USA) algorithm was used for calculations, and the dose report mode selected in this study is dose to medium.[12] The generated DICOM files (plan, dose, structure, and images) were then imported in PRIMO for MC calculations. A voxelized simulation geometry must be generated previous to any simulation.[23] This geometry consists of a set of material and mass density value pairs. The CT scanner calibration curve is used for assigning mass densities to CT numbers. Default curve provided in PRIMO is edited, and the same CT to electron density conversion values were used both in Eclipse and PRIMO. The validated phase space file of Clinac iX for the 6 MV beam was used for simulation. Gamma analysis was performed to compare the simulated dose distribution against the TPS dose. The absolute point dose at the center of PTV volume reported by PRIMO was compared against measurements. The active volume of the chamber (0.13 cc) was contoured as a structure, to get the mean dose received by the ion chamber from PRIMO simulation and from TPS.

Heterogeneous interface phantoms

In order to validate PRIMO dose calculation in heterogeneous regions, a multi-slab virtual phantom geometry was created in Eclipse® with the manual assignment of materials using Acuros®XB physical material data table (Version 13.5) available in Eclipse. A virtual water phantom (HU = 0, density = 1 g/cm^3) of size 20 cm × 20 cm × 20 cm with two 18 cm × 18 cm square insert positioned at 4.0 cm and 12.0 cm depths was created with the following HU and density values assigned to the inserts.

- Insert A: A very low-density lung insert of thickness 4 cm, HU = −975, density = 0.0104 g/cm^3
- Insert B: A bone insert of thickness 4 cm, HU = 1488, density = 1.85 g/cm^3.

The plan was generated in Eclipse for a 6 MV photon beam of field 10 cm × 10 cm incident on the phantom surface. Dose calculations were performed using the Acuros® XB algorithm for 500 monitor units. The generated DICOM files (plan, dose, structure, and images) were then imported in PRIMO for MC calculations. The simulated and Acuros® XB calculated central axis depth dose curves were compared.

Lung computed tomography dataset

In order to investigate the accuracy of dose deposition in realistic anatomical geometries, the simulations were carried out on the CT data set of a lung patient with a tumor mass in the right lung. A plan with a parallel opposed 6 MV beam of field size 14.5 cm × 11.0 cm incident on the tumor mass was generated in Eclipse® TPS. Dose calculations were performed using the Acuros® XB algorithm. The above plan was transferred from Eclipse to PRIMO, and doses were recalculated while maintaining the TPS-calculated MUs and beam arrangement. The simulated lateral dose profile in the isocenter planes in axial and sagittal views was compared against TPS data. The mean dose to PTV, left lung, and right lung was compared against TPS value. Gamma analysis was also performed to compare the dose distributions.

Analysis

The validation of the phase space file was performed by comparing the measured and the simulated PDDs and profiles at different depths for the various field sizes considered.

PRIMO has built-in analysis tools for comparing experimental dose distribution against the simulation. A provision for Gamma analysis is also incorporated in this tool. The PDD and profile curves in the text format were imported to PRIMO code for comparison using gamma analysis method proposed by Low *et al*.[24] The measured data were used as a reference.

For an experimental point p and the dose at that point $d_e(p)$, the gamma index, Γ, is calculated as

$$\Gamma = min\left\{\sqrt{\left(\frac{\Delta d_i}{\Delta D}\right)^2+\left(\frac{\Delta s_i}{\Delta S}\right)^2}\right\} \qquad \text{Eq. (5)}$$

where Δ D and Δ S are the acceptance criteria for the dose difference and for the distance-to-agreement (DTA), respectively. Δd_i is the difference between $d_e(p)$ and the simulated dose at a certain point p_i. Δs_i is the distance between p and p_i. Gamma analysis with acceptance criteria of 2 mm DTA and 2% dose difference was conducted to verify simulation results. The tolerance level for the percentage of points passing the above criteria was set to 95%. These were the parameters used by various authors in the validation of phase-space files for MC dose calculations.[31,32]

Results

Tuning of initial beam parameters

The simulation was started with default values of initial beam parameters available with PRIMO. However, the simulation results could not adapt with the measured data. For PDD curves, the parameter that most affects the result is the initial energy of the electron beam. The simulation was repeated by changing the initial energy from 5.40 MeV to 6.20 MeV in steps of 0.1 MeV, by keeping other parameters constant. A good agreement between measured and simulated PDD curve for 10 cm × 10 cm field was obtained for an initial electron energy value of 5.95 MeV. A similar approach was applied to find the value of focal spot size FWHM by varying the value from 0.8 mm to 1.5 mm in steps of 0.1 mm. The values of energy FWHM and beam divergence values were adjusted iteratively until the closest match between the measured and simulated transverse profiles was obtained for 10 cm × 10 cm field at 10-cm depth. Energy FWHM value was changed from 0 to 0.25 MeV in steps of 0.05 MeV. The beam divergence was adjusted from 1° to 2° in steps of 0.5°. The maximum conformity between the measured and simulated curves was obtained by using the values listed in Table 1. The average statistical uncertainty reported by PRIMO at two standard deviations was around 1% (range over all the simulations 0.99%–1.44%).

The results of the comparison of PRIMO simulation for a 10 cm × 10 cm field with and without applying the variance reduction technique "splitting-roulette" are summarized in Table 2. The results show that splitting-roulette offers a significant improvement in photon simulation efficiency. Statistical uncertainty Δ achieved in a given amount t of simulation time can be substantially reduced. A comparison of PDD curves generated by PRIMO for 10 cm × 10 cm field with and without splitting-roulette is shown in Figure 2.

Comparison of depth dose curves

Statistical uncertainties in simulation results were 0.99% for 10 cm × 10 cm field. The average statistical uncertainties reported by PRIMO for the 20 cm × 20 cm and 30 cm × 30 cm simulated fields were 1.15% and 1.44%, respectively. Large fields require a larger number of histories to reach the same statistical uncertainty.

Table 1: Validated initial simulation parameters for a photon beam of nominal energy 6 MV

Initial energy (MeV)	Energy FWHM (MeV)	Focal spot FWHM (mm)	Beam divergence (°)
5.95	0.2	1.2	1.5

FWHM: Full Width at Half Maximum

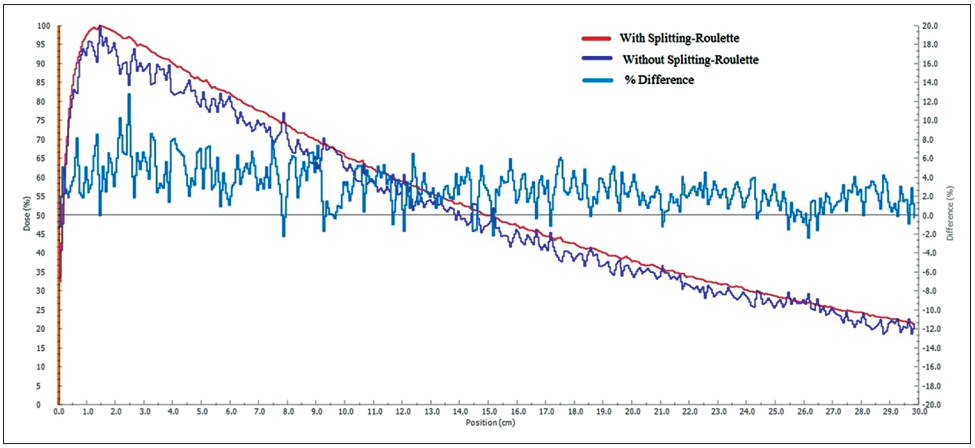

Figure 2: PDD curves generated by PRIMO for 10 cm ×10 cm field with and without splitting- roulette

Table 2: Comparison of photon simulation efficiency with and without variance reduction

Variance reduction technique	Field size (cm^2)	Number of histories	Time (h)	Statistical uncertainty (Δ)%	Efficiency (ε)
Splitting-roulette	10×10	5×10^8	238.06	0.999	117×10^{-8}
None	10×10	5×10^8	311.94	7.697	1.50×10^{-8}

Table 3: Comparison of Monte Carlo simulated percentage depth dose curves with measured value

Field size (cm^2)	PDD (10-cm depth)			PDD (20-cm depth)			Range at 50% dose (cm)		
	Measured	MC calculated	Difference (%)	Measured	MC calculated	Difference (%)	Measured	MC calculated	Difference (%)
4×4	61.73	61.68	0.05	33.4	33.16	0.24	13.37	13.32	0.37
6×6	63.77	63.16	0.61	35.3	34.88	0.42	14.12	14.1	0.14
8×8	65.37	64.83	0.54	36.7	36.51	0.19	14.7	14.65	0.34
10×10	66.53	65.82	0.71	38.28	37.82	0.46	15.19	14.98	1.38
15×15	68.0	67.66	0.34	40.5	40.4	0.10	16	16.02	−0.12
20×20	69.53	69.08	0.45	42.4	41.9	0.50	16.7	16.44	1.56
30×30	70.87	70.49	0.38	44.19	43.66	0.53	17.56	17.5	0.34

MC: Monte Carlo, PDD: Percentage depth dose

Table 4: Gamma analysis of percentage depth dose curves

Field size (cm^2)	Average gamma index before maximum	Average gamma index after maximum	Percentage of points passing the criteria (2%, 2 mm)
4×4	0.23	0.09	99.69
6×6	0.26	0.13	99.67
8×8	0.27	0.13	99.67
10×10	0.37	0.20	99.92
15×15	0.38	0.12	99.68
20×20	0.52	0.24	99.65
30×30	0.59	0.26	99.01

The measured and simulated depth dose curves were normalized to dose maximum (d_{max}). Figure 3 shows the analysis of simulated and measured depth dose curves performed using the PRIMO analysis tool. A graphical comparison between the measured and the calculated PDDs for different field sizes is shown in Figure 4. A comparison of PDD values at 10 cm and 20 cm depths and the depth at which the dose falls to 50% of its maximum value (range at 50% of the dose) for the measured and the calculated field sizes is summarized in Table 3. The table shows that the maximum difference between the measured and simulated PDD is 0.7% at 10-cm depth and 0.5% at 20-cm depth. The gamma analysis with acceptance criteria of 2-mm DTA and 2% percentage dose difference shows a minimum pass rate of 99% between the measured and simulated curves. Both the measured data and the PRIMO simulation results were divided into two regions of interest: the build-up region

in which the dose reaches its maximum value at a depth d_{max} and the region beyond the d_{max}. The agreement between the two distributions within each of these two regions is reported. The result of the gamma analysis of simulated and measured PDD curves is summarized in Table 4. The result shows a pass percentage of 99% or above for all field sizes.

Comparison of dose profiles

The measured and simulated dose profiles were normalized to the central axis. Figure 5 shows the analysis of simulated and measured transverse dose profiles performed using the PRIMO analysis tool. A graphical comparison between the measured and the calculated transverse profiles for a 10 cm × 10 cm

Table 5: Gamma analysis of dose profiles for a field size of 10 cm × 10 cm at different depths

Depth (cm)	Average gamma index inside the field		Average gamma index in penumbra region		Average gamma index outside the field		Percentage of points passing the criteria (2%, 2 mm)	
	Transverse	Longitudinal	Transverse	Longitudinal	Transverse	Longitudinal	Transverse	Longitudinal
1.5	0.29	0.31	0.73	0.77	0.26	0.64	97.92	96.56
5	0.23	0.24	0.69	0.76	0.2	0.58	99.52	97.33
10	0.24	0.21	0.57	0.66	0.17	0.55	98.72	98.96
20	0.27	0.29	0.41	0.38	0.15	0.12	99.16	98.57

Table 6: Gamma analysis of dose profiles for different field sizes at 10-cm depth

Field size (cm^2)	Average gamma index inside the field		Average gamma index in penumbra region		Average gamma index outside the field		Percentage of points passing the criteria (2%, 2 mm)	
	Transverse	Longitudinal	Transverse	Longitudinal	Transverse	Longitudinal	Transverse	Longitudinal
4×4	0.37	0.33	0.64	0.54	0.05	0.08	98.66	98.24
6×6	0.38	0.32	0.6	0.49	0.05	0.07	97.83	98.03
8×8	0.22	0.28	0.57	0.36	0.09	0.12	97.57	97.32
10×10	0.24	0.21	0.57	0.66	0.17	0.55	98.72	98.96
15×15	0.31	0.25	0.5	0.52	0.32	0.36	99.56	99.18
20×20	0.53	0.56	0.51	0.49	0.37	0.32	96.05	96.02
30×30	0.58	0.63	0.63	0.68	0.47	0.52	95.86	95.39

Figure 3: Comparison of simulated depth dose curve against measurements for 10 cm × 10 cm field size. The results of the gamma analysis are also shown in the figure

field size at different depths is shown in Figure 6. Comparison between the measured and the calculated transverse profiles at 10-cm depth for field sizes varying from 4 cm × 4 cm to 30 × 30 cm is shown in Figure 7. The gamma analysis has been carried out for both transverse and longitudinal profiles with acceptance criteria of 2-mm DTA and 2% percentage dose difference. The results of gamma analysis of simulated and measured dose profiles for a field size of 10 cm × 10 cm at different depths are summarized in Table 5. The result shows good agreement between the two profiles with a minimum pass rate of 96.56% at 1.5-cm depth. The result of gamma analysis at 10-cm depth for field sizes varying from 4 cm × 4 cm to 30 cm × 30 cm is given in Table 6. The minimum pass rate is 97.3% for field sizes between 4 cm × 4 cm and 15 cm × 15 cm, 96% for 20 cm × 20 cm field, and 95.4% for 30 cm × 30 cm field. The gamma analysis result shows that for all the curves

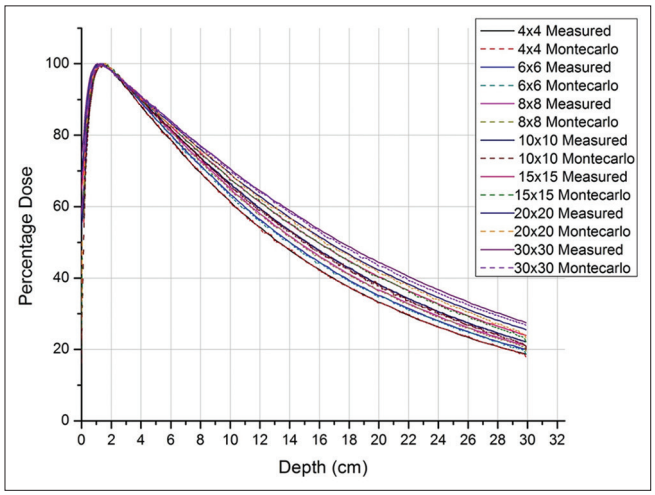

Figure 4: Comparison between the measured and the calculated PDDs

Table 7: Comparison of simulated and measured tissue-phantom ratio$_{20,10}$ values

Field size (cm²)	TPR$_{20,10}$ simulated	TPR$_{20,10}$ measured
10×10	0.668	0.669

TPR: Tissue–phantom ratio

Table 8: Comparison of simulated and measured output factors

Filed size (cm²)	Output factor		Error (%)
	Simulated	Measured	
4×4	0.920	0.927	0.76
6×6	0.957	0.957	−0.01
8×8	0.984	0.98	−0.38
10×10	1.000	1.000	0.00
15×15	1.034	1.038	0.42
20×20	1.059	1.054	−0.49
30×30	1.090	1.082	−0.78

Table 9: Comparison of absolute point dose

Mode	Calculated mean dose (Gy)	Measurement (Gy)	Difference (%)
PRIMO	2.75	2.72	1.10
TPS	2.80		2.94

TPS: Treatment planning system

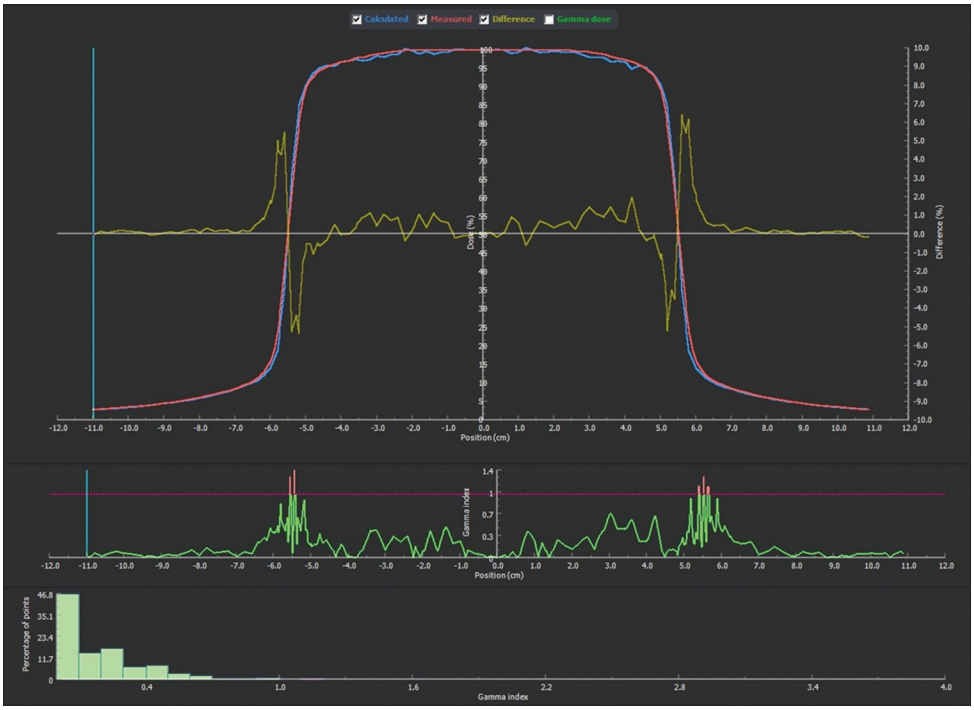

Figure 5: Comparative analysis performed in PRIMO for the transverse profile of a 10 cm × 10 cm field at 10-cm depth. The results of the gamma analysis are also shown in the figure

analyzed, more than 95% of the points pass the acceptance criteria of 2%, 2 mm.

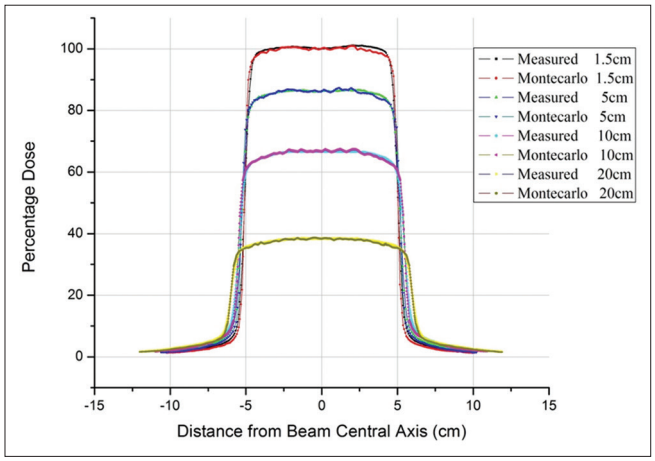

Figure 6: Comparison between measured and simulated transverse profiles at different depths for a 10 cm × 10 cm field size

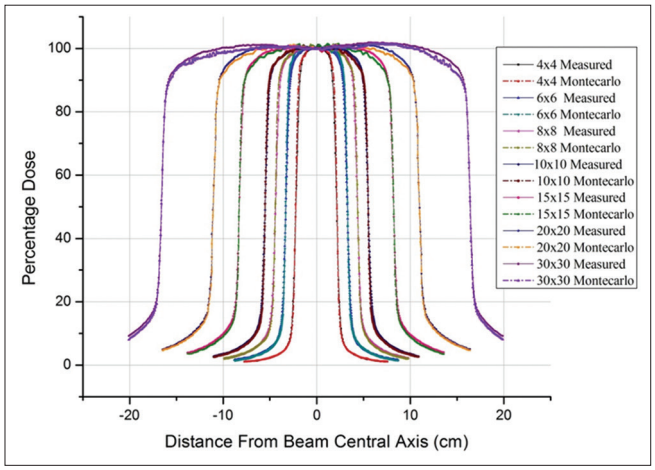

Figure 7: Comparison between measured and simulated transverse profiles at 10-cm depth for different field sizes

Beam quality index

The measured and MC simulated values of $TPR_{20,10}$ for 6 MV are given in Table 7. The deviation between measured and PRIMO simulated data for $TPR_{20,10}$ value is <0.2%.

Absolute dose and output factor

An absolute dose calibration factor of 0.0129 (Gy/MU/g/eV) was obtained using Equation (2).

Output factors show a good agreement between simulation and measurements with a maximum deviation of 0.78%. Table 8 shows the comparison of simulated and measured output factors at 5-cm depth for square fields. Statistical uncertainties in simulation results were below 1.5%.

Plan comparison

The gamma analysis results indicate good agreement between the PRIMO and TPS 3D dose distributions for the four-field plan. The analysis was performed for both the PTV and region inside body structure separately. The passing rates were 99.8% for the PTV and 99.7% for the region inside the body structure with 2%, 2-mm acceptance criteria. The comparison between simulated and TPS (Acuros XB® algorithm) dose distributions is shown in Figure 8. The comparison of the lateral dose profile in the axial plane between simulated and TPS dose distributions is also shown in Figure 8. The comparison of absolute dose measurement at the isocenter against PRIMO calculation and TPS (Acuros® XB) is given in Table 9. The difference between PRIMO and measurement is 1.1%. Difference between TPS and measurements is 2.94%.

Heterogeneous phantom simulations

The PDD curve for the multislab geometry has been generated with PRIMO and compared against Acuros® XB. The simulation results are shown in Figure 9. The gamma analysis (2%, 2 mm) shows good agreement in the build-up region and also within the lung and bone equivalent heterogeneities, with a maximum gamma index < 0.5. The results show that, PRIMO dose

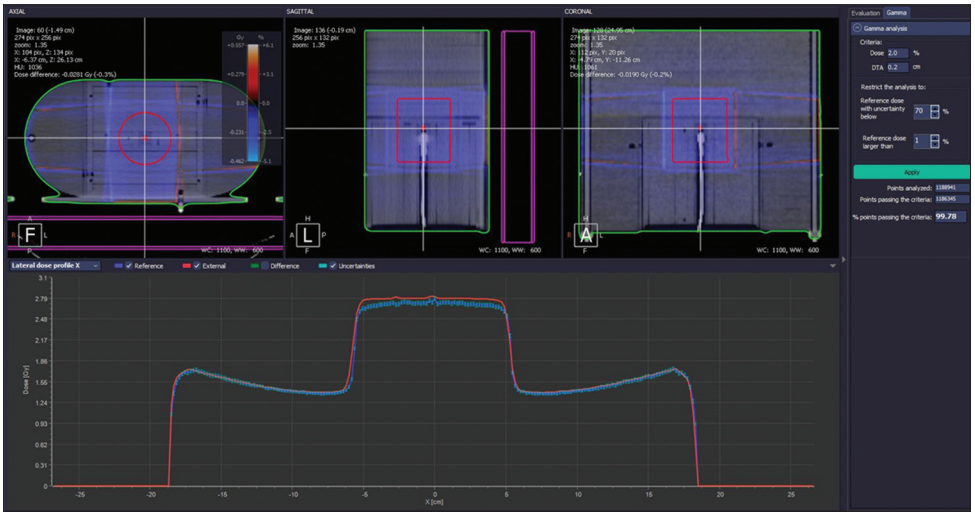

Figure 8: Comparison between the PRIMO and TPS dose calculations. The curves below represent the comparison of the lateral dose profile in the axial plane between the PRIMO (blue) and the TPS (red) dose distributions at the isocenter

distribution shows good agreement with TPS (Acuros XB®) in the presence of different heterogeneities.

Lung computed tomography plan

The MC simulation performed on the CT data set of a lung patient shows good agreement with Acuros® XB calculations. The simulated dose distribution in the axial, sagittal, and coronal isocenter planes is shown in Figure 10. The gamma analysis for the region inside the body structure (2%, 2 mm) shows a pass rate of 98.9%. The comparison of simulated and Acuros®XB calculated lateral dose profiles in the isocenter planes in axial, sagittal, and coronal views is shown in Figure 11: Acuros XB and PRIMO show good mutual agreement in dose profile comparison with a maximum deviation of 3% in the penumbra region. A comparison of the mean dose to different structures obtained from PRIMO simulation and TPS (Acuros® XB) is summarized in Table 10.

Table 10: Comparison of the mean dose to structures from PRIMO simulation and treatment planning system

Structure	Mean dose (cGy)		Difference (%)
	PRIMO	Acuros	
CTV	203.1	205	−0.94
PTV	200.6	203.5	−1.45
Lung			
Left	3.5	3.6	−2.86
Right	130.6	133.1	−1.91

PTV: Planning target volume, CTV: Clinical target volume

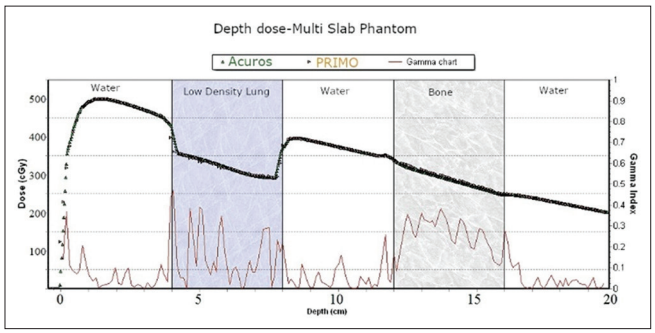

Figure 9: Central axis depth dose plot for the multislab heterogeneous geometry

Discussion

In this study, a 6 MV photon beam of Varian Clinac®iX accelerator has been simulated using PRIMO MC code. The maximum difference between the measured and MC simulated PDD values was 0.7%, and the gamma analysis of PDD curves shows a minimum pass rate of 99%. The agreement between simulated and measured lateral beam profiles was also good with a minimum pass rate of 95.4% for the gamma test. The difference observed in the penumbra region between simulated and measured lateral beam profile scans can be minimized by using small-volume detector for measurement, instead of the CC-13 ionization chamber used in this study. The simulated Beam Quality Index ($TPR_{20,10}$) value shows good agreement with the measurement with a variation of 0.2%. Output factors at 5-cm depth obtained from the simulations agreed with the measured value within 0.78% for Clinac®iX. The validation of PRIMO conformal radiotherapy plan against Acuros® XB calculations in a homogeneous phantom shows a gamma analysis pass rate of 99.7%. The absolute dose comparison at the isocenter shows a variation of 1.1% between PRIMO and measurements. The PDD comparison between PRIMO simulation and Acuros XB calculations in the case of heterogeneous slab phantom geometry shows good agreement at the boundary and within the heterogeneous zones. A good agreement of 98.9% between simulated and experimental dose distributions was observed in the gamma test for the lung CT plan comparison. The lateral dose profile comparison and mean dose to target structures and lung also show good mutual agreement between PRIMO and TPS.

Conclusions

PRIMO is a convenient tool with a user-friendly interface to simulate medical linear accelerators without any coding effort. In this study, appropriate values of initial simulation parameters for 6 MV beam from Varian Clinac® iX were determined, and the MC

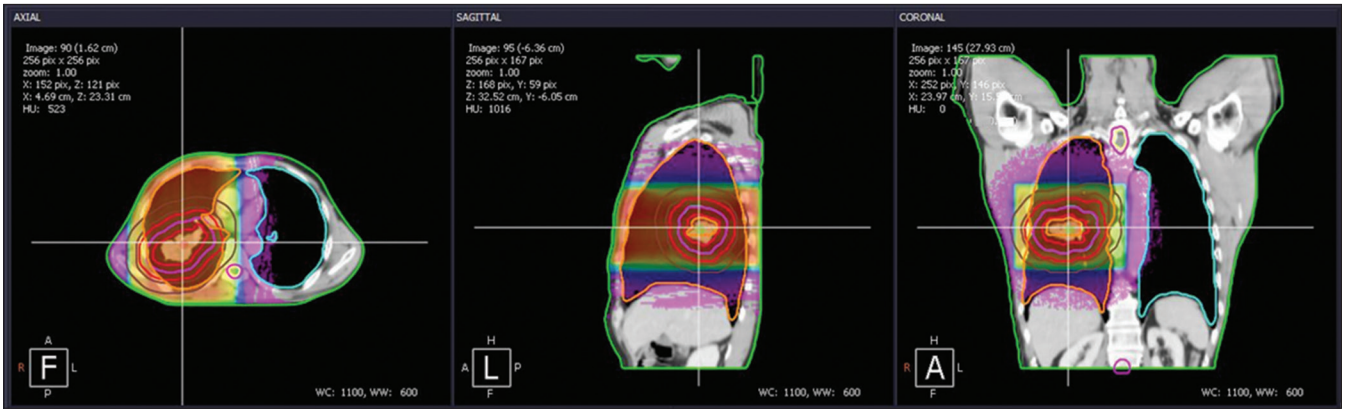

Figure 10: Simulated dose distribution in the axial, sagittal, and coronal isocenter planes

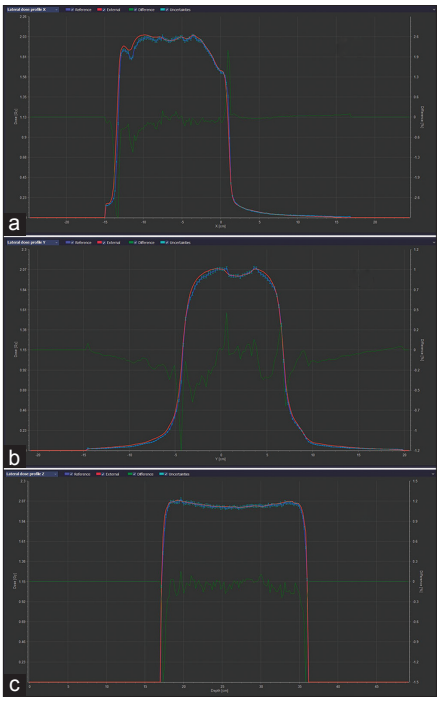

Figure 11: Comparison of lateral dose profiles in the (a) axial, (b) sagittal, and (c) coronal planes along the central axis

model of Varian Clinac® iX has been developed and benchmarked against the measured data. The variance reduction techniques available in PRIMO reduce simulation time and produce fast and accurate results. This study demonstrates that PRIMO can be used as an independent MC-based dose verification and quality assurance tool. Further verification of dose prediction accuracy of PRIMO in the case of dynamic treatment techniques such as IMRT and VMAT has to be investigated.

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Conflicts of interest

There are no conflicts of interest.

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