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Correlation of thickness changes and daily dose detection of delivery analysis (DA) software in helical tomotherapy

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Original Article

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Abstract

Purpose: To assess the correlation between the dose distribution provided by the delivery analysis (DA) software and the measured dose distribution using an ArcCHECK (AC) phantom in the presence of thickness variation.

Materials and Methods: Two sets of targets were established within the phantom. Target A was placed on the detector areas, whereas Target B was positioned at the centre of the phantom. Bolus was applied to the surface of the phantom at different thicknesses ranging from 0 to 2 cm to verify the dose distribution in both TomoHelical (HT) and TomoDirect (TD) techniques. The gamma passing rate (GPRs) were evaluated against predefined thresholds of 3%/3 mm and 3%/2 mm. Correlation study evaluated the level of agreement between DA and AC values.

Results: Both AC and DA exhibited a decline in GPRs as the bolus thickness decreased. Significant correlations were observed between AC and DA for both HT and TD techniques, with a p value of less than 0.001.

Conclusion: The results indicate that DA software has the capability to detect anatomical changes during tomotherapy treatments. This is substantiated by the statistical association found between DA and the standard AC phantom system for dose distributions in both HT and TD methods.

Introduction

Tomotherapy, a modern radiotherapy system, utilises advanced radiation treatment technology. It shares characteristics with computed tomography (CT), employing couch motion to position patients within the gantry. A linear accelerator, serving as the radiation source, is mounted on a gantry capable of 360-degree rotation. The typical therapeutic radiation energy is 6 megavolts (MV), which is reduced to 3.5 MV for imaging purposes to confirm target positioning before treatment commences. To enhance image quality and efficiency within the image-guided radiotherapy system, an additional kilovolt (kV) radiation source has been incorporated, installed perpendicular to the original source for dedicated image acquisition. This rotational image-guided radiation therapy machine offers two delivery techniques: helical tomotherapy (HT), where the radiation source rotates around the patient while the treatment couch moves simultaneously through the gantry. Tomodirect (TD) is another technique where the source remains stationary while the couch traverses the gantry. Both techniques employ intensity-modulated radiation therapy (IMRT), delivering a fan-beam shaped. High-speed, binary movements of the Multileaf Collimator (MLC) rapidly open and close radiation fields during treatment, achieving optimal dose distribution that conforms to the target while minimising exposure to healthy tissues.[1,2] Due to the inherent complexity of IMRT techniques, verifying the accuracy of the radiation therapy system is paramount. This necessitates meticulous monitoring of parameters such as leaf open time and the movement rates of the gantry and treatment couch, ensuring that the dose distribution received by the patient aligns precisely with the treatment plan generated by the TPS.

Delivery Analysis (DA) software complements tomotherapy systems by evaluating machine performance and analysing the radiation dose delivered to patients during each treatment fraction. It offers daily insights into treatment efficiency, including multi-leaf collimator (MLC) positioning, by comparing current data with the initial treatment day. DA software functionalities encompass two primary areas. Firstly, pre-treatment verification ensures the accuracy of MLC data before radiation delivery. This involves the measurement of image detector signal data to generate a sinogram based on Leaf Open Time (LOT) during treatment plan verification. Subsequently, the dose distribution derived from the LOT sinogram is compared with the treatment plan generated by the treatment planning system (TPS). This crucial step safeguards treatment accuracy prior to radiation exposure. Secondly, the software

facilitates in-treatment assessment by evaluating daily treatment data for signal consistency from the image detector. Dose distributions are compared with the first day of treatment, with considerations for variables like patient positioning and potential anatomical changes that may influence data consistency. DA software automatically presents various data visualisations, including trend graphs of Gamma passing rates (%GP), dose distribution and dose volume histograms (DVHs).[3] Discrepancies between patient data from each treatment fraction and the initial fraction data may indicate changes in anatomical characteristics, such as the size of the planning target volume or patient body weight. These changes can lead to deviations in radiation dose distribution compared to the original treatment plan. Consequently, the target may receive insufficient radiation coverage, while normal tissues may be exposed to higher doses. This necessitates adjustments to the treatment plan using adaptive radiotherapy (ART) techniques, which involve replanning processes to guarantee that the delivered radiation dose aligns precisely with the patient's evolving anatomical features.

Therefore, researchers recognise the potential of DA software to automatically display data on changes in radiation delivery for each fraction. This functionality offers a means for its application as a tool to identify optimal time intervals for treatment plan adaptation and re-planning. Thus, this study aims to evaluate how the dose distribution generated by the DA software correlates with the measured dose distribution using a ArcCHECK (AC) phantom in the situation of thickness variation.

Materials and Method

Simulation and target delineation

This study employed the ArcCHECK (AC) system (Sun Nuclear, Melbourne, FL) – a cylindrical phantom with specialised diode array detector designed to identify delivery errors in rotational radiation therapy. The pieces of bolus were placed on the surface of AC phantom to simulate tissue thickness variation. The CT images of the ArcCHECK phantom with bolus 2.0 cm thickness were acquired with a slice thickness of 3 mm. For the experiment, two target sets were created within the phantom. The first target was positioned on the detector areas (Target A), and the other was positioned at the centre of the phantom (Target B), as shown in Figure 1.

Treatment planning

The TomoTherapy treatment planning system, Accuray Precision version 3.3.1.3 (Accuray, Incorporated, Sunnyvale, CA) was used to create two treatment delivery modes on AC phantom images with both Target A and Target B: one with TomoDirect, static gantry with beam angles set at 0, 40 and 320 degrees to specifically deliver radiation to the bolus region, and the other TomoHelical, Helical mode Plan involving a complete 360-degree rotation around the phantom. The total four treatment plans mimicked the characteristics of a specific cancer type: laryngeal cancer with a prescribed dose of 60 Gy in 30 fractions for plans Target A and prostate cancer with a prescribed dose of 70 Gy in 28 fractions for plans at centre Target B.

Dose measurement and dose comparison

The ArcCHECK phantom was set up at Radixact X9 treatment machine (Accuray, Incorporated, Sunnyvale, CA) for dose verification. A bolus, with a thickness starting at 2.0 cm, was placed on the phantom surface during the simulation process in accordance with predetermined specifications. The dose verification was classified into five situations by reducing the bolus thickness in 0.5 cm increments from the original thickness of 2.0 cm to 1.5 cm, 1.0 cm, 0.5 cm and finally without bolus.

Regarding the dose calculation and measurement dose comparison, the planned dose distribution for the ArcCHECK phantom was exported alongside the measured dose data acquired during irradiation. Both datasets were then transferred to the SNC Patient software for a global gamma analysis using established criteria of 3%/3 mm and 3%/2 mm. Additionally, a dose threshold of 10% was applied during the analysis. The resulting gamma passing rates (GPRs) were subsequently recorded.

For the DA software, Interfractional consistency during treatment delivery is evaluated using the DA software. This software analyzes post-treatment detector signals acquired during phantom irradiation to identify potential thickness changes. A detector receives transmitted X-rays throughout treatment, and upon completion, the data are automatically transferred to a separate workstation isolated from the treatment system network. DA software facilitates the assessment of irradiation consistency by generating trend graphs of Gamma passing rates (%GP) for each treatment fraction. These graphs are analysed using global gamma criteria of 3%/3 mm and 3%/2 mm, with a dose threshold of 10%.

Statistical analysis and evaluation

To evaluate agreement between dose distributions from the DA software and the AC phantom for each thickness situation, correlation analyses were conducted for each treatment plan. The choice of test depended on data normality. Pearson's correlation coefficient was used for normally distributed data, while Spearman's rank correlation coefficient was employed for non-normal data. Analysis aimed to achieve passing thresholds based on established guidelines. With a 3%/3 mm gamma analysis criterion, a minimum GPR of 90% is used as the tolerance limit, as recommended by AAPM TG-148.[4] Similarly, for the 3%/2 mm criterion, action and tolerance limits of 90 and 95% GPR were used, respectively, as recommended by AAPM TG-218.[5] These analyses focused on dose distributions for both Helical and TomoDirect delivery techniques at two locations of target within the ArcCHECK phantom: the diode array and the centre. Statistical analyses were performed using SPSS 26.0 (IBM Corp., Armonk, NY, USA).

Results

The agreement between dose distributions generated by the DA software and the ArcCHECK phantom was evaluated using gamma analysis for all plans. The thickness variations of 0 cm, 0.5 cm, 1.0 cm, 1.5 cm and 2.0 cm were introduced to the phantom to assess the impact on GPRs. The analysis employed gamma criteria of 3%/3 mm and 3%/2 mm, as recommended by TG-148 and TG-218, respectively.

Dose distribution comparison for TomoHelical technique

Calculation vs measurement by ArcCHECK (AC)

Figure 2a and 2b demonstrates dose distributions for TomoHelical (HT) treatment plans within the ArcCHECK phantom with Target A and Target B, respectively. The dose distribution deviation between treatment planning and the measurement was revealed in the average GPRs. Under the 3%/3 mm criteria, GPRs on Target A plans showed the ranges from 99.93 to 92.1% on variations in thickness (0–2.0 cm). While Target B plans showed the ranges of

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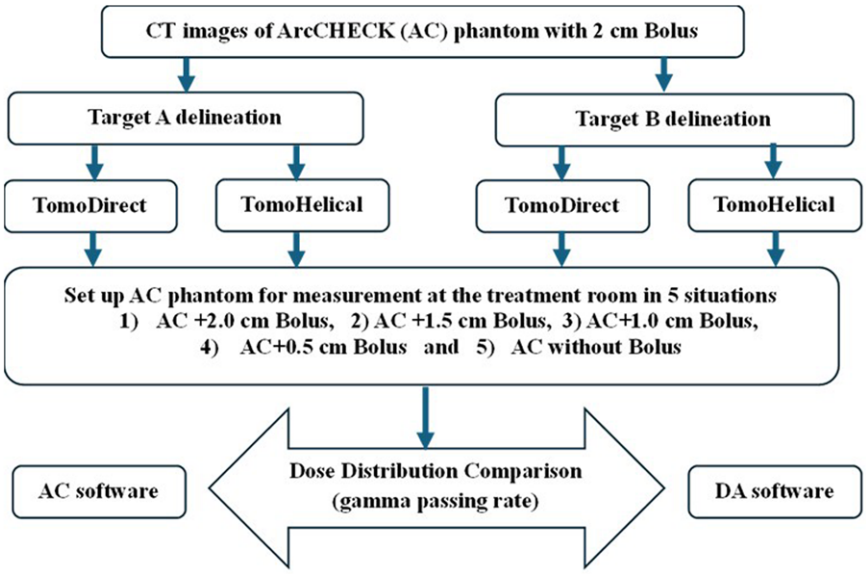

Figure 1. Diagram of the study design.

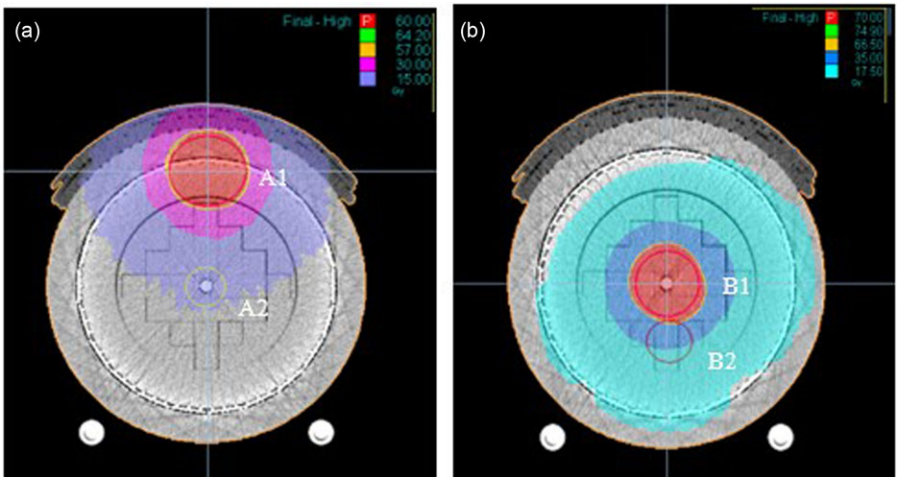

Figure 2. Dose distribution on ArcCHECK phantom in TomoHelical planning for the Target A plans (a) on the target volume (a1) and organ at risk: OAR volume (a2) and the Target B plans (b) on the target volume (b1) and organ at risk: OAR volume (b2).

GPRs from 99.5 to 85.1% on variations in thickness (0–2.0 cm). Moreover, for the 3%/2 mm criteria, the GPRs ranged from 99.73 to 89.6 and 98.87 to 79.4% for the Target A and B plans when varying 0–2.0 cm thickness, respectively.

ArcCHECK (AC) measurement vs DA software

The DA system also exhibited a range of GPRs. Table 1 demonstrates the correlation of dose distributions between DA and AC in 0–2.0 cm thickness variation. For the 3%/3 mm criteria, the GPRs revealed a significant correlation between AC and DA systems for both Target A and B plans (p value <0.001). Likewise, for the 3%/2 mm criteria, the results revealed a statistically significant correlation (p values < 0.001) in dose distribution between the AC and DA systems for both Target A and B plans.

Dose distribution comparison for TomoDirect technique

Calculation vs measurement by ArcCHECK (AC)

Figure 3a and 3b demonstrates dose distributions for TomoDirect (TD) treatment plans within the ArcCHECK phantom with Target A and Target B, respectively. The dose distribution deviation between treatment planning and the measurement was revealed in the average GPRs. Under the 3%/3 mm criteria, GPRs on Target A plans showed the ranges from 100 to 87.6% on variations in thickness (0–2.0 cm). While Target B plans showed the ranges of GPRs from 100 to 74.5% on variations in thickness (0–2.0 cm). Moreover, for the 3%/2 mm criteria, the GPRs ranged from 100 to 86.7% and 100 to 69.2% for the Target A and B plans when varying 0–2.0 cm thickness, respectively.

ArcCHECK (AC) measurement vs DA software

The DA system demonstrated varying GPRs. Table 2 illustrates the correlation of dose distributions between DA and AC across thickness variations from 0 to 2.0 cm. Significant correlations were observed between the AC and DA systems for both Target A and B plans under the 3%/3 mm criteria (p value <0.001). Similarly, for the 3%/2 mm criteria, a statistically significant correlation (p values < 0.001) was found in dose distribution between the AC and DA systems for both Target A and B plans.

Discussion

This study investigated the correlation between dose distribution measurements obtained from two devices: DA software and the

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Table 1. The correlation of gamma passing rates between ArcCHECK phantom (AC) and delivery analysis (DA) software with thickness variation (0–2 cm) for TomoHelical plans

Plan		Thickness changes.	Average Gamma passing rate (%) 0 cm	0.5 cm	1.0 cm	1.5 cm	2.0 cm	*p* Value
Target A	3%/3mm	AC	99.93	100	99.2	97.36	92.1	< .001*
		DA	99.99	99.2	95.32	90.86	88.66	
	3%/2mm	AC	99.73	99.8	98.1	94.13	89.6	< .001*
		DA	99.99	98.95	94.1	89.06	87.09	
Target B	3%/3mm	AC	99.5	99.5	96	91.2	85.1	< .001*
		DA	100	100	99.42	96.8	94.3	
	3%/2mm	AC	98.87	98.3	93.13	86.4	79.4	< .001*
		DA	100	100	99.09	95.97	93.5	

Target A: plan target on the detector areas of ArcCHECK phantom, Target B: plan target at centre of ArcCHECK phantom.
*Spearman's rank correlation was used.

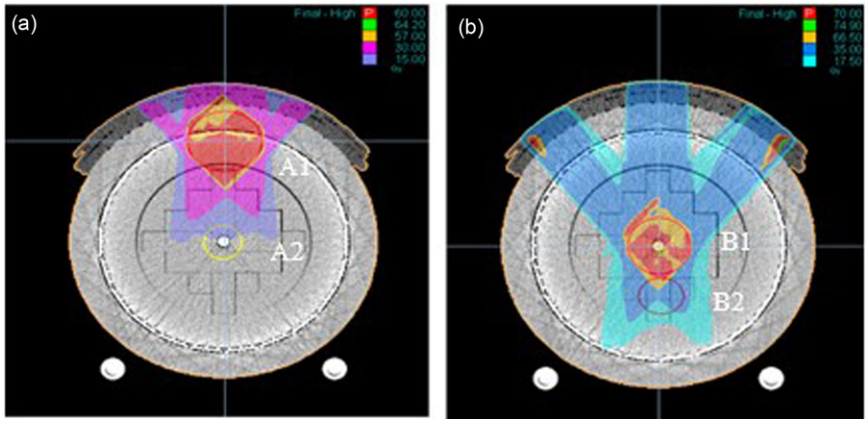

Figure 3. Dose distribution on ArcCHECK phantom in TomoDirect planning in 0, 40 and 320 degrees for the Target A plans (a) on the target volume (a1) and organ at risk: OAR volume (a2) and the Target B plans (b) on the target volume (b1) and organ at risk: OAR volume (b2).

ArcCHECK (AC) phantom, which was the reference method. The analysis focussed on the impact of varying bolus thickness (0 cm to 2 cm) on the phantom in both TomoHelical (HT) and TomoDirect (TD) techniques. Targets were positioned on both the diodes and the centre of the AC phantom. Both DA and AC exhibited a decrease in GPR as the bolus thickness decreased, based on criteria established by AAPM TG-148 (3% dose difference, 3 mm distance to agreement) and AAPM TG-218 (3% dose difference, 2 mm distance to agreement). Statistical analysis confirmed a significant correlation between the two measurement methods.

Within the AC system, Target A plans consistently achieved higher GPRs compared to Target B plans. This finding aligns with the work of Neilson et al.,[6] who observed similar behaviour during delivery quality assurance with ArcCHECK. They categorised targets into two groups: those positioned on the ArcCHECK diodes and those positioned at the centre. Their study revealed that the target on the diode location typically displayed a higher maximum planned dose on the cylindrical surface containing ArcCHECK diodes compared to centre plans, leading to inflated gamma pass rates. This observation highlights the potential influence of target location on GPR within the AC system. Additionally, we emphasise the importance of a meticulous setup process for ensuring accurate measurements.

The DA software, designed to monitor the consistency of post-treatment detector signals throughout a patient's radiation therapy course, also demonstrated a reduction in GPRs with decreasing bolus thickness. This aligns with the work of Wooten et al.,[7] who explored the use of exit detector sinograms to detect anatomical variations during TomoTherapy. Their research demonstrated the ability of exit detector sinograms to identify weight loss and other anatomical changes in patients. Furthermore, Tarutani et al.[3] evaluated the effectiveness of DA in detecting intrafractional motion during TomoTherapy. Their study concluded that DA is a robust tool with high detection sensitivity, capable of identifying body movement during treatment.

Additionally, DA can estimate the radiation dose delivered to each organ based on calculations derived from MLC leaf open time. However, for accurate dose estimation, detector calibration following the recommended Tomotherapy Quality Assurance (TQA) manual protocol is crucial. This study employed both TomoHelical (HT) and TomoDirect (TD) techniques for phantom irradiation. The initial GPR values for the HT technique were lower compared to TD at 0 cm. This can be attributed to the directional nature of radiation entry into the phantom during HT. Additionally, accuracy may be influenced by bolus positioning relative to the treatment simulation. The TD technique exhibited

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Table 2. The correlation of gamma passing rates between ArcCHECK phantom (AC) and delivery analysis (DA) software with thickness variation (0–2 cm) for TomoDirect plans

Plan		Thickness changes	Average Gamma passing rate (%)					*p* Value
			0 cm	0.5 cm	1.0 cm	1.5 cm	2.0 cm	
Target A	3%/3mm	AC	100	100	96 .6	89.0	87.6	< .001*
		DA	100	100	93.18	86.87	84.67	
	3%/2mm	AC	100	100	94.37	88.7	86.7	< .001*
		DA	100	100	90.87	85.53	84.08	
Target B	3%/3mm	AC	100	99.3	91.4	80.8	74.5	< .001*
		DA	100	100	99.1	95.32	89.8	
	3%/2mm	AC	100	96.7	83.67	73.3	69.2	< .001*
		DA	100	100	98.78	93.53	91.37	

Target A: plan target on the detector areas of ArcCHECK phantom, Target B: plan target at centre of ArcCHECK phantom.
*Spearman's rank correlation was used.

greater fluctuations in GPR values due to the specific beam direction used to deliver radiation to the bolus region. The bolus positioning on the phantom, as illustrated in Figure 3, may introduce limitations in this study by potentially restricting beam entry in the TD technique.

The results of this study demonstrate that GPRs varied between the two systems for the same thickness, with some thicknesses passing in one system but failing in the other. These discrepancies can be attributed to several factors. For target A, the higher GPRs observed in AC compared to DA were likely due to the lesion being located directly on the AC diode, consistent with findings by Neilson et al.[6] Conversely, the lower GPRs in DA for target A can be attributed to the lesion's proximity to the region of variable bolus thickness, which can influence detector response. For target B, the lower GPRs in AC were associated with the lesion's central location, unlike target A. In contrast, DA demonstrated higher GPRs for target B due to the lesion being positioned away from the bolus region, thus having less impact on the detector signals. Although the study results show both passing and failing GPRs for the same thickness, there is a consistent trend of decreasing GPRs with changes in thickness for both AC and DA. AC serves as the reference system, following the guidelines of AAPM TG-148 and AAPM TG-218 criteria. For clinical implementation of DA, establishing institution-specific criteria to detect anatomical changes using DA is recommended.

This study demonstrates the potential of in-treatment assessment using DA to detect anatomical changes through the GPR. Future advancements that provide organ-specific dose reports alongside anatomical change detection capabilities could significantly enhance workflow efficiency and convenience.

Conclusion

This study demonstrates the potential of DA software to detect anatomical changes in patients undergoing radiation therapy by analysing dose distribution, which shows the statistically significant correlation with the standard system for both TomoHelical and TomoDirect techniques.

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Competing interests. None.

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