Correlation Between Average Segment Width and Gamma Passing Rate as a Function of MLC Position Error in Volumetric Modulated Arc Therapy

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Abstract

Objective: This study analyzed the correlation between the average segment width (ASW) and gamma passing rate according to the multi-leaf collimator (MLC) position error.

Method: To evaluate the changes in the gamma passing rate according to the MLC position error, 21 volumetric modulated arc therapy (VMAT) plans were generated using pelvic lymph node metastatic prostate cancer patient's data which is sensitive to MLC position errors as they involve several long, narrow, irregular fields. The ASW for each VMAT plan was calculated using our own code developed using Visual Basic for Applications (VBA). The gamma passing rate of the VMAT plan according to the MLC position error was evaluated using ArcCHECK (Sun Nuclear, Melbourne, FL, USA) while inducing symmetric MLC position errors in 0.25 mm intervals from −1 mm to +1 mm in the infinity medical linear accelerator (Elekta AB, Stockholm, Sweden). Finally, we examined the correlation between the change in the passing rate (γ gradient) due to the MLC position error and the ASW in VMAT through linear regression analysis using the least squares method.

Results: The ASW and γ gradient were found to have a linear correlation according to the MLC position error, and the coefficient of determination was 0.88. For a 1 mm position error of MLC in VMAT, the gamma passing rate improved by approximately 11.9% as the ASW increased by 10 mm.

Conclusion: These results are expected to be employed as guidelines to minimize the dose uncertainty due to MLC position error in VMAT.

Introduction

Intensity modulated radiation therapy (IMRT) and volumetric modulated arc therapy (VMAT) are the most common radiation therapy technologies.[1] IMRT and VMAT use a small and complex field created by a multi-leaf collimator (MLC) to generate a dose distribution optimized as per the size and shape of the tumor. Therefore, the role of MLC in IMRT and VMAT is

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considerably more important than that in conventional radiotherapy. Thus, patient-specific delivery quality assurance (DQA) is performed as one of the ways to find mechanical and dosimetric errors in a treatment machine, such as MLC position error, data transmission error, and treatment planning errors.

The effects of position error of MLC on the dose delivery accuracy of VMAT have been researched extensively.[2–7] According to previous studies, some types of mechanical errors, such as incorrect gantry and collimator angles, did not have a significant impact on the DQA results and could be easily checked by an indicator during DQA process.[2,3] On the other hand, MLC is a key mechanical component that produces a variety of dose distributions used in IMRT or VMAT, hence, even a small MLC position error has a significant impact on the DQA results. The DQA renders different results depending on the type of MLC position error. Random errors caused by the position errors of individual leaves have negligible effect on the DQA results, whereas systematic errors caused by incorrect calibration of the MLC position or error in the leaf guide position have a significant impact on the DQA results.[4,5]

Heilemann G et al. evaluated DQA results for VMAT plans for the prostate and head and neck for the systematic error in the MLC position.[6] The results of gamma analysis showed that the gamma passing rate sharply decreased to less than 90% even with a system position error of only 0.5 mm. Thus, a systematic error in the MLC position can cause a serious error in the dose delivery accuracy in VMAT.

Previous studies have shown that systematic MLC positioning errors have a direct effect on dose delivery error. However even for the identical shape and size of the treatment site and the treatment technique, the degree of change in the DQA results by systematic MLC positioning error varies.[4–7] This implies that the effect of MLC positional errors on DQA results varies depending on each segment fields used in the treatment plan, even with the same treatment site and technique. To determine the effect of the minimum width of the segment field on the VMAT plan, Wang et al.[8] evaluated the gamma passing rate and plan quality changes such as coverage(D95%), conformity index (CI) and gradient index (R_{50}) in the treatment plan by limiting the minimum segment width of the VMAT. The minimum segment width parameter determines the minimum leaf separation between two opposing leaves within the segment field of a given segment in the sequencing algorithm of the Monaco Treatment Planning System. The results confirmed that increase in minimum segment width can improve the gamma passing rate without changing the plan quality. Nevertheless, the direct correlation between the segment width and the gamma passing rate is yet to be identified in the VMAT plan.

In this study, we investigated the effect of systematic error in the MLC position on the DQA of the VMAT plan as a function of the average segment width (ASW) as one of the indicators representing the segment field shape. Moreover, we examined the correlation between the gamma passing rate and the ASW for a given MLC position error in VMAT. We also proposed a method of reducing dose uncertainty due to MLC position error in the treatment planning stage.

Method

Figure 1 shows the logical flowchart of our investigation. This study was conducted as follows. First, to evaluate the dose accuracy of the VMAT plan according to the MLC position error, we induced systematic errors in the MLC position by moving the MLC leaf guide of the linear accelerator from −1 mm to +1 mm in the interval of 0.25 mm. Subsequently, we measured the dose distribution for the VMAT plan using ArcCHECK (Sun Nuclear, Melbourne, FL, USA) and evaluated the gamma passing rate using the SNC patient program (version 6.4.0). Finally, we calculated the ASW from the MLC position information of the VMAT plan using our own Visual Basic for Applications (VBA) code and then examined the correlation between the gamma passing rate and ASW according to the MLC position error.

Patient Selection and Treatment Plan

This study was conducted after receiving approval from a certified institutional review board. The data used in this study consisted of data of patients who received radiotherapy for prostate and pelvic lymph nodes. Using this data, we generated 21 VMAT plans to evaluate the changes in the gamma passing rate according to the MLC position error. VMAT plans for prostate including pelvic lymph nodes are sensitive to MLC position errors as they involve several long, narrow, irregular fields.[9]

The VMAT plans for all the patients were designed using the Monte Carlo algorithm of Monaco 5.11 (IMPAC Medical Systems Inc., Maryland Heights, MO [a subsidiary of Elekta AB, Stockholm, Sweden]). The dose delivery was investigated through the infinity linear accelerator with the Agility[TM] multi-leaf collimator (Elekta AB, Stockholm, Sweden), which has 160 leaves of 5 mm width. The prescribed dose for 95% of the planning target volume (PTV) was normalized to 45 Gy in 25 fractions. The cost function of the VMAT plan was set slightly differently depending on the tumor size and organ position.

Every plan case had a dual arc with a collimator angle of 30° including clockwise and anticlockwise 360° reciprocal rotations with an increment of 20° from the gantry angle of 180°. The fluence-smoothing parameter was set to medium mode and the control points per arc were limited to 150. For the calculation of the final dose, we used 2.5 mm grid spacing and 3% statistical uncertainty per control point.

ASW Calculation Using the VBA Code

VMAT plans generate segment fields of various sizes to satisfy the dose distribution desired by the user. The segment field shape is determined by 150~200 control points in general. One segment field has position data for 160 leaves. Therefore, calculating the ASW using the position data of leaves not only takes considerable time but also makes it difficult to guarantee the accuracy of the calculations. Therefore, in this study, we calculated the ASW using our own VBA code.
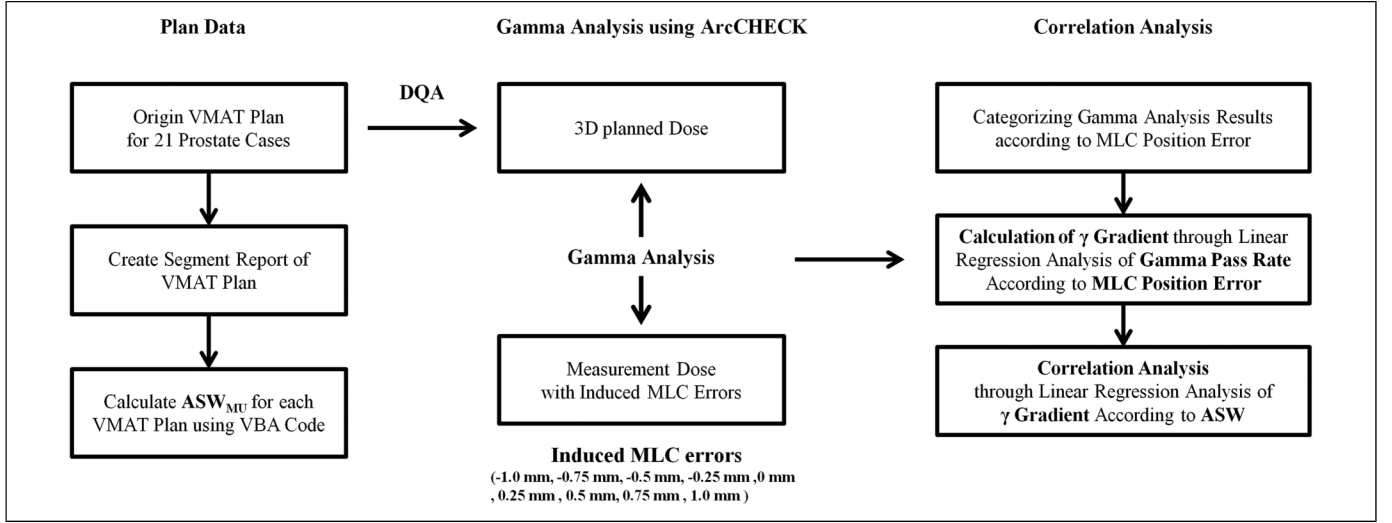
Figure 1. Schematic of the experiment for evaluating the correlation between ASW and gamma passing rate according to MLC position error.

Figure 2 shows the logical flowchart of the VBA code used in this study. The segment field information about each treatment plan is obtained from the segment field report of Monaco RTP. The segment field report provides the position data of all the 160 leaves included in the segment field. To calculate the leaf pair gap used to form the segment field shape, it was determined under the following conditions:

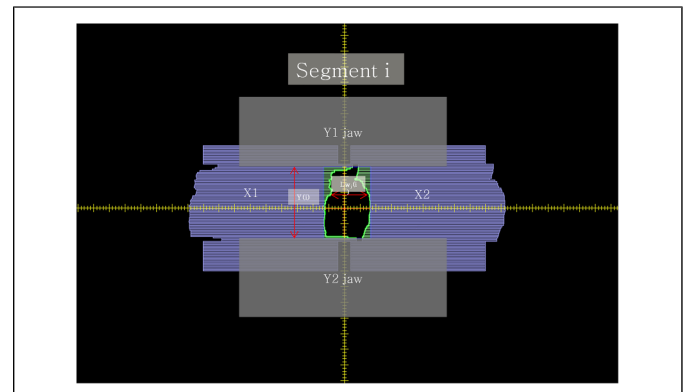$$Lw_j(i) = |X2_j(i) - X1_j(i)|, \quad [\text{if } Y1(i) > LY_j(i) > Y2(i)] \quad (1)$$

$$Lw_j(i) = 0, \quad [\text{if } LY_j(i) > Y1(i) \text{ or } LY_j(i) < Y2(i)] \quad (2)$$

where $Lw_j(i)$ is the gap of the j th leaf pair of segment field i, and $LY_j(i)$ is the Y position of the j th leaf of segment field i. Further, $X1_j(i)$, $X2_j(i)$, $Y1(i)$, and $Y2(i)$ represent the X1 and X2 positions of the j th leaf of segment field i and the Y1 and Y2 positions of the jaw, respectively. ASW is calculated by dividing the area of the segment field that was not shielded by the jaw by the Y-axis distance, as follows:

$$ASW(i) = \sum_{j=1}^{80} [5\text{mm} \times Lw_j(i) / Y(i)] \quad (3)$$

where $ASW(i)$ and $Y(i)$ denote the average segment width of segment field i and the distance between Y1 and Y2 jaws, respectively. Figure 3 shows the leaf pair width $Lw_j(i)$ of segment field i and the distance $Y(i)$ between Y jaws.

To weigh the segment field according to the irradiated monitor unit(MU) for each segment field, we calculated the MU-weighted average segment width (ASW_{MU}) by applying

Figure 2. Logical flowchart of the VBA code for evaluating the correlation between ASW and gamma passing rate according to MLC position error.

Figure 3. Depiction of leaf pair width and Y jaw length for segment *i*.

the MU weight in each segment field as:

$$ASW_{MU} = \sum [MU(i) / MU_{total} \times ASW(i)] \qquad (4)$$

where ASW_{MU}, $MU(i)$, MU_{total}, and $ASW(i)$ denote the MU-weighted ASW, the MU of segment field i, the sum of the MUs over the entire segment field, and the ASW of segment field i, respectively.

Introducing MLC Position Error

Agility^{TM} MLC is composed of 80 pairs of 5 mm leaves, where the leaf position is determined through an optical system included in the linear accelerator head. The position of each leaf is verified by the light from the source at the tip of each leaf, which is transmitted to a charge-coupled device camera via a reflector. The detailed leaf positions are calibrated by adjusting the leaf offset or gain parameter. There are two leaf offset options: the major leaf offset option is used to control the positions of all leaf guides, and the minor leaf offset option is used to adjust the individual leaf position.[10] In this study, the major leaf offset option was adjusted to reproduce the occurrence of various MLC position errors, through which systematic MLC position errors were induced from the reference position of the MLC leaf guides to ± 1 mm distance at 0.25 mm intervals.

Comparison of Dose Distribution Using Gamma Analysis

The treatment plan for DQA was recalculated using the virtual phantom CT provided by the manufacturer as the diode detector of the ArcCHECK phantom caused artifacts in the CT. The densities of the ArcCHECK body and air used in the dose calculation of the DQA plan in Monaco RTP were set to 1.15 and 0.01 g/cm^3, respectively.

The SNC patient program was used to determine the gamma passing rate by comparing the dose distribution measured by ArcCHECK and the dose distribution calculated by the Monaco RTP. The global gamma passing rate was evaluated using the absolute dose mode with the threshold dose of 10%. The tolerance of gamma evaluation was set to 2%/2 mm to examine the effects of fine MLC position errors.

Correlation Analysis

To produce empirical results, we obtained the gamma passing rate according to the MLC position error for each VMAT plan, and the change in the gamma passing rate was represented by the gamma gradient (γ gradient). Here, the γ gradient is calculated by the gradient of the line regression equation using the least square fitting. The γ gradient indicates the sensitivity of each plan to the MLC position error. A large negative gradient indicates that the plan is more sensitive to the reduction of gamma passing rate according to the MLC position error. The correlation between the gamma passing rate and the ASW_{MU} was determined by calculating the linear regression function

between the γ gradient and ASW_{MU} for all types of opened and closed MLC position errors.

Results

Table 1 lists the gamma passing rate and γ gradient according to the MU, the number of segments, ASW_{MU}, and the MLC position error of the treatment plan. The ASW_{MU} of the prostate VMAT plan ranged from 28.1 ± 7.4 mm to 44.0 ± 10.0 mm, and the average ASW_{MU} for all prostate treatment plans was 38.5 ± 4.3 mm. As the MLC position error increased, the gamma passing rate decreased. Figure 4 shows the changes in the average gamma passing rate according to the MLC position error. The average gamma passing rates according to the MLC position error that increased in 0.25 mm intervals from −1.0 to + 1.0 mm were 63.4 ± 4.5%, 76.1 ± 3.3%, 86.8 ± 2.4%, 91.9 ± 2.0%, 94.1 ± 2.1%, 90.8 ± 2.2%, 85.2 ± 3.3%, 75.3 ± 4.4%, and 63.5 ± 5.9%, respectively.

Figure 5(a) and (b) show the change in the average gamma passing rate according to the direction of the MLC position error. The γ gradient s for the opened and closed MLC position errors from the reference position were −30.68%/mm and −30.84%/mm, respectively, and the coefficients of determination of the linear regression function were 0.95 and 0.92, respectively. The change in the γ gradient according to the direction of the MLC position error was negligible.

Figure 6 shows the changes in the gamma passing rate according to ASW_{MU} for each MLC position error. For MLC position errors above 0.75 mm, the gamma passing rate decreased with the reduction of ASW_{MU}. For this parameter, the coefficient of determination of the linear regression function was 0.71 or higher. However, when the MLC error was 0.50 mm or lower, the changes in the gamma passing rate according to the ASW_{MU} were negligible. The standard deviation of the average gamma passing rate increased together with the MLC position error, which means that the sensitivity of the gamma passing rate varies with the MLC position error for each treatment plan.

Figure 7(a) and (b) represent the plot of the γ gradient for 21 plans according to ASW_{MU} for the opened and closed MLC position errors. The correlation between γ gradient and ASW_{MU} was evaluated using the coefficient of determination of the linear regression function, which were found to be 0.88 and 0.89 for opened and closed MLC position errors, respectively. We observed a strong correlation between the γ gradient and ASW_{MU}, regardless of the type of MLC position error. The linear regressions functions of γ gradient and ASW_{MU} are expressed by the following linear expressions:

$$y = 1.19x - 79.48, \quad R^2 = 0.88 \text{(open MLC error)} \qquad (5)$$

$$y = 0.93x - 66.42, \quad R^2 = 0.89 \text{(closed MLC error)} \qquad (6)$$

where x and y denote the ASW_{MU} and γ gradient, respectively. For a 10 mm widened ASW_{MU}, the γ gradient increased by 11.9%/mm and 9.3%/mm for open and closed MLC position

Table 1. Gamma Analysis Results and Gradient of VMAT Plans for Prostate According to MLC Position Error.

| No. | Seg N | MU | ASW$_{MU}$ (mm) | | Gamma passing rate (%) MLC position error (mm) | | | | | γ gradient (%/mm) | R^2 |
					0.00	0.25	0.50	0.75	1.00		
1	236	795.71	36.5±8.8	+	94.5	90.0	83.1	72.2	59.2	−35.38	0.96
				-	94.5	91.3	85.0	73.2	61.4	−33.70	0.95
2	249	867.72	33.9±7.8	+	98.1	92.3	84.0	73.4	60.8	−37.38	0.98
				-	98.1	94.8	88.4	75.7	61.0	−37.30	0.94
3	227	700.30	39.3±8.5	+	90.7	89.7	86.2	74.3	60.3	−30.48	0.87
				-	90.7	90.8	87.8	77.5	63.2	−27.30	0.84
4	208	626.65	42.1±8.9	+	94.7	92.7	88.3	78.8	67.3	−27.48	0.92
				-	94.7	93.1	88.5	79.4	68.2	−26.70	0.92
5	253	834.57	34.9±9.5	+	94.2	88.3	79.9	70.3	58.6	−35.68	0.99
				-	94.2	92.6	88.0	75.2	60.4	−34.00	0.91
6	248	1087.12	31.3±9.4	+	96.3	90.6	82.5	71.4	58.3	−38.08	0.98
				-	96.3	92.4	85.4	73.5	59.5	−37.00	0.95
7	201	821.88	40.0±9.3	+	95.0	92.7	88.0	77.6	65.2	−29.88	0.92
				-	95.0	91.5	85.0	75.9	64.8	−30.40	0.96
8	196	589.30	42.9±9.8	+	91.8	91.5	88.8	79.4	68.0	−23.88	0.85
				-	91.8	90.8	86.8	76.3	63.7	−28.30	0.88
9	245	766.60	35.9±8.1	+	93.7	90.4	84.7	72.8	58.8	−34.98	0.93
				-	93.7	91.2	85.6	73.7	59.7	−34.20	0.92
10	238	708.82	40.7±10.4	+	90.4	87.6	82.3	72.9	61.4	−29.08	0.94
				-	90.4	89.1	84.7	74.5	62.2	−28.40	0.91
11	200	611.48	45.3±10.0	+	91.7	90.8	87.5	80.6	71.7	−20.08	0.90
				-	91.7	91.1	87.4	79.4	69.3	−22.60	0.89
12	237	1036.46	28.1±7.5	+	91.0	86.8	80.1	66.5	50.8	−40.28	0.94
				-	91.0	87.7	81.4	68.3	53.2	−38.00	0.93
13	223	870.38	34.0±7.6	+	92.9	89.2	83.1	72.1	59.1	−33.88	0.95
				-	92.9	89.6	83.3	71.7	58.1	−35.00	0.94
14	213	759.24	39.5±9.3	+	95.6	91.1	84.1	75.2	64.2	−31.48	0.98
				-	95.6	93.5	88.4	77.8	65.2	−30.60	0.93
15	201	830.97	36.7±9.0	+	95.2	92.1	86.6	76.0	63.4	−31.88	0.94
				-	95.2	93.1	88.0	76.1	62.2	−33.20	0.91
16	209	640.27	42.0±8.8	+	95.6	92.3	86.5	80.0	71.5	−24.18	0.98
				-	95.6	92.9	87.1	79.1	69.1	−26.70	0.96
17	195	592.53	43.2±9.3	+	96.4	94.3	89.8	83.4	75.0	−21.48	0.95
				-	96.4	93.7	88.0	81.0	72.0	−24.60	0.96
18	236	699.78	40.1±8.2	+	95.4	94.2	90.5	80.0	67.4	−28.08	0.89
				-	95.4	94.5	90.5	79.0	65.5	−30.10	0.88
19	213	612.43	44.0±10.0	+	96.0	94.7	91.0	82.4	71.7	−24.38	0.90

Table 1. (continued)

No.	Seg N	MU	$ASW_{MU \ (mm)}$		Gamma passing rate (%) MLC position error (mm)					γ gradient (%/mm)	R^2
					0.00	0.25	0.50	0.75	1.00		
				+							
				-	96.0	95.5	91.9	81.9	69.9	−26.30	0.87
20	236	743.50	37.3±8.8	+	93.6	88.3	80.5	71.4	60.2	−33.48	0.98
				-	93.6	90.0	83.3	73.7	62.1	−31.70	0.96
21	225	649.38	40.6±8.8	+	93.3	89.7	83.7	73.6	61.5	−31.88	0.95
				-	93.3	91.7	87.0	75.7	62.4	−31.10	0.91

errors, respectively. As ASW_{MU} increased, each segment width comprising the segment field widened, which implies that even the same MLC position error has a relatively reduced effect on aggravating DQA results.

Figure 8 shows the average ASW_{MU} according to the minimum segment width parameter. The average ASW_{MU} for minimum segment width parameters from 5 mm to 15 mm was 34 ± 3 mm to 42 ± 3 mm. Increasing the minimum segment width parameter by 10 mm increased the ASW_{MU} by about 8 ± 4 mm. This result shows that changing the minimum segment width parameter can adjust ASW_{MU} in the treatment planning stage.

Discussion

The results of this study showed that the gamma passing rates according to various systematic MLC position errors tended to decrease for the MLC position errors of 0.5 mm or higher. This is in good agreement with the previous studies.[8,11] In addition, the rate of change in gamma passing rate as a function of the MLC position error was found to have a linear relation with ASW_{MU}.

The gamma analysis using ArcCheck is one of the most commonly used patient QA method before VMAT treatment. Hilleman et al.[6] noted that gamma analysis using the 2%/2 mm criterion is more effective to check MLC position errors. Therefore, We evaluated gamma analysis results using ArcCheck based on 2%/2 mm criterion, and the difference in gamma passing rate was clearly observed depending on the MLC position error. Gamma analysis based on 2%/2 mm using ArcCHECK is a very useful method to find out the effect of MLC position errors on DQA results in a VMAT plan.

How ASW_{MU} can affect the gamma passing rate when MLC position errors exist is important to analyze DQA results and
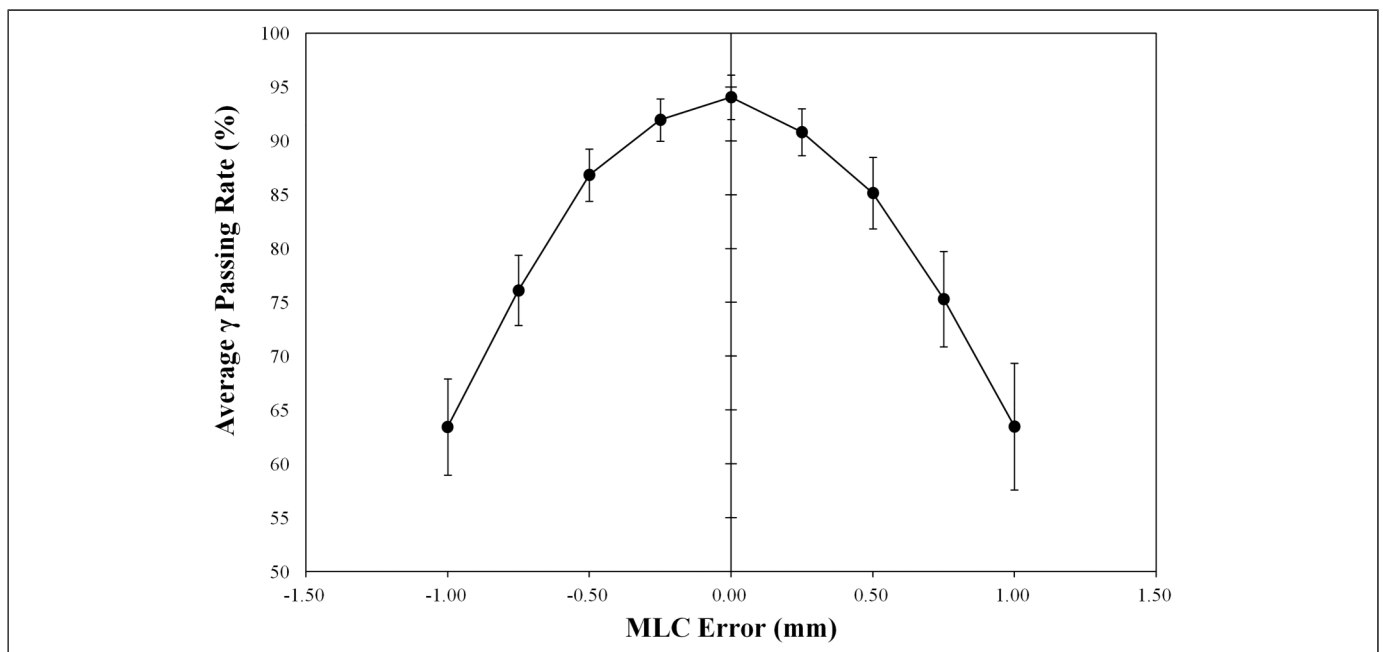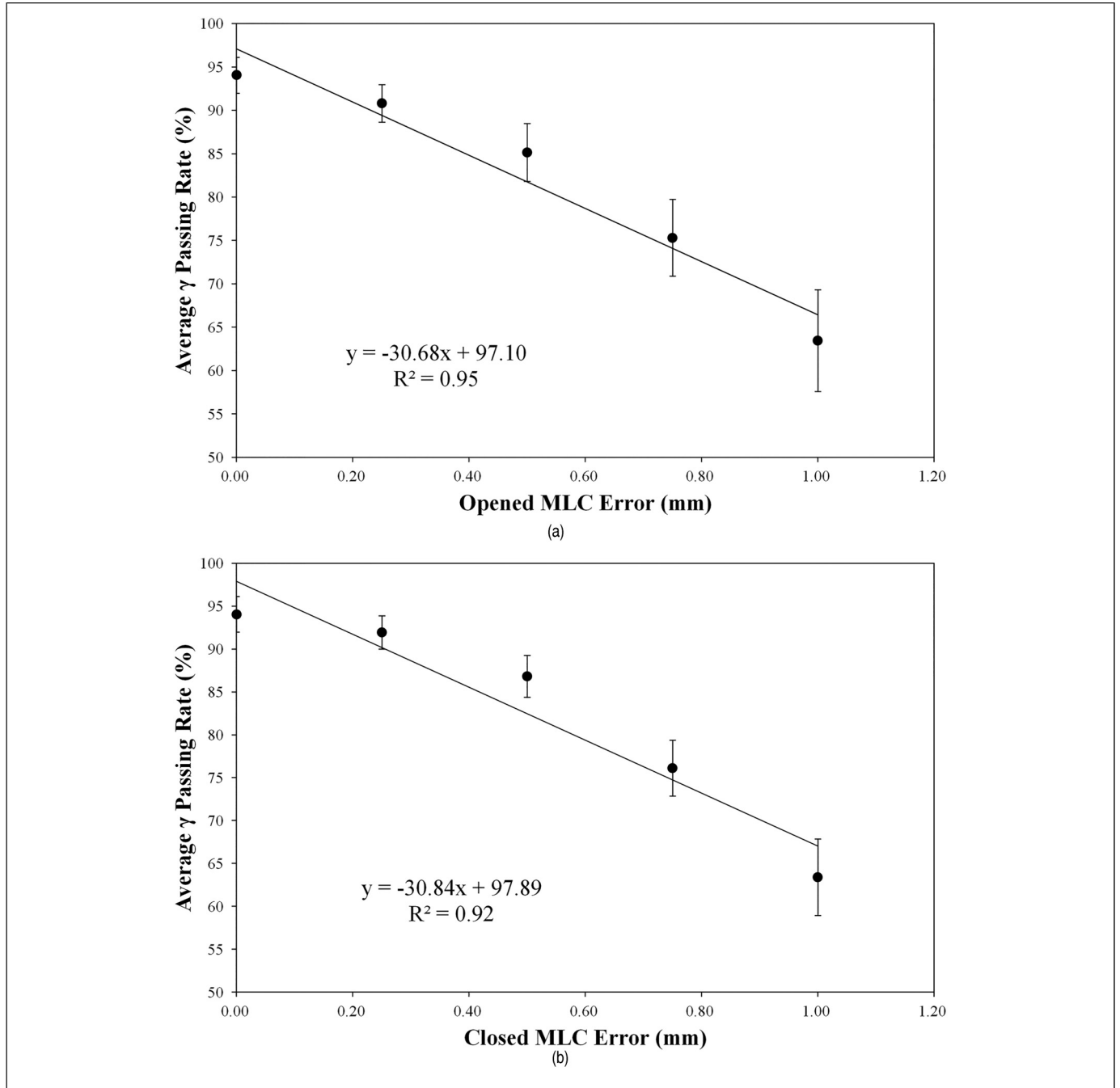
Figure 4. Average gamma analysis results based on 2%/2 mm criterion for each MLC position error.

Figure 5. Gradient of average gamma passing rate due to MLC position error: (a) Opened MLC position error, (b) Closed MLC position error.

re-plan to make DQA results better. As the ASW_{MU} of the VMAT plan increased, the relative influence of the MLC position error on the gamma passing rate decreased. As a result, the dose delivery uncertainty relatively decreased even for the same MLC position error. For a treatment plan established using a large number of narrow segment widths, a narrow ASW_{MU} maybe advantageous for the quality improvement of the treatment plan; but even then, a small MLC position error can cause serious discrepancies between the calculated and the delivered dose distribution, so the DQA must be carried out before the treatment. In contrast, the reduction of gamma passing rate due to an unwanted MLC position error can be offset by creating a plan with a wider ASW_{MU} by adjusting the minimum segment width option in the treatment planning stage. Thus, ASW_{MU} must be treated as a key indicator for the sensitivity of dose accuracy for MLC position error in the VMAT treatment planning stage.

Systematic MLC position error are confirmed by picket fence QA after MLC position calibration. However, systematic MLC position error can occur over time due to mechanical
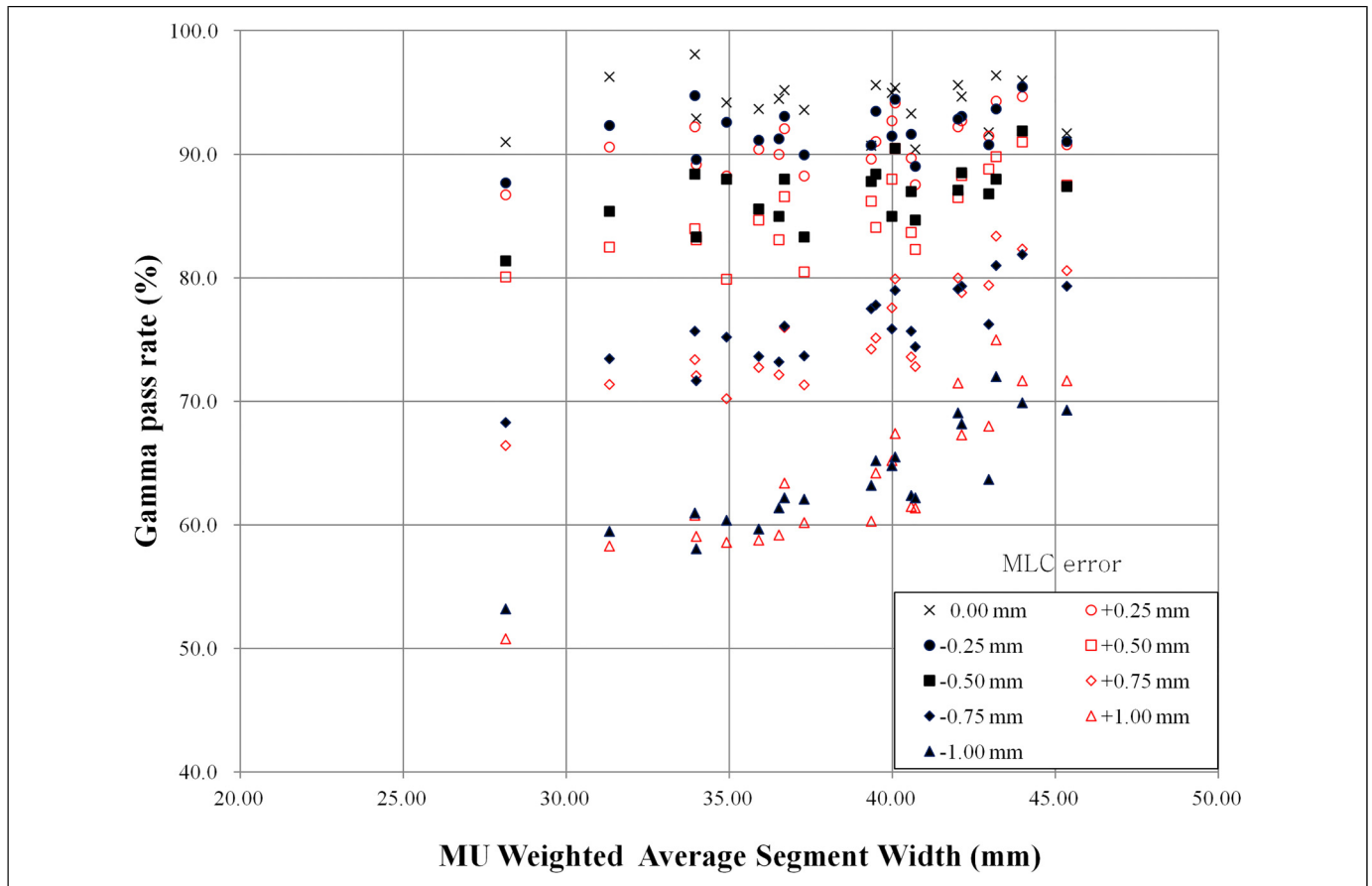
Figure 6. Gamma passing rate versus the MU weighted AWS for each position error. Each symbol shows a gamma passing rate according to the MLC position error, this graph shows that the change in the gamma passing rate for the MLC position error differs depending on each ASW_{MU}.

defects (loosening of motor belt, change of motor rotational power with respect to motor current value, etc), and even after picket fence QA, if the QA result does not exceed the tolerance, correction is not performed every time. However, even small systematic position errors have been found to have a large impact on gamma pass rate.[4,5,9,10] It is important to manage this risk. Therefore, it is recommended to check the plan's ASW_{MU} before treatment to see how resistant the plan can be to MLC position error.

Since this study was limited to prostate cases and VMAT plan, the correlation between ASW_{MU} and the dose delivery uncertainty resulting from an MLC position error cannot be applied to all treatment sites and various plan types. However, previous studies on the correlation between the minimum segment width and gamma passing rate obtained a better gamma passing rate upon increasing the minimum segment width irrespective of the site.[8,10] The minimum segment width is a parameter that determines the minimum leaf pair width in the treatment plan, and as it increases, the ASW_{MU} will also increase. Therefore, this study suggests that ASW_{MU} will behave in the same way even for other treatment sites. In contrast, plan type is an important factor in determining the shape of a segment field. It may affect the DQA results due

to MLC error because the movement and position of MLC vary depending on the plan type. Therefore, it is necessary to evaluate the effect of segment width on DQA according to MLC position error for various plan types. We plan to continue our research on various sites and plan types to verify our conjecture. Furthermore, this study forms important preliminary research that can be expanded to find correlations between the ASW_{MU} and the dose delivery uncertainty caused by MLC position error for various treatment sites and plan types.

This study used only Monaco RTP to evaluate the effect of ASW_{MU} on DQA results due to MLC position error. Other RTPs do not have parameters to control the minimum segment width, making it difficult to control the direct ASW_{MU}. Also, even in the same VMAT plan, a method of determining the shape of the segment field can be different for each RTP. Therefore, further studies using different RTPs are required to equally apply the results of this study to other RTPs. Nevertheless, since Monaco is a representative RTP of Elekta corporation and many research on Monaco RTP is being conducted recently, we belive the results of this study will be very useful for Monaco users.

Our study revealed a linear correlation between the ASW_{MU} and the γ gradient, which is crucial information for identifying
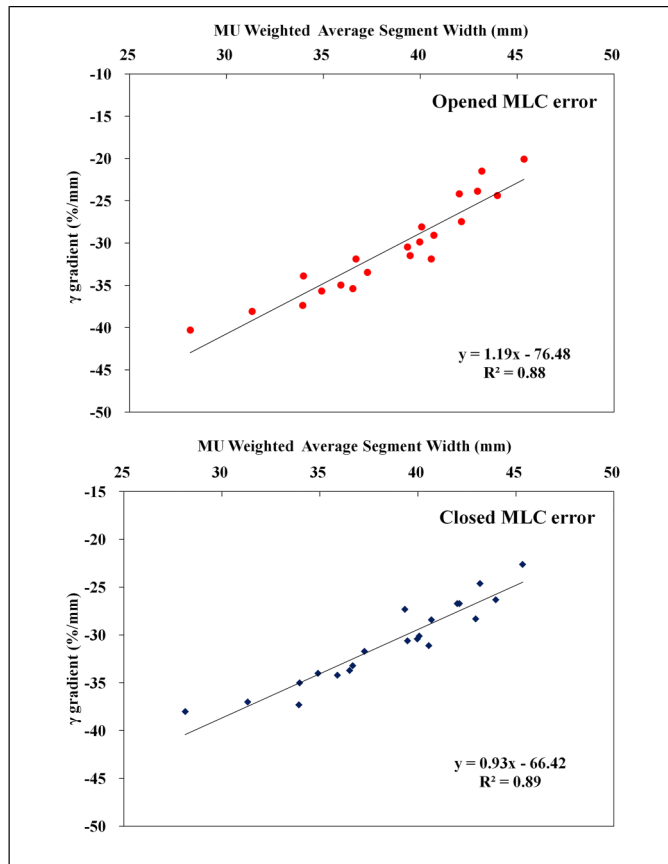
Figure 7. Correlation between the average segment width and the gradient as a function of MLC position error: (a) Opened MLC position error, (b) Closed MLC position error. A lower gamma gradient means that MLC position error has less impact on the gamma passing rate.

the dose delivery uncertainty caused by MLC position error in VMAT. As described in Table 1, the larger the ASW_{MU}, the better the gamma passing rate when identical MLC position error exists, especially the larger the MLC position error, the greater is the effect. These results constitute critical information
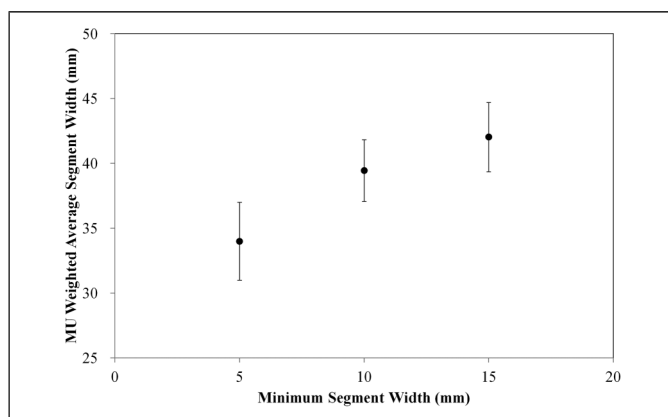
Figure 8. The average MU weighted AWS according to the minimum segment width parameter for prostate plans.

for guiding the establishment of the optimal treatment plan that minimizes the effect of a potential MLC position error while satisfying the clinical requirements in the treatment planning stage.

As a supplementary study, we established the VMAT plans for the same prostate patient by applying only the minimum segment width parameters differently as 5 mm and 15 mm, respectively. In addition, we evaluated gamma analysis using the 2%/2 mm criterion for VMAT plan with 0.25 mm systematic MLC position error. The results were 90.4% and 94.3% for 5 mm and 15 mm of the minimum segment width parameters, respectively. With a minimum segment width parameter of 15 mm, gamma passing rate is improved by approximately 3.9%. If ASW_{MU} is managed to the desired level by adjusting the minimum segment width parameter in the treatment planning stage, it is possible to establish a VMAT plan that is less sensitive to DQA results according to the systematic MLC position error.

For example, if the minimum segment width is set to a small value when establishing the treatment plan, it will result in improved plan quality and a relatively narrow ASW_{MU}. However, if the dose distribution is not significantly different and the dose-volume histogram of the surrounding organs meets the clinical dose constraints, then a treatment plan with a wider minimum segment width is preferable as it reduces the dose delivery uncertainty due to the MLC position error. ASW_{MU} value could also provide the criteria for determining whether MLC position calibration should be performed first or whether radiation therapy should be performed when MLC position errors are recognized to the extent that they do not exceed quality control tolerances.

Conclusion

We investigated the effect of MLC position error on the correlation between the change of gamma passing rate and ASW_{MU}, and proposed a method of minimizing the dose delivery uncertainty of ASW_{MU}. We verified the significant linear correlation between ASW_{MU} and the γ gradient according to the MLC position error. For the same MLC position error, the reduction of the gamma passing rate was smaller for a large ASW_{MU} than with a small ASW_{MU}. According to the results of this study, when there was an error of 1 mm in the position of MLC, a 10 mm increase in ASW_{MU} could improve the gamma passing rate by approximately 11.9%. We showed that ASW_{MU} is a critical indicator of the sensitivity of dose accuracy to the MLC position error in VMAT and should be controlled carefully to minimize the dose uncertainty according to the MLC position error in the treatment planning stage.

Authors' Note

This study was conducted after receiving approval from a certified institutional review board (D-1901-030-002, Dongnam Institute of Radiological & Medical Sciences Institutional Review Board). There is no probability of toxicity and side effect on the patient because it

is a retrospective planning study conducted with the patient's existing records.

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References

1. Webb S. The physical basis of IMRT and inverse planning. *Br J Radiol*. 2003;76(910):678-689. doi:10.1259/bjr/65676879
2. Zhen H, Nelms BE, Tome WA. Moving from gamma passing rates to patient DVH-based QA metrics in pretreatment dose QA. *Med Phys*. 2011;38(10):5477-5489. doi:10.1118/1.3633904
3. Hussein M, Rowshanfarzad P, Ebert MA, Nisbet A, Clark CH. A comparison of the gamma index analysis in various commercial IMRT/VMAT QA systems. *Radiother Oncol*. 2013;109(3):370-376. doi:10.1016/j.radonc.2013.08.048
4. Rangel A, Dunscombe P. Tolerances on MLC leaf position accuracy for IMRT delivery with a dynamic MLC. *Med Phys*. 2009;36(7):3304-3309. doi:10.1118/1.3134244
5. Oliver M, Gagne I, Bush K, Zavgorodni S, Ansbacher W, Beckham W. Clinical significance of multi-leaf collimator positional errors for volumetric modulated arc therapy. *Radiother Oncol*. 2010;97(3):554-560. doi:10.1016/j.radonc.2010.06.013
6. Heilemann G, Poppe B, Laub W. On the sensitivity of common gamma-index evaluation methods to MLC misalignments in rapidarc quality assurance. *Med Phys*. 2013;40(3):031702. doi:10.1118/1.4789580
7. Younge KC, Matuszak MM, Moran JM, McShan DL, Fraass BA, Roberts DA. Penalization of aperture complexity in inversely planned volumetric modulated arc therapy. *Med Phys*. 2012;39(11):7160-7170. doi:10.1118/1.4762566
8. Wang Y, Chen L, Zhu F, Guo W, Zhang D, Sun W. A study of minimum segment width parameter on VMAT plan quality, delivery accuracy, and efficiency for cervical cancer using monaco TPS. *J Appl Clin Med Phys*. 2018;19(5):609-615. doi:10.1002/acm2.12422
9. Ung NM, Harper CS, Wee L. Dosimetric impact of systematic MLC positional errors on step and shoot IMRT for prostate cancer: a planning study. *Australas Phys Eng Sci Med*. 2011;34(2):291-298. doi:10.1007/s13246-011-0062-8
10. Nithiyanantham K, Kadirampatti Mani G, Subramani V, et al. Influence of segment width on plan quality for volumetric modulated arc based stereotactic body radiotherapy. *Rep Pract Oncol Radiother*. 2014;19(5):287-295. doi:10.1016/j.rpor.2014.03.003
11. Nithiyanantham K, Mani GK, Subramani V, Mueller L, Palaniappan KK, Kataria T. Analysis of direct clinical consequences of MLC positional errors in volumetric-modulated arc therapy using 3D dosimetry system. *J Appl Clin Med Phys*. 2015;16(5):296-305. doi:10.1120/jacmp.v16i5.5515