A PRIMER ON FACILITY SPECIFIC PRIMO MONTE CARLO MODELING AND INITIAL VALIDATION OF A 6 MV PHOTON BEAM ELEKTA INFINITY LINAC

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Abstract— **PRIMO Monte Carlo (MC) software is widely used to simulate clinical linear accelerators. This study presents a facility-specific primer for PRIMO modeling of a 6 MV photon beam from an Elekta Infinity single-energy LINAC, with emphasis on accurate LINAC geometry construction and absorbed-dose estimation in water phantom. A 6 MV photon beam was modeled in PRIMO to simulate absorbed-dose distributions in water, and the results were compared with experimental measurements. Percentage depth dose (PDD) curve and lateral beam profiles were evaluated, and agreement between simulated and measured data was quantified using a local gamma index criteria of 2.0% dose difference and 2.0 mm distance-to-agreement, with a 95.0% pass-rate threshold. The simulated and measured PDDs showed excellent agreement, with a gamma passing rate of 99.66%. Gamma passing rates for the in-plane and cross-plane beam profiles were 95.30% and 95.97%, respectively, within acceptable tolerances. PRIMO MC-based modeling was feasible for the facility's 6 MV photon beam LINAC. Measurement-based verification of absorbed-dose distributions in water showed that the facility's LINAC can be simulated with high fidelity for future clinical quality assurance (QA) and treatment planning system (TPS) verification.**

Keywords— **PRIMO MC-based software, Percentage depth dose, Beam profiles, Elekta Infinity LINAC.**

I. INTRODUCTION

Radiotherapy plays a central role in cancer management, relying on precise dose delivery to achieve therapeutic effectiveness while minimizing exposure to surrounding healthy tissues. Modern external beam radiotherapy commonly employs medical linear accelerators (LINACs), which generate high energy photon beams capable of targeting tumors with sub-millimeter precision. In these systems, electrons are accelerated through a waveguide vacuum to energies in the megavolt range. Upon exiting the accelerating structure, the electron beam typically exhibits a narrow spatial and energy distribution, forming the starting point for most Monte Carlo (MC) simulations, which assume a primary electron source with predefined characteristics [1–2].

Advances in computational power and algorithm development have established MC methods as the gold standard for radiotherapy dose calculation, owing to their ability to model particle transport with high fidelity, even in the presence of complex geometries and tissue heterogeneities. PRIMO, a user-friendly MC platform, has been developed specifically for simulating medical LINACs and has demonstrated accuracy and efficiency across a range of clinical applications [3–6].

This study used photon beam data from the Centre International de Cancérologie de Lomé (CICL), in Lome, Togo, with the objective of providing an initial evaluation of PRIMO's accuracy in modeling absorbed dose distributions for its 6 MV photon beam. By comparing the simulated absorbed dose distributions with measured data using a 2.0% Dose Difference (DD), 2.0mm Distance-to-Agreement (DTA) gamma index analysis criteria with a 95.0% gamma index passing rate. The study assesses the level of agreement between the two datasets and examines PRIMO's reliability as a possible independent dose verification tool [7].

Ultimately, this study serves as a facility-specific primer on PRIMO Monte Carlo modeling for an Elekta Infinity LINAC, offering an initial benchmark for accurate dose calculation and verification in support of clinical radiotherapy practice.

II. MATERIALS AND METHODS

Using a refrence10 × 10 cm² field size, percentage depth dose, cross-plane and in-plane dose profiles were measured and compared with the PRIMO-calculated/simulated absorbed dose distribution parameters. The depth of maximum dose (dmax) and dose at depth of 10.0 cm were analyzed to assess PRIMO's photon beam modeling accuracy for the single 6 MV beam-LINAC.

Elekta Infinity Linear Accelerator

The single-photon-beam Elekta Infinity provides clinical flexibility for treating a wide range of cancers. Its Agility multileaf collimator (MLC) system improves target conformity through rapid beam shaping and ultra-low transmission, helping reduce dose to critical structures. The system includes 160 leaves, each 5 mm wide, for precise beam shaping; a 15% larger dynamic field size; fast leaf speed; ultra-low MLC leakage; and a high-dose-rate flattening-filter-free (FFF) mode. Rubicon optical technology enables real-time MLC leaf positioning, while integrated imaging supports treatment verification and patient positioning.

PRIMO Monte Carlo-based Simulation Software

Simulations were performed using PRIMO *v0.1.5.1307*, a software package designed for LINAC modeling and radiotherapy dose calculation. PRIMO uses the PENELOPE Monte Carlo (MC) code to model particle transport and particle interactions, enabling accurate dose distribution calculations. The software was installed and run on an HP Pavilion 15 laptop equipped with an Intel Core i7-6700HQ processor, 8.0 GB RAM, CPU speed of 2.44 GHz and a 1 TB HDD. PRIMO was used to model the Elekta Infinity LINAC, including the treatment head geometry and beam-shaping components, define the water phantom geometry, and calculate percentage depth dose (PDD) curves and lateral dose profiles for the 6 MV photon beam.

Dosimetry equipment

This study utilized PTW's dosimetry equipment, including the following.

Beamscan water phantom: The PTW BEAMSCAN water phantom is a 3D scanning system used to measure LINAC beam-output data for comparison with PRIMO simulations. It includes a built-in two-channel electrometer for field and reference detector connections, as well as software for data acquisition, analysis, and processing. The phantom was positioned at a source-to-surface distance (SSD) of 100 cm. Measurements were acquired from 30.0 cm to 0.0 cm depth for percentage depth dose (PDD) curves and at 10.0 cm depth for lateral dose profiles using 3D ionization scanning chambers.

Semiflex 3-D detectors: The PTW Semiflex 3-D waterproof ionization chamber was used for the relative dosimetry. Its small sensitive volume of 0.07 cm^3 and high spatial resolution make it well suited for the LINAC's relative beam data dosimetry. In this study, the 3-D chambers were used to acquire PDD curves and beam profiles.

Beamscan software (MEPHYSTO): The BEAMSCAN software provides advanced tools for rapid and accurate beam data acquisition and data processing. In this study, MEPHYSTO was used to acquire, process, analyze, save, and export the measured PDD and beam profile data.

Experimental measurements

Photon relative dose measurements included percentage depth dose profile, cross-plane profile, and in-plane profile were performed with the BEAMSCAN water phantom placed directly under the LINAC. PDD data for the 6 MV energy were acquired for reference 10 x 10 cm^2 field size at SSD of 100 cm. The PDD measurement was carried out in 1.0 mm increment from 0.0 cm to 3.0 cm depth and in 2.0 mm increments from 3.0 cm to 30.0 cm depth using the PTW semiflex 3-D ion chamber (TM31021). For photon beam profile measurements, the water phantom was set up with a source-to-detector distance (SDD) of 110 cm, at an isocenter depth of 10 cm, with the collimator and gantry angle fixed at 0 degree. The PTW MEPHYSTO data acquisition software *version 3.4* was used for data analysis using the Elekta 2020 protocol for beam profiles analysis (Flatness and Symmetry) and the AFSSAPS No. 93 protocol used for the PDD analysis respectively.

PRIMO software simulation

The simulation began by modeling the facility's Elekta Infinity LINAC in PRIMO. Using PRIMO's predefined configurations for commercial LINACs, the Elekta Infinity model was reconstructed to obtain final primary beam parameters. The 6 MV photon beam mode was selected, and photon production was simulated by modeling the interaction of the electron beam with the tungsten target in the LINAC head. All four laptop central processing units (CPUs) were used during the simulation, achieving a speed of 16.9 histories/s per CPU. The vendor-provided initial electron beam parameters included an energy of approximately 6 MeV and a Gaussian spot size. These parameters were iteratively refined to improve agreement with experimental measurements, particularly the PDD curve and lateral dose profiles.

To ensure accurate simulation of beam shaping and attenuation processes, the Infinity's treatment head was modeled to include four key components. The primary collimator, flattening filter, secondary collimators and the MLCs. The primary collimator was simulated to shape the initial photon beam and to eliminate off-axis photons, ensuring proper alignment with the treatment field. For the flattening filter, a conical tungsten filter was modeled to produce a uniform dose distribution across the treatment

field, also attenuating the photon beam to create the characteristic 6 MV energy spectrum. The X and Y jaws were configured to define a 10 × 10 cm^2 field size at the isocenter, playing a critical role in shaping the beam to match the treatment field. The last component (MLC) although not actively used in this study, was included in the simulation for completeness, as it is an integral part of the Elekta Infinity LINAC's beam-shaping system.

PRIMO generated a phase-space file at the end of the treatment head, containing detailed information for all particles leaving the LINAC head. This file was used as input for the subsequent dose calculation stage in the water phantom. Absorbed dose distributions were then calculated in a virtual water phantom designed to replicate the experimental measurement setup. A 30 × 30 × 30 cm^3 water phantom was modeled to provide adequate scatter conditions for the photon beam. The phantom was divided into 2 × 2 × 2 mm^3 voxels to achieve high spatial resolution while maintaining computational efficiency and accurately representing dose gradients, particularly in the build-up and penumbra regions. The SSD was set to 100 cm, matching the experimental setup. The field size was defined as 10 × 10 cm^2 at the isocenter, which was achieved by configuring the positions of the secondary collimators (jaws) in the LINAC model. These parameters ensured that the simulation conditions were identical to those used in the experimental measurements.

Segments Simulation Process

The simulation was divided into two main stages, S1+S2 and S3, which correspond to the Monte Carlo modeling workflow shown in Figure 1. In the first stage, particle transport through the LINAC head (S1+S2) was simulated, including interactions among photons, electrons, and treatment head components such as the target, primary collimator, flattening filter, and jaws. This stage produced a phase-space file describing the beam exiting the treatment head. To improve efficiency without compromising accuracy, variance reduction methods, including enhanced bremsstrahlung splitting, were applied. In the second stage, the phase-space file was used for dose calculation in the water phantom (S3). Using the EGSnrc-DOSXYZnrc module, PRIMO calculated the absorbed dose in each voxel while accounting for secondary-particle interactions, including Compton scattering, pair production, and electron transport. The resulting 3-D dose distribution was used to generate PDD curve and lateral dose profiles, as shown in Figure 1. The total simulation time was 34 hours, 25 minutes, and 13 seconds.

Prior to simulation, the particle histories were configured to minimize statistical uncertainties. A total of 10^8 particle histories was simulated based on convergence tests, ensuring that the relative uncertainty in the dose calculation was below 1.0% in regions of clinical interest (d_{10cm} and d_{max}). The energy cutoffs were also configured and set to 10 keV for photon transport, and for electron transport to 521 keV (corresponding to the rest mass energy of electrons). These cutoffs ensured accurate modeling of low-energy interactions while optimizing computational efficiency. The final configuration was the variance reduction techniques. Variance reduction techniques such as the range rejection and directional bremsstrahlung splitting were implemented to enhance computational speed without compromising the accuracy of the dose calculations.

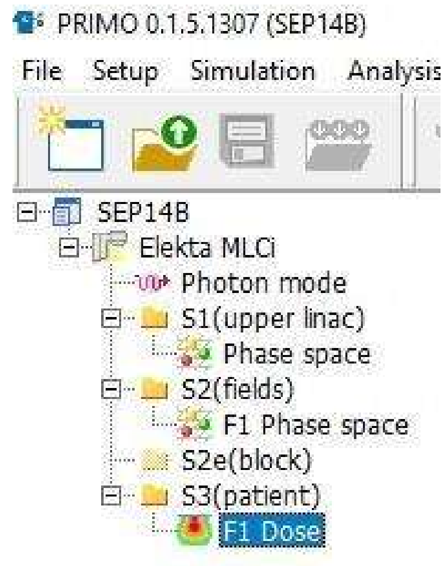

Fig. 1 PRIMO interface showing the three various simulated segments.

Simulation Output Analysis

The simulated (calculated) absorbed dose distributions were compared with experimental measurements (measured). The relative dose as a function of depth in the water phantom was generated and normalized at 100% of maximum dose. This curve (calculated PDD) was compared with the measured PDD using a local gamma index passing criteria of 2.0%, 2.0 mm to assess the accuracy of the simulation in modeling dose penetration as captured in Figure 2. The red smooth curve is the measured PDD while the violet rough curve is the Primo calculated PDD.

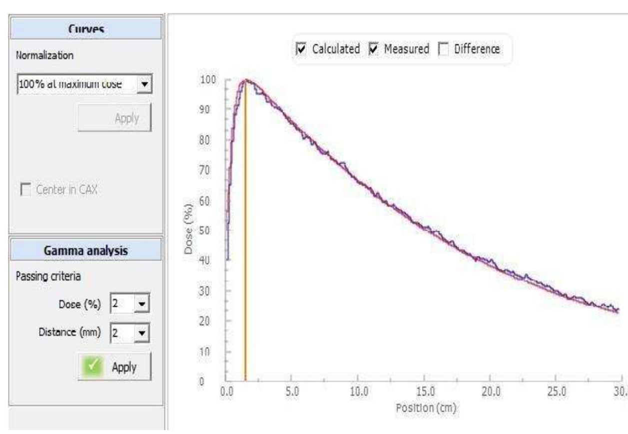

Fig. 2 PDD curves in PRIMO interface using gamma analysis

III. RESULTS AND DISCUSSIONS

Table 1 summarizes the final simulated electron parameters obtained after optimizing the initial electron beam parameters provided by the PRIMO developers for Elekta LINACs.

Table 1. Final simulation parameters

Initial Energy (MeV)	Energy FWHM (MeV)	Focal spot FWHM (cm)	Beam divergence (degree)
6.495	0.022	0.190	0.000

Table 2 summarized the statistics of particle transport during the PRIMO MC simulation of the facility's LINAC 6 MV photon beam. A total of 39,569,578 particles were simulated, including electrons, photons, and positrons, with detailed tracking of their energy ranges and production per history. The total particle counts included all three particle types, with an average of 1.6401 particles per history. The energy range for the total particles extended from 0.02 MeV to 6.490 MeV. These statistics highlight the dominance of photons in the simulation, reflecting the nature of a 6 MV photon beam, while secondary particles like electrons and positrons contributed to dose deposition through scattering and other interactions.

Table 2. Particle transport statistics for the simulated 6 MV photon beam

Particles	Counts	Particles/History	Min E (MeV)	Max E (MeV)
Electrons	178,552	0.022202	0.000	6.103
Photons	39,385,536	4.897345	0.020	6.490
Positrons	5,490	0.000683	0.102	5.050
TOTAL	39,569,578	4.920230	n/a	n/a

From figure 2 above, a strong correlation was observed between the simulated and measured PDD curves. The dmax was consistently located at a depth of 1.5 cm in both datasets, aligning with expected characteristics of 6 MV photon beams. Beyond the build-up region, the dose decreases progressively, with the simulated and measured curves demonstrating agreement within 5.0% throughout the dose fall-off region. All statistical assessments of the PDD dosimetric parameters analysed and compared are presented in Table 3.

The build-up region, extending from the surface to the depth of maximum dose (d_{max}), showed a rapid dose increase mainly due to the generation and scattering of secondary electrons. The PRIMO simulation reproduced this rise closely and agreed well with the experimental data, supporting the accuracy of the modeled initial beam energy and focal spot size. Minor differences in the build-up region may be attributed to experimental uncertainties, such as detector positioning errors, or to limitations in modeling secondary electron transport.

Table 3. Measured and calculated PDD comparison analysis

Points of comparison	Measured	Simulated	Abs difference
Position of Max (cm)	1.50	1.50	0.00
Dose at 10 cm depth	66.29	65.77	0.52
Gamma index			
Percentage of points passing the 2.0%/2.0mm criteria (%)	**99.66**		

A detailed comparison of the measured and calculated PDD curves analyzed using the PRIMO software is presented in Figure 3. This figure provides a comprehensive visualization of the agreement between the two curves, highlighting the accuracy of the PRIMO simulation in replicating the experimental data.

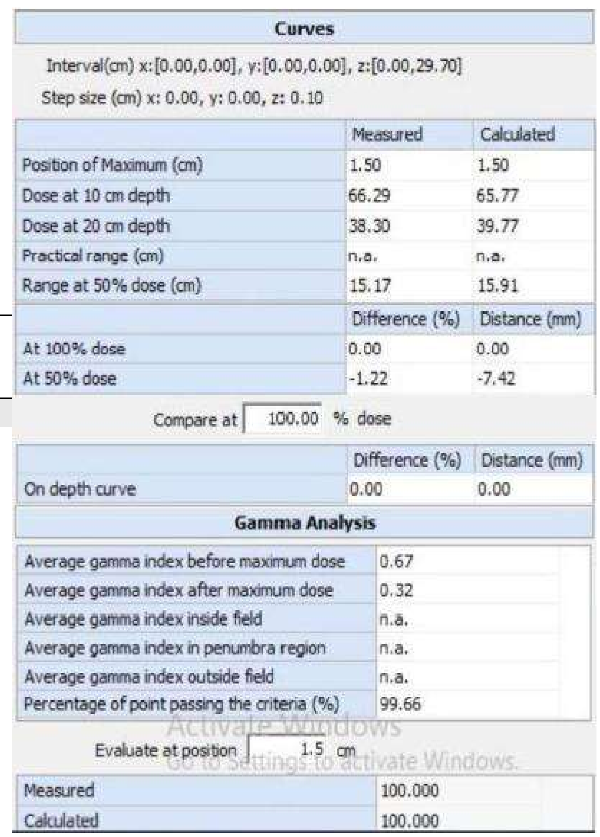

Fig. 3 Measured and calculated PDD comparison in PRIMO interface.

The simulated and measured depth dose curves both exhibited a maximum dose (d_{max}) at approximately 1.5 cm, consistent with the characteristic behavior of 6 MV photon beams. Normalizing both measured and PRIMO-calculated doses to 100% at d_{max} established a consistent reference point for comparison. The close agreement at dmax confirms the accuracy of the simulated energy spectrum characteristics.

Accurately reproducing d_{max} is crucial for clinical applications, particularly in treating superficial tumors, where precise dose delivery is essential for effective treatment outcomes. Beyond the depth of maximum dose, the dose gradually decreases due to the attenuation and scattering of photons within the water phantom. The PRIMO simulation demonstrated excellent agreement with the experimentally measured dose fall-off curve, accurately capturing photon interactions at increasing depths. This concurrence is critical for ensuring reliable dose predictions in deeper tissues, particularly for tumors situated in midline or posterior regions, where accurate dosimetry is vital for effective treatment planning.

At the depth of 10 cm, the measured dose was 66.3%, while the PRIMO-calculated dose was 65.8%. The percentage difference between the measured and simulated doses at depth of 10 cm was 0.79%, which falls well within clinically acceptable 1.0% limit. This close agreement underscores the accuracy of the Monte Carlo model in predicting dose attenuation and scatter effects, which are essential for ensuring precise dose delivery to deep-seated tumors. For the 10 × 10 cm² field size, the gamma passing rate surpassed 95% under the 2.0%/2.0 mm criteria, a standard benchmark for clinical dose verification. The gamma index evaluates both dose magnitude differences and spatial discrepancies between simulated and measured data. Achieving a passing rate above 95% indicates that the PRIMO simulation demonstrated excellent agreement with experimental measurements centrally. This high passing rate of 99.66% underscores PRIMO's reliability for future clinical quality assurance, dose verification, and treatment planning system validation for the facility.

The profiles were also examined in two perpendicular directions; the transverse (X-profile/In-plane) and longitudinal (Y-profile/ Cross-plane), at a depth of 10 cm using a reference 10 × 10 cm² field size. These profiles play a crucial role in assessing the accuracy of PRIMO Monte Carlo simulations in replicating the dose distributions delivered by the facility's LINAC, providing valuable insights into the reliability of the simulation model.

Table 4 and Table 5 respectively present the beam profiles in both transverse and longitudinal directions which demonstrated a high degree of agreement between PRIMO simulations and experimental measurements. The flatness and symmetry of the central region were modeled with high precision. Both the simulated in-plane and cross-plane beam profiles when compared to the measured profiles recorded local gamma index pass rate above the 95.00% threshold criteria. PRIMO effectively captured the rapid dose fall-off beyond the field edges, accurately accounting for scatter and leakage radiation.

Table 4. Measured and calculated transverse beam profile comparison analysis

Points of comparison	Measured	Simulated	Abs. difference
Left off-axis distance at 50% dose (cm)	-6.05	-5.98	0.07
Right off-axis distance at 50% dose (cm)	6.10	5.99	0.11
Gamma index			
Percentage of points passing the 2.0%/2.0mm criteria (%)	**95.30**		

Table 5. Measured and calculated longitudinal beam profile comparison analysis

Points of comparison	Measured	Simulated	Abs. difference
Left off-axis distance at 50% dose (cm)	-6.20	-6.12	0.08
Right off-axis distance at 50% dose (cm)	6.20	6.07	0.13
Gamma index			
Percentage of points passing the 2.0%/2.0mm criteria (%)	**95.97**		

IV. CONCLUSION

The simulation of the facility's single-energy 6 MV Elekta Infinity LINAC was demonstrated to be fully feasible using the PRIMO Monte Carlo software. The study successfully established an accurate, facility-specific PRIMO model through careful reconstruction of the LINAC geometry and detailed configuration of beam parameters. PRIMO achieved excellent agreement with the machine's measured data, reproducing the reference percent depth dose (PDD) curve and lateral dose profiles with high fidelity. These results confirm that PRIMO can reliably estimate absorbed dose in water phantom for this LINAC, supporting its use as a robust tool for independent dose verification and advanced radiotherapy simulation tasks. Although the simulation achieved strong dosimetric agreement, the simulation-based data verification would benefit from higher particle histories or longer simulation times, or alternatively, the use of a more powerful CPU (e.g., an 8-core system). These improvements would further smooth the calculated curves and help achieve a 100% gamma pass rate with minimal deviations from other vital absorbed dose distribution measured parameters (points of comparison). With enhanced computational resources, the total simulation time could be reduced to 1–3 hours, compared to the 34 hours required in this study.

Further research should extend PRIMO validation to more complex treatment scenarios, including small and irregular fields as well as dynamic techniques such as intensity modulated radiotherapy (IMRT) and volumetric modulated arc therapy (VMAT). As PRIMO becomes more routinely implemented in the facility, it can be incorporated into routine QA workflows as an independent verification tool, particularly for this busy facility with limited LINAC access for patient-specific QA. Beyond clinical use, PRIMO can also be used for education and research, enabling investigations into advanced LINAC modeling, dose optimization strategies, and emerging treatment modalities.

Overall, this work serves as a starting point for the facility, providing a validated PRIMO configuration and a pre-calculated phase-space file that future users can adopt and refine for subsequent modeling, verification, and research applications.

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