Analysis of Setup Errors in ArcCHECK for dose Verification of SBRT Plans of HT

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Abstract: Objective: To explore the impact of introducing setup errors in the phantom positioning on the verification pass rate of body stereotactic helical tomography (HT) radiotherapy plans when using the ArcCHECK system. Methods: A total of 25 body stereotactic HT plans from a department, collected between August 2023 and December 2024, were validated using the ArcCHECK system. The plans were analyzed using two methods: the Distance-to-Agreement (DTA) analysis and Gamma analysis, with pass rate criteria set at 3%/3 mm and 2%/2 mm, respectively. The dose distribution maps were recorded under two conditions: with the center location unchanged and after simulating setup errors using software. The pass rates were averaged and compared. Results: Under the 3%/3 mm standard, both RD and AD pass rates for both methods were above 95%. Under the 2%/2 mm standard, both RD and AD pass rates were above 90%, For setup errors under the 3%/3 mm standard: rotation errors within 0.5°, X-axis translation errors within 3 mm, and Y-axis translation errors within -1, 1, and 2 mm maintained RD and AD pass rates above 90%. After introducing ArcCHECK setup errors in three directions, the dose verification pass rate of SBRT to a certain extent, and the higher the error, the lower the pass rate. Conclusion: The positioning errors in the rotational direction and Y-direction of ArcCHECK have a significant impact on the dose verification pass rate of HT plans for the body. Attention should be paid to errors in the rotational direction and Y-direction during both radiotherapy positioning and verification phantom positioning.

Keywords: Gmana Passing; ArcCHECK; SBRT; TOMOtherapy; Setup Errors

1. Introduction

Helical Tomotherapy (HT) is a technique that combines intensity-modulated radiation therapy (IMRT) and Image-Guided Radiotherapy (IGRT), utilizing the principle of inverse CT imaging. It employs modulated fan-shaped beams to deliver radiation therapy in a helical rotation pattern [1]. Stereotactic and conformal intensity modulation are the two main approaches in radiation therapy. Stereotactic body radiation therapy (SBRT) offers higher precision. SBRT is a high-precision radiotherapy method with fewer fractions and a large single radiotherapy dose. It can provide a sufficiently high irradiation dose to the tumor target area, maximally preserve surrounding normal tissues, and has a shorter treatment course. It has strict requirements for target position verification [2]. During the clinical implementation of SBRT, positioning is the most important factor affecting the accuracy of target area irradiation and treatment efficacy [3]. However, in body radiotherapy, factors such as respiratory and organ motion can affect positioning accuracy, thus impacting the precision of the target area. Because of the positioning errors encountered in clinical radiotherapy, there is an effect on the actual dose distribution, particularly in stereotactic radiation therapy, where a single large dose is applied to the patient. This necessitates the verification of the treatment plan prior to radiotherapy and position verification of the target area before each treatment session. ArcCHECK is a three-dimensional radiation dose distribution measurement quality control system consisting of a cylindrical equivalent water phantom and 1386 semiconductor detectors, with a detector size of 0.8mm × 0.8mm and a spacing of 1cm. It is used for the verification of rotational IMRT plans, and the analysis comparison software used is Sun Nuclear's SCN Patient. ArcCHECK has advantages such as high

sensitivity, reproducibility, and good dose response linearity, making it well-suited for dose verification in rotational plans [4-6]. The ArcCHECK phantom has been widely implemented in dose verification for radiotherapy plans across various cancer types. Extensive studies have demonstrated that ArcCHECK-based dose verification protocols achieve Gamma pass rates consistently exceeding 95%, fulfilling clinical requirements for dose validation. The use of ArcCHECK for stereotactic body radiation therapy (SBRT) plan verification involves collecting delivered dose data under clinically realistic conditions by artificially introducing setup errors of the ArcCHECK phantom in three orthogonal directions (X, Y, Z axes). This methodology aims to investigate the impact of phantom positioning deviations on Gamma pass rates during SBRT quality assurance (QA), thereby providing actionable data to optimize clinical practices in SBRT patient setup alignment and immobilization techniques. Many researchers, have been conducted by scholars both domestically and internationally on the impact of setup errors in intensity-modulated radiation therapy (IMRT) verification using conventional accelerators on the pass rate [7], and some have studied the effect of HT plan ArcCHECK positioning errors on verification pass rates [8, 9]. However, research on ArcCHECK verification of positioning errors in HT-based stereotactic plans is limited. but studies on the effect of positioning errors in helical tomotherapy SBRT are relatively limited. This study utilizes ArcCHECK analysis software to simulate the generation of positioning errors during plan verification. By classifying and standardizing, it explores the impact of introducing positioning errors into the verification plan for HT stereotactic body radiotherapy, specifically focusing on the effect of errors in various directions on pass rates. The goal is to reduce positioning errors and provide clinical data for HT-based stereotactic body radiation therapy for tumors.

2. Materials and Methods

2.1 Inclusion Criteria

Patients with a KPS score ≥ 70, histologically or cytologically confirmed malignant tumors, no history of thoracic radiation therapy, and who meet the criteria for stereotactic radiotherapy, are eligible for the study. Patients who provide informed consent to undergo stereotactic radiotherapy, with a single dose of 300-800 cGy, are included.

2.2 General Information

Select 25 patients who underwent SBRT radiotherapy with HT at our hospital's radiotherapy center from December 2023 to December 2024. Among them, 18 were male and 7 were female. The cases included 5 liver cancers, 5 lung cancers, 8 liver metastatic cancer , 4 lung metastatic cancer , and 3 other (Thoracic and abdominal tumors).There were 2 cases with a single dose of 300cGY, 3 cases with a single dose of 400cGY, 15 cases with a single dose of 500cGY, 2 cases with a single dose of 600cGY, and 3 cases with a single dose of 800cGY; targets located at the edge of the body were not included in this study.

2.3 Equipment

Tomotherapy Radiation Therapy (HT);64-slice Siemens Large Bore Positioning CT.MIM Software Target delineation system; TomoTherapy@H planning workstation (version 5.1.16); ArcCHECK; SNC Patientanalysis software. Stereotactic radiotherapy positioning system.

2.4 Position Fixing

The vacuum pad is placed on the human body positioning board, and the patient lies supine on the vacuum pad with both hands raised and placed on the hand support frame. The position of the hand support frame is adjusted according to the differences in hand posture. The patient adjusts their posture according to their own comfort [10]. For chest tumor patients, positioning is done using a vacuum pad + wing plate + fixation frame, as shown in Figure 1. For abdominal tumor patients, positioning is done using a vacuum pad + thermoplastic film.

Figure 1. Positioning Device for Chest Radiotherapy Patients

2.5 Target Area, Critical Organ Contouring, and Treatment Planning

The CT images of the patients in DICOM

format are transmitted to the MIM Sortware system for organ and volume contouring, and then sent to the HT planning system for treatment plan design. The planning parameters are as follows: field width of 2.5 cm, Modulation Factor of 2.6 to 3.2, Pitch of 0.287, and a calculation grid of 0.4 (fine). The designed plan is imported into DQA software for the creation of a QA plan, and the RT-plan and RT-dose (AreCHECK) file is subsequently exported.

2.6 Simulation Error Handling

The optimized plan system (RT Plan and RT Dose files) is imported into SNC Patient software and compared with the actual dose distribution cloud map measured by the ArcCHECK 3D matrix. Gamma analysis and DTA (Distance-to-Agreement) analysis are performed using 3%/3 mm and 2%/2 mm standards, with the respective RD (Reference Dose) and AD (Actual Dose) pass rates analyzed. Additionally, the shift function in SNC Patient software is used to simulate displacements of -5, -3, -2, -1, 1, 2, 3, and 5 mm along the X and Y axes. Further, clockwise rotations around the center point of -2°, -1.5°, -1°, -0.5°, 0.5°, 1°, 1.5°, and 2° are simulated. Gamma analysis and DTA analysis are again performed under the 3%/3 mm and 2%/2 mm standards to evaluate the respective RD and AD pass rates.

2.7 Statistical Methods

Statistical analysis is performed using SPSS 24.0 software. One-way ANOVA is conducted, followed by pairwise comparison (LSD) to analyze pass rate data. A P value of < 0.05 is considered statistically significant.

3. Results

3.1 Comparison of Pass Rates Using Gamma Analysis and DTA Analysis Methods

The average pass rates of RD and AD under both the Gamma analysis and DTA analysis methods at two different standards are shown in Table 1. When the 3%/3 mm standard is selected, the pass rate of DTA analysis is approximately 1.3% lower than that of the Gamma method. When the 2%/2 mm standard is selected, the pass rate of DTA analysis is about 2.3% lower than that of the Gamma method. Under the 3%/3 mm standard, the average pass rates for both AD and RD in both methods are above 95%. When the standard is changed to 2%/2 mm, the average pass rates of AD and RD for both methods decrease by 4-7%, showing a significant decline. The data indicates that at the 3%/3 mm standard, both the Gamma and DTA methods achieve pass rates above 90%. When the threshold is set to (3%/3 mm, 10%), it meets the clinical requirements.

Table 1. Average Pass Rates of AD and RD for the Two Analytical Methods under Different Standard Conditions

	Gamma analysis		DTA analysis	
Standards	RD Dose (%)	AD Dose (%)	RD Dose (%)	AD Dose (%)
3%/3 mm	99±1.1	97.1±3.1	98±1.8	95±4.3
2%/2 mm	95.5±2.7	91.5±6.5	93.9±3.4	88.2±7.6

3.2 Impact of Rotation, X-Axis, and Y-Axis Directional Positioning Errors on Pass Rate

Figure 2 shows the Gamma pass rate curve for rotational direction errors based on the 3%/3mm standard. Figure 3 presents DTApass rate curve for rotational direction errors based on the 3%/3mm standard. In the 3%/3 mm standard case, when the rotational error is within ±0.5°, both the AD and RD average pass rates for the Gamma analysis method exceed 90%. When the rotational error is ±1°, the RD pass rate for the Gamma analysis method decreases on average by 20.03%. The RD pass rate using the DTA analysis method decreased by an average of 22.1%. As shown in Figures 2 and 3, when the rotational error is less than 0.5°, there is no significant difference in pass rates for the Gamma analysis method, and the difference is not statistically significant. When the rotational error exceeds 0.5°, the AD and RD pass rates have p-values greater than 0.05, indicating that when the rotational error is less than or equal to 0.5°, the impact on pass rates is minimal for both analysis methods. However, when the rotational error exceeds 0.5°, the result is statistically significant ($P < 0.05$). The data indicates that when the rotational error exceeds 0.5°, the impact on plan verification is

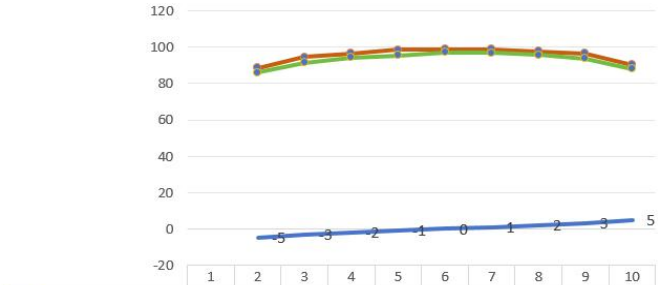
substantial.

	1	2	3	4	5	6	7	8	9
Rotation errors（°）	-2	-1.5	-1	-0.5	0	0.5	1	1.5	2
RD Dose（%）	50.50	59.80	73.40	94.60	98	95.00	76.10	61.60	51.10
AD Dose（%）	45.90	55.10	67.70	87.80	95	90.10	71.40	59.30	49.70

Figure 2. Gamma Pass Rate Curve for Rotational Direction Errors Based on the 3%/3mm Standard

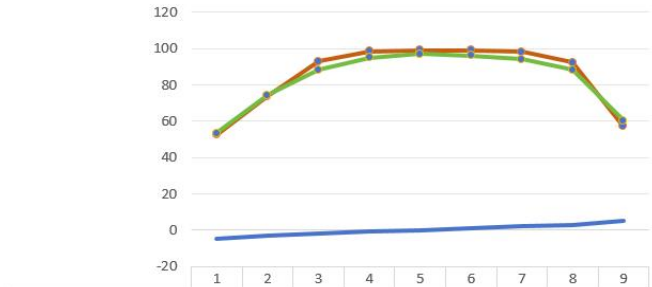
	1	2	3	4	5	6	7	8	9
rotation errors（°）	-2	-1.5	-1	-0.5	0	0.5	1	1.5	2
RD Dose（%）	54.1	64	77.6	96.4	99	96.9	80.4	65.7	54.8
AD Dose（%）	51.2	59.9	75.5	93.9	97.1	93.6	79.3	65.1	54.6

Figure 3. DTA Pass Rate Curve for Rotational Direction Errors Based on the 3%/3mm Standard



	1	2	3	4	5	6	7	8	9	10
Shift distance（mm）		-5	-3	-2	-1	0	1	2	3	5
RD Dose（%）		88.7	94.7	96.6	98.5	99	98.8	97.7	96.7	90.5
AD Dose（%）		86.1	91.4	94.3	95.6	97.1	96.9	95.9	93.7	88.1

Figure 4. Gamma Pass Rate Curve of X-axis Setup Errors under 3%/3 mm Gamma Analysis Criteria



	1	2	3	4	5	6	7	8	9
Shift distance（mm）	-5	-3	-2	-1	0	1	2	3	5
RD Dose（%）	52.3	73.6	93	98.5	99	99	98.2	92.3	57
AD Dose（%）	53.4	74.2	88.1	94.8	97.1	96	94	88.1	60.4

Figure 5. Gamma Pass Rate Curve of X-axis Setup Errors under 3%/3 mm Criteria Based on Gamma Analysis

Figure 4 is Gamma pass rate curve of X-axis setup errors under 3%/3 mm criteria based on Gamma analysis. A one-way analysis of variance and pairwise comparison were performed on the AD and RD pass rates. The results comparing the pass rates with and without positioning errors are shown in Figure 4. Under the 3%/3 mm standard, for all X-axis displacement errors, except when the displacement error reaches 5 mm, the Gamma

pass rate for other X-axis errors less than ±5 mm remains greater than 90%. Figure 5 is Gamma pass rate curve of X-axis setup errors under 3%/3 mm criteria based on Gamma analysis. As shown in Figure 5, for Y-axis displacement errors, only errors smaller than 2 mm yield a Gamma pass rate greater than 90%, while for Y-axis displacements greater than 2 mm, the Gamma pass rate is less than 90%. When the X-axis positioning error is 5 mm, and the Y-axis positioning error exceeds 2 mm, the difference between the translated and original results is statistically significant ($P < 0.05$). As the translational error increases, the pass rate for the Y-axis decreases more significantly than that for the X-axis. The data analysis results under the 3%/3 mm standard for the DTA method show similar trends to the Gamma analysis method, and specific data are not listed here.

4. Discussion

Stereotactic Body Radiation Therapy (SBRT) is a high-precision radiotherapy technique that delivers a high dose in fewer fractions to the tumor, while minimizing damage to surrounding normal tissues. Positional errors are a critical factor influencing the accuracy of radiation delivery to the target area. Helical Tomotherapy (HT) is a powerful tool that enables SBRT, offering non-coplanar 360° irradiation and continuous bed motion during treatment, which distinguishes it from conventional linear accelerators. This study used ArcCHECK to perform dose verification on 25 body-area HT stereotactic plans, employing both the Gamma analysis method and DTA analysis method with 3%/3 mm and 2%/2 mm standards for relative and absolute dose verification. The overall results showed that under the 3%/3 mm standard, the RD and AD average pass rates for both analysis methods were greater than 95%, with the RD pass rate being higher than the AD pass rate. When rotational directional errors were introduced, there was a significant impact on the RD and AD pass rates for both Gamma and DTA analysis methods, with errors exceeding 0.5° causing a marked decrease in pass rates. For X-axis errors, the largest displacement of 5 mm led to an average RD and AD pass rate of 88.7% and 86.1%, respectively, using Gamma analysis. For Y-axis errors, when the displacement exceeded ±2 mm, the Gamma RD and AD pass rates were both below 90%. Rotational and Y-axis errors had a more significant impact on pass rates. Due to the unique dynamic delivery mode and complex functional architecture of the Tomotherapy (HT) system, the multi-leaf collimator (MLC) must modulate tens of thousands of subfields while maintaining precise synchronization between gantry rotation, couch movement, and MLC motion during irradiation. Any deviation in this process directly impacts the patient's dose distribution. Consequently, HT imposes more stringent requirements for treatment plan verification compared to conventional linear accelerators. In the Y-axis (couch longitudinal direction), the continuous couch movement synchronized with 360° gantry rotation in helical tomotherapy demands not only higher positioning accuracy but also strict alignment between the couch travel direction and the Y-axis coordinate system. This study demonstrates that when Y-axis translational errors exceed 2 mm, the Gamma pass rate declines significantly ($p<0.05$), failing to meet clinical requirements. These findings further emphasize the critical importance of quality control (QC) for Y-axis laser alignment and couch travel accuracy [10]. This study showed that when the rotational error exceeds 0.5° and the Y-axis translation error exceeds 2 mm, there is a significant decrease in the Gamma pass rate, with statistical significance. Therefore, both ArcCHECK positioning and patient treatment positioning should focus closely on rotational and Y-axis errors during treatment. In summary, the ArcCHECK system can be used for the verification of rotational intensity-modulated radiotherapy plans and also for SBRT radiotherapy plan verification. Its positioning errors come from many aspects, either from the quality control related to the laser light and treatment bed of helical tomotherapy, or from the direction dependency of the ArcCHECK semiconductor probe. From the experimental results, it can be seen that errors in the rotational direction can lead to a sharp decline in the pass rate, which is considered to be related to the angle dependency of ArcCHECK [11, 12]. However, the high dose conformity of the SBRT plan target area, the dose fall-off of critical organs and surrounding areas, especially small-volume critical organs or high-dose

parts, can easily lead to large deviations. Whether this is also the reason why small rotational direction errors have a significant impact on the pass rate should be considered in future research, along with the inconsistency between stereotactic radiotherapy and conventional fractionation.

Future research should integrate the dose distribution of the original plan, DVH, and other factors to perform a multi-dimensional analysis of dose distribution pass rates. Identifying specific factors affecting dose errors will provide more accurate data for patient positioning and plan design in radiation therapy.

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[1] Thiyagarajan R, Nambiraj A, Sinha S N, et al. Analyzing the performance of ArcCHECK diode array detector for VMAT plan. Rep Pract Oncol Radiother, 2015, 21(1): 50-56.

[2] Kollar L, Rengan R. Stereotactic body radiotherapy Semin Oncol, 2014, 41(6):776-789.Cuevas F T, Fernandez P D. Quality assurance of dosimetric parameters with varying gantry angle with ArcCHECK. Phys Med, 2016, 32(3): 331.

[3] Li, Y., Xu, H. J. The Modern Physics of Radiation Oncology. Beijing: China Atomic Energy Press, 2015.Abel s, Lee S, Ludmir EB, et al. Principles and Applications of Stereotactic Radiosurgery and Stereotactic Body R adiation Therapy. Hematol Oncol Clin North Am, 2019, 33(6):977-987.

[4] Wu A L, Wu A D, Geng G X, et al. Application of PTW729 and ArcCHECK detectors in dose verification of intensity modulated radiation therapy. Chinese Journal of Medical Physics, 2016, 33(5): 473-477.

[5] Cuevas F T, Fernandez P D. Quality assurance of dosimetric parameters with varying gantry angle with ArcCHECK. Phys Med, 2016, 32(3): 331.

[6] Li, Y., Xu, H. J. The Modern Physics of Radiation Oncology. Beijing: China Atomic Energy Press, 2015.

[7] Shen, H., Xia, B. VMAT Plan Verification Based on ArcCHECK and the Impact of Positional Errors on Dose Verification. Chinese Journal of Medical Physics, 2020, 37(4): 431-438.

[8] Chen, J. H. Application of ArcCHECK in Dose Verification for Nasopharyngeal Cancer HT Plans. 2018, 7(13): 1-2.

[9] Du Hongling, Wang Zhenli, et al. Study on the sensitivity of ArcCHECK to manual error correction in helical tomotherapy plans. China Medical Devices, 2019, 34(5): 65-67, 72.

[10] Li Chengjun, Ma Guangdong, Wang Luzhou, et al. The effect of upper limb position changes on positioning accuracy when using a vacuum bag with a positioning frame to fix chest tumor patients. Chinese Journal of Medical Physics 2009, 26(6): 1472-1473, 1484.

[11] Li CQ, LiGJ·JiCX. et al. The characteristics and clinical appli- cation of the ArcCHECK diode array for volumetrie-modulated are therapy verification. Chinese journal of radiation oncology, 2013, 22(3):253-257.

[12] Wang T, Cheng XY. Guo YX, Measurement of the dosimetric characteristics of ArcCheck and its application in VMAT plqn verification. Chinese journal of medical physics, 2019, 36(3):277-281.

