Dosimetric Effects of Differences in Multi-Leaf Collimator Speed on SBRT-VMAT for Central Lung Cancer Patients

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Abstract

Purpose: We aimed to investigate the effects of different multi-leaf collimator (MLC) speed constraints in volumetric modulated radiotherapy (VMAT) on the robustness of treatment plans for central lung cancer patients. **Method and Materials:** Twenty patients with central lung tumor who underwent stereotactic body radiotherapy (SBRT) with the VMAT technique at our hospital were included in this retrospective study. The reference plans were created with 3 different MLC speed constraints (Plan A: 0.1 cm/deg., Plan B: 0.3 cm/deg., and Plan C: 0.5 cm/deg.) with a 50-Gy/8Fr, planning target volume (PTV) $D_{95\%}$ prescription. In each of these plans, setup errors from 1 to 5 mm were intentionally added in the direction of the central organ at 1-mm intervals (300 plans [20 cases × 3 MLC speeds × 5 error plans] were created in total). Each plan was then calculated by the same beam conditions as each reference plan. The actual average MLC speed and dose difference between the reference plan and the error-added plan were then calculated and compared among the 3 MLC speeds. **Results:** In the reference plans, the actual average MLC speeds were 0.25 ± 0.04, 0.34 ± 0.07, and 0.39 ± 0.12 cm/deg. for Plan A, Plan B, and Plan C, respectively ($P < .05$). For PTV and OARs, many dose indices tended to improve as the MLC speed increased, while no significant differences were observed among the 3 MLC speed constraints. However, in assessments of robustness, no significant differences in dose difference were observed among the 3 MLC speed constraints for most of the indices. **Conclusions:** When necessary, increasing the MLC speed constraint with a priority on improving the quality of the dose distribution is an acceptable approach for central lung cancer patients.

Keywords

radiation therapy, radiation dosimetry, lung cancer, IMRT, x-ray

Introduction

Stereotactic body radiotherapy (SBRT) is a widely used treatment modality for lung cancer and has yielded good treatment outcomes in many cases.[1] In general, SBRT is often performed on peripheral tumors, although some reports have described its use for central tumors.[2,3] In cases involving central lung tumors, the tumor is located in close proximity to the bronchi, heart, and great vessels, increasing the likelihood of toxicity. Thus, treatment planning with careful attention to these doses is essential in such cases.[4]

Three-dimensional conformal radiotherapy (3DCRT) combined with a noncoplanar beam has been used for SBRT of lung cancer, and its robustness for respiratory motion has been evaluated by several authors.[5] However, volumetric modulated arc therapy (VMAT) has been used more frequently in clinical practice in recent years, and its advantages include increased throughput, improved conformity index (CI), and ease of achieving dose constraints for compromised organs.

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Nevertheless, some reports have suggested that overly complex multi-leaf collimator (MLC) movements in VMAT can affect the results of patient-specific dose verification.[6] Although this issue can be prevented by setting the MLC speed constraint using the treatment planning system in advance, the characteristics of this setting parameter have been described in only a few studies.[6] Since no previous report has specifically evaluated the robustness of this setting value in relation to the treatment plan, we investigated the effect of different MLC speed constraints of SBRT-VMAT on the robustness of the treatment plan, assuming a setup error for central lung cancer cases.

Materials and Methods

Treatment Planning

This retrospective study was approved by the institutional review board (IRB) of the University of Yamanashi (receipt number: 2271). From January 2019, the treatment plans in 20 cases of central lung cancer that were treated with SBRT-VMAT at our hospital were consecutively included in the study. We have de-identified all patient details, and informed consent was obtained in the form of opt-out on the website. Those who rejected were excluded. For all 20 cases, the clinical target volume (CTV) and the internal target volume (ITV) given the reproducibility of respiration in the individual cases were established, from which the planning target volume (PTV) was created by adding 3 mm. For normal organs, only organs in particular proximity were contoured and evaluated, since the location of the tumor differed from case to case. Therefore, it is noted that the normal organs evaluated in each case were different. Radiation therapy was administered using an Elekta Synergy unit with an Agility gantry head, which has 160 MLC leaves of 5 mm (Elekta AB, Stockholm, Sweden). All treatment plans were re-planned at 50 Gy/8 Fr (prescribed to a dose covering 95% volume [$D_{95\%}$] for the PTV) with 3 different MLC speed constraints (0.1 cm/deg., 0.3 cm/deg., and 0.5 cm/deg.) using the treatment planning system RayStation ver. 6.3 (RaySearch Laboratories, Stockholm, Sweden). In this system, the speed was defined by the constrain leaf setting in the optimization window. Optimization conditions were the same among the 3 MLC speed constraints. For all treatment plans, the x-ray energy was 6FFF, the collimator angle was 15°, and the gantry rotation was set to a half arc in the clockwise direction. The dose calculation was performed by collapsed cone convolution with a 2-mm grid size. Table 1 shows the initial values of the optimization conditions used in this study. The optimization conditions of the targets were standardized for all cases, and those for normal organs were adjusted as appropriate for each case. To ensure uniform plan quality, the number of iterations was set to 40 times and the number of optimization calculations was set to 3 times.

Simulation of Setup Error

Figure 1 shows the outline of this study. First, a reference plan was created for 3 MLC speeds, which was followed by the addition of setup errors from 1 to 5 mm in 1-mm intervals in the central direction. This process was performed using the "compute perturbed dose" function in RayStation. Since the tumor location differs from case to case, the direction of the shift was shifted in the direction that increased the dose at the central organ in the left–right or anterior–posterior directions. The normal tissues evaluated in this study are esophagus, aorta, heart, pulmonary artery, and trachea, and the D_{1cc}, D_{5cc}, D_{10cc}, and D_{15cc} of these organs were examined on the basis of previous clinical trials.[2,3] A total of 300 plans (20 cases $\times$ 3 MLC speed constraints $\times$ 5 error plans) were investigated.

Statistical Analysis

For a comparative evaluation of the 3 MLC speed constraints, a parameter comparison of the reference plans was first determined by calculating the actual average MLC speed from the header information of the DICOM RT plan by using the following formula:

$$Average\ MLC\ Speed\ = \sum_{i=1}^{k} \left(\frac{\sum_{n=1}^{N-1}\left(\dfrac{x_{n+1} - x_n}{\theta_{n+1} - \theta_n}\right)}{N - 1} \right)_i$$

where k is the active MLC number that may vary for each plan, N is the number of control points, x_n is the coordinate of the MLC at control point n, and θ_n is the gantry angle at control point n. The analysis was performed using MATLAB 2021b (Mathworks, Natick, MA). In addition, other dose indices were compared for each reference plan. Then, for evaluation of plan robustness, the dose difference from the reference plan was evaluated when setup errors from 1 to 5 mm were added. Comparisons among the 3 groups were performed at the significance level ($P < .05$) by using the Wilcoxon test using JMP Pro 15 (SAS Institute Inc., NC) for each combination.

Table 1. The Initial Values of the Optimization Conditions in the Treatment Planning System.

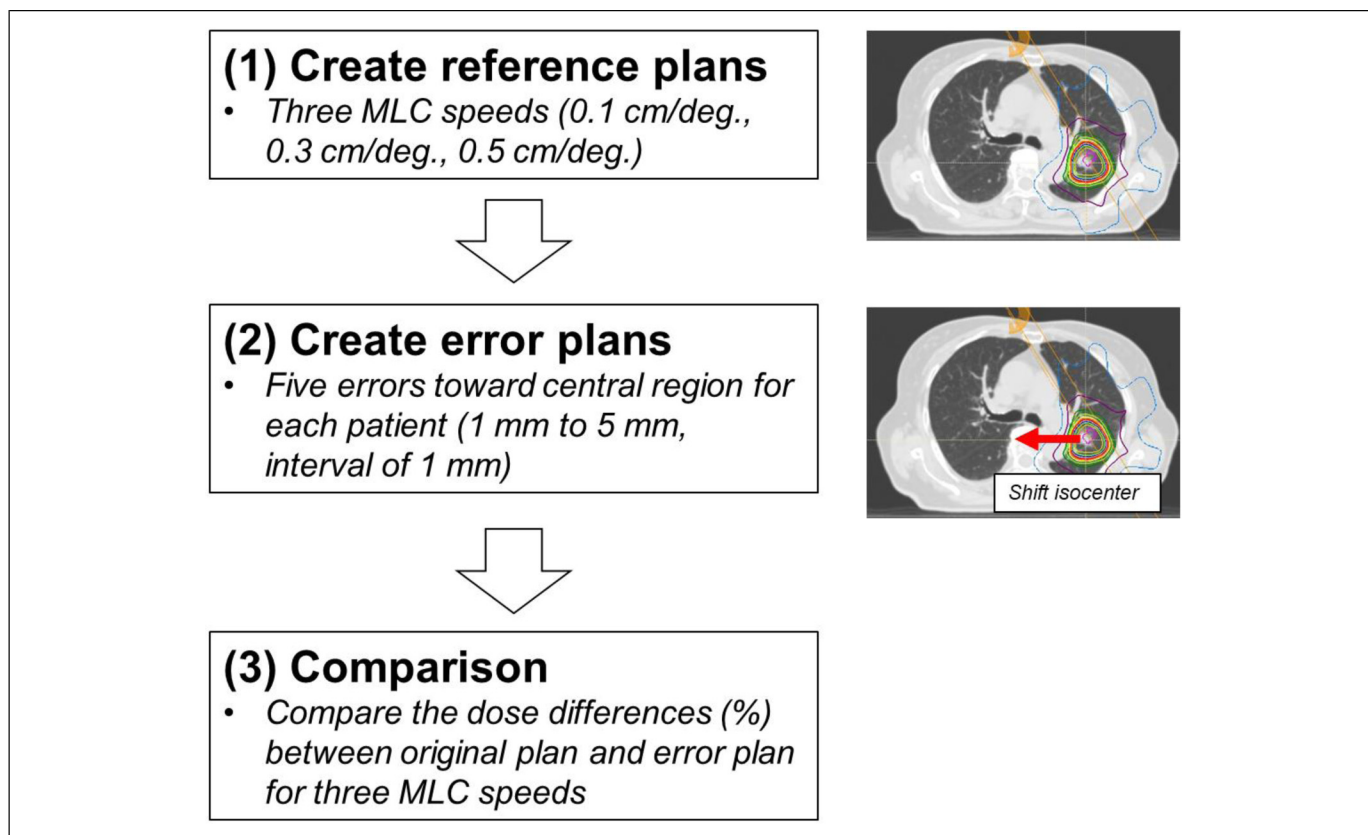| ROI	Function description	Weight
PTV	Min DVH 5000 cGy to 95% volume	10
	Max Dose 5750 cGy	10
External	Dose fall-off [H]5000 cGy [L]2500 cGy, Low dose distance 0.75 cm	1
Canal	Max dose 2500 cGy	0.01
Others	As low as possible (trachea, heart, esophagus, aorta, pulmonary artery)	0.01

Figure 1. Outline of this study. The study protocol consisted of 3 steps: (1) creation of the reference plan, (2) creation of error plans, and (3) comparison of each plan.

Results

Reference Plan Analysis

Table 2 shows the comparisons of each parameter for the 3 original plans. For each parameter, the results of comparisons at 0.1 cm/deg., 0.3 cm/deg., and 0.5 cm/deg. are shown as A, B, and C, respectively. First, although the actual MLC speed did not exactly reflect the constraint value, it increased significantly as the MLC speed constraint was increased ($P < .0001$). As for the PTV dose index, it tended to decrease with increasing MLC speed, especially for PTV $D_{2\%}$, which decreased significantly with increasing MLC speed. For normal organs, comparisons were performed for each index at the esophagus ($n = 12$), heart ($n = 7$), aorta ($n = 11$), pulmonary artery ($n = 9$), and trachea ($n = 6$). As for normal organs, it also tended to decrease with increasing MLC speed, but only a few significant differences between MLC speeds were observed.

Error Plan Analysis

Figure 2 shows a comparison of the dose differences between the reference plan and the error plan for PTV. The horizontal axis shows the magnitude of the error, and the vertical axis shows the dose difference from the reference plan. For PTV D_{mean}, $D_{50\%}$, and $D_{2\%}$, the dose difference remained within 5% even when an error of 5 mm was added. On the other hand, for $D_{98\%}$, the dose difference showed a negative correlation as the error was increased, and a dose difference of about -20% was observed at 5 mm. For most of these dose differences, no significant differences were found among the 3 MLC speed constraints. Figure 3 also shows a comparison of the dose differences between the reference plan and error plan for normal organs. For all organ dose indices, a positive correlation was observed between the dose difference and error, with a dose difference of about 20% observed for 5 mm. On the other hand, no significant difference in dose difference was identified among the 3 MLC speed constraints for most of the indices. The P-values are summarized in Supplemental Table 1. In addition, the correlation coefficients between dose differences and setup errors are also summarized in Supplemental Table 2.

Discussion

While attempts to create a highly modulated dose distribution to reduce normal organ doses may result in a higher MLC speed, this study examined the feasibility of treatment plans with different MLC speeds for central lung cancer cases and evaluated the robustness of these plans against setup errors. Our results suggested that higher MLC speeds could improve the degree of freedom in treatment plan creation. The results in Table 2

Table 2. Comparison of each parameter in the 3 original plans. The results of the comparison are shown for 0.1 cm/deg., 0.3 cm/deg., and 0.5 cm/deg. as A, B and C, respectively.

|		A = 0.1 cm/deg.	B = 0.3 cm/deg.	C = 0.5 cm/deg.	A versus B *P*-value	B versus C *P*-value	A versus C *P*-value
Actual MLC speed (*n* = 20) [cm/deg.]		0.25 ± 0.04	0.34 ± 0.07	0.39 ± 0.12	<.0001*	<.0001*	<.0001*
PTV (*n* = 20) [Gy]	D_{mean}	55.29 ± 0.29	54.79 ± 1.01	54.76 ± 0.97	.0050*	.8394	.0010*
	$D_{98\%}$	48.39 ± 0.50	48.38 ± 0.56	48.42 ± 0.52	.6574	.4116	.7754
	$D_{50\%}$	55.41 ± 0.97	55.00 ± 1.12	55.00 ± 1.06	.0094*	.7419	.0172*
	$D_{2\%}$	60.92 ± 2.05	59.30 ± 1.88	59.11 ± 1.87	<.0001*	.0310*	<.0001*
Esophagus (*n* = 12) [Gy]	D_{1cc}	19.80 ± 8.98	19.76 ± 9.28	19.45 ± 8.99	.8501	.0137*	.4238
	D_{5cc}	8.52 ± 6.21	8.55 ± 6.26	8.46 ± 6.21	.9849	.1641	.3101
Heart (*n* = 7) [Gy]	D_{10cc}	19.73 ± 5.30	19.36 ± 5.77	19.18 ± 5.64	.5625	.1250	.4375
	D_{15cc}	17.68 ± 4.38	17.37 ± 4.93	17.18 ± 4.77	.6875	.6250	.4375
Aorta (*n* = 11) [Gy]	D_{1cc}	36.20 ± 15.22	35.59 ± 14.76	35.59 ± 14.87	.0503	.9541	.0425*
	D_{10cc}	21.08 ± 8.20	22.94 ± 13.09	20.42 ± 7.79	.1099	.1641	.0142*
Pulmonary artery (*n* = 9) [Gy]	D_{1cc}	31.30 ± 15.54	30.76 ± 14.68	30.39 ± 14.71	.4316	.0977	.0645
	D_{10cc}	13.61 ± 7.57	12.77 ± 7.23	13.94 ± 7.87	.0137*	.8438	.1602
Trachea (*n* = 6) [Gy]	D_{1cc}	17.06 ± 6.95	16.93 ± 6.88	16.93 ± 6.91	.2813	1.0000	.3125
	D_{10cc}	7.28 ± 5.85	7.81 ± 6.45	7.83 ± 6.45	.1563	1.0000	.1563
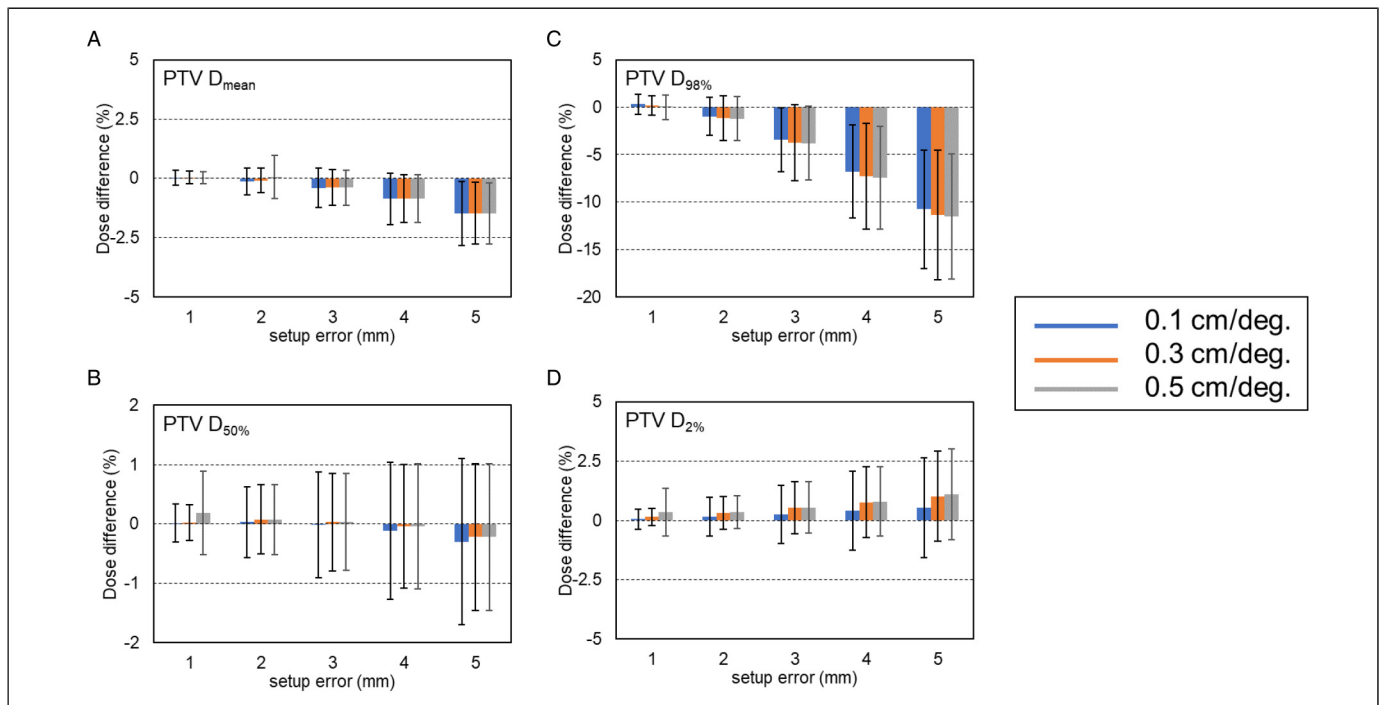
Figure 2. A comparison of the dose difference between the reference plan and error plan for planning target volume (PTV). The horizontal axis shows the magnitude of the error, and the vertical axis shows the dose difference from the reference plan: (A) PTV D_{mean}, (B) PTV $D_{50\%}$, (C) PTV $D_{98\%}$, and (D) PTV $D_{2\%}$. Blue, orange, and gray represent 0.1, 0.3, and 0.5 cm/deg., respectively.

show that the more the MLC speed constraint was increased, especially at $D_{2\%}$ of PTV, the dose decreased significantly. Thus, for PTV, the optimization condition was set at 5750 cGy of the max dose, which made the restriction more effective.

Three MLC speeds were studied in this study. These were chosen because they are the most realistic values for stereotactic irradiation of lung cancer using IMRT. In this technique, the leaf speed is usually not fast because of the smaller irradiation field and less modulation, compared to IMRT for other site in general. Therefore, we considered the range (from 0.1 to 0.5 cm/deg.) in this study to be optimal. Similar values were used in the previous literature.[7] On the other hand, if faster MLC speeds are used in this study, the planned dose distribution is expected to be better, but the robustness is unknown and needs to be further investigated.
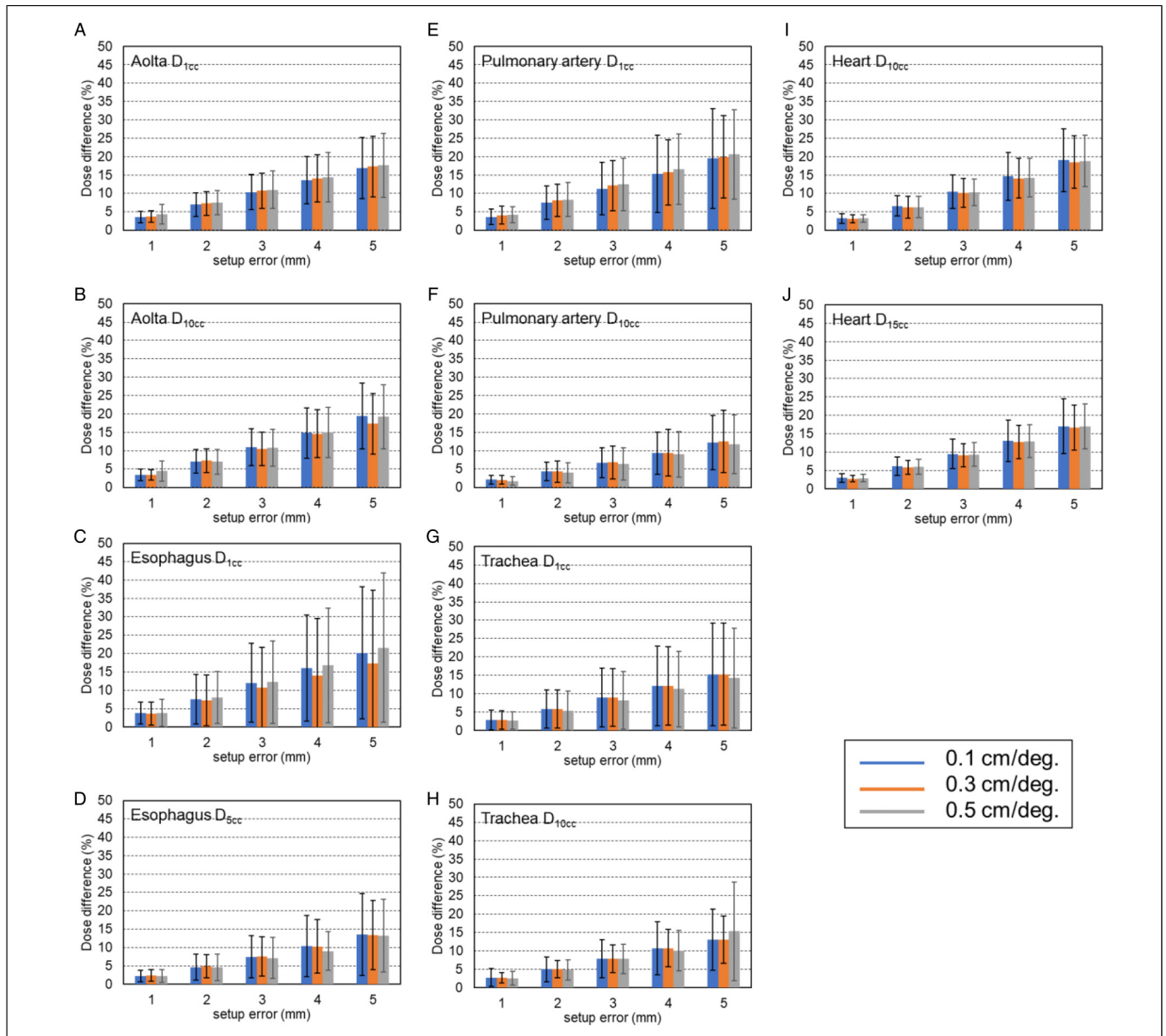
Figure 3. A comparison of the dose difference between the reference plan and error plan for normal organs. The horizontal axis shows the magnitude of the error, and the vertical axis shows the dose difference from the reference plan: (A) aorta D_{1cc}, (B) aorta D_{10cc}, (C) esophagus D_{1cc}, (D) esophagus D_{5cc}, (E) pulmonary artery D_{1cc}, (F) pulmonary artery D_{10cc}, (G) trachea D_{1cc}, (H) trachea D_{10cc}, (I) heart D_{10cc}, and (J) heart D_{15cc}. Blue, orange, and gray represent 0.1, 0.3, and 0.5 cm/deg., respectively.

In this study, setup errors were added from 1 to 5 mm to investigate the robustness of each plan for PTV or normal organ dose. Although a setup error of 5 mm is an unlikely situation in clinical practice, we thought it would be useful to examine large errors in order to understand the impact of MLC speed. Several robust studies on lung cancer SBRT have reported the dangers of PTV-based optimization for a setup error.[8,9] Moreover, in this study, for the PTV dose, the setup error affected the dose, especially near the lowest dose ($D_{98\%}$). Figure 2 shows that $D_{98\%}$ is particularly affected by setup errors and is reduced from the original plan. This is because the setup error prevents the dose prescription from

being applied to the PTV limb. On the other hand, MLC speed was not involved in relation to these features. To improve the robustness of the plan with respect to targets, the robust optimization function[10] and GTV-based prescriptions[11] should also be used instead of focusing solely on MLC speed.

Some previous reports on the correlation between MLC speed and irradiation accuracy during VMAT have reported that the γ-pass rate tends to worsen with higher MLC speeds, and that small segments and MUs increase.[6,7] In addition, many studies have recently been conducted using several indices of modulation complexity (MU, MLC position/speed, and dose rate).[12] These approaches also actively involved the

development of irradiation accuracy prediction indices including MLC parameters (MCS, MCSv); however, these indices cannot substitute all QA results and are not routinely usable at present.[13,14] As a basis for this, one study reported that there was no correlation between the results of multi-institution QA using the IROC head and neck phantom and the results of MCS.[15] Therefore, it is necessary to ensure the accuracy during the commissioning phase for other factors that directly affect planning accuracies, such as beam modeling and MLC modeling. Then, worsening of dose verification results due to increased MLC rates should be carefully checked in individual plans and operated in clinical practice.

This study had some limitations. First, because this study only evaluated the effect on setup error by using isocenter shift, it did not take into account the variations caused by the respiratory motion of the patient. Second, MLC speed constraints were evaluated for 0.5 cm/deg. or less, but not for faster MLC speed constraints. Third, only limited beam conditions (1-half arc, 6MVFFF) were evaluated. Fourth, this study used a relatively small sample size. Finally, no actual measurements of individual plans were made. Although we have had some experience in the past with lung cancer SBRT using the cylindrical phantom (Delta4),[16] this is only a homogeneous phantom, so we cannot evaluate the impact on actual individual cases of lung cancer. Therefore, this study was limited to dosimetric evaluation for treatment planning in order to assess the clinical impact, and actual measurement verification is a future issue.

Conclusion

In SBRT-VMAT for central lung cancer, a faster MLC speed could improve the dose distribution and not affect the robustness against setup errors in the central direction. Thus, when necessary, increasing the MLC speed constraint with a priority on improving the quality of the dose distribution is an acceptable approach.

Declaration of Conflicting Interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Ethics Statement

This retrospective study was approved by the institutional review board (IRB) of the University of Yamanashi (receipt number: 2271).

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Supplemental Material

Supplemental material for this article is available online.

References

1. Onishi H, Shirato H, Nagata Y, et al. Stereotactic body radiotherapy (SBRT) for operable stage I non-small-cell lung cancer: can SBRT be comparable to surgery? *Int J Radiat Oncol Biol Phys*. 2011;81(5):1352-1358.

2. Kimura T, Nagata Y, Harada H, et al. Phase I study of stereotactic body radiation therapy for centrally located stage IA non-small cell lung cancer (JROSG10-1). *Int J Clin Oncol*. 2017;22(5):849-856.

3. Karasawa K, Hayakawa S, Machitori Y, et al. Accelerated hypo-fractionated radiotherapy versus stereotactic body radiotherapy for the treatment of stage I nonsmall cell lung cancer—A single institution experience with long-term follow-up. *Technol Cancer Res Treat*. 2018;17:1-8.

4. Timmerman R, Paulus R, Galvin J, et al. Stereotactic body radiation therapy for inoperable early stage lung cancer. *Jama*. 2010;303(11):1070-1076.

5. Saito M, Sano N, Kuriyama K, et al. Evaluation of the robustness of 3-dimensional conformal technique with MLC position control into the planning target volume in stereotactic body radiotherapy for lung cancer. *Med Dosim*. 2020;45(1):e1-e5.

6. Park JM, Wu HG, Kim JH, et al. The effect of MLC speed and acceleration on the plan delivery accuracy of VMAT. *Br J Radiol*. 2015;88(1049):20140698.

7. Yang K, Yan D, Tyagi N. Sensitivity analysis of physics and planning SmartArc parameters for single and partial arc VMAT planning. *J Appl Clin Med Phys*. 2012;13(6):34-45.

8. Miura H, Ozawa S, Nagata Y. Efficacy of robust optimization plan with partial-arc VMAT for photon volumetric-modulated arc therapy: a phantom study. *J Appl Clin Med Phys*. 2017;18(5):97-103.

9. Liang X, Zheng D, Mamalui-Hunter M, et al. ITV-based robust optimization for VMAT planning of stereotactic body radiation therapy of lung cancer. *Pract Radiat Oncol*. 2019;9(1):38-48.

10. Shang H, Pu Y, Wang Y. Robust optimization of SBRT planning for patients with early stage non-small cell lung cancer. *Technol Cancer Res Treat*. 2020;19:1-12.

11. Komiyama T, Saito M, Kuriyama K, et al. Dose prescription methods in stereotactic body radiotherapy for small peripheral lung tumors: approaches based on the gross tumor volume are superior to prescribing a dose that covers 95% of the planning target volume. *Technol Cancer Res Treat*. 2020;19:1-7.

12. Chiavassa S, Bessieres I, Edouard M, et al. Complexity metrics for IMRT and VMAT plans: a review of current literature and applications. *Br J Radiol*. 2019;92(1102):20190270.

13. Masi L, Doro R, Favuzza V, et al. Impact of plan parameters on the dosimetric accuracy of volumetric modulated arc therapy. *Med Phys*. 2013;40(7):071718.

14. McNiven AL, Sharpe MB, Purdie TG. A new metric for assessing IMRT modulation complexity and plan deliverability. *Med Phys*. 2010;37(2):505-515.

15. Glenn MC, Hernandez V, Saez J, et al. Treatment plan complexity does not predict IROC Houston anthropomorphic head and neck phantom performance. *Phys Med Biol*. 2018;63(20): 205015.

16. Saito M, Suzuki H, Sano N, et al. Evaluation of the target dose coverage of stereotactic body radiotherapy for lung cancer using helical tomotherapy: a dynamic phantom study. *Rep Pract Oncol Radiother*. 2020;25(2):200-205.