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Original paper

Evaluation of organ-at-risk dose reduction with jaw tracking technique in flattening filter-free beams in lung stereotactic body radiation therapy

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ABSTRACT

Purpose: (i) to investigate the capability of organ-at-risk (OAR) dose reduction with the jaw tracking (JT) technique in flattening filter-free (FFF) beams in lung stereotactic body radiation therapy (SBRT), (ii) to propose a novel metric to quantify the jaw movements during JT, and (iii) to examine the relationships between the quantified jaw movements and reduction rate of OAR doses.

Methods: The individual SBRT plans with volumetric modulated arc therapy using the JT technique (JT-VMAT) and VMAT plans with a fixed jaw (FJ-VMAT) were created for 15 patients, and dosimetric parameters were compared. A jaw tracking complexity score (JTCS) was defined and compared with the multi-leaf collimator (MLC) modulation complexity score (MCS). The correlations between the JTCS and reduction rate of OAR doses were examined.

Results: The decrease of OARs doses was statistically significant in the JT-VMAT plans (1.2% in V20 of the lung and < 1% in all other OARs). The correlations between the JTCS and MCS were not significant. There were significant correlations between the JTCS and the reduction rates in V_{20}, $V_{2.5}$, and D_{mean} of the lung, $D_{1\%}$ of the spinal cord, and $D_{90\%}$ of the body.

Conclusions: A significant decrease of dosimetric parameters of OARs was found with JT-VMAT in FFF beams. This reduction is very small and probably not clinically relevant. JTCS, a novel metric to quantify the jaw movements during JT, was proposed, and the complexity of jaw movements did not correlate with that of the movements of MLC leaves. There were significant correlations between the JTCS and some dosimetric parameters of OARs.

1. Introduction

Stereotactic body radiation therapy (SBRT) achieves escalation of the fractional dose to the target while minimizing the radiation dose to normal tissue. As a result, SBRT has excellent local control and survival rates with limited toxicity in patients with medically inoperable early-stage non-small cell lung cancer [1]. SPACE is the first randomized study comparing SBRT and conventional fractionated radiotherapy in stage I non-small cell lung cancer patients [2]. Although it did not show any difference in terms of progression free survival, overall survival or local control between SBRT and conventionally treated patients, quality of life was significantly better with SBRT, and less radiotherapy related toxicities were observed. Volumetric modulated arc therapy (VMAT) with flattening filter-free (FFF) beams (FFF-VMAT), a novel and new irradiation technique for SBRT, can reduce the treatment time for removing a flattening filter (FF) [3–5]. FFF-VMAT also allows for a high local control rate with low toxicity compared with the FF method [6], and limited an acute toxicity in various lesion sites [7].

In Varian linear accelerators such as TrueBeam (Varian Medical Systems, Palo Alto, CA, USA), the jaw tracking (JT) technique can be used in intensity modulated radiation therapy (IMRT) and VMAT. The JT technique can minimize the leakage and transmission through the multi-leaf collimator (MLC) leaves by the jaws following the MLC apertures [8]. Owing to the advantages of the JT technique, the doses to

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organs at risk (OARs) and normal tissues around the target were significantly reduced in flattened beams [9,10]. Feng et al. assessed the potential advantages of the JT technique with sliding window IMRT (d-IMRT) in various location sites and observed that the JT d-IMRT plans can reduce the doses to the normal tissues, especially in low-dose regions [9]. V_5, V_{10}, V_{20}, and D_{mean} of the lungs in the JT d-IMRT plans were significantly lower than the static-jaw-technique d-IMRT plans. This finding suggested that the risk of pulmonary toxicity could be reduced with the JT technique because the radiation pneumonitis rate is correlated with low dose volumes [11]. Joy et al., on the other hand, examined the potential of jaw collimation around each MLC aperture in step-and-shoot IMRT and found that the maximum reduction in V_5 was 16.7%, but typically less than 3%, and they concluded that the amount of dose reduction with jaw collimation in step-and-shoot IMRT is probably not clinically significant [12].

However, the dosimetric impact of JT in FFF beams has not been investigated yet, though there are some reports that mentioned about dosimetric changes of JT in flattened beams. It is still unclear whether dose reduction provided by JT in FFF beams could be observed or not, because the FFF beams have unique beam characteristics owing to the absence of FF, which is different from flattened beams [13,14]. Other studies mentioned that the FFF beams already have sufficiently low peripheral doses compared with the flattened beams owing to a lack of scatter radiation from FF [15,16]. On the other hand, the advantage of JT in FFF beams cannot be denied yet since the fractional dose of SBRT plan is generally much larger than conventional fractionated radiotherapy plans, and required monitor units (MU) for the SBRT plans will be increased, especially in the use of VMAT in SBRT plans. Increased MUs might cause an increase of transmission through the MLC leaves and scatter radiation from treatment head, resulting in larger of undesired doses to the patients. The JT technique might minimize those undesired doses to the patients in FFF beams.

Additionally, even as the jaw movements during JT are an important parameter in determining the efficacy of JT, the movements have not been quantified, and the relationships between the complexity of jaw movements and that of the movements of MLC leaves also have not been investigated. We consider that the improvement of dose sparing for OARs would be observed as increase the amount of the jaw movements because the leakage and MLC transmission can be reduced by the JT technique. Therefore, the goals of this study were (i) to investigate the capability of OAR dose reduction with the JT technique in FFF beams in lung SBRT, (ii) to propose a novel metric to quantify the jaw movements during JT and examine the correlations between the complexity of jaw movements and that of MLC movements, and (iii) to examine the relationships between the quantified jaw movements and the reduction rate of OAR doses by the JT technique.

2. Materials and methods

2.1. Treatment planning

A flowchart of our methods is shown in Fig. 1. Fifteen patients with pulmonary lesions treated by SBRT between August 2016 and April 2017 at our institution were retrospectively enrolled in this study. The inclusion criteria of the present study were as follows: (i) medically diagnosed as early-stage primary or metastatic lung cancer and (ii) prescribed 55 Gy in four fractions to the 95% of the planning target volume (PTV). Table 1 summarizes the patients' characteristics. Tumor size was determined as the maximum diameter of the tumor measured in axial computed tomography (CT) plane with the use of a pulmonary window setting. The study was approved by the ethics committee of the Cancer Institute Hospital of the Japanese Foundation for Cancer Research (2017-1135).

The SBRT plans with VMAT using the JT technique (JT-VMAT) were created for all patients in accordance with the JCOG1408 protocol [17]. The treatment planning system (TPS) was Eclipse, ver. 13.6 (Varian Medical Systems), and the treatment beam was a 6-MV photon with FFF using the TrueBeam linear accelerator (Varian Medical Systems). The maximum dose rate of the FFF beams was selected as 1400 monitor units (MU)/min. The leaf transmission factor was obtained from the measurement in commissioning of linear accelerator and set the value as 1.29% in TPS. The value of transmission factor was comparable to one in other institutions (< 0.1%, absolute difference) [18]. The MLC transmission of FFF beams is lower than that of FF beams (e.g., 1.51% of the leaf transmission factor in 6X-FF in our institution) because the X-ray spectra of the FFF beams are softer than those of flattened beams [13]. Acuros XB was applied for a dose calculation. Beam arrangements for the JT-VMAT plan included two partial arcs of 200° with a coplanar technique in terms of the ipsilateral lung to maximally reduce doses to the contralateral lung [19]. From 10 to 20°, a collimator rotation adjusted to the shape of the target was used for two different arcs.

The internal target volume (ITV) was defined as the volume based on slow-scanning CT. The PTV was determined by the ITV plus a margin of 3 mm in all directions. The main OARs of the present study were determined as the bilateral-lungs minus PTV (Lung), spinal cord, and skin. Other OARs including the heart, esophagus, trachea, ribs, chest wall, liver, pulmonary artery, and aorta were contoured depending on the target location. The skin was delineated at an inside volume of 5 mm from the chest wall surface.

The prescribed dose was 55 Gy in four fractions aimed to cover the PTV with 95% of the prescribed dose ($D_{95\%}$ to 55 Gy). The dose

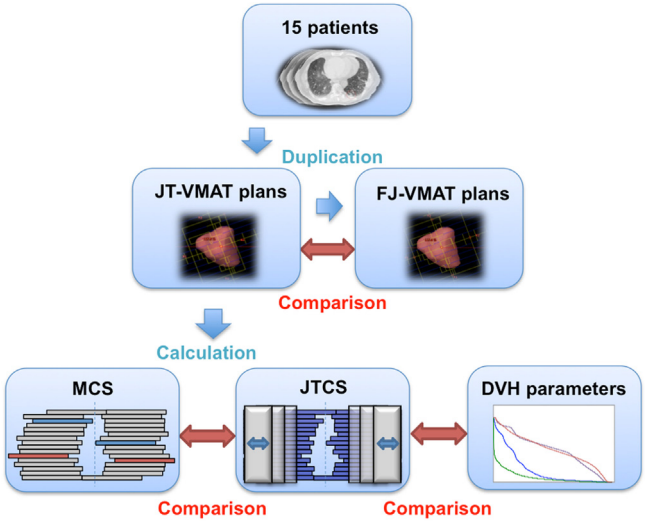

Fig. 1. Flowchart of our methods. SBRT plans with JT-VMAT were created for all patients. Then, all JT-VMAT plans were duplicated, and JT technique was disabled in all duplicated plans to create FJ-VMAT plans. Next, MCS and JTCS were calculated in all JT-VMAT plans, and correlations between MCS and JTCS were compared. In addition, correlations between JTCS and reduction rate of dosimetric parameter of OARs calculated from DVHs were compared.

Table 1
Patient characteristics.

Characteristic	No. (Median)
Number of patients	15
Sex	
Male	9
Female	6
Age	60–83 (78)
Diagnosis	
Primary	9
Metastasis	6
Tumor size [cm]	1.0–3.1 (1.9)
PTV volume [cm^3]	3.3–45.1 (15.1)

Table 2
Dose constraints for PTV and OARs.

Objects	Dose volume parameters	Objects	Dose volume parameters
Lung	$V_{40} \leq 100$ cc	Spinal cord	$D_{max} \leq 25$ Gy
	$V_{20} \leq 20\%$	Skin	$D_{max} \leq 40$ Gy
	$V_{15} \leq 25\%$	PTV	$D_{2\%} \leq 120\%$
	$D_{mean} \leq 4$ Gy		CN[a] ≤ 0.75

[a]CN: conformation number.

constraints used in treatment planning for PTV and OARs are listed in Table 2. The conformation number (CN) [20] was defined as

$$CN = \frac{Vt_{100}^2}{(Vt_{vol} \bullet V_{100})}, \quad (1)$$

where Vt_{100} is the target volume receiving at least the prescribed dose, Vt_{vol} is the target volume, and V_{100} is the total volume receiving at least the prescribed dose. A value close to unity means identical target coverage. Planning objectives for other OARs were adopted in accordance with the JCOG1408 protocol [17]. The normal tissue objective was used for optimization.

To compare the plan quality with regard to dosimetric parameters and dose distributions with and without the JT technique, JT-VMAT plans for all patients were duplicated, and the JT technique was disabled in all duplicated plans to create VMAT plans with a fixed jaw (FJ-VMAT). The jaw positions in each FJ-VMAT plan were fixed at the maximum opening in the duplicated JT-VMAT plan. The planning parameters (e.g., field arrangements, dose constraints, field weight, and MLC movements) of the FJ-VMAT plans, other than the use of JT, were totally identical to the JT-VMAT plans.

2.2. Dosimetric parameters

To evaluate JT-VMAT and FJ-VMAT, some dosimetric parameters were calculated for each patient from a dose-volume histogram (DVH). Table 3 shows details of the dosimetric parameters.

2.3. Jaw tracking complexity score

To quantify the jaw movements during JT and evaluation of relationships between the complexity of jaw movements and that of the movements of the MLC leaves in the plan, the jaw tracking complexity score ($JTCS_{plan}$) was defined. First, the complexity of the jaw movements in the arc was calculated as

$$JTCS_{arc} = \frac{\sum_{n=1}^{CPs-1} |Pos_n - Pos_{n+1}|_{X1-jaw} + \sum_{n=1}^{CPs-1} |Pos_n - Pos_{n+1}|_{X2-jaw}}{CPs - 1}, \quad (2)$$

where CPs is number of control points, and Pos is the coordinate of the jaw position. Finally, $JTCS_{plan}$ was calculated as the mean of applied arcs in the plan by using the following equation:

$$JTCS_{plan} = \frac{\sum_{n=1}^{F} (JTCS_{arc_n})}{F}, \quad (3)$$

Table 3
Evaluated dosimetric parameters.

Objects	Criteria	Objects	Criteria
Lung	V_{20} [%]	Body	$D_{90\%}$ [cGy]
	V_5 [%]		$D_{80\%}$ [cGy]
	$V_{2.5}$ [%]	PTV	$D_{2\%}$ [Gy]
	D_{mean} [Gy]		$D_{98\%}$ [Gy]
Spinal cord	$D_{1\%}$ [Gy]		D_{mean} [Gy]
Skin	D_{max} [Gy]		

where F is the number of arcs in the plan. As the $JTCS_{plan}$ value is larger, it indicates more complex jaw movements during JT.

To calculate the complexity of the movements of the MLC leaves, the modulation complexity score (MCS) was adopted in this study. The MCS was defined by Masi et al. [21] for VMAT, and it can be calculated from the DICOM-RT plan information incorporating variability in leaf positions, aperture area, and normalized monitor unit (MU) values. To derive the MCS, first, the maximum distance between positions for a leaf bank in the CP was calculated as follows:

$$Pos_{max}(CP) = \langle max(Pos_{n\in N}) - min(Pos_{n\in N}) \rangle_{leafbank}, \quad (4)$$

where Pos is the coordinate of the leaf position. Second, to consider the differences between adjacent MLC leaves in each bank, the leaf sequence variability (LSV) is defined as

$$LSV_{cp} = \left[\frac{\sum_{n=1}^{N-1} (Pos_{max} - |(Pos_n - Pos_{n+1})|)}{(N-1) \times Pos_{max}} \right]_{leftbank} \times \left[\frac{\sum_{n=1}^{N-1} (Pos_{max} - |(Pos_n - Pos_{n+1})|)}{(N-1) \times Pos_{max}} \right]_{rightbank}, \quad (5)$$

where N is the number of moving leaves inside the jaws. Third, to consider the area defined by apertures of opposing leaves in a single control point normalized to the maximum area in the arc, the aperture area variability (AAV) is defined as

$$AAV_{cp} = \frac{\sum_{a=1}^{A} (\langle Pos_a \rangle_{leftbank} - \langle Pos_a \rangle_{righttbank})}{\sum_{a=1}^{A} (\langle max(Pos_a) \rangle_{leftbank\in arc} - \langle max(Pos_a) \rangle_{rightbank\in arc})}, \quad (6)$$

where A is the number of leaves in the arc. Finally, the MCS can be calculated by combining the LSV, AAV, and normalized MU values as follows:

$$MCS_{arc} = \sum_{i=1}^{I-1} \left[\frac{(AAV_{cp_i} + AAV_{cp_{i+1}})}{2} \times \frac{(LSV_{cp_i} + LSV_{cp_{i+1}})}{2} \times \frac{MU_{CP_{i,\ i+1}}}{MU_{arc}} \right], \quad (7)$$

where I denotes the number of control points in the arc. $MU_{CPi,\ i+1}$ indicates the MU delivered between two successive control points. MCS_{arc} allows for a quantitative assessment of the plan complexity, and this can be applied to all treatment sites. However, because MCS_{arc} was evaluated as the complexity of VMAT plan for each arc, we slightly modified MCS_{arc} as the mean of applied arcs in the plan. MCS_{plan} was defined as

$$MCS_{plan} = \frac{\sum_{i=1}^{F} (MCS_{arc_i})}{F}, \quad (8)$$

where F is the number of arcs in the plan. MCS_{plan} ranges from 1.0 to 0 as does MCS by Masi et al. A value of 1.0 indicates no modulation, that is, a fixed rectangular aperture with no leaves moving during the arc. When MLC modulation increases, MCS is close to zero. MCS_{plan} was calculated for all JT-VMAT plans and compared with $JTCS_{plan}$. Moreover, to examine the clinical usefulness of $JTCS_{plan}$, the correlations between $JTCS_{plan}$ and the reduction rate of the dosimetric parameters of OARs by the JT-VMAT plans were investigated.

2.4. Accuracy of jaw tracking

To investigate the mechanical reproducibility and deliverability of the jaw movements during JT, trajectory log files were acquired for each patient. The TrueBeam linear accelerator records actual axis positions (including Y-jaw, X-jaw, and MLCs) and MU delivered during treatment [22]. After the delivery is completed, the information is stored to the trajectory log file every 20 ms. The errors between the expected jaw position (i.e., taken from the DICOM-RT file created

during planning) and the actual jaw positions were calculated with in-house software, which evaluated errors by using the root mean square error (RMSE). The RMSE was calculated for each arc, and the means of both RMSEs were used for the evaluation.

2.5. Statistical analysis

Data were statistically analyzed using JMP Pro 11 software (SAS Institute, Inc., Cary, NC, USA). The dosimetric parameters of the OARs and PTV were compared between the JT-VMAT and FJ-VMAT plans with a Wilcoxon signed rank test. Both datasets were analyzed as paired data and calculated a p value. Correlations between $JTCS_{plan}$ and MCS_{plan}, and $JTCS_{plan}$ and the reduction rate of the dosimetric parameters of OARs were examined with Spearman's correlation coefficient (ρ). All p values were two-sided, and the p value of < 0.05 was considered a statistically significant difference.

3. Results

3.1. Dosimetric parameters

A summary of dosimetric parameters is listed in Table 4. All dosimetric parameters of the lung, $D_{1\%}$ of the spinal cord, D_{max} of the skin, and all dosimetric parameters of the body were significantly decreased in the JT-VMAT plans (range of 0–1.2%). $D_{2\%}$ and D_{mean} for PTV were significantly increased in the JT-VMAT plans, whereas $D_{98\%}$ showed no significant difference between the JT-VMAT and FJ-VMAT plans. Fig. 2 shows a subtracted dose distribution image and the DVHs in one patient. Without the JT technique, the irradiated doses and volumes were increased, and these mostly existed around the target. The irradiated doses to the rib and chest wall in the patient rose by 0.63 Gy and 0.77 Gy at the maximum, respectively.

3.2. Jaw tracking complexity score

Table 5 lists a summary of mechanical parameters in the JT-VMAT plans. The median values of $JTCS_{plan}$ and MCS_{plan} were 0.84 cm and 0.35 cm, respectively. The correlations between $JTCS_{plan}$ and MCS_{plan} were not significant (Spearman's correlation coefficient $\rho = -0.28$). The positional errors of the X-jaw were negligible since the mean of the RMSEs between the expected and actual jaw positions was less than 0.002 mm (Table 5). Please note that the positional errors of the Y-jaw were not calculated in this study because the Y-jaw had no dynamic movement during delivery in the JT-VMAT plans. Fig. 3 and Fig. 4 show the correlations between $JTCS_{plan}$ and the reduction rates of the OARs. In V_{20}, $V_{2.5}$, and D_{mean} of the lung, there were significant correlations between $JTCS_{plan}$ and the reduction rates, and the coefficients were 0.55, 0.67, and 0.62, respectively. In addition, $D_{1\%}$ of the spinal cord and $D_{90\%}$ of the body showed significant differences ($\rho = 0.53$ for the spinal cord, $\rho = 0.71$ for the body).

4. Discussion

The present study investigated whether OAR doses can be decreased using the JT technique in FFF beams in lung SBRT. $JTCS_{plan}$, a new metric for jaw movements during JT, was proposed. The correlations between the complexity of jaw movements and that of the movements of MLC leaves were examined. Additionally, the relationships between $JTCS_{plan}$ and the reduction rate of OARs were examined. Our results indicated that the dose reduction with JT-VMAT plans is statistically significant, though the rate of dose reduction was relatively small (1.2% in V_{20} of lung and $< 1\%$ in all other OARs). Although the complexity of the jaw movements did not correlate with that of the movements of the MLC leaves, there were significant correlations between $JTCS_{plan}$ and the reduction rate of some dosimetric parameters of the OARs.

Flattening filter-free beams are known to have unique beam characteristics owing to the absence of FF, which is different from flattened beams [13,14]. The X-ray spectra of the FFF beams are softer than those of flattened beams [13]. As a result, MLC transmission of the FFF beams was decreased compared with that of the same energy in flattened beams. Additionally, the FFF beams allowed for decreasing peripheral doses owing to a lack of scatter radiation from FF [15,16]. According to these findings, it is assumed that leaf leakage and scatter radiation from the treatment head were estimated to be less than those of flattened beams.

One concern is dose calculation accuracy of the Acuros XB algorithm in out-of-field regions in FFF beams. Fogliata et al. assessed the dose calculation accuracy in the regions shielded by jaw, or by MLC, or by both [23]. As a consequence, good agreement between calculated and measured out-of-field doses was found using the Acuros XB for all points measured at depth greater than 3 cm. The mean dose differences relative to the open beam central axis dose in 6-MV photon with FFF beams ($\pm$1SD) were $-0.1\% \pm 0.4\%$.

$D_{2\%}$ and D_{mean} for PTV were significantly increased in the JT-VMAT plans compared with the FJ-VMAT plans, except for $D_{98\%}$ (Table 4). This was caused by dynamic changes in the collimator scatter factor (Sc) during delivery in the JT-VMAT plans. Actually, a mean field area formed by the jaw of the JT-VMAT plans was decreased by approximately 3 cm over that of the FJ-VMAT plans (Table 5). As a consequence, the MUs of the JT-VMAT plans were slightly increased compared with the FJ-VMAT plans. In fact, the MU increase percentage of the JT-VMAT plans was significantly increased at 0.41% over the FJ-

Table 4
Summary of dosimetric parameters.

Objects	Criteria	JT-VMAT	FJ-VMAT	Ratio[a] [%]	P value
		Median (interquartile range)			
Lung	V_{20} [%]	2.42 (1.52–3.47)	2.45 (1.52–3.49)	−1.2	< 0.001
	V_5 [%]	12.21 (8.91–16.91)	12.24 (8.94–16.98)	−0.3	< 0.0001
	V2.5 [%]	20.05 (14.25–24.32)	20.15 (14.26–24.39)	−0.5	< 0.0001
	D_{mean} [Gy]	2.71 (1.69–3.23)	2.72 (1.69–3.24)	−0.4	0.001
Spinal cord	$D_{1\%}$ [Gy]	8.24 (6.29–9.94)	8.25 (6.31–9.99)	−0.1	0.01
Skin	D_{max} [Gy]	19.76 (18.28–21.76)	19.83 (18.49–21.77)	−0.4	< 0.001
Body	$D_{90\%}$ [cGy]	2.34 (1.32–3.07)	2.35 (1.32–3.11)	−0.4	0.001
	$D_{80\%}$ [cGy]	4.68 (2.63–5.99)	4.71 (2.64–6.02)	−0.6	0.0001
PTV	$D_{2\%}$ [Gy]	63.06 (61.62–63.39)	62.47 (61.57–63.04)	0.9	0.01
	$D_{98\%}$ [Gy]	54.17 (54.12–54.30)	54.16 (54.12–54.31)	0.02	0.25
	D_{mean} [Gy]	58.98 (58.65–59.30)	58.96 (58.61–59.29)	0.03	< 0.01

Value = median (interquartile range), [a]Ratio [%]: ratio of median value between JT-VMAT and FJ-VMAT [(JT-VMAT–FJ-VMAT)/FJ-VMAT].

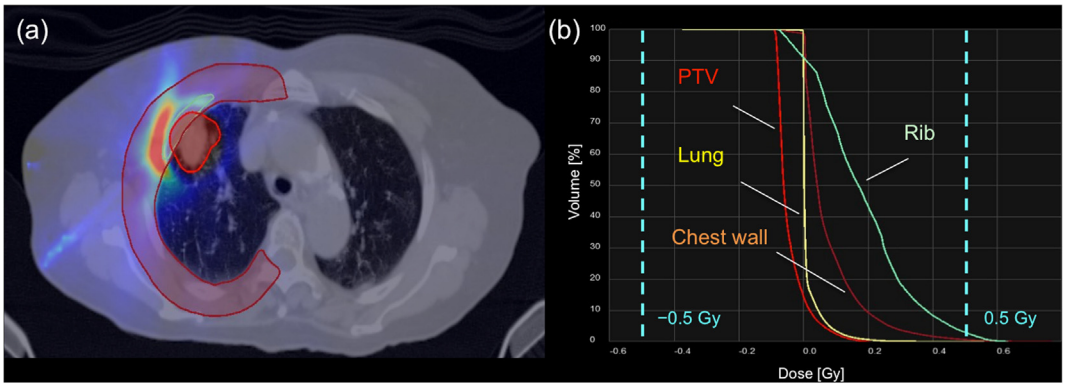

Fig. 2. Examples of subtracted dose distribution image and DVHs in one patient. (a) Dose distribution, which subtracts JT-VMAT plan from FJ-VMAT plan with contoured PTV (red), chest wall (brown), and rib (green). The highlighted dose distribution ranges from −0.5 Gy to 0.5 Gy. As highlighted color is close to red, it denotes that intensity of irradiated dose is high, while as highlighted dose is close to blue, it indicates that intensity of irradiated dose is low. (b): DVHs of dose differences in Fig. (a) with PTV (red), chest wall (brown), rib (green), and lung (yellow). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 5
Summary of mechanical parameters in JT-VMAT plans.

Criteria	Median (Range)
$JTCS_{plan}$ [cm]	0.84 (0.57–1.07)
MCS_{plan}	0.35 (0.28–0.40)
Subtracted field area [cm^2][a]	2.98 (1.02–6.48)
RMSE[b] [mm]	< 0.002

[a]Subtracted field area: subtracted mean field area formed by jaw in all control points in JT-VMAT plan from field area fixed by jaw in FJ-VMAT plan.
[b]Value of RMSE was represented as mean.

VMAT plans ($p < 0.01$), although the results were not the main focus of this study. In a previous work, the change ratio of Sc was significantly affected for small fields, and Sc varied more effectively in flattened beams than in FFF beams [24]. Although the FFF beams were adapted to the JT-VMAT plans in this study, $D_{2\%}$ and D_{mean} for PTV were significantly increased by 0.9% and 0.03% compared with the JT-VMAT plans, respectively. We note that variations of the output would be sensitive to use of the JT technique even for the FFF beams when the targets are relatively small.

The MCS assesses the variability of leaf positions and aperture areas between segments, which was originally proposed for step-and-shoot IMRT [25]. After that, the MCS was slightly modified by Masi et al. [21] to evaluate the plan complexity of VMAT. The assessment of plan complexity with the MCS was considered an alternative approach to reduce the quality assurance (QA) workload such as patient-specific QA [21,25,26]. However, although the correlations between the MCS and the gamma-passing rate in VMAT was well known in several studies [21,26,27], the relationship between the MCS and the complexity of jaw movements has not been clarified. From our results, the MCS did not correlate with the complexity of jaw movements. Other factors such

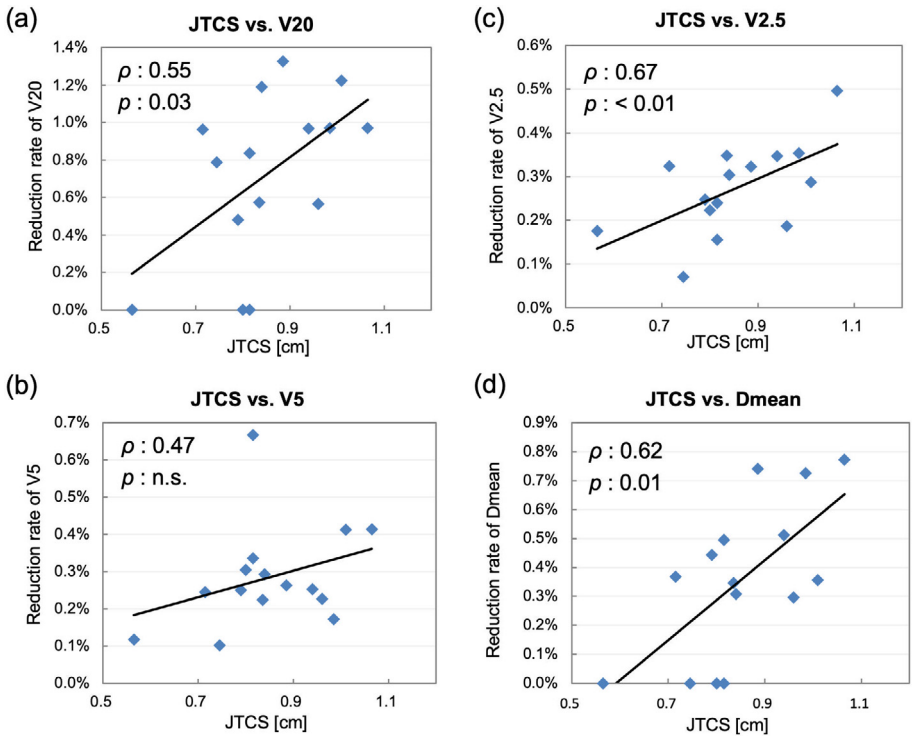

Fig. 3. Correlations between $JTCS_{plan}$ and reduction rate of dosimetric parameters in lung. (a) JTCS vs. V_{20}, (b) JTCS vs. V_5, (c) JTCS vs. $V_{2.5}$, and (d) JTCS vs. D_{mean}.

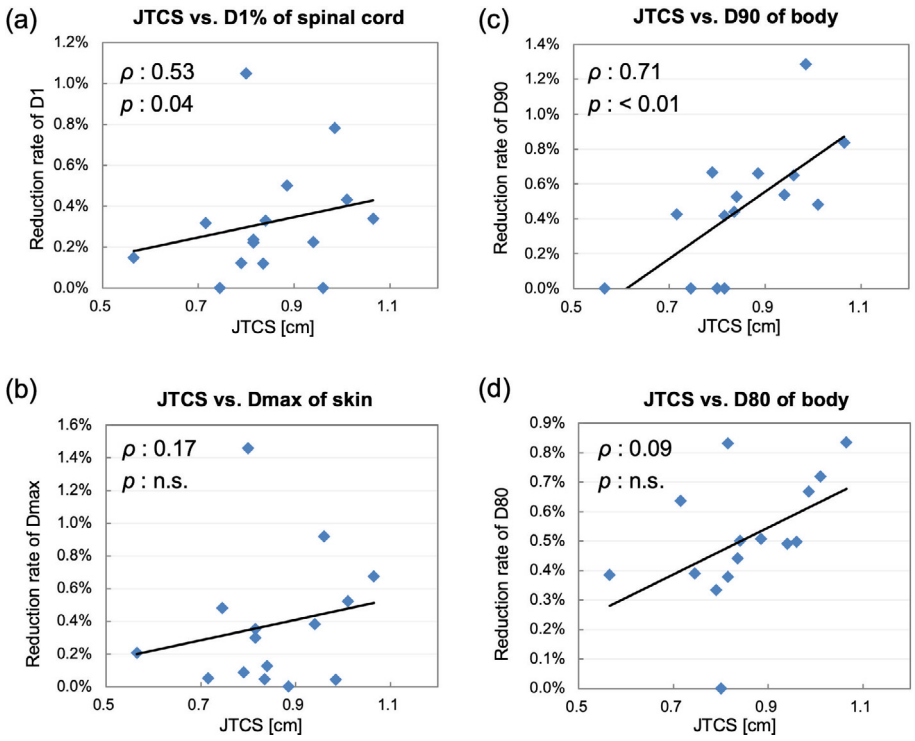

Fig. 4. Correlations between $JTCS_{plan}$ and reduction rate of dosimetric parameters in spinal cord, skin, and body. (a) JTCS vs. $D_{1\%}$ of spinal cord, (b) JTCS vs. D_{max} of skin, (c) JTCS vs. D_{90} of body, and (d) JTCS vs. D_{80} of body.

as target size, shape, and optimization parameters might correlate with the complexity of jaw movements. Moreover, even as the jaw movements during JT are an important parameter in determining the efficacy of JT, the jaw movements have not been quantified. In the present study, $JTCS_{plan}$ was defined as a quantitative parameter of the jaw movements during JT, and correlations between $JTCS_{plan}$ and the reduction rate of OARs were examined. As a consequence, the reduction rates of V_{20}, $V_{2.5}$, and D_{mean} in the lung were significantly improved as increase the movements of JT (Fig. 3). In addition, there were significant correlations between $JTCS_{plan}$ and the reduction rates of $D_{1\%}$ of the spinal cord and $D_{90\%}$ of the body (Fig. 4). It is suggested that $JTCS_{plan}$ might be useful as a quantitative parameter to evaluate the JT technique.

We investigated the mechanical reproducibility or deliverability of the jaw movements by using the trajectory log file. As a result, actual positions of the jaw movements in JT-VMAT plans were in good agreement with the expected positions, and the mean RMSE was less than 0.002 mm. The results indicated that the JT technique accurately followed the MLC movements within a range between 0.57 and 1.07 cm of $JTCS_{plan}$ (Table 5). In the AAPM task group 142 (TG-142) report, there is a recommendation that the mechanical accuracy of symmetric and asymmetric jaws in IMRT is set within 2 mm and 1 mm, respectively [28]. This task group considered that maintaining these accuracies is important for ensuring that the equipment is suitable for high-quality and safe radiation treatment. However, this report did not mention the accuracy of a jaw that has dynamic movement during treatment, such as with the JT technique in the Varian machine. Therefore, the positional accuracy of the jaw movements during JT should be tested with any methodologies such as assessments with log files when the JT technique employs the treatment strategies. Fuangrod et al. reported on an algorithm that enables the independent measurement of jaw positions during dynamic IMRT and VMAT deliveries using electric portal imaging device (EPID) images, and found a method that detected the jaw position with an accuracy of ±1 mm of RMS error for static jaws and within ±1.5 mm of RMS error for dynamic jaws [29]. These findings suggested that the method could be implemented as a jaw QA tool for clinical IMRT and VMAT treatment. However, this requires many processes such as EPID scatter removal and histogram clustering to detect the jaw error, and the accuracy of error detection was declining owing to an occurrence of EPID and gantry sag during the gantry rotation in VMAT. We note that assessment of the jaw positional accuracy with log files should be recommended because this method does not affect the accuracy of jaw detection by geometric uncertainties such as EPID and gantry sag. On the other hand, Matsubayashi et al. investigated the influence of jaw position accuracy on dose variation in VMAT with the JT technique, and found that the maximum dose variations in the parotid gland were 0.179% and 1.23%, respectively, when jaw errors occurred at 1 mm and 10 mm in clinical oropharynx plans [30]. Following these results, the influence of dose variation owing to positional errors by the jaw would be negligible if users maintain the mechanical accuracy of the jaw correctly.

A limitation of our study was that it was quite difficult to discuss whether observed OAR dose reduction with JT technique would be clinically meaningful from the point of view of the radiation pneumonitis risk or not. Barriger et al. reported the thresholds of radiation pneumonitis [31], but observed values in this study were already lower than those values. In addition, the threshold value of the radiation pneumonitis risk may vary depending on patient's medical history and tumor characteristics. However, it was confirmed that the motion of the JT was accurately following the MLC movements and that the JT technique certainly contributed to the reduction of OAR doses in lung SBRT cases, though the rate of dose reduction was relatively small (Table 4). Moreover, our selected patients were limited to lung SBRT cases, that is, the sizes of the targets were smaller than those of other treatment sites. Therefore, the potential for OAR dose reduction using JT might be under- or overestimated owing to a limitation of the jaw movements. We assumed the dose reduction with JT in FFF beams for large targets such as head and neck cases would be smaller than for small targets because the peripheral dose of the FFF beams decreases as far from central axis. We should clarify the clinical advantages of the JT technique with FFF beams in other treatment sites, as well as the potential of $JTCS_{plan}$, and those must be future work.

5. Conclusions

The present study indicated that the dose reduction of the JT technique used in VMAT treatment with FFF beams in lung SBRT is statistically significant, though it is probably not clinically relevant. The study also proposed $JTCS_{plan}$, a novel metric to quantify jaw movements during JT, and indicates that the complexity of jaw movements did not correlate with that of the movements of the MLC leaves using the proposed metric. There were significant correlations between $JTCS_{plan}$ and the reduction rates of some dosimetric parameters of OARs, and the authors believe that $JTCS_{plan}$ is a useful as a quantitative parameter to evaluate the JT technique.

Declarations of interest

None.

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Conflict of interest

This study was conducted in the absence of any commercial or financial relationships.

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