Double CT imaging can measure the respiratory movement of small pulmonary tumors during stereotactic ablative radiotherapy

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ABSTRACT

Purpose: The purpose of this study was to investigate the application of double CT imaging to measuring the respiratory movement of small pulmonary tumors during stereotactic ablative radiotherapy (SABR).

Methods: A total of 122 small pulmonary tumors were measured in 45 patients. CT scans were conducted twice in all 122 tumors, once at the end of quiet inhalation and once at the end of exhalation. CT scans were conducted three times including at the end of quiet inhalation, at the end of exhalation and at free breathing in 36 tumors of 17 patients. The displacement of the tumor center in three directions was measured.

Results: The 3D motion of 122 tumors was 10.10±7.16 mm. On average, the tumors moved 1.96±2.03 mm (rang, 0-9 mm) in the X direction, 5.19±4.69 mm (rang, 0-19 mm) in the Y direction, and 7.38±6.48 mm (rang, 0-26 mm) in the Z direction. The 3D motion of tumors in the lower lung (13.00±7.64 mm) was significantly greater than that in the upper lung (7.15±5.14 mm), P<0.01. The 3D motion of the lower left lung was 16.35±7.31 mm, which was significantly greater than that of the lower right lung (11.40±7.04 mm), P<0.05. Movement in the anterior lung in the Y direction was significantly larger than in the posterior lung. The motion was 7.49±5.43 mm and 4.04±3.82 mm respectively, P<0.01.

Conclusions: Double CT imaging provides accurate data for determining the outline of each target area during stereotactic ablative radiotherapy plane. The location of small pulmonary tumor foci was significantly affected by respiratory and cardiac motion.

KEY WORDS Double CT scan; Small pulmonary tumors; Respiratory movement; Stereotactic ablative radiotherapy

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Introduction

In recent years, the stereotactic ablative radiotherapy (SABR) or stereotactic body radiotherapy (SBRT) has been widely used in cancer treatment, which has achieved good results in patients with lung cancer (1-5). Senan *et al.* reviewed recent advances and controversies of SABR for stage I non-small cell lung cancer (NSCLC) (2). In order to avoid missing the target and overdosing surrounding critical structures, image guidance (particularly volumetric image guidance) for each treatment and motion management in cases with tumor motion greater than 1 cm are highly recommended (3). SABR allows treatment with increased irradiation doses to the site of the primary tumor by optimal lung sparing using modern radiotherapy technologies such as breathing motion compensation and image-guidance (4). Respiratory movement has been an important consideration for the delineating the targeted lung cancer area, especially in SABR treatment of small pulmonary tumors. The ICRU62 report separated the changes of the tumor target area due to the movement from planning target volume (PTV) and proposed

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the concept of internal target volume (ITV) (6). There are several ways to measure respiratory movement, including cone-beam computed tomography (CBCT) (7,8), electronic portal imaging device (EPID) (9), gold point tracking method (10,11), dynamic nuclear magnetic resonance (12), six-CT scan (13), and 4D-CT method (14-16). Measurement of respiratory movement based on all of these methods has resulted in a similar conclusion that within a given set of data from one patient, the respiratory movement is larger in the lower lung than in the upper lung. Heart movement also affects respiratory movement. Among the methods mentioned above, some involve many steps, are tedious to perform, and expose patients to high levels of radiation (7,8). Some methods are time-consuming (14-16). Other method such as gold point tracking is an invasive procedure, which has the risk of causing pneumothorax and is not suitable for the elderly or patients with poor lung function (10,11). Based on the above consideration, the purpose of this study was to investigate the application of double CT imaging to measuring the respiratory movement of small pulmonary tumors during SABR treatment, in order to find a convenient and simple way to provide an accurate reference to delineate the target area.

Materials and methods

Patients receiving SABR treatment for lung disease in our institute between December 2009 and October 2010 were included in the current study. The 4-slice spiral CT from Siemens Company, Germany was used for scanning. During scanning, the patient was in a supine position with both hands holding the head. The body was fixed and scanned from the neck to the liver. The layer thickness was 2.5 mm, and the scan time was 10-15 seconds. Patients were trained to do regular and quiet breathing before CT scanning. Prior to scanning, each patient was instructed through the microphone to maintain quiet breathing and to hold their breath at the end of quiet inhalation and at the end of exhalation so that CT scanning could be performed during the inhalation and exhalation processes. Additionally, 17 patients received CT scanning during free breathing. CT images were transferred to the planning system, and the corresponding markers were calibrated. The positions of the tumor centers were measured at the end of both inhalation and exhalation, and during free breathing; the size of each tumor was measured by CT at the end of quiet inhalation; and the target area was outlined.

The center position of each tumor was measured at the end of inhalation. f_{SI} in the head-leg (superior-inferior, SI) Z direction was defined as the ratio of the distance from the lung tip to the tumor center to the lung height on the same side; the larger the ratio, the closer the tumor to the bottom of the lung. A ratio ≤0.5 indicated the tumor was in the upper lung and >0.5 in the lower lung; f_{LR} in the left-right (LR) X direction was defined on the horizontal axis as the ratio of the distance from the upper body midline to the tumor center to the distance from the body midline to the inner thoracic wall; the larger the ratio, the closer the tumor was to the lung edge. A ratio ≤0.5 indicated that the tumor was closer to the midline and >0.5 closer to the left or the right border of the lung. f_{AP} in the anterior-posterior (AP) Y direction was defined on the vertical axis as the ratio of the distance from the anterior thoracic wall to the tumor center to the distance from the anterior thoracic wall to the posterior thoracic wall; the larger the ratio, the closer the tumor was to the anterior thoracic wall. A ratio ≤0.5 corresponded to the anterior portion of the lung, while a ratio >0.5 corresponded to the posterior portion of lung. The free breathing position was defined as the ratio of the total distanced moved during quiet inhalation in the Z direction. A value of 0 indicated the same position as the end of inhalation, 1 the same position as the end of exhalation, and 0.5 the middle position between the end exhalation position and the end inhalation position. The respiratory movement in the X, Y, and Z directions, calculated as the 3D motion (total movement) $D^2=X^2+Y^2+Z^2$.

Statistical analysis

SPSS10.0 software was used for the statistical analysis. The relationships between respiratory movement and the tumor position, between respiratory movement and factors such as tumor size, age, and gender, and between free breathing and the end inhalation and exhalation positions were examined. The t test was performed to compare the differences between the groups. Multiple linear regressions were conducted to analyze the impact of various factors on respiratory movement.

Results

General clinical data are shown in Table 1. Pathology, staging and treatment are shown in Table 2. All of the tumors were lung cancers or lung metastases. Nine cases were at stage I NSCLC, 1 case was at stage II who had not received medical treatment due to old age, 1 case was at stage III who had not received medical treatment due to myocardial infarction, and 2 cases had not received medical treatment due to adenoid cystic carcinoma. The other patients had received medical treatment before the SABR treatment. Of the 45 patients, 24 patients had one tumor, 7 patients with two tumors, 2 patients with three tumors, 4 patients with four tumors, 2 patients with five tumors, 1 patient with six tumors, 1 patient with seven tumors, 2 patients with eight tumors, 1 patient with nine tumors, and 1 patient with fourteen tumors. The range of the maximum tumor diameter was 4.3-50.0 mm, the median was 10.1 mm, and the average was 16.90±12.90 mm; there were 60 tumors with diameters in the range of 4.3-10 mm, 27 tumors in the range of 10.1-20 mm,

Table 1. General description of the patients and tumors.

	No. of cases (45)	No. of Tumors (122)
Gender		
Male	29	77
Female	16	45
Age		
Median (range)	59 (11-85)	54 (11-85)
<65	30	99
≥65	15	23

Table 2. The pathology, staging, and treatment of 45 patients.

Pathology	TNM Stage	No. of cases	Without medical treatment	One line cases	Two lines cases	Three lines and above
NSCLC	I	9	9	-	-	-
	IIB	2	1*	1	-	-
	IIIA	1	1#	-	-	-
	IV	10	-	7	2	1
SCLC	Localized	2	-	2	-	-
Colorectal cancer	IV	4	-	1	1	2
Hepatic carcinoma	IV	4	-	2	2	-
Breast cancer	IV	2	-	1	-	1
Adenoid cystic carcinoma	IV	2	2	-	-	-
Sarcoma	IV	2	-	2	-	-
Laryngeal	IV	1	-	1	-	-
Renal cancer	IV	1	-	1	-	-
Neurofibromatosis	IV	2	-	2	-	-
Endometrial cancer	IV	1	-	1	-	-
Bladder cancer	IV	1	-	1	-	-
Thyroid cancer	IV	1	-	1	-	-

NSCLC, non-small cell lung cancer; SCLC, small cell lung cancer; *81-year-old; #myocardial infarction.

17 tumors in the range of 20.1-30 mm, and 18 tumors in the range of 30.1-50 mm. The tumor volume ranged from 44.1 to 93, 744.5 mm^3. The median was 922.6 mm^3. A total of 27 tumors were located in the left upper lung, 20 were in the left lower lung, 34 were in the right upper lung, and 42 were in the right lower lung.

The respiratory movement for all 122 tumors in all directions and the single-factor analysis of the total respiratory movement are shown in Table 3. The tumors moved 1.96±2.03 mm (rang, 0-9 mm) in the X direction, 5.19±4.69 mm (rang, 0-19 mm) in the Y direction, and 7.38±6.48 mm (rang, 0-26 mm) in the Z direction. The greater the position in the Z direction, the closer a tumor was to the lower lung. The position in the Z direction was related to the total movement in the Z direction (Figure 1,2). Movement and total movement in both left and right lower lungs in the Z direction were significantly greater than the movement in both upper lungs ($P<0.001$). The movement and total movement in the left lower lung in the Y direction were significantly larger than in the right lower lung, which may be related to the heart beats ($P<0.001$ and $P=0.017$, respectively). Movement in the anterior lung in the Y direction was significantly larger than in the posterior lung ($P<0.001$). In addition, Y, Z, D movements in patients under 65 years of age were significantly greater than in patients over 65 years of age ($P=0.015$, $P=0.035$, $P=0.017$, respectively); the movement in the X direction of tumors with a diameter less than or equal to 20 mm was greater than tumors larger than 20 mm in diameter ($P=0.046$).

Table 3. Average movement of 122 tumors [mean±standard deviation (mm)].

Factor (no.)	X	T value	P value	Y	T value	P value	Z	T value	P value	D	T value	P value
All (122)	1.96±2.03			5.19±4.69			7.38±6.48			10.10±7.16		
Lower lung (62)	1.90±1.95	0.309	0.758	5.84±4.99	1.562	0.121	10.62±6.94	6.451	<0.001	13.00±7.64	4.952	<0.001
Left lung (46)	2.04±2.16			5.34±4.61			8.44±6.30			11.01±7.28		
Right lung (76)	1.91±1.95	0.357	0.722	5.09±4.77	0.284	0.777	6.73±6.70	1.424	0.157	9.53±7.07	1.11	0.267
Upper left (26)	2.11±2.59			5.11±4.83			4.24±4.21			7.78±5.94		
Upper right (34)	1.94±1.61	0.313	0.756	4.06±3.69	0.958	0.342	3.97±3.29	0.279	0.781	6.64±4.36	0.861	0.393
Lower left (20)	2.50±2.52			8.85±6.31			12.25±7.31			16.35±7.31		
Lower right (42)	1.62±1.59	1.667	0.101	4.40±3.53	3.544	<0.001	9.85±6.76	1.272	0.208	11.40±7.04	2.461	0.017
Anterior (40)	2.22±2.10			7.49±5.43			7.07±5.46			11.32±6.80		
Posterior (82)	1.83±1.99	1.007	0.316	4.04±3.82	4.085	<0.001	7.54±6.96	0.373	0.710	9.49±7.30	1.339	0.183
Inside (47)	1.72±1.81			4.30±4.14			7.18±7.02			9.31±7.49		
Outside (75)	2.11±2.14	1.016	0.312	5.74±4.93	1.664	0.099	7.51±6.12	0.270	0.788	10.59±6.50	0.963	0.388
Male (77)	1.83±2.10			4.85±4.35			7.06±6.15			9.64±6.15		
Female (45)	2.22±1.89	1.029	0.306	5.82±5.25	1.094	0.276	8.08±7.04	0.873	0.404	11.05±7.89	1.052	0.295
<65 (99)	1.97±2.12			5.71±4.87			8.03±6.87			10.90±7.58		
≥65 (23)	2.00±1.60	0.064	0.949	3.09±3.16	2.456	0.015	4.87±3.49	2.138	0.035	6.98±3.57	2.418	0.017
≤20 mm (87)	2.21±2.21			5.49±5.05			7.80±6.81			10.77±7.51		
>20 mm (35)	1.40±1.35	2.014	0.046	4.51±3.68	1.041	0.300	6.51±5.56	0.994	0.322	8.65±6.00	1.490	0.139

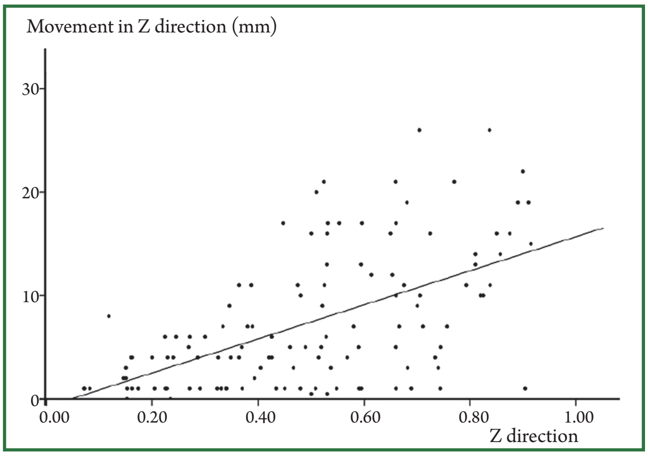

Figure 1. The effect of Z direction position on movement in Z direction.

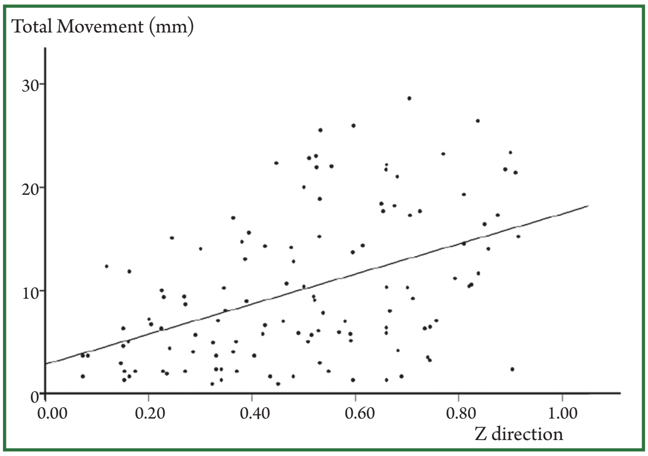

Figure 2. The effect of Z direction position on total movement.

The largest respiratory movement of some tumors occurred in other directions though most tumors occurred in Z direction. For 20 out of 122 tumors, the largest respiratory movement occurred in two or more directions. Of the remaining 102 tumors, 59.8% (61/102) underwent movement in the Z direction 11.16±6.38 mm (rang, 1-26 mm); 30.4% (31/102) in the Y direction 8.58±5.42 mm (rang, 2-19 mm); and 9.8% (10/102) in the X direction 3.50±2.01 mm (rang, 2-8 mm) (Figure 3,4).

The multi-factor analysis of all directions and the total movement are shown in Table 4. Impact factors include age, location (the right or the left side of the lower lung), tumor size, and the Y and Z direction positions. There was no effect of age on respiratory movement. Tumor size had an effect in the movement in X direction (the smaller the tumor, the larger the movement in X direction, P=0.015) but had no significant effect on total movement (P=0.107); movement and total movement of tumors in the left lower lung in Y direction were significantly greater than in the right lower lung (P=0.021). The position in the Y direction had a significant effect on Y direction

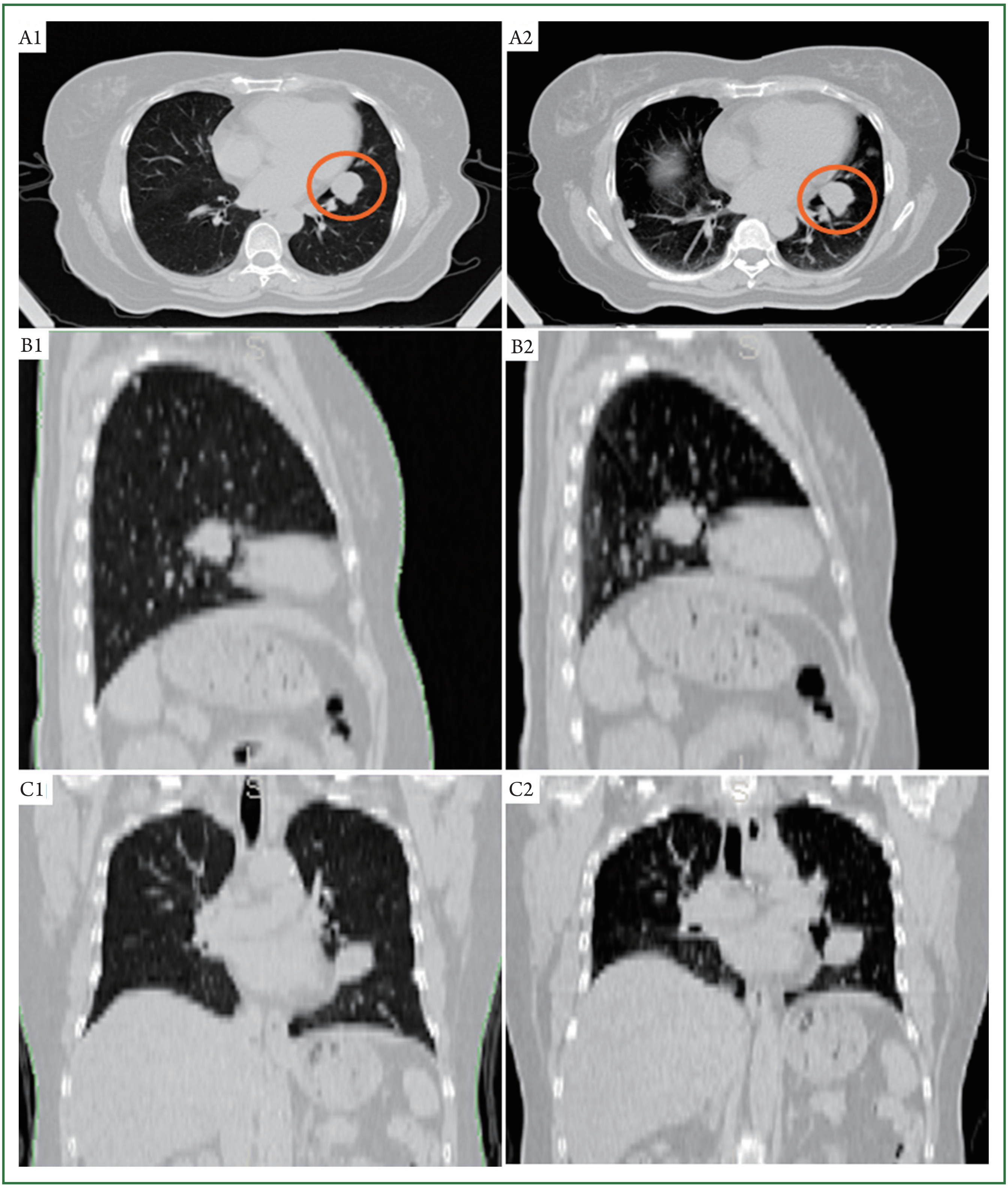

Figure 3. For a tumor in the lower left lung, the movement was 2 mm in the X direction, 14 mm in the Y direction, and 17 mm in the Z direction.

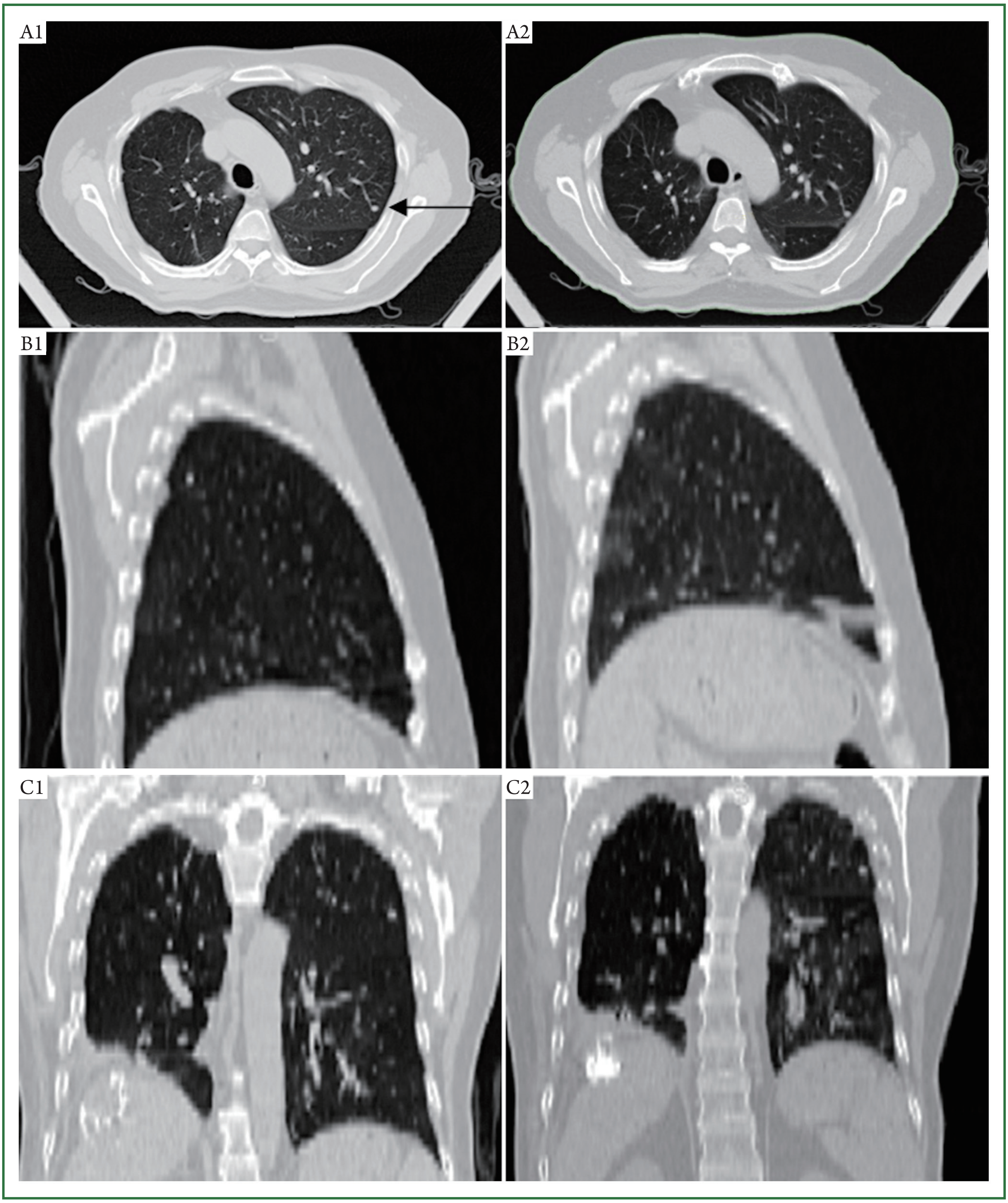

Figure 4. For a tumor in the upper left lung, the movement was 8 mm in the X direction, 12 mm in the Y direction, and 6 mm in the Z-direction.

Table 4. Multivariate analysis of all directions and total respiratory movement.

Factors	X direction		Y direction		Z direction		Total movement D	
	F	Sig.	F	Sig.	F	Sig.	F	Sig.
Age	0.013	0.908	0.714	0.400	1.993	0.161	1.883	0.173
Diameter	6.038	0.015	1.643	0.202	1.021	0.314	2.635	0.107
Left and right lower lung	1.850	0.176	5.438	0.021	1.538	0.217	4.048	0.047
Y position	1.143	0.287	18.856	<0.001	0.102	0.750	4.223	0.042
Z position	2.322	0.130	0.165	0.685	16.824	<0.001	5.896	0.017

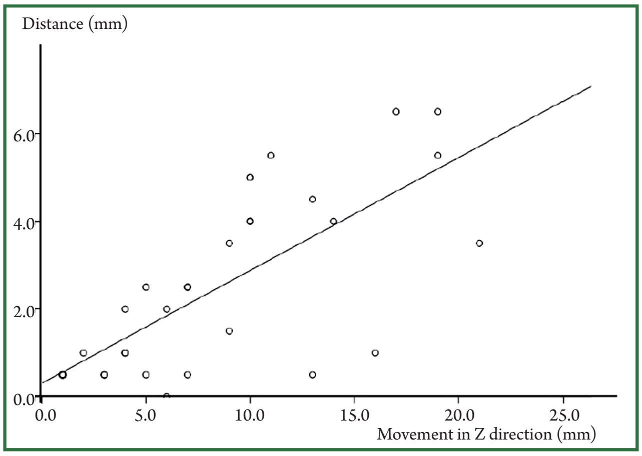

Figure 5. Relationship between the distance of the tumor position from the center in the Z direction and respiratory movement during free breathing.

and total movement (P<0.001 and P=0.042, respectively). The position of Z direction had a significant effect on movement in the Z direction and total movement (P<0.001 and P=0.017, respectively).

The positions of 36 tumors were measured during free breathing. The position and respiratory movement in the Z direction during free breathing deviated from the axis by 0 to 6.5 mm. There were 24 tumors that moved from 0 to 2.5 mm, 6 from 3.5 to 4.5 mm, 6 from 5 to 6.5 mm. Overall, 94.4% (34/36) of the tumors moved a distance ≤5.5 mm. Figure 5 shows the relationship between a tumor's distance from the center in the Z direction and its respiratory movement during free breathing (data from 12 tumors were the same, so 24 points are showed). In 24 tumors with a small degree of movement, the respiratory movement ranged from 1 to 16 mm, with a median of 4 mm (mean±SD: 4.54±3.94 mm). In 12 tumors with a great degree of movement, the respiratory movement ranged from 9 to 21 mm, with a median of 12 mm (mean±SD: 13.58±4.32 mm). The off-axis distance was significantly related to movement in the Z direction (t=6.685, P<0.001). When respiratory movement was 1, the ratio of the positions of 36 tumors during free breathing represented the relative position. A total of 36.1% (13/36) of the tumors were close to the position of the end inhalation (a ratio of 0 to 0.2), 16.7% (6/36) close to the position of the end inhalation (a ratio of 0.2 to 0.4), 11.1% (4/36) in between (a ratio of 0.4 to 0.6), and 27.8% (10/36) close to the position of the end exhalation (a ratio of 0.8 to 1).

Discussion

In 2003, Erridge *et al*. reported the measurements of 25 tumor cases (9). The tumor sizes were unknown, the movement in X direction was 7.3±2.7 mm, the movement in the Y direction was 9.4±5.2 mm, and the movement in the Z direction was 12.5±7.3 mm. In 2007, Liu *et al.* reported measurements of 166 foci obtained using 4D-CT; the average movement in X direction was 1.2 mm, the average movement in the Y direction was 2.1 mm, and the average movement in the Z direction was 5.0 mm (14). Among these tumors, 79 had GTV >100 cm^3, and those with larger diameters had smaller ranges of movement. In 2011, Dobashi *et al.* reported the results of 17 tumors obtained using 4D-CT (15). According to these data, the movement was 1.55±0.97 mm in the X direction, 2.44±1.04 mm in the Y direction, and 7.94±6.67 mm in the Z direction. There were two cases of T1 tumors (≤3 cm), eight cases of T2 tumors (3 cm< diameter ≤5 cm), six cases of metastatic tumors of unspecified size, and one case of a T3 tumor (diameter >5 cm). The present study used double CT imaging to measure 122 tumors, and we report movement of 1.96±2.03 mm in the X direction, 5.19±4.69 mm in the Y direction, and 7.38±6.48 mm in the Z direction. The largest tumors in this study had diameters ≤5 cm, 104 tumors had diameters ≤3 cm, and 18 had diameters ranging from 30.1 to 50 mm. The results of the current study are similar to Dobashi's report (15).

In 2008, Michalski *et al.* reported the use of 4D-CT to measure 23 lung tumors before and after treatment, some were shrunk by more than 10%, but 3 movement values did not change significantly (16). In the present study, tumors with small diameters showed greater movement in the X direction, but the absolute value was small, and there was no significant effect on the target borderline; tumor size had no effect on movement in the Y or Z direction or total movement, and movement may be more related to the number of tumors.

Respiratory movement of the upper lung was significantly less than that of lower lung. Shimizu *et al*. (10) measuring 6 tumors in middle lung and 8 tumors in lower lung using gold point tracking method; the average movement in Z direction was 6.2 (2.4-11.3) mm and 9.1 (3.4-24.0) mm, respectively. Seppenwoolde *et al.* (11) used the gold point tracking method to measure 21 tumors and found that the movement of upper lung in Z direction was 2±2 mm while that in the lower lung was 12±6 mm, P=0.005. Plathow *et al.* (8) reported in 2004 on 6, 4, and 9 tumors in upper, middle, and lower lung, respectively. During quiet breathing, the movement of the upper lung in 3 directions (X, Y, Z) was 3.4±1.6, 2.8±1.3, and 4.3±2.4 mm; that in the middle lung was 4.3±2.4, 4.3±2.2, 7.2±1.8 mm; and that in the lower lung was 6.0±2.8, 6.1±3.3, 9.5±4.9 mm. The movements of lower lung tumors in 3 directions were significantly greater than the movements of upper lung tumors, P<0.05. Likewise, the movements of middle lung tumors in the Z and Y directions were significantly greater than the movements of upper lung tumors, P<0.05. The movements of lower lung tumors in the Z-direction were significantly greater than the movements of tumors in the middle lung, P<0.05.

van Sörnsen de Koste JR *et al*. (13) described the use of CT scanning to measure the movement of 29 lung tumors. Regardless of whether they were grouped by anatomical location or by lobe, the movements of different groups of tumors in the Z direction were not statistically different. The authors explained the difference did not translate into a statistical significance due to the small sample size (13). A report by Michalski *et al*. (16) indicated that the average movement of the tumors in the upper lung before treatment was 2.2±0.5 mm in the X direction, 4.5±2.8 mm in the Y direction, and 7.2±3.8 mm in the Z direction, while movement in the lower lung was 3.3±1.9 mm in the X direction, 3.7±1.9 mm in the Y direction, and 10.8±9.4 mm in the Z direction. Even without performing any statistical analysis, from a numerical point of view, it is clear that lower lung movement in the Z direction was significantly greater than that in the upper lung movement. In the 122 tumors in this study, the movements of the upper and lower lung in the X and Y directions were similar, but the average movement in the Z direction in the lower lung (10.62±6.94 mm) was significantly greater than the movement in the upper lung (4.09±3.72 mm), P<0.0001. These results are similar to most reports in the literature.

In addition to the location of tumors in the lungs, other factors that impact their respiratory movement include thoracic breathing and cardiac motion. In this study, we found that movement in the Y direction was related to the location of the tumor on the Y axis, which may be related to thoracic breathing. Total movement and movement in the Y direction of tumors in the left lower lung were significantly greater than those of tumors in the right lower lung, and this can be related to the heart beat. The Y position had a significant effect on the total movement and movement in the Y direction, indicating that the closer the tumor is to the anterior chest wall, the greater the movement; total movement and movement in the Y direction for tumors in the left lower lung were greater than in the right lower lung, which demonstrates the effect of the heart beat on tumor movement.

Our data revealed that the maximum direction of the movement was not in the Z direction for 40.2% of the patients, suggesting that many patients may be accustomed to thoracic breathing. Movement in Y direction was greater than in the Z direction, as shown in Figure 1. In some patients, however, movement in Y direction was smaller than in Z direction, and in others, their actual movement was greater than the conventionally estimated movement, as described in Figure 2. Consistent with this, Erridge (9) reported that the maximum movement in the Y direction was 34 mm, which was greater than the movement in the Z direction (21 mm). In addition, the movement of the heart has a significant effect on the movement of tumors in the left lower lung tumor in the Y direction, and this should be considered when delineating the ITV. Our results indicate that respiratory movement is the lowest for tumors in the lower lung and highest for tumors in the upper lung.

Due to the specificity of the respiratory movement of each tumor, each of the patients was asked to undergo respiratory movement measurements to accurately outline the ITV boundaries and to understand the movement of tumors in different positions during quiet breathing. A larger deviation occurs when only group data are used to mark the target area boundaries.

There are many methods to determine the location of tumors in the lung. Lung tumors were divided into groups according to whether they occurred in the middle and lower lobes in several reports (9-11). van Sörnsen de Koste (13) used X-ray films to indicate the boundaries between the upper and lower, the anterior and posterior, and the median and lateral portions of the lung. Michalski (16) used the T5 vertebral body as the boundary between the upper and lower, the anterior and posterior, and the median and lateral halves of the lung. Plathow (12) used the T3/4 vertebral space as the boundary between the upper and middle lung, and T6/7 was used as the boundary between the middle and lower lung. This study quantified the tumor position based on the ratio of the three-dimensional coordinates of each tumor. More accurate positioning allows for more detailed analysis of the data.

The general law of lung tumor movement can provide an important practical reference (17,18). It provides the basis for the ITV boundaries. It can initially determine tumor movement based on tumor position compare the estimated value according to the tumor site and population data with the actual measured value. We found one patient whose tumor movement in the Z direction exceeded 40 mm, which is greater than the movement observed during quiet breathing movement in all other patients. After repeated investigation, we found that the patient was taking deep breaths during the CT scan. When we performed a new CT scan during quiet breathing, we found that the tumor movement in the Z direction was 20 mm. Therefore, it is important to repeatedly remind the patient to breathe quietly and to avoid deep breathing. Dobashi S. (15) used the bandage method to reduce the breathing movement in young patients. This is an effective method, but it may make elderly and ill persons or persons with poor lung function feel sick.

Currently, many scholars use free breathing in the SBRT treatment positioning methods (20-22). This study found that the tumor position was random during free breathing; only 11.1% of the tumors were in the same position at the end of exhalation and the middle of inhalation. Our results indicate that only using the data collected at the free breathing site will result in errors in the ITV outline sometimes. However, expanding the ITV range to avoid missing the target area will lead to unnecessary damage to normal tissue. For large tumors, the loss caused by these deviations may not be obvious. However, most of the tumors treated by SBRT are small, and expanding the outline will result in greater harm to normal tissue.

There are many ways to measure respiratory movement. The use of EPIs (9) or X-ray examination (19) is not as accurate as CT or magnetic resonance imaging (several groups have used fluoroscopy to image and calculate displacements of the tumor during the respiratory cycle, but this technique is not very accurate either). CBCT (7) can be performed in real time after placement, and in essence, the measurement is carried out using CT, but the image clarity is not sufficient. The gold point tracking method is an invasive operation (10,11). Measurement using nuclear magnetic resonance is time-consuming (12). With both fast and slow methods of CT (13), if the breathing phase is ignored, the measured data may be less accurate. The accuracy of 4D-CT is higher (14,15), but the equipment is more expensive and is not widely available. This method also requires multiple scans, resulting in the potential exposure of patients to more radiation. It is also more time-consuming and is difficult to implement practically because of the heavy workload.

Baba *et al.* (23) reported the use of methods similar to those described in the present study, i.e., they scanned once during free breathing and twice during inhalation and exhalation, with the breath held in between. However, their paper did not illustrate whether measurements were taken during quiet inhalation and at the end of exhalation. In this study, CT images were collected twice, once at the end of quiet inhalation and once at the end of exhalation to obtain the range of movement. This is more practical and provides accurate results, but it requires repeated training of the patients by illustrating how to hold the breath after quiet inhalation and at the end of exhalation.

In conclusion, double CT imaging is a convenient, accurate, and practical method for measuring the movement of lung tumors. This method should be investigated further in future studies.

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