

Article

Validation of RayStation Monte Carlo Beam Model for Matched LINACs

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Abstract

Accurate dose calculation is crucial in radiation therapy, particularly when employing advanced techniques such as VMAT. Monte Carlo (MC) algorithms are widely recognized as the gold standard for dose calculation. This study aimed to validate an MC dose calculation model in RayStation® TPS and to compare its performance against the Collapsed Cone (CC). The MC model was evaluated using measured data from four matched Elekta® Versa HD LINACs. Validation followed AAPM TG-157, TG-244 and IAEA TECDOC guidelines, including homogeneous media, heterogeneous media and advanced techniques (VMAT, IMRT, dMLC). MC showed high agreement with measurements, with most results within a 2% dose difference or passing a gamma criteria $\geq 95\%$. Performance was comparable or superior to CC in many cases, especially in small-field stereotactic plans. Impact of grid size and statistical uncertainty was assessed to find the optimal values. This study indicated a 2 mm grid size with 0.5% uncertainty as the optimal balance between accuracy and computation time. In conclusion, this study demonstrated that the MC model can provide accurate dose calculations for treatment plans, with computation times compatible with clinical practice. The use of MC appears to be particularly advantageous for advanced techniques and in the presence of tissue heterogeneities.

Keywords: external beam radiation therapy; absorbed dose calculation; treatment planning systems; Monte Carlo

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1. Introduction

Radiation therapy is one of the most widely used modalities in cancer treatment, requiring a delicate balance between maximizing tumour control and minimizing radiation-induced toxicity in surrounding normal tissues. With the advent of advanced techniques such as Intensity Modulated Radiation Therapy (IMRT), Volumetric Modulated Arc Therapy (VMAT) and stereotactic radiosurgery (SRS), the importance of accurate and efficient dose calculation algorithms has become even more crucial [1,2]. Treatment planning

systems must therefore ensure not only precision in modelling dose distributions but also computational efficiency to meet the demands of modern clinical workflows.

Accurate dose calculation is a critical step in the radiation therapy workflow, as the precision of dose distribution directly impacts the quality and effectiveness of treatment, particularly in regions with high tissue heterogeneity [3,4]. To address these demands, several dose calculation algorithms have been developed for integration into treatment planning systems (TPS), each offering specific advantages and limitations. Examples include Collapsed Cone (CC) Convolution, Monte Carlo (MC) and Pencil Beam, among others [5,6]. Among these, MC algorithms are widely recognized as the gold standard for dose calculation in radiation therapy, offering superior accuracy by simulating the physical interactions of individual particles and secondary radiation through stochastic methods [7,8]. Consequently, MC-based calculations inherently include statistical uncertainty, which can be reduced by increasing the number of simulated particles, at the expense of longer computation times. The user can therefore balance desired accuracy against computation time, depending on clinical requirements.

Technological advances have progressively reduced MC calculation times to clinically acceptable levels, often within a few minutes. As a result, several manufacturers—including Elekta®, Varian®, and RaySearch—now provide MC-based dose calculation engines integrated into their TPS platforms [9–11].

The objective of this study is to validate an MC beam model implemented in RayStation® TPS for matched Elekta® Versa HD LINACs and to compare its dosimetry and computational performance with the clinically established CC algorithm.

This study extends the preliminary work by Manco et al. [12], which demonstrated the feasibility of implementing a single Monte Carlo beam model in RayStation® for multiple beam-matched Elekta® Versa HD linear accelerators. Building on that experience, the present work provides a broader and more clinically oriented validation, including an increased number of beam-matched LINACs, data from a recently commissioned accelerator, and the use of an updated version of the treatment planning system. In addition, the scope of the validation is expanded to include stereotactic applications verified with high-resolution detectors, addressing small-field and high-gradient scenarios that are particularly challenging for analytical dose calculation algorithms. Finally, a systematic investigation of Monte Carlo calculation parameters, namely dose grid size and statistical uncertainty, is performed to support their optimal selection for routine clinical implementation.

2. Materials and Methods

In this study, a photon MC beam model was validated using the RayStation® (RaySearch laboratories, Stockholm, Sweden) treatment planning system (TPS) version 11B and compared with a clinically available CC model. Two photon beam energies were modelled: 6MV with flattening filter (6MV) and 6MV flattening filter free (6FFF). The MC model employed was obtained using the RayStation® modelling module with a further manual optimization, as described in the previous model validation work by Manco et al. [12].

This study involved four Elekta® (Stockholm, Sweden) Versa HD linear accelerators, designated as VMO1, VMO2, VMO3 and VCR1. The first three LINACs are located at the Policlinico of Modena, while VCR1 is installed at the Carpi Hospital. All machines are dosimetrically matched, allowing patients to be treated interchangeably across LINACs in the event of machine downtime. These machines were clinically commissioned for multiple energies (6MV, 6FFF, 10MV, 10FFF, and VMO2 and VCR1, as well as 15MV) using a CC algorithm. Commissioning of VMO3 was completed recently in 2024. The final aim is to accomplish a MC model applicable across all beam-matched LINACs.

The datasets used for model validation included measurements acquired during the commissioning of VMO3. Given that the machines are beam-matched, a single model can be used for each of them.

Validation of the model against measured data was divided into different phases, following guidelines AAPM TG244 5b [13] and TG157 [14]. The validation involved initial measurements in a water tank, followed by evaluations in heterogeneous medium, and lastly the verification of advanced techniques such as IMRT and VMAT.

MC calculations were performed using uncertainty 0.5% and 2 mm of grid size, since these parameters were considered the most appropriate for the initial validation.

Finally, a dedicated study was carried out to investigate how calculation accuracy and computation time depend on uncertainty and grid size, to identify the optimal setup for clinical implementation.

2.1. Beam Model Validation

To assess the quality of the modelling within the TPS, the model was validated by comparing the calculated and the measured data using gamma analysis.

In particular, the agreement between Percent Depth Dose (PDD) and Inline/Crossline profile curves was investigated, these being fundamental parameters for beam characterization. The measured data were taken in a water phantom, by employing an ionization chamber with the water surface at the Source to Surface Distance (SSD) of 90 cm. All the profile curves were measured at a depth of $z = 10$ cm, while the PDD curves were taken over a depth range going from 1.5 to 30 cm. Both open fields and the available physical wedges (60°) for several square field sizes were considered and the correspondent curves were collected. The fields analyzed are respectively 2×2 , 5×5 , 10×10 , 20×20 , 30×30 .

The water phantom employed is a water tank (PTW, Freiburg, Germany) characterized by PMMA walls with a thickness of 20 mm and with an irradiation area of $600 \times 500 \times 408$ mm³. The measurements were performed using a Semiflex vented cylindrical ionization chamber (PTW) with an active volume of 0.125 cm³, selected for its excellent measurement stability. For the 2×2 cm² field, a microDiamond detector (PTW) with an active volume of 0.004 mm³ was employed instead, as its miniature sensitive volume is ideally suited for small-field dosimetry as it minimizes volume-averaging effects and ensures high spatial resolution.

To enable the measurement automatization, these devices were mounted on a stainless-steel mechanical arm whose movements in the tank are controlled through the Mephysto PTW software (version 3.4 mc²). A 1D gamma analysis to probe the fit among the measured and calculated curves was performed, as suggested by AAPM Guideline 5.b [13], with 2%/2 mm tolerance and 10% threshold.

This procedure was done for both the 6MV and 6FFF energies, with the only difference being that for 6FFF no wedges were considered. The measurements were carried out using the VMO3 LINAC.

2.2. Homogeneous Media Validation

The validation in homogeneous media was performed using the cubic water phantom. Different geometries of the field, angles of incidence of the beam and wedge angles were put under analysis.

A series of tests were carried out, as reported in the TECDOC 1540 guideline [15], whose list can be consulted in the following Table 1.

Table 1. Test cases carried out for the validation in cubic water phantom as indicated in the TECDOC 1540 guideline.

Field Geometry	Test Name	Size cm ²
Square Field	1D	1 × 1
	1A	5 × 5
	1B	10 × 10
	1C	25 × 25
Rectangular Field	2A	5 × 25
	2B	25 × 5
Square Field SSD = 100 cm	3D	10 × 10
Square Field Wedge 60°	4A	9 × 9
	4B	20 × 20
Square Field Gantry 45° SSD = 100 cm	9	10 × 10
Asymmetric Field	11A	15 × 15
Geometric centre (7.5 cm, 0 cm) and (7.5 cm, 7.5 cm)	11B	15 × 15
Asymmetric Field	12A	15 × 15 W = 25°
Different Wedges	12B	15 × 15 W = 45°
	12C	15 × 15 W = 60°

Measurements were collected using the same water phantom and Semiflex vented cylindrical ionization chamber described in the previous paragraph. Detector positioning was controlled by the Mephysto software. Measurements were performed across all four LINACs.

Point dose measurements for each test were taken at different depths, respectively of 5 cm, 10 cm and 20 cm. Both the 6MV and 6FFF energies were examined in the validation process, with the exception of test cases with a wedge at 6 FF energy which were not considered.

As for the comparison of the measured and calculated data, called respectively D_{meas} and D_{calc} , the TECDOC 1540 suggests a different approach depending on either if the point of interest is in the field or outside the field. Therefore, in the first case the relative percentage error can be obtained using Equation (1):

$$\epsilon = \left(\frac{D_{calc} - D_{meas}}{D_{meas}} \right) \times 100 \quad (1)$$

whereas in the opposite case Equation (2) must be exploited:

$$\epsilon = \left(\frac{D_{calc} - D_{meas}}{D_{meas,cax}} \right) \times 100 \quad (2)$$

where $D_{meas,cax}$ is the measure dose at the central axis at the same depth of the measured point considered.

Tolerance levels differed for the MC and CC algorithms. In accordance with AAPM TG-157, a 2% tolerance was applied to all points, except for the reference point (0.5%). This choice follows the TG-157 recommendation for Monte Carlo algorithms to maintain uniform tolerance levels regardless of the specific dose region (e.g., central axis or penumbra).

Dose values calculated using MC and CC were statistically compared using the Wilcoxon signed-rank test after non-normality of the data had been verified using the Kolmogorov–Smirnov test, which guided the selection of a non-parametric approach. Data agreement was further evaluated using Bland–Altman analysis.

2.3. Heterogeneous Media Validation

To assess model performance under clinically realistic conditions, validation in heterogeneous media was performed. Inhomogeneity measurements were carried out using solid water slabs with 2 cm of air in between, following the setup used by Snyder et al. [10]. A picture of the home-made phantom is shown in Figure 1.



Figure 1. Schematic representation of the heterogeneous phantom employed for the validation.

A CT scan of the phantom with inserted chambers was acquired with Toshiba Aquilion® Large Bore CT (Canon Medical®, Ōtawara-shi, Japan) and imported into the RayStation® TPS for dose calculation. The regions corresponding to the RW3 slabs and air gaps were contoured and manually overridden. Point dose measurements were performed using the Semiflex vented cylindrical ionization chamber, at the reference point. The ionization chamber was located on the central axis at a depth of 6 cm in the phantom, 1 cm below the lower air-gap interface, in correspondence of the beam isocenter. These measurements were performed only for the VMO3 LINAC. We used alignment and centering marks engraved directly onto the commercial RW3 slabs, performing alignment with the room lasers before each irradiation, to ensure positioning reproducibility within 1 mm.

Several geometrical irradiations were tested, readapted by the IAEA 1583 guidelines [16] for 6MV energy. Additionally, a VMAT plan was included using dummy ROIs for optimization functions.

The list of the beam tests and their description can be consulted in Table 2.

Table 2. Irradiation setup for measurements with the heterogeneous phantom.

Test Case	Irradiation Geometry	Field Size (cm ²)	Gantry Angle (°)	Collimator Angle (°)	Beam Modifier
1	Single-square field	10 × 10	0	0	None
2	Diamond-shaped field	14 × 14	0	45	None
3	Four-field box	15 × 10 Ant	0	0	None
		15 × 10 Post	180	0	None
		15 × 8 RL	270	0	None
		15 × 8 LL	90	0	None
4	Three fields, two wedge-paired	10 × 12	0	0	None
		10 × 6	90	According to wedge orientation	25° wedge
		10 × 6	270		45° wedge
5	Non-coplanar fields	4 × 16 LL	90	330	None
		4 × 16 RL	270	30	None

		4 × 4 (couch 270°)	30	0	None
6	VMAT plan		360° arc		None

The percentage error coming from the comparison of calculated and measured data was obtained using Equation (1).

The tolerance threshold for each test was set to 2% difference, independently of the geometry and any presence of beam modifiers, as suggested by AAPM TG157 for MC dose calculation in TPS.

2.4. Advanced Technique Validation (VMAT, IMRT, dMLC)

The final step of validation was focused on the analysis of advanced techniques such as VMAT, IMRT and dMLC, to verify the TPS on various districts and types of clinical plans. The tests exploited are taken from two different guidelines, the AAPM TG 119 [17] and TG 244 [18]. From TG 119, four test cases were appropriately adapted to be employed, Test I1 Multitarget, Test I2 Prostate, Test I3 Head/Neck and Test I4/I5 Cshape, respectively. All of these were treated with the VMAT technique, apart from Tests I2 and I3 which were also done with the IMRT and dMLC techniques. From TG 244, three patient plans were taken instead, the 'Abdomen case', the 'Anal case' and the 'Lung case', respectively, all done using the VMAT technique. All the test cases were performed with both the 6MV and 6FFF energies. Regarding the VMAT plans under analysis, each of them is characterized by two arcs, apart from Test I3 Head/Neck, which consists of four arcs. As for the ones performed with the IMRT and dMLC, Test I2 Prostate was realized through five beams, while Test I3 Head/Neck consisted of nine beams.

The comparison between the measured and the calculated distributions was done through gamma analysis performed on dose maps. In this study the 2%/2 mm gamma analysis criterion was used, with a 10% threshold, as indicated by the guidelines [13]. The passing rate was set at 95%. The dose map of the measured distribution was obtained using the MatriXX Evolution 2D ionization chamber array (IBA® Dosimetry, Schwarzenbruck, Germany), while the calculated one performing the QA plan calculation using a CT scan of the MatriXX Evolution inserted in the correspondent mini-phantom [19]. MatriXX Evolution features an active area of 24.4 × 24.4 cm² with a 7.6 mm centre-to-centre detector spacing. The mini-phantom features external alignment marks to ensure precise and reproducible setup positioning (within 1 mm) via room lasers, while the dosimetry system automatically applies temperature and pressure corrections to guarantee measurement stability.

Gamma analysis was performed using MyQA software version 2024-001 (2.19.15.1) (IBA® Dosimetry), where measured and calculated dose maps from all four LINACs were imported and compared.

2.5. SRS Phantom

An additional analysis was also conducted by employing the SRS phantom for the QA plan calculation. The SRS Detector (IBA® Dosimetry) is preferable to the MatriXX in cases of small targets and steep dose gradients. The SRS used is characterized by a CMOS solid state detector array, with an active area of 12 × 14 cm² and a total of 105,000 detectors, each 0.4 × 0.4 mm. The overall resolution of this device, considering the centre-to-centre distance, is of 0.4 mm. Both FF and FFF energies are supported by this detector [20]. The advantage of the SRS is therefore that it provides a greater resolution, at the same time requiring a lower area. Additionally, it enables performing an efficient QA for single-isocenter multiple targets in one measurement.

The SRS Phantom CT scan was imported into the TPS. As suggested by the user manual, the phantom into the TPS was entirely overwritten as RW3 material (both for phantom and detector area). The same procedure described in the previous paragraph was followed for the QA plan calculation, with the only difference that an appropriate correction factor was applied to the calculated dose map. The necessity of this correction comes from the fact that the MC algorithm reports the dose absorbed to the medium D_{med} , while the CC report dose absorbed to water D_w due to historical reasons [21]. Considering this, a divergence among the CC and MC arises since the SRS phantom calibration is performed through an ionization chamber that provides a dose-to-water measure. Hence, to access a calibration that supplies dose-to-medium, a corrective factor should be applied, still leading to a loss of agreement with the CC [22]. The proper scaling factor that was employed in this study is the one obtained by Seet et al. [23]’s measurements by exploiting the stopping-power ratios, corresponding to 1.040. This single nominal factor was applied to both the 6MV and 6FFF modalities, as water-to-medium stopping-power and mass energy-absorption coefficient ratios remain highly stable and flat within the average energy spectra of both beams. Once the appropriate correction of the dose maps was performed, it was then possible to further proceed with the gamma analysis between the scaled calculated dose maps and the measured ones as described in the previous section Paragraph 2.4.

For the SRS study, specific treatment plans were selected, in particular stereotactic plans characterized by small targets and a high dose gradient. For both the 6MV and 6FFF energies, two plans were analyzed, the ‘SRS Prostate’ and the ‘SRS Encephalon’ plan. Additionally, for the 6FFF, three other plans were considered, the ‘SRS Multiple Brain’, the ‘QASRS Encephalon’ and the ‘QASBRT Lung’. All these plans were realized with the VMAT technique and through the employment of arcs. Each of the plans considered in this study consists of two arcs, with the only exception being the ‘SRS Multiple Brain’ plan that has six non-coplanar arcs. All the comparisons between calculated and measured dose distributions in this analysis were made by considering the measurements taken with the VMO3 LINAC due to its new commissioning.

2.6. Uncertainty and Grid Size Study

A dedicated study was performed to evaluate how the MC dose calculation accuracy and computation time depend on key parameters, namely the uncertainty and grid size. The aim was to determine an optimal configuration that balances dosimetric accuracy with clinically acceptable calculation times.

Two representative clinical treatment plans were selected for this analysis: the TG-244 Abdomen case, representative of a conventional VMAT plan with moderate modulation and dose gradients, and the SRS Prostate plan, representative of a stereotactic scenario characterized by small targets and steep dose gradients. These plans were chosen to probe the behaviour of the Monte Carlo algorithm under clinically distinct conditions.

The study was structured in two complementary parts. In the first part, the effect of statistical uncertainty was investigated while keeping the dose grid size fixed at 2 mm. For each plan, dose calculations were performed using uncertainty values ranging from 0.2% to 1.0%. Each resulting dose distribution was compared against a reference calculation obtained with 0.1% uncertainty, which was assumed to represent the best achievable statistical accuracy. Gamma analysis was performed using a 2%/2 mm criterion, and the Average Gamma value was extracted for each comparison. Computation time was recorded automatically using a dedicated Python-based scripting framework within the TPS (version 3.8).

In the second part, the impact of dose grid size was evaluated while fixing the statistical uncertainty at 0.5%. Dose calculations were performed using grid sizes of 1 mm, 2 mm and 3 mm. In this case, each calculated dose distribution was compared against the 1

mm grid size calculation, considered the reference for spatial resolution. As in the uncertainty analysis, Average Gamma values and computation times were recorded for each configuration.

3. Results

3.1. Comparison of Model and Measured Curves

A total of 33 curves were analyzed using the gamma criteria to compare acquired and calculated PDD, and Inline and Crossline profiles. The passing rates obtained for each curve with the 2%/2 mm criterion, are reported respectively in Table 3 for the 6MV and in Table 4 for the 6FFF energies.

Table 3. Passing rates for the Percent Depth Dose (PDD), and the Inline and Crossline profile curves taken at different field sizes with 6MV energy.

Field Size (cm)	Curve Type	Gamma Percentage 2%/2 mm
2 × 2	PDD	100.0
	Inline	99.4
	Crossline	100.0
5 × 5	PDD	100.0
	Inline	100.0
	Crossline	100.0
10 × 10	PDD	100.0
	Inline	100.0
	Crossline	100.0
10 × 10 With wedge	PDD	100.0
	Inline	99.7
	Crossline	95.0
20 × 20	PDD	100.0
	Inline	100.0
	Crossline	100.0
30 × 30	PDD	100.0
	Inline	99.0
	Crossline	99.9

For the 6MV, results showed good agreement with the measurements for the cases with open fields, with just few exceptions deviating from 100.0% in correspondence of the Inline of the 2 × 2 field, with 99.4%, and of the Inline and Crossline of 30 × 30 field, with 99.0% and 99.9% respectively. Regarding the wedged case instead, lower agreement was observed, with even 95.0% for the Crossline curve. This trend is indicative of a sub-optimal modelling of the physical wedges within the MC algorithm.

Table 4. Passing rates for the Percent Depth Dose (PDD), and the Inline and Crossline profile curves taken at different field sizes with 6FFF energy.

Field Size (cm)	Curve Type	Gamma Percentage 2%/2 mm
2 × 2	PDD	100.0
	Inline	98.8
	Crossline	100.0
5 × 5	PDD	97.7
	Inline	100.0

10 × 10	Crossline	100.0
	PDD	100.0
	Inline	99.7
20 × 20	Crossline	100.0
	PDD	100.0
	Inline	100.0
30 × 30	Crossline	99.8
	PDD	100.0
	Inline	100.0
	Crossline	99.3

Even for the 6FFF, the gamma percentages obtained for the cases under analysis are representative of a good consistency between calculated and measured curves. Indeed, a majority of 100.0% was achieved and the remaining values are still above 99.0%, with just the exception of two values below it, specifically the Inline of the 2 × 2 field, with 98.8%, and the PDD of the 5 × 5 field, with 97.7% (lowest value obtained).

3.2. Cubic Water Tank

For the validation in homogeneous media conditions a total of 288 points were collected for the 6MV and 220 points for the 6FFF.

For the 6MV energy, the MC algorithm was characterized by a majority of the analyzed points falling within the 2% dose difference tolerance recommended by the TG157 guideline.

The passing rates according to TG157 tolerance for both MC and CC 6MV algorithms are reported in Table 5. The few deviations exceeding 2% tolerance are primarily associated with measurement points located near the build-up region, where dose measurements are inherently less stable due to the presence of high dose gradients. It is worth noting that the lower cumulative passing rate for VMO2 (91.0%) in Table 5 is predominantly low-score driven by the physical wedge test cases. When isolating open beam configurations, all three linear accelerators demonstrate a highly uniform agreement.

Table 5. Passing rates for the cubic water tank measurements with TG157 and TG244 tolerances, for both MC and CC algorithms, with 6MV energy. Please note that for the machines VMO1 and VCR1 the number of points is lower than other machines because no wedge beams are available.

Algo-rithm	Linear Accel-erator	Number of Points	Number of Points Within 2% Difference	Passing Rate Within 2% Difference
MC	VMO1	55	52	94.5%
	VMO2	89	81	91.0%
	VMO3	89	86	96.6%
	VCR1	55	53	96.4%
	All	288	272	94.4%
CC	VMO1	55	50	90.9%
	VMO2	89	82	92.1%
	VMO3	89	83	93.3%
	VCR1	55	51	92.7%
	All	288	266	92.4%

Under reference conditions (10 × 10 cm² field, depth 10 cm, SSD 90 cm), the MC algorithm meets the 0.5% tolerance for all LINACs, with the following relative deviations: 0.22% for VMO1, −0.20% for VMO2, 0.20% for VMO3 and −0.2% for VCR1.

The Kolmogorov–Smirnov test indicated non-normal distributions for both datasets (p -value < 0.001), justifying the use of non-parametric statistical analyses. No statistically significant differences were observed between MC and CC dose calculations (p -value = 0.071). The Bland–Altman analysis (Figure 2) further confirmed the agreement between the two algorithms. Large relative differences were only observed for out-of-field, low-dose regions.

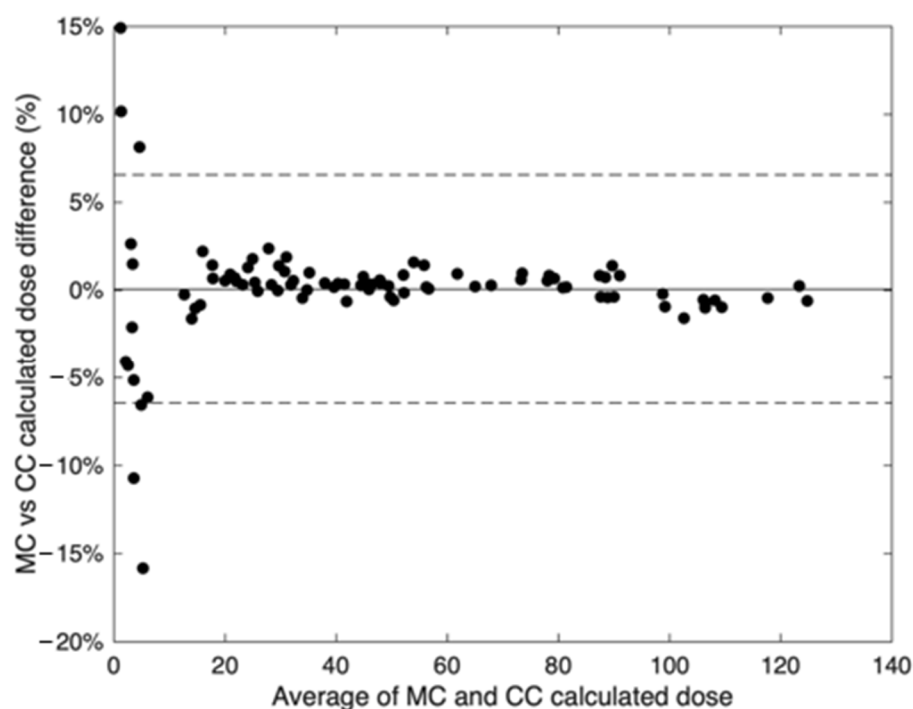


Figure 2. Bland–Altman plot for MC- and CC-calculated absorbed doses in cubic water tank phantom for 6MV energy.

For the 6FFF energy, the MC algorithm also demonstrated good agreement with measurements, with a majority of points showing dose differences within 2%. The few deviations observed are mainly located at the field edges and in the build-up region, where measurements are more sensitive to local instabilities and steep dose gradients; nevertheless, the relative errors remain below 3%.

The passing rates according to TG157 tolerance for both the MC and CC 6FFF algorithms are reported in Table 6.

Table 6. Passing rates for the cubic water tank measurements with TG157 and TG244 tolerances, for both the MC and CC algorithms, with 6FFF energy.

Algorithm	Linear Accelerator	Number of Points	Number of Points Within 2% Difference	Passing Rate Within 2% Difference
MC	VMO1	55	53	96.4%
	VMO2	55	53	96.4%
	VMO3	55	51	92.7%
	VCR1	55	52	94.5%
	All	220	209	95.0%
CC	VMO1	55	55	100%
	VMO2	55	55	100%
	VMO3	55	54	98.2%
	VCR1	55	53	96.4%

All	220	217	98.6%
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Under reference conditions for 6FFF, the MC algorithm also met the 0.5% tolerance for all LINACs, with the following relative deviations: −0.23% for VMO1, −0.54% for VMO2, −0.45% for VMO3 and −0.23% for VCR1.

Similar results in the statistical analysis obtained with 6MV were found with 6FFF energy: non-normality distributions (p -value < 0.001) with Kolmogorov–Smirnov, no statistical difference between MC and CC with Wilcoxon test (p -value = 0.078) and good agreement with Bland–Altman analysis (Figure 3). Similarly to 6MV, even for 6FFF, larger differences were only observed for out-of-field dose points.

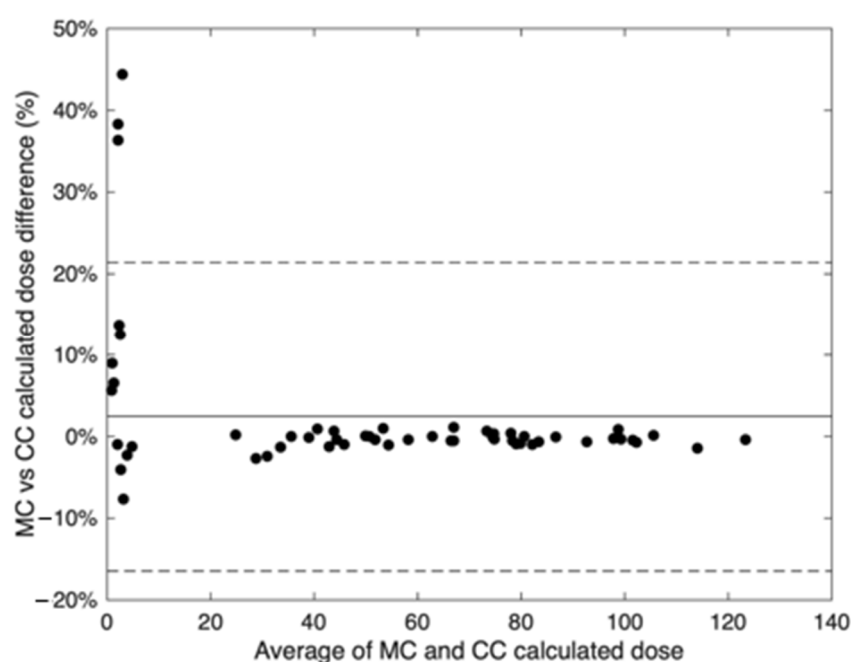


Figure 3. Bland–Altman plot for MC- and CC-calculated absorbed doses in cubic water tank phantom for 6FFF energy.

3.3. Heterogeneous Phantom

The comparison between calculated and measured point doses in the heterogeneous phantom is reported in Table 7. Overall, the MC algorithm showed excellent agreement with measurements, with all test cases falling within the 2% tolerance recommended by AAPM TG-157. The average absolute difference across all irradiation geometries was 1.2% for MC, compared with 1.8% for CC, indicating a systematically improved performance of the MC model in the presence of density discontinuities. Across all beams, MC consistently outperformed or matched CC. The largest deviations were observed in oblique-beam and non-coplanar geometries—particularly in lateral fields (Test Case 3) and the non-coplanar setup (Test Case 5). The CC algorithm, although clinically acceptable, showed larger deviations in several cases.

Table 7. Relative percentage difference (calculated vs. measured) for heterogeneous phantom measurements.

Test Case	Field Size (cm ²)	Beam	Calculated vs. Measured	
			MC	CC
1	10 × 10	B1:0°	1.3%	1.9%

2	15 × 10 Ant	B1:0°	0.7%	2.0%
	15 × 8 RL	B1:0°	1.8%	1.8%
3	15 × 8 LL	B2:90°	1.8%	2.4%
	10 × 12	B3:270°	−1.8%	−1.6%
	10 × 6	B4:180°	2.0%	2.9%
4	4 × 16 LL	B1:0°	1.6%	2.0%
	4 × 16 RL	B2:90°	2.3%	2.3%
	4 × 4 (couch 270°)	B3:270°	1.7%	2.5%
	14 × 14	B1:90°	−1.1%	2.0%
5	15 × 10 Ant	B2:270°	0.7%	2.3%
	15 × 10 Post	B3:330°	1.4%	2.2%
6	VMAT arc		1.1%	1.9%
	Average		1.0%	1.9%
	Standard Deviation		1.9%	1.1%
	Average of Absolute Values		1.5%	2.1%

Statistical analysis pointed out differences between the MC and CC calculations in heterogeneous phantom. As the distributions were non-normal (Kolmogorov–Smirnov p -value < 0.001), a Wilcoxon test was used to compare the medians. The results showed a significant difference between the absorbed dose distributions (p -value = 9.77×10^{-4}). Furthermore, Bland–Altman analysis (Figure 4) showed a positive bias between MC and CC calculations.

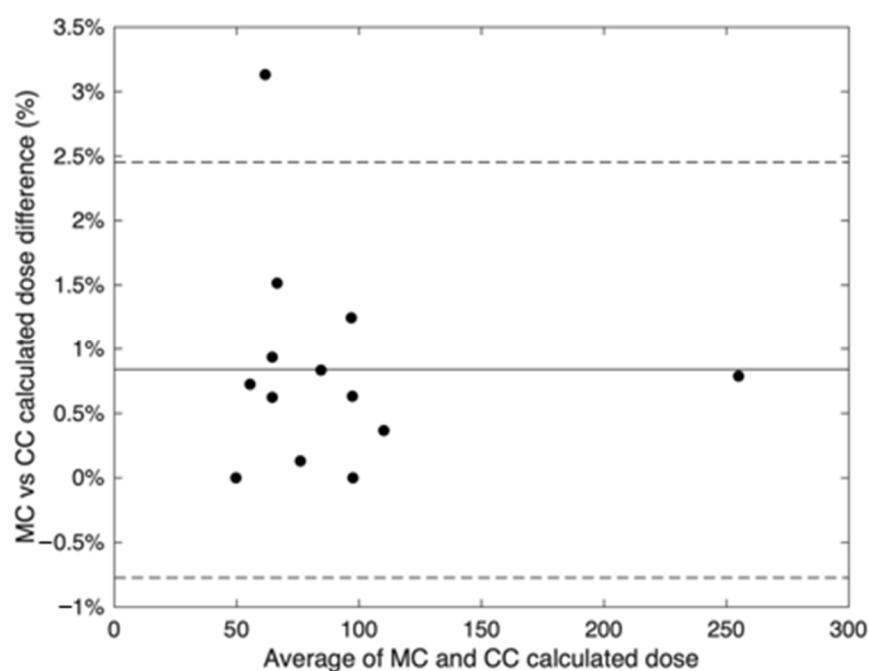


Figure 4. Bland–Altman plot for MC- and CC-calculated absorbed doses in heterogeneous phantom for 6MV energy.

3.4. Advanced Technique Validation (VMAT, IMRT, dMLC)

For the advanced technique study conducted with the Matrixx phantom, both the individual arcs or beams and their summed dose maps were analyzed to ensure a comprehensive evaluation. In total, 51 maps were acquired for each LINAC (23 VMAT, 16 IMRT and 12 dMLC), resulting in 204 dose maps for the 6MV and 6FFF energies. Table 8

reports the average passing rates obtained for each plan with both the MC and CC algorithms.

Table 8. Passing rates obtained for 2%/2 mm gamma analysis for both MC and CC. For each test, the average passing rate across all four LINACs is shown.

Energy MV	Technique	Test Case	Global Dose 2%/2 mm	
			MC	CC
6MV	VMAT	Test I1	99.2%	97.7%
		Test I2	99.9%	99.1%
		Test I3	98.5%	97.9%
		Test I4/I5	97.9%	96.2%
		Abdomen	98.1%	99.3%
		Anal	97.4%	95.9%
	IMRT	Lung	96.3%	92.1%
		Test I2	98.7%	99.8%
		Test I3	98.7%	99.3%
	dMLC	Test I2	98.5%	99.6%
		Test I3	94.9%	97.3%
		Test I1	99.1%	96.0%
6FFF	VMAT	Test I2	97.7%	94.7%
		Test I3	97.5%	95.1%
		Test I4/I5	94.0%	95.5%
		Abdomen	98.1%	95.4%
		Anal	96.8%	96.0%
		Lung	96.2%	95.8%
	IMRT	Test I2	98.4%	96.3%
		Test I3	97.4%	96.0%
	dMLC	Test I2	99.4%	98.4%
		Test I3	95.8%	97.0%

For VMAT at 6MV, the MC algorithm yields passing rates above 95.0% for all tests, fulfilling the acceptance criteria. Additionally, an analysis of the individual LINACs shows that all of them achieved an average passing rate above 95.0% across all tests. The only exception is VMO1 in the Lung case, with a value of 93.9%, which falls within a warning, yet still acceptable, tolerance range. With the CC algorithm, all tests also satisfy the criterion except for the Lung case (92.1%), and although the CC values are generally slightly lower than those of MC, they remain within the required limits.

For VMAT at 6FFF, all MC results exceed 95.0% except for Test I4/I5 (94.0%), with all machines still maintaining values above 90%. With CC, all tests meet the threshold apart from Test I2 (94.7%), due to slightly reduced performances of VMO1, VMO2 and VCR1; a few additional deviations appear for some machines, although without significantly affecting the overall outcome.

In the case of IMRT, for both energies and for both algorithms, all tests exceed the 95.0% threshold, with CC typically providing slightly higher values than MC. At 6FFF, some machines show minor deviations with CC, though the overall averages remain compliant.

For dMLC at 6MV, MC results fall below 95% but remain above 90% for both tests, with the reduced performance primarily attributable to VMO2, which shows considerably lower passing rates. Using CC improves the overall scores, although VMO2 still displays a reduced value in one test. At 6FFF, MC provides acceptable results for all tests, with VMO2 showing a noticeable improvement relative to 6MV; only VMO3 and VCR1 slightly

miss the 95% threshold. With CC, both the overall averages and the individual machines satisfy the acceptance criteria.

Figure 5 and Figure 6 summarize the general trends of MC and CC at the 2%/2 mm criterion for all the techniques analyzed, for 6MV and 6FFF respectively.

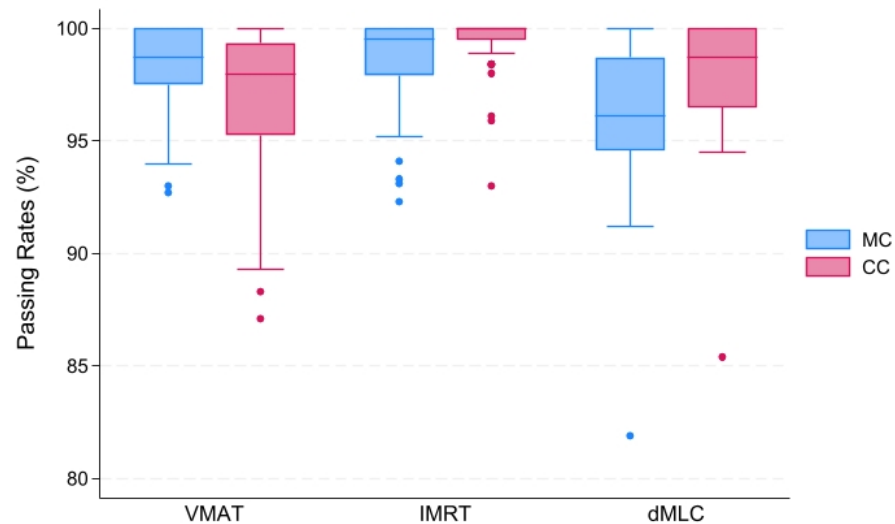


Figure 5. Passing rates at 2%/2 mm in percentage of both MC and CC with 6MV energy obtained for VMAT, IMRT and dMLC techniques. This graph is representative of the whole trend of both algorithms.

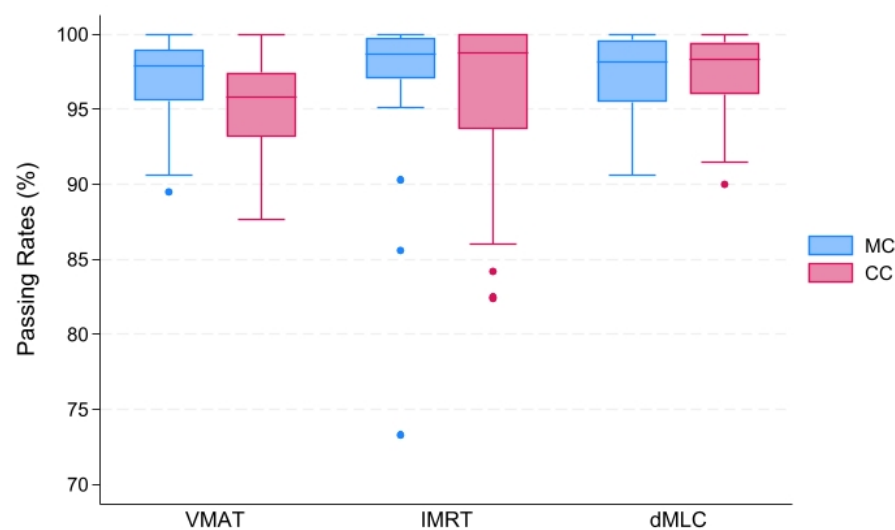


Figure 6. Passing rates at 2%/2 mm in percentage of both MC and CC with 6FFF energy obtained for VMAT, IMRT and dMLC techniques. This graph is representative of the whole trend of both algorithms.

3.5. SRS Phantom

In the SRS study, a total of 25 maps were analyzed, six acquired with 6MV and 19 with 6FFF energies. The resulting average passing rates from the 2%/2 mm Global Dose Gamma analysis are reported in Table 9 for both MC and CC.

Table 9. Passing rates for both MC and CC obtained for all the tests under analysis by considering their correspondent beam dose maps outcomes with the 6MV and 6FFF energies, by employing SRS phantom.

Energy (MV)	Patient Test	Global Dose 2%/2 mm	
		MC	CC
6MV	SRS Prostate	99.2%	99.3%
	SRS Encephalon	100.0%	100.0%
	SRS Prostate	97.8%	98.0%
	SRS Multiple Brain	97.5%	93.0%
6FFF	SRS Encephalon	100.0%	98.9%
	QASRS Encephalon	99.4%	97.8%
	QASBRT Lung	96.1%	98.0%

For the 6MV energy, both algorithms show average passing rates above the 95.0% threshold, displaying almost identical values and therefore indicating strong consistency between MC and CC. All results exceed 98.0%, with MC showing only a slightly wider distribution but a mean value comparable to CC.

For the 6FFF energy, instead, some differences can be highlighted for the two algorithms. While MC provides passing rates above the threshold for all tests, CC falls below 95.0% for the SRS Multiple Brain case, where reduced values are observed at both criteria (93.0% and 94.3%). With MC, only one value (93.4%) lies below the limit, whereas CC presents four values below 95.0%, two of which drop under 90.0% (87.8% and 87.0%). These critical values all correspond to the SRS Multiple Brain test.

3.6. Uncertainty and Grid Size Study

The results of the uncertainty and grid size analysis for the Abdomen and SRS Prostate plans are summarized in Figure 7 and Figure 8, respectively. For each plan, the left panel illustrates the dependence of Average Gamma and computation time on statistical uncertainty at fixed grid size (2 mm), while the right panel shows the corresponding dependence on grid size at fixed uncertainty (0.5%).

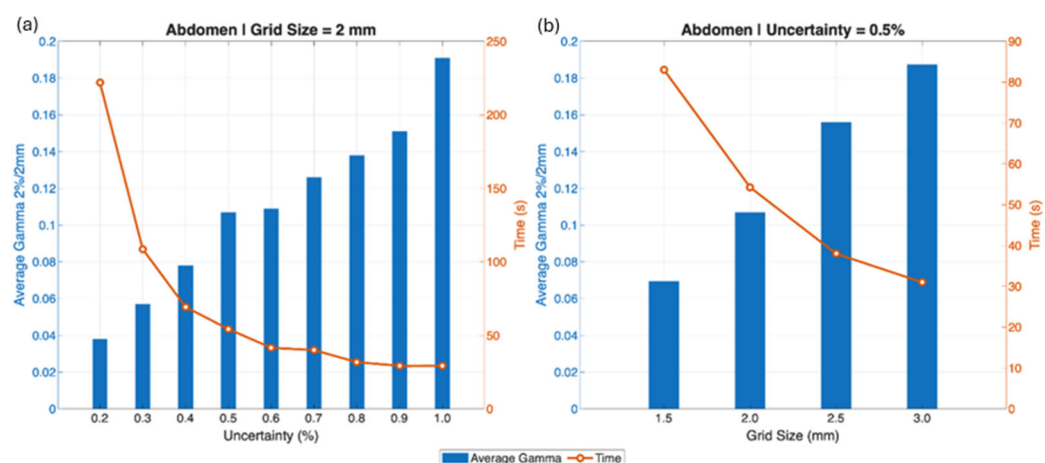


Figure 7. (a) Average Gamma and time of calculation (s) as a function of uncertainty (%), (b) Average gamma and time of calculation (s) as a function of grid size (mm) for the Abdomen case. Gamma analysis was performed by comparing each dose distribution with the reference calculation obtained using the lowest parameter value (i.e., 0.1% uncertainty or 1.0 mm grid size), assumed to represent the highest achievable accuracy.

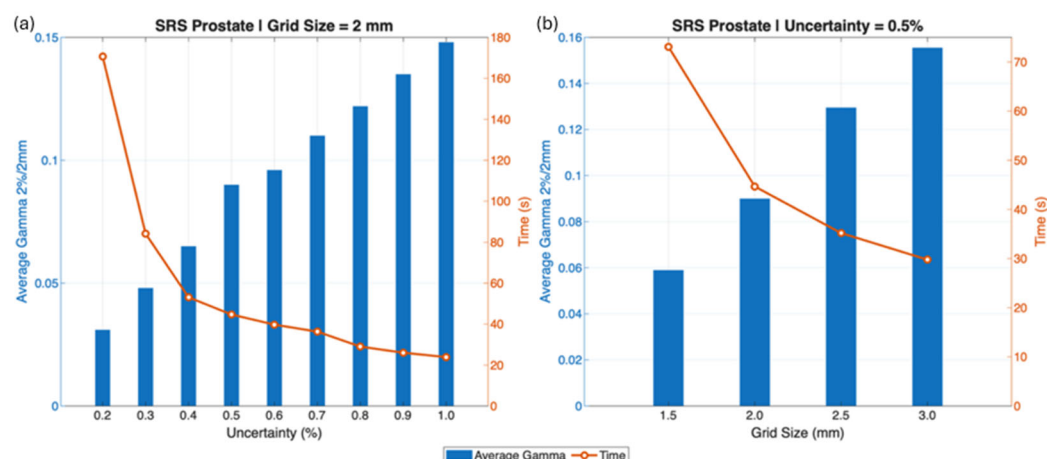


Figure 8. (a) Average Gamma and time of calculation (s) as a function of uncertainty (%), (b) average gamma and time of calculation (s) as a function of grid size (mm) for the SRS Prostate case. Gamma analysis was performed by comparing each dose distribution with the reference calculation obtained using the lowest parameter value (i.e., 0.1% uncertainty or 1.0 mm grid size), assumed to represent the highest achievable accuracy.

For both plans, increasing the statistical uncertainty resulted in a progressive increase in the Average Gamma value, indicating a gradual loss of agreement with the reference calculation. Computation time decreased rapidly with increasing uncertainty, particularly below 0.5%, whereas further increases above this value produced only limited additional reductions in calculation time.

Variation in the dose grid size produced a clear effect on dosimetric agreement. Increasing the grid size from 1 mm to 3 mm resulted in progressively higher Average Gamma values relative to the 1 mm reference calculation, indicating a loss of spatial resolution, while providing a corresponding reduction in computation time.

Overall, the combined analysis demonstrates that a 2 mm dose grid combined with 0.5% statistical uncertainty provides the best compromise between accuracy and efficiency. Specifically, for this optimal configuration, the absolute calculation times were 54 s for the Abdomen plan and 45 s for the SRS Prostate plan. This configuration maintains low Average Gamma values relative to the best-case reference calculations while ensuring computation times compatible with routine clinical workflows, as well as with the more demanding requirements of stereotactic treatments.

4. Discussion

This study presents a comprehensive validation of a Monte Carlo dose calculation model implemented in the RayStation® treatment planning system for four dosimetrically matched Elekta® Versa HD linear accelerators. The validation strategy followed international recommendations (AAPM TG-157, TG-244 and IAEA TECDOCs), spanning from basic beam data to complex clinical techniques, and included a direct comparison with the clinically established Collapsed Cone algorithm.

Compared with the previous study by Manco et al. [12], the present work extends the validation of the RayStation® MC dose calculation algorithm to a wider and more clinically representative set of conditions. While earlier studies primarily addressed the feasibility of using a single MC beam model across multiple beam-matched LINACs, this work provides a more comprehensive clinical validation by including an additional accelerator, recently commissioned data, and an updated version of the treatment planning system.

The comparison of PDDs and beam profiles demonstrated excellent agreement between MC calculations and measurements for open fields across all investigated field sizes and energies. Gamma passing rates were consistently high, often reaching 100% at the 2%/2 mm criterion, confirming the robustness of the MC beam model under reference and standard clinical conditions. Reduced agreement was observed for wedged fields, particularly in Crossline profiles. This behaviour is likely related to the specific configuration of the wedge parameters within the treatment planning system. While this agreement could potentially be improved by a dedicated optimization of these parameters [24], it was not further investigated since it is outside our current clinical interest. Indeed, the primary goal of commissioning this MC algorithm is its deployment for VMAT treatments, where physical wedges are not used.

Point dose measurements in homogeneous water phantoms further confirmed the accuracy and stability of the MC model. For both the 6MV and 6FFF energies, the majority of points satisfied the 2% tolerance recommended by TG-157, with deviations mainly confined to build-up and penumbral regions, where steep dose gradients and detector limitations inherently affect measurement reliability. Importantly, the MC model met the stringent 0.5% tolerance under reference conditions for all four LINACs, demonstrating its suitability for absolute dose calculation. Statistical analyses revealed no significant differences between MC and CC calculations in homogeneous media, indicating comparable performance for conventional beam geometries.

The validation in heterogeneous media highlighted the strengths of the MC approach. In the custom heterogeneous phantom, MC calculations consistently matched or outperformed CC, yielding lower mean absolute dose differences across all test geometries. The most pronounced discrepancies were observed for oblique and non-coplanar beams, as well as at density interfaces, where the limitations of analytical algorithms such as CC are well known. These results underscore the advantage of MC in accurately modelling particle transport in the presence of strong density heterogeneities.

For advanced treatment techniques, including VMAT, IMRT and dMLC, both algorithms generally fulfilled the acceptance criteria of a 95% passing rate at 2%/2 mm. MC showed slightly superior performance for VMAT plans, particularly in anatomically complex cases such as lung treatments, whereas CC yielded marginally higher passing rates for some IMRT and dMLC plans. The slightly lower performance observed for dMLC compared to VMAT under MC calculations can be attributed to the specific geometric modelling of the MLC leaves. In dMLC, fields often feature narrow, sliding slits where leaf-tip penumbra, inter-leaf leakage, and tongue-and-groove effects dominate the dose distribution. Under highly modulated dMLC conditions, minor discrepancies in the parametric approximations used by the MC algorithm for leaf-tip transmission become more pronounced. Conversely, in VMAT plans, the continuous rotation of the gantry and the variable dose rate tend to average out and blur these localized MLC modelling limitations.

The stereotactic validation using the high-resolution SRS phantom provided further evidence of the robustness of the MC model in small-field high-gradient scenarios. After applying the appropriate dose-to-medium to dose-to-water correction for the RW3 phantom material, MC achieved excellent agreement with measurements, particularly for complex multitarget SRS plans, where CC exhibited reduced passing rates. These findings confirm the suitability of MC algorithms for stereotactic applications, provided that material-dependent dose reporting is properly addressed.

Finally, the dedicated uncertainty and grid size study demonstrated that calculation parameters significantly affect both dosimetric accuracy and computation time. While finer grids and lower uncertainties improve agreement with measurements, the associated increase in computation time limits their clinical practicality. A dose grid of 2 mm combined with a statistical uncertainty of 0.5% was identified as the optimal compromise,

offering high dosimetric accuracy with computation times compatible with routine clinical workflows (calculation times below 55 s for complex VMAT and SRS treatments). Nevertheless, while a 2 mm grid represents an excellent baseline compromise for larger volumes, a case-by-case adaptive strategy is recommended in clinical practice. For small target volumes with steep dose gradients, a 1 mm grid size (0.5% uncertainty) should be preferred to maximize accuracy.

Overall, the results confirm that the validated MC model provides reliable and consistent dose calculations across multiple matched LINACs and a wide range of clinical scenarios. Remaining limitations are mainly related to wedge beam modelling, which warrant further investigation and potential refinement.

This work has some limitations. To take into account the difference between D_{med} and D_w in MC computation, a fixed correction factor based on stopping-power ratios for RW3-to-water, taken from the literature, was applied. This choice was made to avoid a possible local overfitting, to ensure reproducibility and to reduce possible biases in a multi-LINAC validation. In a future specific study, a correction factor could be empirically determined taking into account multiple phantoms with different water equivalent materials. Another limitation is that measurements were performed only once per LINAC. Nevertheless, evaluating the amount of data acquired at the four matched LINACs with two different photon energies mitigates this restriction by providing a comprehensive multi-machine validation.

5. Conclusions

A Monte Carlo dose calculation model implemented in the RayStation® treatment planning system was successfully validated for four dosimetrically matched Elekta® Versa HD linear accelerators. The model demonstrated high accuracy and consistency across a broad range of test conditions, including reference measurements, homogeneous and heterogeneous phantoms, and advanced clinical techniques such as VMAT, IMRT, dMLC and stereotactic radiosurgery.

The MC algorithm showed dosimetry performance comparable to, and in several clinically relevant scenarios superior to, the Collapsed Cone algorithm, particularly in heterogeneous media and small-field stereotactic applications. This study also confirmed that appropriate selection of calculation parameters is essential for clinical implementation, with a 2 mm dose grid and 0.5% statistical uncertainty providing an optimal balance between accuracy and computation efficiency, although an adaptive strategy may be recommended in smaller target treatment.

The consistent performance observed across all matched LINACs supports the use of a single MC beam model in multi-machine environments, facilitating flexible and robust clinical workflows. While further improvements are desirable for wedge beam modelling and dose accuracy in build-up and penumbral regions, the validated MC model is suitable for routine clinical use and represents a reliable solution for advanced radiotherapy treatment planning.

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Abbreviations

The following abbreviations are used in this manuscript:

CC	Collapsed Cone
dMLC	Dynamic Multileaf Collimator
IMRT	Intensity Modulated Radiation Therapy
MC	Monte Carlo
PDD	Percentage Depth Dose
SRS	Stereotactic Radiosurgery
SSD	Source to Surface Distance
TPS	Treatment Planning System

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