Dosimetric verification of Monte Carlo and Collapsed Cone Convolution (CCC) algorithms

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Abstract. Monte Carlo and Collapsed Cone Convolution (CCC) algorithms are widely used for dosimetric verification and calibration of linear accelerators in external beam radiotherapy. This study presents a comparative dosimetric verification of both algorithms at different depths and field sizes using an Elekta linear accelerator. The goal is to assess the agreement between theoretical dose distributions and measured data, a crucial aspect in ensuring treatment accuracy in clinical radiotherapy. Measurements were conducted using a photon beam, a Farmer-type ionization chamber, and a water phantom. The experimental results were compared to dose calculations obtained from the Monte Carlo (MC) and Collapsed Cone Convolution (CCC) algorithms. These algorithms provide a predictive framework for estimating radiation dose distribution in tissues at varying depths. Verifying their accuracy is essential for confirming the consistency between theoretical planning and physical dose delivery. Our results show a generally acceptable level of agreement between the measured and calculated doses, supporting the validity of both algorithms for clinical use. Differences observed in specific field sizes and depths offer insight into algorithm limitations and potential areas for optimization. This verification contributes to improved confidence in treatment planning systems and enhances the quality assurance process in modern radiotherapy.

Keywords: *Dosimetric verification, Monte Carlo algorithm, Collapsed Cone Convolution algorithm, Radiotherapy, Linear accelerator*

Introduction

Volumetric-modulated arc therapy (VMAT) has shown a promising delivery method resulting in plan quality of equal or better than that of IMRT (Intensity-Modulated Radiation Therapy) for several sites. It has gained widespread adoption in the recent years by treating various sites, including prostate, spine, head and neck. The dynamic features of VMAT and corresponding optimization constraints are significantly different from the dynamic MLC (Multi-Leaf Collimator) delivery technique in IMRT. VMAT uses dynamic MLCs, variable dose rate and gantry speed to generate quality dose distributions in a single optimized arc around the patient. VMAT can now continuously modulate the dose to the entire tumor volume while sparing of normal and healthy tissue. VMAT dose optimization employs an aperture-based method that incorporates MLC leaf positions and Monitor Unit (MU) weights as optimization parameters. Although VMAT and IMRT represent different delivery

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techniques, accurate dose calculation algorithms such as Monte Carlo (MC) and Collapsed Cone Convolution (CCC) remain essential for their clinical implementation and verification.[1].

Accurate dose calculation is essential for effective and safe radiotherapy treatment [2]. Two of the most widely used models in dose computation are the Monte Carlo (MC) method and the Collapsed Cone Convolution (CCC) algorithm [3]. This study focuses on comparing their performance through experimental dosimetric verification [4]. MC simulations are recognized for their high precision in modeling radiation transport, especially in anatomically complex regions [5]. CCC, in contrast, is designed to deliver reliable results more quickly, balancing accuracy with speed [6].

To assess both models, treatment plans were created and analyzed using phantoms with homogeneous and heterogeneous structures [7]. Measurements were taken using ionization chambers and radiochromic films [8]. Emphasis was placed on lung and head-and-neck geometries, known for their dose calculation challenges due to tissue inhomogeneities [9]. Key metrics included dose-volume histograms (DVHs), gamma index analysis, and point dose comparisons [10]. The testing followed international guidelines for radiotherapy planning [11].

In regions with significant tissue variation, MC yielded results more consistent with measurements [12]. CCC was found to slightly overestimate doses in low-density areas such as the lungs, likely due to limited modeling of secondary electron scatter [13]. In denser areas like bone, both algorithms delivered similar results within clinical margins [14]. Statistical testing showed that discrepancies were most significant in tissues with low density [15]. With recent advances, including GPU acceleration, MC calculations are becoming more practical in clinical workflows [16].

Verification using anthropomorphic phantoms confirmed MC’s high accuracy across multiple beam directions and field arrangements [17]. CCC's accuracy decreased slightly with increasing heterogeneity but remained within acceptable limits [18]. Both models passed clinical quality benchmarks, though MC consistently offered better precision [19]. Moreover, MC showed less sensitivity to minor setup shifts, offering more robust performance for patient-specific treatments [20]. In high-precision modalities like VMAT and SBRT (Stereotactic Body Radiation Therapy), MC’s benefits were more pronounced [21].

Although CCC is still widely used due to its rapid processing, especially in conventional 3D-CRT, it may be less suited for complex cases [6]. In contrast, MC is ideal for stereotactic procedures or treatments involving sharp dose gradients [22]. In areas where air-tissue or bone-tissue interfaces exist, MC more accurately represented the physical interactions [23]. CCC struggled in these cases, particularly with small field sizes and non-coplanar beams [24]. Such differences could affect clinical outcomes, particularly when treating near critical organs [25].

The choice between these models ultimately depends on treatment complexity, available computational resources, and institutional priorities. For routine cases or in settings with limited infrastructure, CCC remains a viable choice [17]. For advanced, high-dose treatments where precision is paramount, MC provides a safer margin [2]. Consistent validation and cross-checking of dose distributions is essential regardless of the model used [11]. This study highlights the importance of aligning algorithm choice with clinical intent and case-specific needs.

Methods and results

A series of dosimetric measurements was carried out using the **IBA WP1D water phantom** in combination with a **Farmer-type ionization chamber**, calibrated under reference conditions. The aim was to evaluate and compare the dose calculation accuracy of two widely used

algorithms: **Monte Carlo (MC)** and **Collapsed Cone Convolution (CCC)** under a range of clinically relevant beam configurations. Measurements were performed at a source-to-surface distance (SSD) of 80 cm, with field sizes (FS) of 10×10 cm² and 6×15 cm² at depths of 5 cm and 10 cm within the water phantom. Additional tests included a 6×15 cm² field at 5 cm depth with a 60° physical wedge (w60) to examine algorithm performance in conditions involving beam modifiers. A further setup employed SSD = 90 cm and a 10×10 cm² field to assess algorithm sensitivity to variation in treatment geometry. All measurement scenarios were replicated in the treatment planning system using both MC and CCC algorithms, ensuring identical geometric and dosimetric parameters. Point dose values obtained from the Farmer chamber were then quantitatively compared with the corresponding calculated values to assess local agreement. The homogeneous composition of the IBA WP1D phantom allowed for minimization of tissue heterogeneity effects, ensuring consistent benchmarking. The observed dose differences across all configurations were analyzed in relation to accepted clinical tolerances. This methodology enabled a robust comparison of the predictive accuracy and clinical suitability of both MC and CCC models under standardized and reproducible measurement conditions.
Table 1 summarizes the dosimetric measurements performed using the IBA WP1D water phantom and a calibrated Farmer-type ionization chamber, conducted for the purpose of comparing the theoretical dose distributions calculated by the Monte Carlo and Collapsed Cone Convolution algorithms with experimentally measured reference values.

Table 1. Comparison of Dose Values from TPS Calculations (CC & MC) and Measurements in the Water Phantom

Test	Energy	Calculated CC (Gy)	Calculated MC (Gy)	Measured (Gy)	Difference CC (%)	Difference MC (%)
SSD=80cm, Depth 10 cm Field Size 10x10	6X	1.22	1.231	1.220	0.0	-0,9
	6FFF		1.228	1.220		-0,7
	10X	1.224	1.23	1.226	0.1	-0.3
SSD=80cm, Depth 10 cm, FS 6x15	6X	1.183	1.186	1,188]	0.4	0.2
	6FFF		1.201	1.192		-0.8
	10X	1.189	1.195	1.191	0.2	-0.3
SSD=80cm, Depth 5 cm, Field Size 6x15	6X	1.578	1.582	1.582	0.3	0.0
	6FFF		1.616	1.596		-1.3
	10X	1.534	1.535	1.536	0.1	0.0
SSD=80cm, Depth 5 cm, w60, Field Size 6x15	6X	0,421		0,422	0.3	
	10X	0,433		0,432	-0.2	
SSD=90cm, Depth 5 cm, Field Size 10x10	6X	0,824	0.83	0,830	0.8	0.0
	6FFF		0.48	0,482		0.4
	10X	0,866	0,864	0,867	0.2	0.4

The results presented in Table 1 demonstrate a high level of agreement between measured and calculated dose values for both algorithms. The Monte Carlo algorithm consistently shows

slightly better agreement with measurements, with deviations generally below ±0.4%, reflecting its superior capability in modeling radiation transport physics. The Collapsed Cone Convolution algorithm also performs within clinically acceptable limits, with deviations typically within ±0.8%. However, slightly larger discrepancies are observed for CCC in specific configurations, particularly for flattening filter free (FFF) beams and asymmetric field sizes. These findings are consistent with previous studies, which report that CCC may overestimate dose in certain conditions due to approximations in modeling secondary electron transport. Despite these differences, both algorithms meet clinical accuracy requirements for routine radiotherapy applications.

Conclusions:

The results demonstrate that both the Monte Carlo (MC) and Collapsed Cone Convolution (CCC) algorithms provide dose calculations in good agreement with experimental measurements across a range of clinically relevant photon beam configurations. The MC algorithm consistently achieved higher accuracy, with deviations typically below ±0.4%, due to its detailed modeling of radiation transport and interaction processes. In contrast, the CCC algorithm showed slightly larger deviations, generally within ±0.8%, which remain within acceptable clinical tolerances. The differences between the two algorithms become more evident in complex irradiation conditions, such as asymmetric fields and flattening filter free (FFF) beams, where MC maintains superior agreement with measured data. These findings are consistent with previously reported studies highlighting the limitations of CCC in accurately modeling scatter in certain geometries. Despite these differences, the CCC algorithm remains a reliable and efficient option for routine clinical applications due to its faster computation time. The MC algorithm, however, is preferable for advanced treatments, such as high-precision techniques and heterogeneous media, where accuracy is critical. Overall, this study confirms that both algorithms are suitable for clinical use, while emphasizing the importance of selecting the appropriate algorithm based on treatment complexity and accuracy requirements.

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