Comparison of MLC Positioning Deviations Using Log Files and Establishment of Specific Assessment Parameters for Different Accelerators With IMRT and VMAT

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Research

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Abstract

Background and purpose: The study evaluated the differences in leaf positioning deviations by the log files of three advanced accelerators with two delivery techniques, and established specific assessment parameters of leaf positioning deviations for different types of accelerators.

Methods: A total of 300 treatment plans with 5 consecutive treatment log files were collected from the Trilogy, TrueBeam and Halcyon accelerators. 50 IMRT and 50 VMAT plans were selected randomly on each accelerator. The log files information was parsed by SunCheck software from Sun Nuclear Corporation. The maximum leaf RMS errors, 95th percentile errors and percentages of different leaf positioning errors were statistically analyzed. The correlations between these evaluation parameters and accelerator performance parameters (maximum leaf speed, mean leaf speed, gantry and arc angle) were analyzed.

Results: The average maximum leaf RMS errors of the Trilogy in the IMRT and VMAT plans were 0.45±0.1mm and 0.80±0.07mm, respectively, which were higher than the TrueBeam's 0.03±0.01mm, 0.03±0.01 mm and the Halcyon's 0.06±0.01 mm, 0.07±0.01mm. Similar data results were shown in the 95th percentile error. The maximum leaf RMS errors were strongly correlated with the 95th percentile errors. The leaf positioning deviations in VMAT were higher than those in IMRT for all accelerators. In TrueBeam and Halcyon, leaf position errors above 1 mm were not found in IMRT and VMAT plans. The main influencing factor of leaf positioning deviation was the leaf speed, which has no correlation with gantry and arc angles.

Conclusions: Compared with the quality assurance guidelines, the MLC positioning deviations tolerances of the three accelerators should be tightened. For both IMRT and VMAT techniques, the 95th percentile error and the maximum RMS error are suggested to be tightened to 1.5 mm and 1 mm for the Trilogy accelerator respectively. In TrueBeam and Halcyon accelerators, the 95th percentile error and maximum RMS error of 1 mm and 0.5 mm, respectively, are considered appropriate.

Introduction

The multileaf collimator (MLC) is one of the key components of the accelerator, and its invention marked the beginning of accurate radiotherapy. With the development, the MLCs were constantly changing in different types of accelerators, such as Varian's C-series accelerators, and later updated T-series and O-series accelerators. Intensity modulated radiation therapy (IMRT) and volumetric modulated arc therapy (VMAT) techniques can achieve more conformal dose distribution with the dynamic MLCs. Previous studies have shown that the dose distribution could be directly affected by MLC positioning deviations [1,2], so the use of specific MLC assurance procedure is recommended for the accelerators providing IMRT or VMAT delivery [3].

The MLC log files record the data of the MLCs during the dose delivery, containing MLC leaf positioning and speed. These log files can help to find MLC positioning errors or be used for specific quality assurance (QA) [4-6]. Previous studies [7-10] have verified the accuracy of log file data with film, diode array, and electronic portal image device (EPID), so log files can be an effective tool for IMRT and VMAT delivery verification.

Traditional QA guidelines have inconsistent specifications for MLC positioning tolerances. The TG-51 recommends a tolerance of 0.5mm for static MLC leaf position accuracy, and the values of the maximum leaf root mean square (RMS) and 95th percentile leaf positioning error were not proposed [11]. In TG-142 and the latest TG-198, the tolerance of MLC leaf position accuracy is ±1mm, and the RMS and 95th percentile errors should be < 0.35 cm [12,13]. The above guidelines recommended annual assessments for the both tests. The recommended reference values in these guidelines may lag due to the changes in the MLC structures of accelerators and the continuous improvement of equipment accuracy.

Although there have been many studies on MLC log files in the past, no studies have established more detailed tolerances of MLC positioning deviations relative to the guidelines based on different types of accelerators (especially more advanced accelerators) and different radiotherapy techniques.

This study is based on Varian's Trilogy (C-series), TrueBeam (T- series), and Halcyon (O- series) accelerators. We reviewed MLC log files of the three accelerators with IMRT and VMAT techniques. These log files are not the standard test files used for annual QA, but the actual treatment records. By comparing the log files, the differences of MLC position errors between different accelerators and techniques were analyzed to determine the variability. Finally, in order to better evaluate the MLC performance of different accelerators and provide help for the prospective detection and avoidance of MLC position errors, we established individualized action thresholds and evaluation values of MLC position errors for different accelerators.

Methods And Materials

Equipment

Three Varian accelerators (Varian Medical Systems, Palo Alto, CA, USA) were involved in this study. The mechanical characteristics of the three accelerators are described below:

a. Trilogy accelerator: This accelerator and previous Varian accelerators are collectively referred to as the "C-series", but it is more advanced than the previous series and can implement VMAT technique. It is equipped with a Millennium MLC, and the projection width at the isocenter are 5mm and 10 mm in the middle 80 leaves and the outer 40 leaves respectively. The maximum leaf speed is 2.5 cm/s. A passive MLC controller is used.
b. TrueBeam accelerator: This accelerator is one of the new series of digital representatives, known as the “T-series”. The Millennium MLC is also used in this accelerator. Although the mechanical parameters of the MLCs in TrueBeam are the same as those in Trilogy, this accelerator has a more perfect digital control system, and use an active MLC controller.

c. Halcyon accelerator: It is the latest accelerator developed by Varian company, known as the “O series” because of its O-shell setup. The design of the MLCs is different from the structure of the traditional MLC. Jaw is removed and double-layer MLCs are used instead. There are 29 pairs and 28 pairs leaves at the proximal bank and distal bank respectively. The projection width at the isocenter is 1cm, and the maximum leaf speed is 5 cm/s. The MLC controller adopted is active.

On each accelerator, 50 IMRT and 50 VMAT plans were randomly selected. IMRT and VMAT plans were designed in the Varian Eclipse version 15.5 treatment planning system (Varian Medical Systems, Palo Alto, CA, USA). The numbers of fields and arcs were determined by the physicists according to the location of the patient's tumor and the difficulty of the plan. When selecting the plan, we did not require the number of fields. The dose rates were set at 400 MU /min in the IMRT plans. In the VMAT plans, the dose rates were 600 MU /min in Trilogy and TrueBeam plans and 800 MU /min in the Halcyon plans respectively. Sliding window technique was used in the IMRT plans which means the MLC moves continuously when beam is on. In the VMAT plans, when beam is on, the MLC position, leaf speed, gantry, and dose rate may all change.

MLC log files

MLC log files are created by the MLC controller. The recording modes of log files have changed with the development of equipment. Before Varian's T-series accelerators, the C-series accelerators (such as Trilogy, EX, iX) adopted passive log file recording methods, and their files were named Dynalogs. After each field delivery, the MLC controller automatically saves two dynamic log files, one for each bank. The log files record the treatment delivery parameters every 50 milliseconds, including the MUs, collimator and gantry angle, expected (planned) MLC positions, and the actual MLC positions recorded by the encoder connected to the motor on each leaf [14]. Through these log files, the positioning errors of MLCs can be calculated.

Starting from Varian's T-series accelerator, such as TrueBeam, VitalBeam and Halcyon, the log file recording modes are active. The log files are named Trajectory logs. Trajectory logs are binary files recording planned and actual MLCs positions at a sampling rate of 50 Hz [15]. The treatment delivery parameters are collected every 20 milliseconds. Because of the active MLC controller design, the leaves will not be delayed in the planned position. Therefore, compared to Trilogy accelerators, TrueBeam and Halcyon accelerators have no delay effect on MLC positioning [16].

Data analysis

Machine QA function in Suncheck version 3.1 software (Sun Nuclear Corporation, Melbourne, Florida, USA) was used to establish MLC positioning and leaf speed analysis projects for the three accelerators, and one analysis project was generated for each patient. Real treatment log files of 50 IMRT and other 50 VMAT plans were collected from each accelerator. The log files of 5 consecutive deliveries for the 300 plans were analyzed, including MLC position and leaf speed. In Trilogy, due to the storage characteristics of log files, each IMRT plan has multiple log files depending on the number of fields, whereas VMAT plan has only 2 log files, bank A and bank B. In TrueBeam and Halcyon, both IMRT and VMAT plans generate only one bin file.

The analysis parameters of leaf position errors were maximum leaf RMS error, 95th percentile error, the number of failed leaves and the percentage of different leaf positioning errors. The first two analysis parameters are recommended in the TG-142 and TG-198 report, and the report believes that these two parameters are helpful for analyzing the state of the MLC performance [12,13]. The maximum leaf RMS error is a single value, which is the maximum RMS error of all leaves in bank A and bank B. It takes into account the error of each leaf during the entire dose delivery, regardless of the direction of the positioning error. The 95th percentile error is a single value extracted from the list of leaf position errors. The threshold value of leaf position error was set to ±1mm due to the existence of two error directions of the leaf position. Failed leaves referred to the leaves with the positioning error exceeding the threshold in any direction. The percentages of the number of leaves with different position error values of 0, ±0.05 mm, ±0.5 mm, and ±1mm were counted. The analyzed maximum and mean leaf speed were the maximum and mean speed of the single leaf, and the single leaf speed was calculated independent of the beam state.

Statistical Analysis

All data were statistically analyzed using the Origin v10.5 software (OriginLab Corporation, Northampton, Massachusetts, USA). The data of different accelerators and dose delivery techniques were grouped, and the non-parametric test was used to analyze the differences of the leaf position deviations among the groups. The differences were considered statistically significant when $p < 0.05$. Correlation analysis was conducted among the analysis parameters of leaf position deviations. The correlations between the evaluation parameters of leaf positioning errors and the mechanical parameters (maximum and mean leaf speed, gantry or arc angles) were analyzed. Pearson correlation coefficient was adopted for correlation analysis, and the correlation coefficients between ± (0.5, 1) were considered to be strongly correlated.

Results

Comparisons of bank A and bank B for the three accelerators

The box plots of the maximum leaf RMS and 95th percentile errors for the three accelerators with IMRT and VMAT techniques are shown in Figure 1. In all three accelerators, no statistical differences were observed between bank A and bank B in the maximum leaf RMS and 95th percentile errors. No statistical differences were observed between bank A and its counterpart bank B for each accelerator in terms of maximum leaf RMS and 95th percentile errors. Correlations were observed between bank A and bank B in the two leaf-position-error evaluation parameters of all accelerators and techniques, and the Pearson correlation coefficients were all greater than 0.5. Figure 2 shows the correlation analysis of bank A and bank B in the maximum leaf RMS and 95th percentile errors of the three accelerators with IMRT and

VMAT. Compared to IMRT, VMAT increased the maximum leaf RMS and 95th percentile errors in all accelerators.

Table 1 Evaluation parameters of leaf positioning errors for IMRT and VMAT plans on the three accelerators

	95th error (mm)	Max RMS error(mm)	Max leaf speed (mm/s)	Mean leaf speed (mm/s)	Fail leaves number	
Trilogy	IMRT	0.66±0.17	0.45±0.10	22.72±2.21	3.37±1.13	4.89±4.97
	VMAT	1.11±0.19	0.80±0.07	36.31±2.41	7.92±0.68	23.11±7.69
TrueBeam	IMRT	0.03±0.01	0.03±0.01	22.73±2.21	1.62±1.00	0
	VMAT	0.05±0.01	0.03±0.01	23.44±3.04	4.05±1.82	0
Halcyon	IMRT	0.08±0.02	0.06±0.01	56.01±1.38	3.19±1.32	0
	VMAT	0.09±0.01	0.07±0.01	59.16±1.00	12.25±3.61	0

IMRT, intensity-modulated radiation therapy; VMAT, volumetric-modulated arc therapy

Comparison between the three accelerators

For the IMRT technique, the mean values of maximum leaf RMS error and 95th percentile error were 0.45±0.1 mm, 0.66±0.17 mm in Trilogy, 0.03± 0.01 mm, 0.03±0.01 mm in TrueBeam, and 0.06±0.013mm, 0.08±0.02 mm in Halcyon respectively. For the VMAT technique, the mean values of maximum leaf RMS error and 95th percentile error were 0.80±0.07 mm, 1.11±0.19 mm in Trilogy, 0.03±0.01 mm, 0.05±0.01 mm in TrueBeam, and 0.07±0.01 mm, 0.09±0.01 mm in Halcyon, respectively. The data are shown in Table 1. The maximum leaf RMS and 95th percentile errors in Trilogy were significantly higher than in the other two accelerators. Halcyon significantly increased the values of the two parameters compared to TrueBeam. The differences in the pairwise comparison of the three accelerators were statistically significant ($p<0.05$). Supplementary Fig. 1 shows the comparison of maximum leaf RMS error and 95th percentile error among the three accelerators with IMRT and VMAT technique.

Separate analysis for each accelerator

1. **Trilogy**

In IMRT plans, the maximum leaf RMS and 95th percentile error showed strong correlation with the mean leaf speed, with R values of 0.71 ($p=0.00$) and 0.61 ($p=0.00$), respectively. The maximum leaf RMS error also showed a correlation with the maximum leaf speed ($R=0.76$, $p=0.00$). There was no correlation between the 95th percentile error and the maximum leaf speed ($R= 0.36$, $p=0.00$). Figure 3 showed the density plot which displayed the maximum leaf RMS and 95th percentile error as a function of the maximum and mean leaf speed in IMRT plans.

In VMAT plans, a strong correlation was observed between the maximum leaf RMS error and the maximum leaf speed (R= 0.85, $p<0.05$) and mean leaf speed (R= 0.75, $p<0.05$). The 95th percentile error was also correlated with the maximum leaf speed (R= 0.76, $p<0.05$) and mean leaf speed (R= 0.60, $p<0.05$). The density plots in Supplementary Fig. 2 shows the maximum leaf RMS and 95th percentile error as a function of the maximum and mean leaf speed in VMAT plans.

Through the analysis of the number of failed leaves with a position error of more than 1mm, it was found that the number of failed leaves was correlated with the 95th percentile error both in IMRT (R=0.51, p=0.00) and VMAT (R=0.57, p=0.00). The number of failed leaves in VMAT was also correlated with the mean leaf speed (R=0.53, P=0.00), and the number of failed leaves increased with the increase of leaf speed. The data are shown in Supplementary Fig. 3. There was no correlation between the number of failed leaves and the maximum leaf speed, and the correlation coefficients were 0.45 and 0.41 in IMRT and VMAT, respectively. Supplementary Fig. 4 showed the specific values of the correlation coefficients among the evaluation parameters.

2. TrueBeam

In IMRT plans, the 95th percentile error was correlated with maximum and mean leaf speed (R= 0.59, 0.60, respectively). No correlation was observed between the maximum leaf RMS error and the maximum and mean leaf speed (R=0.41 and 0.45, respectively).

In VMAT plans, both the maximum leaf RMS and the 95th percentile error were correlated with the mean leaf speed (R= 0.70 and 0.55, $p<0.05$). No correlation was observed between the maximum leaf RMS and 95th percentile error and the maximum leaf speed (R=0.28 and 0.22, respectively). Supplementary Fig. 5 shows the correlation between the maximum leaf RMS and 95th percentile error and leaf speed in TrueBeam.

In TrueBeam, leaf position error above the threshold (1 mm) were not found in IMRT and VMAT plans. The specific percentages of different leaf position errors are shown in the subsequent analysis.

3. Halcyon

No correlation was observed between the maximum leaf RMS and 95th percentile error and the maximum leaf speed in IMRT and VMAT plans. The maximum leaf RMS error had no correlation with the mean leaf speed in IMRT and VMAT plans (R= 0.18, 0.36). Only 95th percentile error was found to be correlated with the mean leaf speed (R=0.59 and 0.52 in IMRT and VMAT, $p<0.05$). Supplementary Fig. 6 shows the correlation between the 95th percentile error and mean leaf speed in IMRT and VMAT plans of Halcyon.

Like TrueBeam, leaf positioning error exceeding 1mm was not found in IMRT and VMAT plans in Halcyon.

Percentages of leaf positioning errors

The percentages of different leaf positioning errors are shown in Figure 4. Almost all leaf positioning errors occured within ±0.05mm in TrueBeam. The data dispersion between 0 and ±0.05mm of the leaf positioning error in Halcyon was higher than that in TrueBeam, indicating that the leaf positioning accuracy of TrueBeam was better than that of Halcyon.

As can be seen in Table 1, some of the leaf positioning deviations for the Trilogy accelerator showed exceeding the threshold (1 mm), and the leaf positioning deviations data within the threshold also appeared discrete (Figure 4). The Trilogy VMAT chart in Figure 4 showed the worst results for percentages of different leaf positioning errors. The leaf positioning errors in VMAT were higher than those in IMRT for all accelerators.

Correlation between leaf positioning error evaluation parameters and gantry or arc angles

In IMRT plans, no correlation was found between the two leaf-positioning-error evaluation parameters and the gantry angles, and the number of failed leaves was not correlated with the gantry angles as well. As shown in the radar plot in figure 5, this plot is composed of IMRT data from the Trilogy. No significant aggregation bias was seen for the maximum leaf RMS and 95th percentile error at different gantry angles, and angles with small values of the evaluation parameters do not necessarily represent small leaf errors, possibly due to the fact that these angles were set less in the treatment plan, as the number and angles of the fields in all plans were inconsistent. In TrueBeam and Halcyon, the data distributions of the two leaf-positioning-error evaluation parameters and the gantry angles were similar to that in Trilogy. Similar results were also generated between the degrees of arc and the evaluation parameters in the VMAT plans, showing that the leaf positioning errors of all three accelerators were independent of the gantry and arc angles for IMRT and VMAT techniques.

Discussion

The study based on log files showed the variability in the 95th percentile error and the maximum leaf RMS error for all three accelerators, regardless of IMRT or VMAT techniques. The leaf positioning errors of the Trilogy in IMRT technique were significantly higher than the other two accelerators, and showed a correlation with the mean leaf speed. In addition, the maximum leaf RMS error of Trilogy was also correlated with the maximum leaf speed. Although previous study has shown that the maximum leaf speed and the mean leaf speed tend to be correlated [16], the results of this study showed that some of the leaf-positioning-error evaluation parameters were not correlated with the maximum leaf speed, such as the maximum leaf RMS error in the TrueBeam and the two evaluation parameters in the Halcyon, where the leaf-positioning-error evaluation parameters were only correlated with the mean leaf speed. The reason may be that the maximum leaf speed included the beam-off state in this study, which is why it happened that the maximum leaf speed exceeded the limit of 25 mm/s. Another reason may be the non-compliance with the maximum leaf speed constraint in leaf sequencing algorithm. It was reported that 14% fields in sliding window IMRT technique exceeded the maximum speed limit in multiple leaves due to the sudden movement of bank B at the end of the MLC sequence [17].

In this study, the MLC construction of Trilogy and TrueBeam are the same, and the maximum leaf speed is all set to 25 mm/s. The differences in the percentages of different leaf positioning errors in Figure 4 demonstrated that TrueBeam's active MLC controller does bring a great improvement compared to Trilogy's passive MLC controller, and the results is similar to previous studies [18]. The main reason for this is that the active design of the MLC controller reduces the delay effect. Olasolo-Alonso et al. [16] have demonstrated that the leaf positioning errors caused by the MLC communication delay is significant and may be greater than that caused by factors such as friction, complexity and the gravity. The active MLC controller is also used on Halcyon, so the values of leaf-positioning-error evaluation parameters of Halcyon were also significantly lower than those of Trilogy, as shown in Figures 4 and Supplementary Fig. 1. In Halcyon, the maximum leaf speed was set to 50 mm/s and the MLC structure is different from the other two accelerators. The leaf-positioning-error evaluation parameters of Halcyon showed slightly worse than those of the Truebeam probably due to the difference in the leaf speed. In Halcyon, the dose rate of VMAT plans was set to 800 MU/min, which was significantly higher than the 600 MU/min of the other two accelerators. The increase of dose rate leads to the increase of leaf speed, and the mean leaf speed is correlated with the maximum leaf RMS error and the 95th percentile error in both IMRT and VMAT techniques. These may be the reasons why leaf-positioning-error evaluation parameters of Halcyon were slightly higher than those of TrueBeam in both IMRT and VMAT techniques.

In both IMRT and VMAT plans of the Trilogy, a strong correlation between the 95th percentile error and the number of failed leaves (threshold: 1mm) was found in our study, as demonstrated in Supplementary Fig. 3. The number of failed leaves was not correlated with the gantry angles. In TrueBeam and Halcyon, leaf positioning error exceeding 1mm was not found, and the 95th percentile error showed a correlation with the mean leaf speed. The maximum leaf RMS error was also correlated with the leaf speed in some of the data. Therefore, the leaf positioning error is mainly determined by the leaf speed, independent of the gantry angle, which is similar with the results of previous study [19].

The maximum leaf RMS and 95th percentile errors are very important as two parameters recommended by TG-142 and TG-198 to assess the leaf positioning errors. These parameters may reveal the characteristics of the leaf positioning error for different type of accelerators, which is helpful for understanding the accelerator performance and setting the thresholds of leaf positioning error. The setting of the action threshold for leaf positioning deviation is controversial. If the tolerance of leaf positioning deviation is set too high, it will lead to excessive deviation of leaf positioning and resulting in dose delivery error, while setting it too small may increase the number of delays, thus increasing the treatment time and dosimetric error. Some authors recommended an action threshold of 2 mm for dynamic MLC positioning deviation [14]. Hernandez et al. [17] suggested that the action threshold for MLC positioning deviation should be 1.5 mm. The action threshold of leaf positioning deviation is set to 1 mm in the Suncheck software we used in this study. In the Trilogy accelerator, a large number of leaf positioning errors exceeding the threshold were found, but none was found in TrueBeam or Halcyon. Therefore, we also believe that a 1mm action threshold might be strict for Trilogy, and a 1.5mm action threshold might be appropriate. However, based on the results in this study, tightening the action threshold of leaf positioning deviation to 1mm is obviously more suitable for the Truebeam and Halcyon. On the basis of establishing action threshold of the leaf positioning errors, in order to detect errors more accurately, we think that the two leaf-positioning-error evaluation parameters of TG142 and TG-198 should be tightened rather than using the uniform recommended value of 3.5mm, which is consistent with Kerns et al. [20]. Due to the differences in factors such as the MLC controller and leaf speed, we suggest that the independent MLC action threshold and evaluation parameters should be established for different types of accelerators.

Mcgarry et al. [21] studied the VMAT delivery accuracy of different Varian linear accelerators using the leaf RMS error and concluded that Truebeam has higher MLC positioning accuracy than Varian Clinacs in VMAT delivery. Their results were consistent with ours, but they did not recommend a specific threshold standard. In the past, no studies have been conducted to compare the evaluation parameters of leaf positioning deviations of the three types of Varian accelerators synchronously.

Although the VMAT technique of the three accelerators showed significantly higher leaf positioning deviations than IMRT due to factors such as gantry rotation and dose rate variation, there is no absolutely meaningful deviation component of the leaf positioning deviation for both techniques. As shown in Figure 4, in Trilogy, the overall dispersion of VMAT data was greater than that of IMRT, and the data values cannot be compared to IMRT in a one-to-one correspondence. That is, there will be smaller values in the analysis parameters of VMAT and larger values in the analysis parameters of IMRT and the difference between IMRT and VMAT data values was very small, especially in the TrueBeam and Halcyon accelerators. One reason is that the cases studied in this research were not unified, and there will be differences in the complexity of different plans. The second reason is that the active MLC controller can better execute the treatment plan, regardless of IMRT or VMAT. Therefore, we do not recommend a stricter assessment threshold for IMRT than for VMAT in the study.

In summary, for both IMRT and VMAT techniques, we recommend that in the Trilogy accelerator, due to the delay effect, the thresholds of the 95th percentile error and the maximum RMS error are set to 1.5 mm and 1 mm, respectively. In TrueBeam and Halcyon accelerators, the thresholds of the 95th percentile error and the maximum RMS error are set to 1 mm and 0.5 mm, respectively. The settings are appropriate for IMRT and are not overly strict for VMAT. These parameters can make it easier for us to evaluate the MLC positioning deviations for different types of accelerators and are meaningful for earlier detection of MLC positioning deviations before the action threshold is reached.

The disadvantages of this study are that the mechanical parameters (such as gantry speed, number and structure of leaves, dose rate, accelerator usage time, and maintenance status of leaves) were not completely unified, which may be very difficult to achieve for accelerators with different configurations. In addition, the complexity of the different plans may also be an influencing factor. From another point of view, these disadvantages are also advantages, since any conclusions and correlations drawn from the data in this study will be independent of these unincorporated parameters. Our future work will extend the collection of log files to include more parameters for further analysis.

Conclusion

The study demonstrates the variability of leaf positioning accuracy for different types of accelerators performing IMRT or VMAT, and uniform thresholds for evaluation parameters are inaccurate. The recommended action thresholds of MLC positioning deviations are 1.5 mm for Trilogy, and 1mm for Truebeam and Halcyon, respectively. For the evaluation parameters recommended by TG-142 and TG-198, the 95th percentile error and the maximum RMS error are suggested to be tightened to 1.5 mm and 1 mm for the Trilogy accelerator respectively. In TrueBeam and Halcyon accelerators, 1 mm and 0.5 mm for the 95th percentile error and maximum RMS error, respectively, are considered appropriate.

Declarations

Acknowledgements

Not applicable.

Conflict of Interest Statement

The authors have no relevant conflicts of interest to disclose.

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Availability of data and materials

The data are available upon request.

Ethics approval and consent to participate

This study was approved by the Research Ethics Board of the Shandong Cancer Hospital.

Written informed consent was waived by the Institutional Review Board.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

Author contributions

X L and Y Y designed the study. X L and T S collected the data. X L and G Z analyzed the data. X L and T S wrote the paper. All authors read and approved the final manuscript.

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Figures

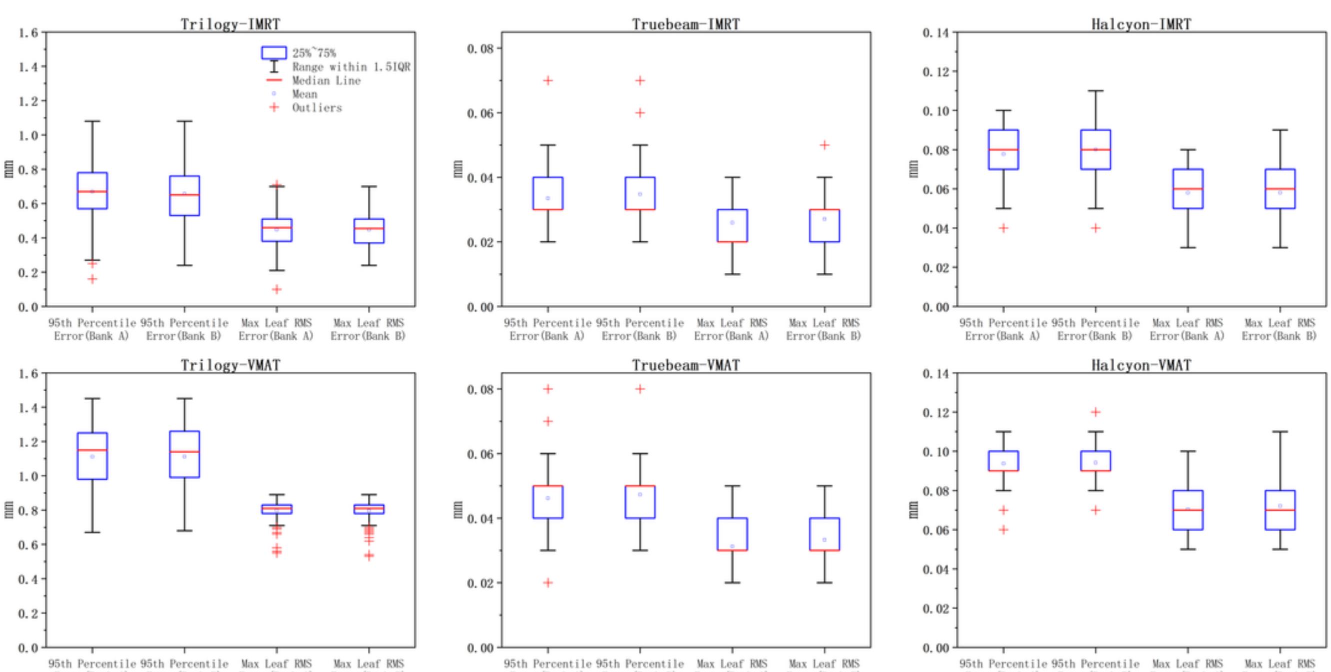

Figure 1

Box plot of max leaf RMS and 95th percentile error values in the three accelerators with IMRT and VMAT techniques. The edges of the box represent the 75th (q3) and 25th (q1) percentile values and the middle mark represents the median. The upper and the lower lines represent the largest and the smallest non-outlier values. Data points higher than q3 + 1.5 or lower than q1-1.5 are considered and painted in red as outliers.

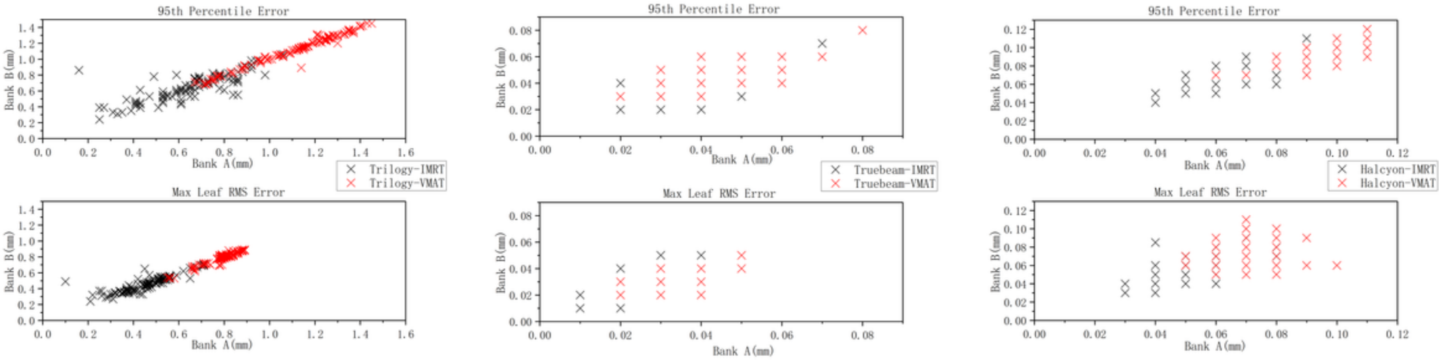

Figure 2

Correlation analysis of bank A and bank B in the maximum leaf RMS and 95th percentile errors of the three accelerators with IMRT and VMAT

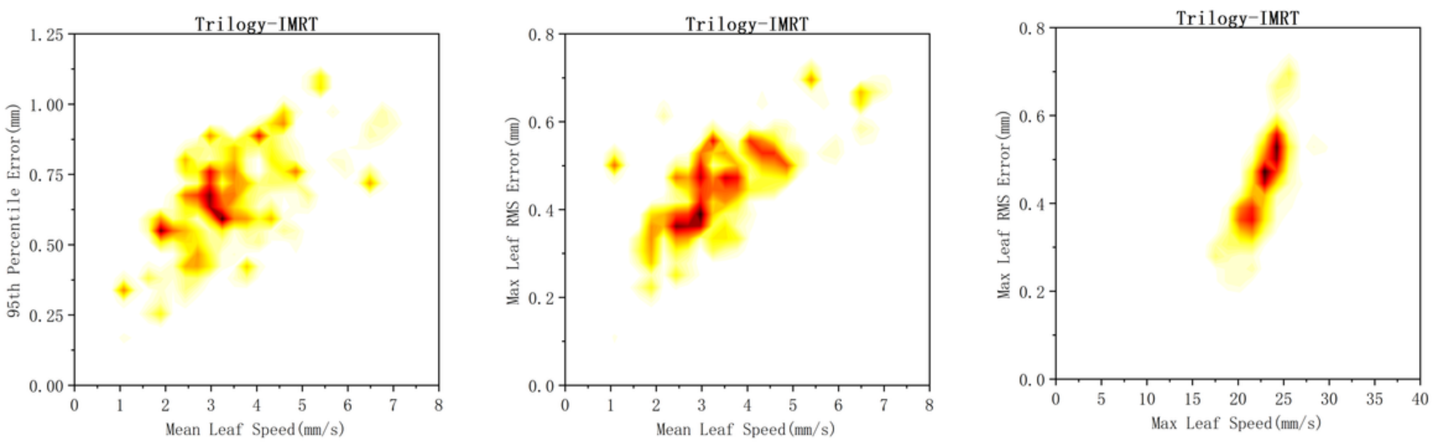

Figure 3

The density plots of correlation between the maximum leaf RMS and the 95th percentile error and leaf speed in Trilogy with IMRT technique. Data densities are indicated by color changes. Yellow represents low density, red represents high density, and black represents the highest density.

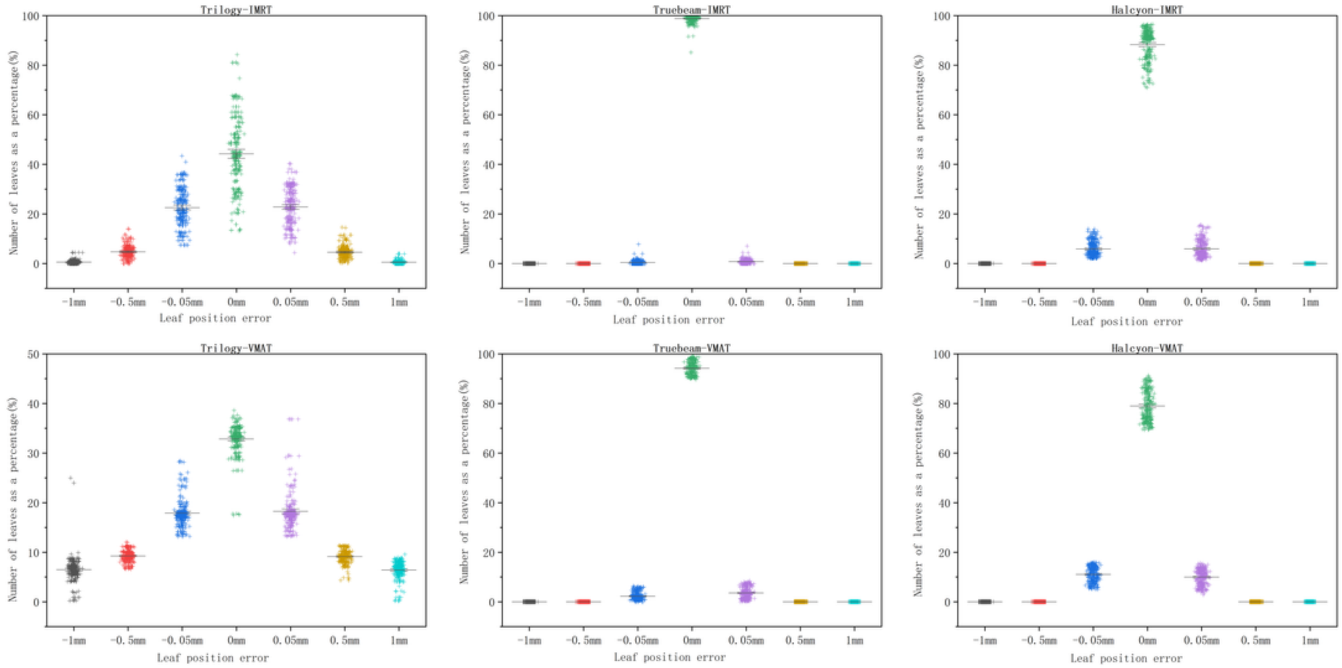

Figure 4

Percentages of different leaf positioning errors in the three accelerators with IMRT and VMAT techniques. The vertical coordinates represent percentages of leaf positioning errors. The horizontal coordinates represent the values of different leaf positioning errors.

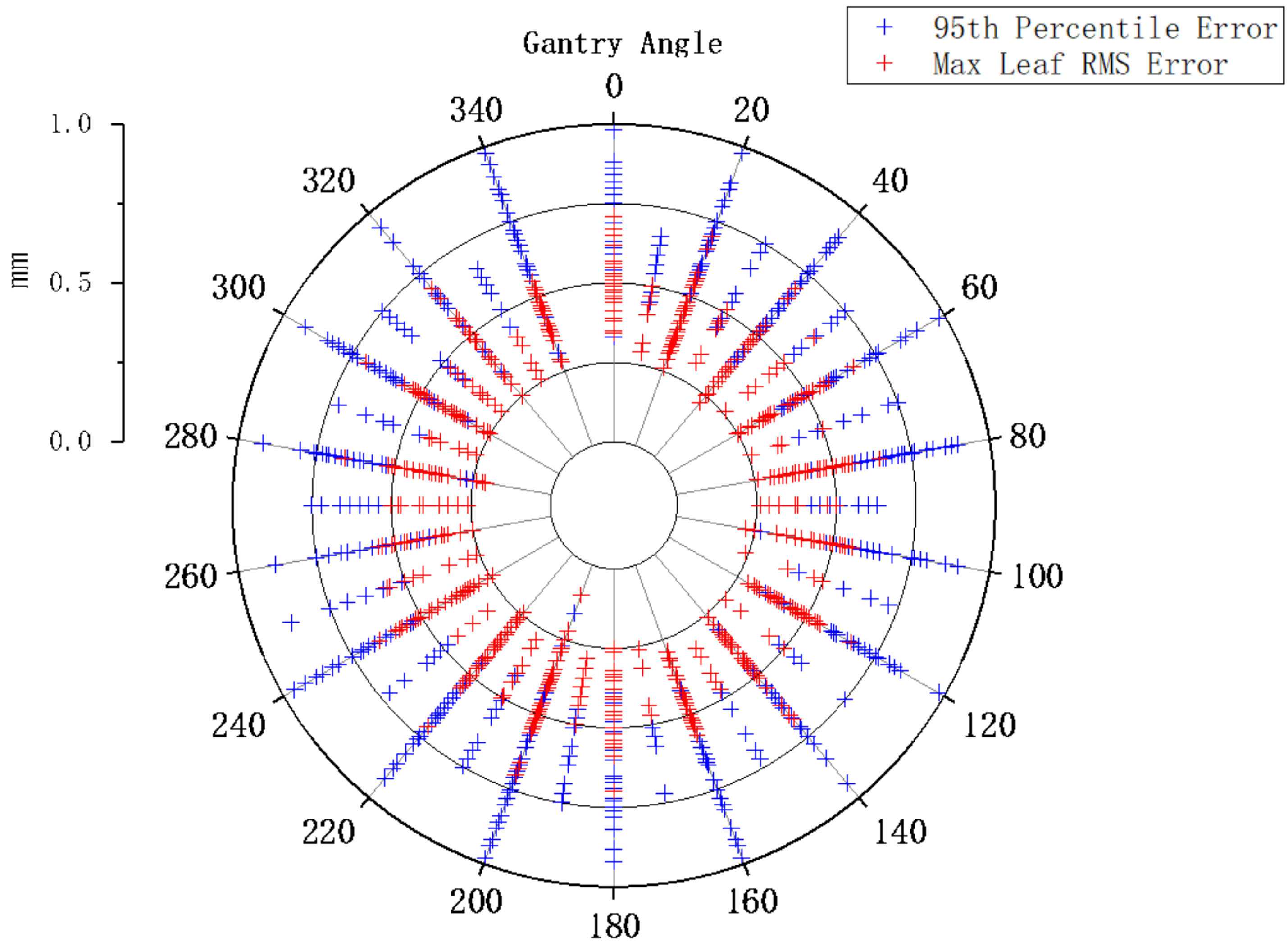

Figure 5

The radar plot of the maximum leaf RMS and 95th percentile error at different gantry angles in Trilogy with IMRT technique. Blue represents the 95th percentile error and red represents the maximum leaf RMS error.

Supplementary Files

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- supplementarymaterial.pdf