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Technical note

Evaluation of the target dose coverage of stereotactic body radiotherapy for lung cancer using helical tomotherapy: A dynamic phantom study

Masahide Saito*, Hidekazu Suzuki, Naoki Sano, Kazunari Ashizawa, Kazuya Yoshizawa, Yuki Shibata, Koji Ueda, Takafumi Komiyama, Kan Marino, Shinichi Aoki, Ryo Saito, Yoshiyasu Maehata, Hiroshi Onishi

Department of Radiology, University of Yamanashi, Yamanashi, Japan

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ABSTRACT

Aim: To evaluate the target dose coverage for lung stereotactic body radiotherapy (SBRT) using helical tomotherapy (HT) with the internal tumor volume (ITV) margin settings adjusted according to the degree of tumor motion.
Background: Lung SBRT with HT may cause a dosimetric error when the target motion is large.
Materials and methods: Two lung SBRT plans were created using a tomotherapy planning station. Using these original plans, five plans with different ITV margins (4.0–20.0 mm for superior-inferior [SI] dimension) were generated. To evaluate the effects of respiratory motion on HT, an original dynamic motion phantom was developed. The respiratory wave of a healthy volunteer was used for dynamic motion as the typical tumor respiratory motion. Five patterns of motion amplitude that corresponded to five ITV margin sizes and three breathing cycles of 7, 14, and 28 breaths per minute were used. We evaluated the target dose change between a static delivery and a dynamic delivery with each motion pattern.
Results: The target dose difference increased as the tumor size decreased and as the tumor motion increased. Although a target dose difference of <5 % was observed at ≤10 mm of tumor motion for each condition, a maximum difference of -9.94 % ± 7.10 % was observed in cases of small tumors with 20 mm of tumor motion under slow respiration.
Conclusions: Minimizing respiratory movement is recommended as much as possible for lung SBRT with HT, especially for cases involving small tumors.

1. Introduction

Several previous clinical trials that used stereotactic body radiotherapy (SBRT) to treat non-small cell lung cancer (NSCLC) have demonstrated high local control with limited toxicity and outcomes comparable to surgery.[1,2] With regard to treatment techniques, most clinical studies traditionally assessed the effectiveness of 3-dimensional conformal radiotherapy (3DCRT), while intensity modulated radiation therapy (IMRT) and volumetric modulated arc therapy (VMAT) are still being refined. Although some reports show that VMAT and IMRT, including helical tomotherapy (HT), provide a better dose distribution than 3DCRT, which helps in sparing critical structures,[3,4] an interplay effect between respiration-induced tumor motion and multi-leaf collimator (MLC) motion may affect the accuracy of the VMAT dose prescription.[5–9] Furthermore, the accuracy of delivery using VMAT is affected not only through patient movement during treatment but also through MLC positioning errors and the limited accuracy of MLC modeling in the treatment planning system.[10] In short, the techniques of intensity modulation involving IMRT, VMAT, and HT have multiple layers of uncertainties in the treatment process when compared to the 3DCRT technique.

Weyh et al., showed that HT has a better dose distribution as compared to seven-field coplanar IMRT and two-arc coplanar RapidArc, reducing maximum rib dose, as well as improving dose conformity and uniformity.[11] However, another major issue remains; there are no motion management systems currently available. Therefore, many institutions use a delivery technique that involves free breathing, abdominal pressure,[12] and shallow

* Corresponding author at: Department of Radiology, University of Yamanashi, 1110 Shimokato, Chuo-city, Yamanashi, 409-3898, Japan.
E-mail address: masahides@yamanashi.ac.jp (M. Saito).

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breaths[13] to treat the thoracic region. Furthermore, a treatment planner needs to pay attention to physical planning parameters, such as the modulation factor (MF), which is defined as the longest leaf opening time divided by the average of all non-zero leaf opening times[14] and the jaw size (a large jaw size is more robust than a small one because the penumbra region is compensated by the target dose (15)). However, two studies have shown uncertainties in relation to SBRT using an HT machine for lung cancer.[12,15]

To characterize SBRT in the treatment of lung cancer using an HT machine, we evaluated the target dose coverage using an original dynamic motion phantom with the internal target volume (ITV) margin settings adjusted according to the degree of tumor motion.

2. Materials and methods

2.1. Treatment plan

Two treatment plans of NSCLC patients who were treated with Elekta Synergy (Elekta AB, Stockholm, Sweden) were retrospectively used. All treatments were performed by a breath-holding technique using Abches, which is a respiratory indicator used for respiratory motion management.[16,17] For the planning CT, the settings for image acquisition were 120 kV of the tube voltage and 250 mA of the tube current with a slice thickness of 2.0 mm. The clinical target volume (CTV) was defined as the gross tumor volume (GTV), and the planning target volume (PTV) margin was 3 mm in all directions. Case 1 had a CTV of 3.8 cm in diameter and case 2 had a CTV of 1.8 cm in diameter.

In this study, from the two original plans, five plans with different ITV margins (4.0, 6.0, 8.0, 10.0, and 20.0 mm for superior dimension) were generated. Then, we modified these plans for the HT plan with TomoHD (Accuray, Sunnyvale, CA). First, all contours and CT images from the original plans were transferred into the Tomotherapy Planning Station ver. 5.1.0.2. (Accuray, Sunnyvale, CA). Then, plans for HT were created from each original plan with a dynamic jaw mode using a modulation factor (MF) of 2.0 and 1.8 for case 1 and case 2, respectively. The MF is used during the optimization process and is defined as the relation of the maximum leaf opening time to the average leaf opening time, but only the times greater than zero are averaged, reducing its value results in shortening the duration of daily treatments. However, this may adversely affect the dose distribution. Further details about the MF were mentioned in some previous studies.[18,19] Furthermore, other factors of treatment planning were also tuned because there are some constraints to perform SBRT in HT.[20] For each plan, a field width (FW) of 2.51 cm and a pitch factor (PF) of 0.143 cm were used. Although the size of FW was conventionally used in our institute, the PF was smaller than the clinical condition (the default value was 0.287 cm)

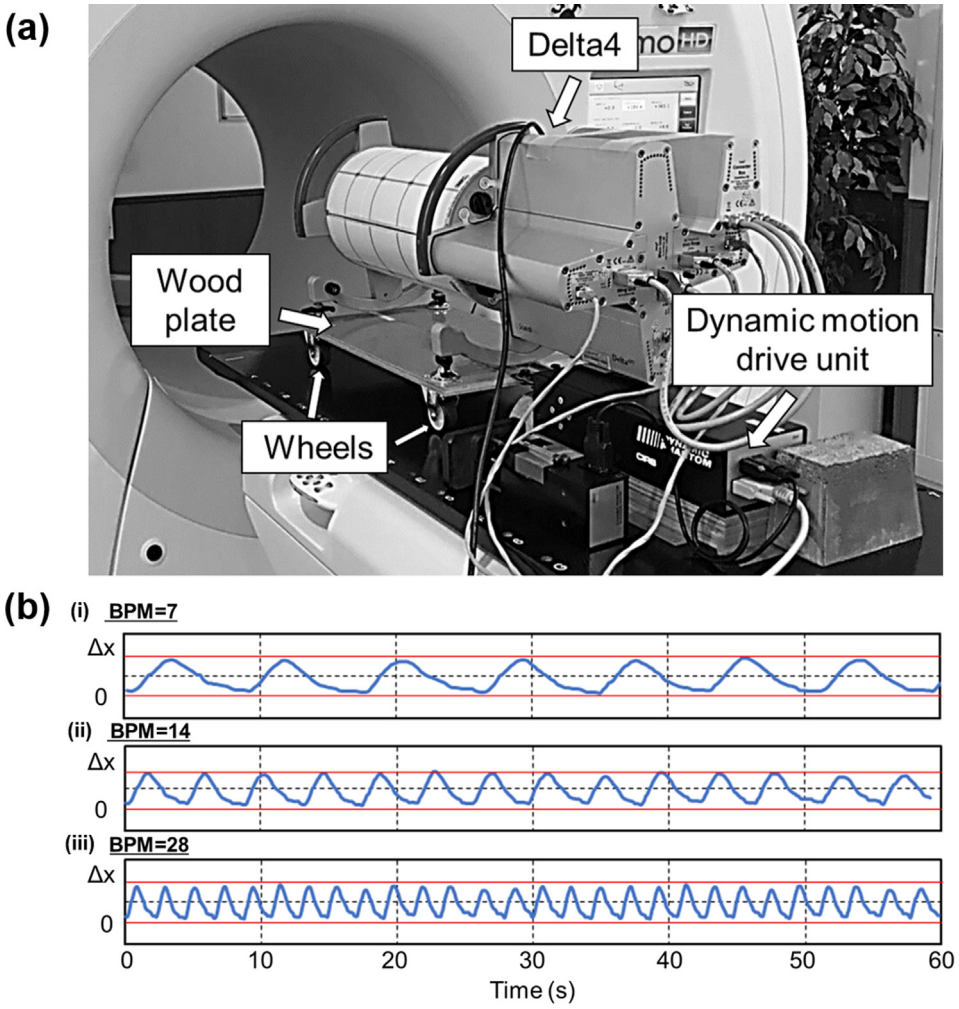

Fig. 1. An original dynamic motion phantom (a) comprised a Delta4 detector, a wood plate to support the detector, four wheels to move the wood plate with Delta4, and a dynamic motion drive unit modified from a Dynamic Thoracic Phantom. The phantom was moved by human respiratory waves shown in (b). The blue line shows the respiratory waves, and the red line shows upper and lower (zero) lines. The ΔX refers to the amplitude (mm) of each respiratory motion. Three patterns of breathing speed were used: (i) 7, (ii) 14, and (iii) 28 breaths per minute (BPM).

to deliver high dose within the specs of the HT machine. The dose calculation grid size was set as "fine" for all cases. Dose prescription was 55 Gy/4 Fr to cover 95 % of the PTV, and dose constraints on organs at risk corresponded with those stated in the Japan Clinical Oncology Group Study JCOG1408 (J-SBRT trial).[21]

2.2. Respiratory motion dosimetry with dynamic motion phantom

To evaluate the respiratory motion effects on HT, an original dynamic motion phantom was developed, as shown in Fig. 1(a). The phantom consisted of a Delta4 detector (ScandiDos, Uppsala, Sweden), a dynamic motion drive unit that was modified from a Dynamic Thoracic Phantom (CIRS, Virginia, USA), a wood plate to support Delta4, and four wheels to move the wood plate with Delta4. Our system only allowed for superior-inferior (SI) motion; however, the latest HexaMotion platform (ScandiDos, Uppsala, Sweden) allows for 6-dimensional (6-D) motion.[22] As a measure of typical respiratory motion, the respiratory wave of a healthy volunteer acquired from Abches was used. Five patterns of the motion amplitude that corresponded to five ITV margin sizes and three breathing cycles of 7, 14, and 28 breaths per minute (BPM) were used, as shown in Fig. 1(b).

2.3. Dose profile and dose volume histogram analysis

The target dose changes between static and dynamic deliveries with the same motion for each ITV plan were evaluated. All phantom setups were the same for both static and dynamic deliveries, but the latter were performed with three different BPM values. Furthermore, to evaluate the variation of dose changes during treatment fractions, the dynamic delivery was repeated four times for all conditions. In total, 120 measurements of the dynamic delivery (2 cases × 5 amplitudes × 3 BPM × 4 repetitions) were performed in this study.

The change in GTV dose ($D_{98\,\%}$, $D_{50\,\%}$, and $D_{2\,\%}$) calculated from a dose volume histogram (DVH) was evaluated. The DVH was reconstructed from Delta4 measurement data using Delta4 software. Furthermore, global gamma analysis was performed between the static and dynamic deliveries with a criterion of 3 %/3 mm (10 % low dose threshold [TH]).

3. Results

For the treatment parameters of case 1, average values for the gantry period, couch speed, couch travel, and duration were 43.1 ± 3.3 s, 0.008 ± 0.001 cm/s, 7.1 ± 0.6 cm, and 855.0 ± 31.7 s, respectively. For those of case 2, in the same manner, the average values were 33.3 ± 3.6 s, 0.011 ± 0.001 cm/s, 5.6 ± 0.6 cm, and 513.5 ± 44.9 s, respectively.

Fig. 2 shows the SI dose profile comparisons between static and dynamic deliveries for small and large tumor motion (4 mm and 20 mm in the SI direction). For cases 1 and 2, the dose profiles of the dynamic deliveries were negatively shifted in relation to the static deliveries and the gradient of the penumbra region increased, although there were no differences between the three breathing cycles. Comparing cases 1 and 2, the latter had a larger difference in the tumor region.

Fig. 3 shows the gamma passing rate (3 %/3 mm, TH = 10 %) between the static and dynamic deliveries for each tumor motion. The gamma passing rate of the large tumor was better than that of the small tumor, and it decreased as the tumor motion increased for each case.

Fig. 4 shows the fractional average DVH of the GTV for small and large tumor motion. The dose difference between static and dynamic deliveries was larger as the tumor motion increased. All dose indices of GTV are summarized in Table 1. For each condition, $D_{98\,\%}$ was more affected than the others (the greatest difference was −9.94% ± 7.10% in case 2 with 20 mm tumor motion under 7 BPM). However, a difference of <5 % was observed with tumor motion of ≤10 mm for each condition.

4. Discussion

Radiotherapy techniques for lung SBRT are continuously diversifying as new concepts and techniques are developed. Planning

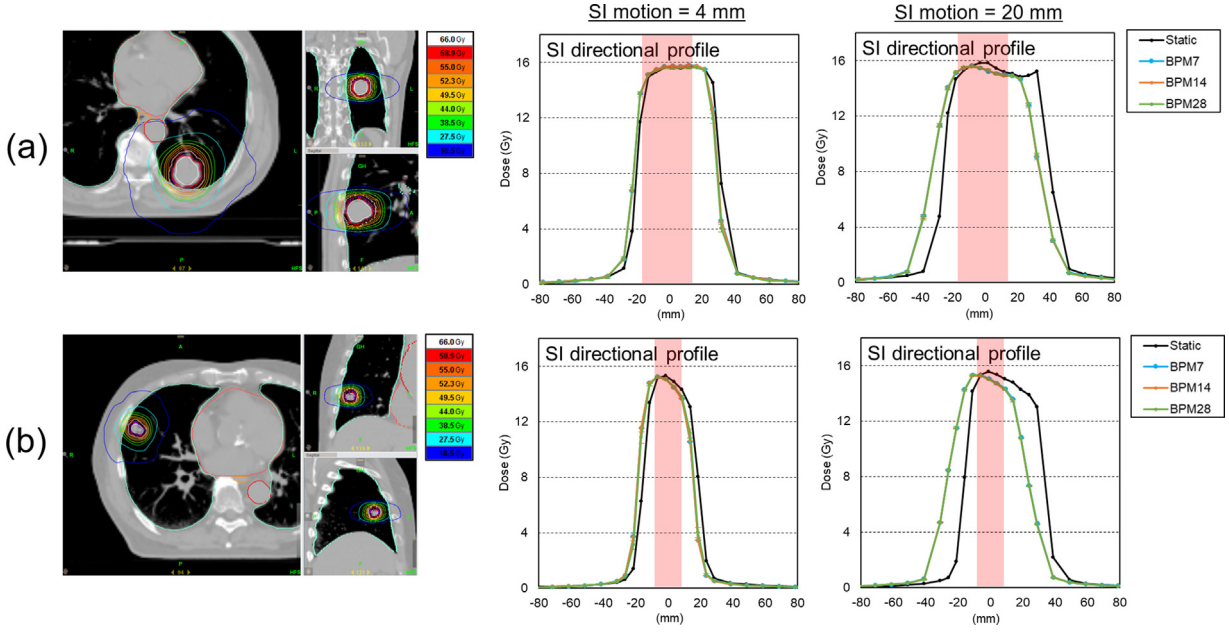

Fig. 2. The original two treatment plans (left figure) and delivered superior-inferior (SI) dose profiles (right figure). (a) shows case 1 in which the tumor diameter was 3.8 cm, and (b) shows case 2 in which the tumor diameter was 1.8 cm. SI dose profile comparisons between static and dynamic deliveries for all BPMs are shown as the four times average values for small tumor motion (4 mm) and large tumor motion (20 mm), respectively. The central red region in each figure indicates the tumor position.

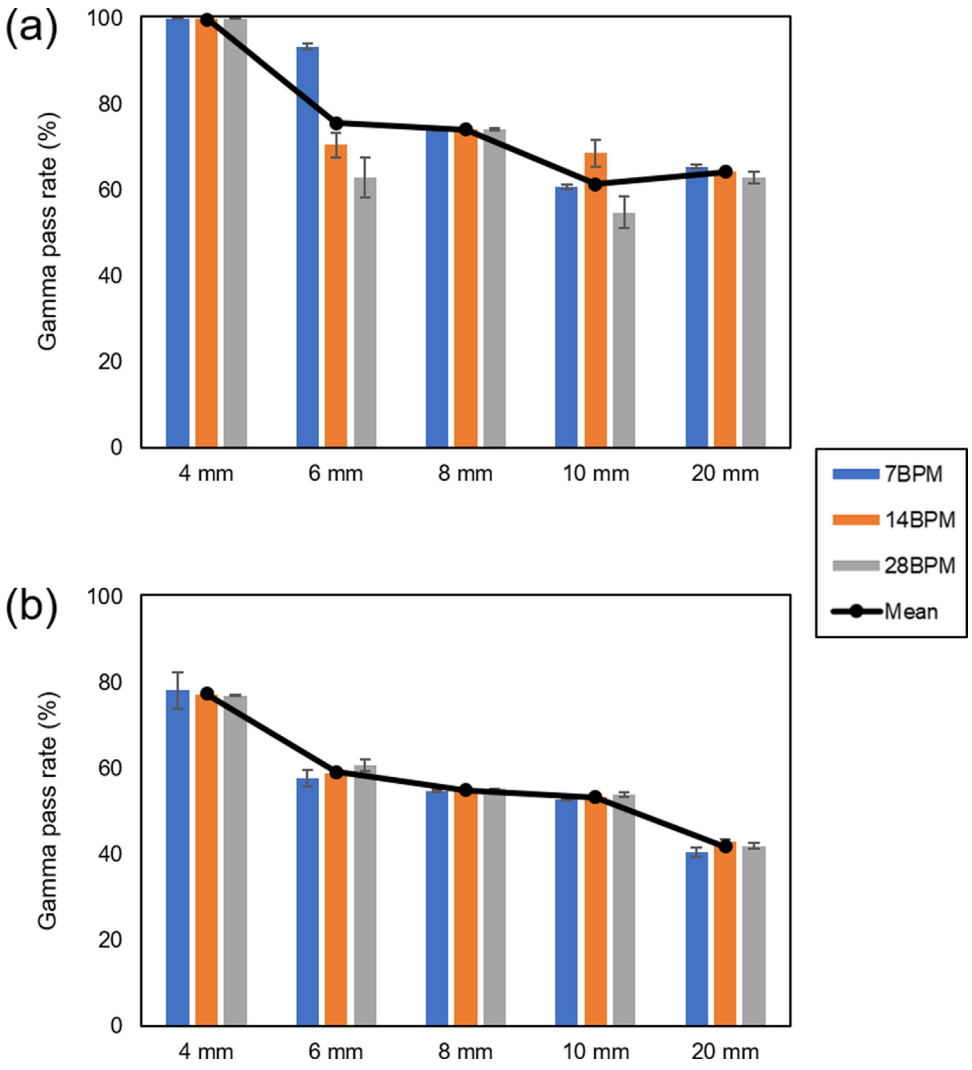

Fig. 3. Gamma passing rate (3 %/3 mm, 10 % threshold) between static and dynamic deliveries for each tumor motion. (a) Case 1 and (b) case 2. Three bars of breathing speed are shown as the four times average value and deviation value in each graph, and the mean value of them is also shown as a polyline.

Table 1
GTV ($D_{98\,\%}$, $D_{50\,\%}$, and $D_{2\,\%}$) changes between static and dynamic deliveries for each tumor motion and breathing speed.

		GTV dose change between static and dynamic deliveries [%]					
		Case 1 ($\varphi = 3.8$ cm)			Case 2 ($\varphi = 1.8$ cm)		
Tumor motion [mm]	Breathing speed [BPM]	GTV $D_{98\,\%}$	GTV $D_{50\,\%}$	GTV $D_{2\,\%}$	GTV $D_{98\,\%}$	GTV $D_{50\,\%}$	GTV $D_{2\,\%}$
4	7	−0.58 ± 0.69	−0.61 ± 0.35	−0.93 ± 0.42	−1.97 ± 2.71	−1.22 ± 0.95	−0.39 ± 0.28
	14	−0.47 ± 0.00	−0.41 ± 0.00	−0.37 ± 0.00	−0.77 ± 0.36	−1.02 ± 0.20	−0.19 ± 0.19
	28	−0.47 ± 0.00	−0.41 ± 0.00	−0.19 ± 0.19	−0.44 ± 0.82	−0.71 ± 0.18	−0.10 ± 0.17
6	7	0.33 ± 0.19	0.40 ± 0.28	0.37 ± 0.00	−3.71 ± 1.58	−3.14 ± 2.74	−1.19 ± 0.65
	14	−0.78 ± 1.24	−0.70 ± 1.11	−0.55 ± 0.92	−2.48 ± 2.04	−2.51 ± 3.15	−0.92 ± 0.55
	28	−0.78 ± 1.11	−0.20 ± 0.60	0.18 ± 0.32	−0.74 ± 0.74	0.00 ± 0.51	−0.46 ± 0.16
8	7	3.77 ± 0.38	1.12 ± 0.18	0.09 ± 0.16	−1.16 ± 0.52	−1.96 ± 0.54	−1.74 ± 0.30
	14	2.40 ± 0.88	0.51 ± 0.34	0.00 ± 0.27	−1.63 ± 0.23	−2.07 ± 0.29	−1.65 ± 0.18
	28	2.97 ± 0.51	0.31 ± 0.34	−0.38 ± 0.00	−2.33 ± 0.57	−2.58 ± 0.68	−2.11 ± 0.91
10	7	−0.47 ± 0.20	−0.53 ± 0.00	−0.41 ± 0.16	−1.25 ± 0.25	−0.11 ± 0.38	−0.98 ± 0.20
	14	−0.11 ± 0.00	0.27 ± 0.45	0.20 ± 0.27	4.13 ± 8.59	4.66 ± 6.57	0.20 ± 1.72
	28	−0.52 ± 0.32	−0.22 ± 0.18	0.22 ± 0.26	−0.50 ± 2.03	0.80 ± 2.46	−0.59 ± 1.06
20	7	−2.59 ± 0.53	−1.80 ± 0.35	−0.74 ± 0.31	−9.94 ± 7.10	−7.51 ± 4.63	−3.18 ± 1.73
	14	−3.17 ± 0.88	−1.91 ± 0.43	−1.93 ± 0.00	−3.90 ± 5.48	−3.31 ± 2.92	−2.00 ± 0.47
	28	−1.40 ± 0.36	−1.10 ± 0.17	−0.84 ± 0.31	−3.39 ± 5.04	−2.64 ± 2.80	−1.73 ± 0.45

BPM, breaths per minute; GTV, gross tumor volume.

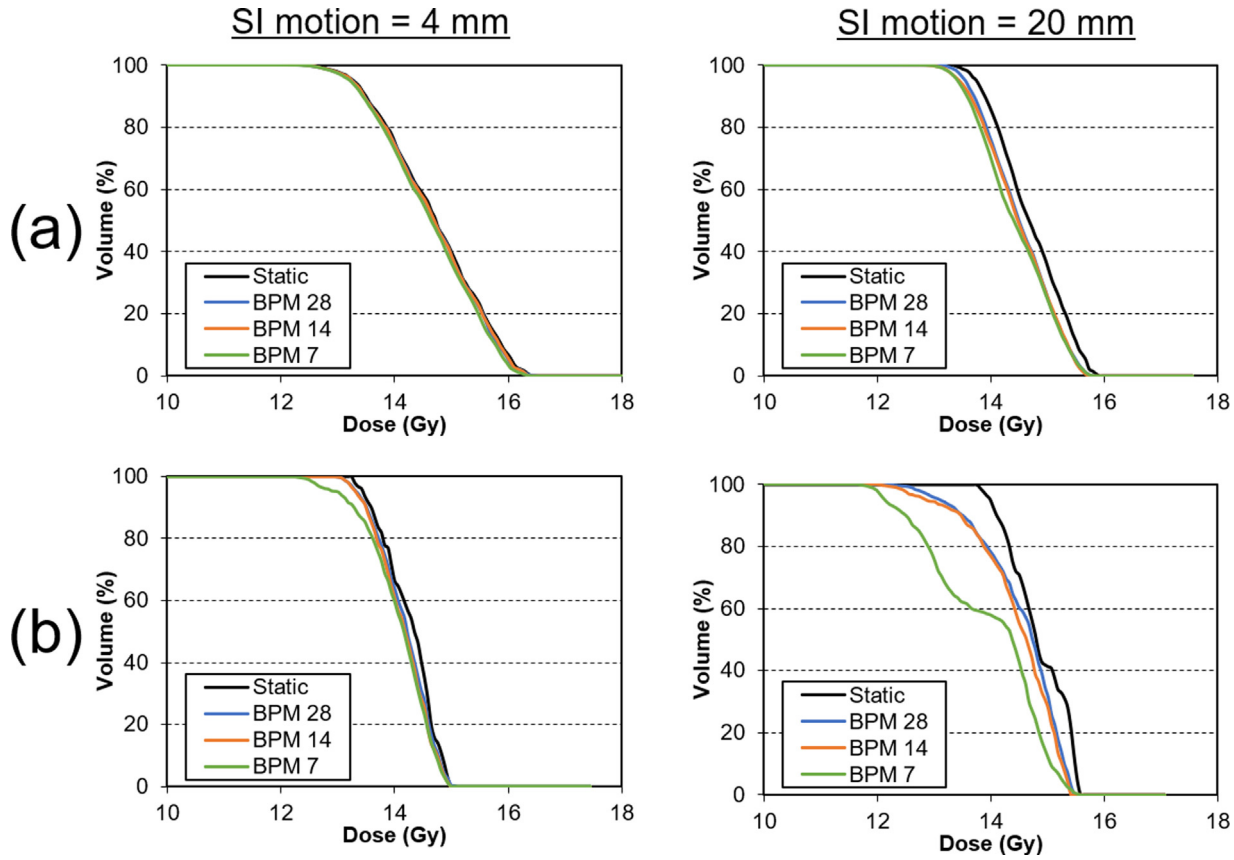

Fig. 4. Dose volume histogram (DVH) of gross tumor volume (GTV) for case 1 (a) and case 2 (b). Each curve is shown as four times average value. The magnitudes of superior-inferior (SI) tumor motion are 4 mm and 20 mm for left and right figure, respectively. The dose difference between static and dynamic deliveries became larger as the tumor motion increased.

studies comparing various techniques have resulted in IMRT techniques, including VMAT and HT, that can spare lungs and other organs at risk with reasonable treatment time.[11,23,24] However, some studies have shown uncertainties concerning SBRT when using an HT machine for lung cancer. Kanagaki et al. performed film dosimetry under static and moving conditions using HT[15] and showed that owing to the size of the penumbra, the 2.47 cm jaw plans provided an adequate coverage for smaller amplitudes of motion. They concluded that HT is a safe technique for the treatment of a moving target. However, they did not evaluate this under real clinical conditions using ITV margins according to the tumor motion. Moreover, they used a 2D DVH created from film measurements to evaluate the dosimetric effect of the target's motion, which is considered insufficient to evaluate error under moving conditions. Therefore, we evaluated the target dose coverage using ITV margins according to the tumor motion for lung SBRT with HT delivery using a DVH obtained from 3D measurements.

A previous study reported that the disagreement between planned and delivered doses could be neglected for maximal amplitudes below 4 mm, while the amplitudes above 5 mm and 7 mm lead to significant changes in IMRT and 3DCRT dose distribution, respectively.[25] Although it is difficult to compare our results with theirs because of the difference of the phantom, detector, and motion modeling, their results were similar to our study. Namely, the condition with 4 mm of motion showed better agreement between static and dynamic doses than conditions with larger motions. However, if the target volume was smaller, the agreement was worse. Therefore, especially for small tumor volumes, we recommend that tumor motion should be limited as much as possible for lung SBRT using currently available HT.

One of the limitations in this study was that the dynamic simulation was performed in one direction (SI direction only). Some previous clinical studies have shown that lung tumors move in three dimensions. One of the limitations in this study was that the dynamic simulation was performed in one direction (SI direction only). Some previous clinical studies have shown that lung tumors move in three dimensions.[26–28] The reason for selecting only the SI direction in this study was that movement in this direction was likely to be larger than that in the other directions,[29] making our result easier to interpret. However, focusing on three-dimensional motion would be more ideal for a dynamic phantom study, so further research is needed using e.g. the latest 6D motion phantom.[22] The other limitation was that the phantom was homogeneous while lung cancer in real patients would include inhomogeneous regions. In the future, these dose effects should be evaluated using a heterogeneous phantom. In addition, the uncertainty of 3D dose reconstruction using Delta4 software was not evaluated sufficiently, and its accuracy needs to be evaluated in the future. Finally, we only reported on two cases and three breathing patterns. More cases, including non-SBRT cases, should be evaluated with various respiratory patterns such as baseline shift, drift, and breath-holding in future studies.

In our study, we evaluated the target dose coverage under respiratory motion for an older HT system. However, tumor tracking systems have recently been introduced on new HT systems.[30,31] Therefore, the agreement between the static and dynamic delivered dose could be improved over our current result by using these newer systems, so further studies are warranted.

5. Conclusions

We evaluated the target dose coverage of lung SBRT via HT using a dynamic motion phantom. We found that the target dose difference increased as tumor motion increased, while a target dose difference of <5 % was observed with a tumor motion of ≤10 mm for each condition. We recommend minimizing respiratory movement as much as possible for lung SBRT via HT, particularly in cases of small tumors.

Conflict of interest

None declared.

Financial disclosure

None declared.

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