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FULL PAPER

Impact of treatment planning with deformable image registration on dose distribution for carbon-ion beam lung treatment using a fixed irradiation port and rotating couch

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Objective: When using a fixed irradiation port, treatment couch rotation is necessary to increase beam angle selection. We evaluated dose variations associated with positional morphological changes to organs.

Methods: We retrospectively chose the data sets of ten patients with lung cancer who underwent respiratory-gated CT at three different couch rotation angles (0°, 20° and -20°). The respective CT data sets are referred to as CT₀, CT₂₀ and CT₋₂₀. Three treatment plans were generated as follows: in Plan 1, all compensating bolus designs and dose distributions were calculated using CT₀. To evaluate the rotation effect without considering morphology changes, in Plan 2, the compensating bolus designed using CT₀ were applied to the CT_{±20} images. Plan 3 involved compensating bolus designed using the

CT_{±20} images. The accumulated dose distributions were calculated using deformable image registration (DIR).

Results: A sufficient prescribed dose was calculated for the planning target volume (PTV) in Plan 1 [minimum dose received by a volume ≥95% (D_{95}) > 95.8%]. By contrast, Plan 2 showed degraded dose conformation to the PTV (D_{95} > 90%) owing to mismatch of the bolus design to the morphological positional changes in the respective CT. The dose assessment results of Plan 3 were very close to those of Plan 1.

Conclusion: Dose distribution is significantly affected by whether or not positional organ morphology changes are factored into dose planning.

Advances in knowledge: In treatment planning using multiple CT scans with different couch positions, it is mandatory to calculate the accumulated dose using DIR.

The use of particle beam therapy is rapidly growing worldwide.¹ Some particle beam systems use a rotational gantry to allow irradiation from multiple directions. However, as the gantry for carbon-ion beam therapy is larger and heavier than that for proton beam therapy,² many carbon-ion beam treatment systems feature a fixed gantry with one or two beam ports placed at the sides of the treatment couch. The treatment couch is rotated around its long axis to allow beam entrance at oblique angles, eliminating the need for gantry rotation. It is necessary to consider changes in organ morphology when treating a patient with a fixed irradiation port and rotating couch. Usually, two or three treatment planning CT data sets are acquired at different couch rotation angles. Treatment planning parameters and patient accessories (patient collimators and compensating bolus) are designed at each beam angle using the respective CT images acquired in the planned rotation positions. Deformable image registration (DIR)^{3,4} is used to calculate the accumulated dose

distribution from multiple beam directions using more than two CT data sets to factor in morphological changes of organs with treatment couch rotation. Compared with single planning CT, multiple planning CTs require extra time for clinical workflow both for CT acquisition and deformation planning. To date, however, patient and target dose variations owing to position-dependent morphological changes with treatment couch rotation have not been evaluated.

Here, we evaluated patient and target dose variations owing to position-dependent morphological changes with treatment couch rotation.

METHODS AND MATERIALS

Image acquisition

The pre-treatment data sets of ten subjects (mean age, 76.4 ± 6.7 years) with lung cancer who had undergone carbon-ion therapy were randomly selected. Patient characteristics are

summarized in Table 1. During the planning CT and treatment stages, each patient had been kept immobile using a low-temperature thermoplastic device (Shellfitter; Keraray Co., Ltd, Osaka, Japan) in order to improve the interfractional patient positional reproducibility and to prevent the patient's position from shifting with treatment couch rotation.

Since our treatment centre uses orthogonal beam ports (0° and 90°), the treatment couch needs to be rotated around its long axis (ϕ : standard International Electrotechnical Commission table top rolling angle)⁵ to extend the range of angles. Respiratory-gated CT image data were acquired with a 16-slice CT scanner (Light Speed® 16-slice; GE Healthcare, Waukesha, WI). An infrared source was placed on the patient's abdomen to acquire a respiratory signal, allowing the patient to be scanned in peak-expiratory phase. The first CT acquisition was obtained without couch rotation ($\phi = 0$) and defined as CT₀. The second and third CT acquisitions were obtained with couch rotations of 20° and -20° and defined as CT₂₀ and CT₋₂₀, respectively.

Treatment planning

Three gross tumour volumes (GTVs) were contoured manually, one for each data set (CT₀, CT₂₀ and CT₋₂₀). The clinical target volumes (CTVs) were defined with a 10-mm margin outside of the GTVs. Planning target volumes (PTVs) were defined equal to the CTVs. We calculated the carbon-ion beam distributions as

follows: beam energy, 290–350 MeV with patient collimator; prescribed dose of 60.0 Gy relative biological effectiveness (RBE)⁶ in a single fraction, and administration to the PTV via four different beam angles from the side ipsilateral to the tumour.⁷

Plan 1

Compensating boli were designed for the first CT data set without couch rotation (CT₀) (Figure 1a). The treatment beams were administered to the target via four different beam ports with the two beams of each pair tilted $\pm 20^\circ$ from the horizontal to minimize the beam overlap regions (Figure 1a, the first and second columns). The compensating boli were applied using a smearing algorithm to account for patient set-up error and multiple scattering (calculation grid of 3×3 mm).⁸ The characteristics of this plan were that all dose distributions at each beam port were calculated using the same CT data set (CT₀) (Figure 1a, the third column).

Plan 2

Using the treatment beams and the same compensating boli as in Plan 1 for CT₀, treatment was adapted to the second and third CT data sets with couch rotation (CT _{± 20}) for calculation of the dose distribution (Figure 1b, the first and second columns). The treatment couch was rotated -20° to irradiate at a beam angle of 20° (Figure 1b, the second column). This plan was evaluated for the effect of morphological variation with treatment couch rotation

Table 1. Summary of patient characteristics and deformable image registration (DIR) accuracy

Patient number	Gender	Age (years)	T stage	Tumour size (cm) (left–right $\times$ anteroposterior $\times$ superioinferior)	Location	DIR accuracy (mm)			
						CT ₋₂₀ to CT ₀		CT ₂₀ to CT ₀	
						Mean	SD	Mean	SD
1	Female	68	Metastasis	$6.1 \times 7.6 \times 7.0$	Left upper lobe	3.3	2.4	3.9	2.0
2	Male	70	T1N0M0	$2.0 \times 2.1 \times 2.2$	Right lower lobe	0.7	0.3	0.5	0.2
3	Female	87	T1N0M0	$2.1 \times 2.1 \times 1.8$	Left upper lobe	0.8	0.4	0.7	0.4
4	Female	73	T1N0M0	$3.0 \times 2.2 \times 2.2$	Right upper lobe	0.4	0.2	0.5	0.2
5	Male	86	T2NxM0	$4.6 \times 5.4 \times 4.5$	Right upper lobe	1.7	0.7	0.4	0.2
6	Male	70	T2N0M0	$4.6 \times 4.3 \times 3.6$	Right upper lobe	0.5	0.2	0.4	0.2
7	Female	77	T1N0M0	$2.8 \times 2.1 \times 3.0$	Right upper lobe	0.3	0.1	0.5	0.2
8	Male	74	T1N0M0	$2.0 \times 1.9 \times 1.3$	Right upper lobe	0.3	0.1	0.3	0.2
9	Male	77	T2N0M0	$3.2 \times 3.5 \times 2.9$	Right lower lobe	3.2	1.3	2.8	1.8
10	Male	82	T1N0M0	$2.2 \times 2.0 \times 1.8$	Left upper lobe	0.3	0.1	0.5	0.2
Mean		76.4		$3.3 \times 3.3 \times 3.0$		1.1		1.1	
SD		6.7		$1.4 \times 1.9 \times 1.7$		1.2		1.2	

SD, standard deviation.

Figure 1. Schematic drawing of the three types of treatment planning. (a) Plan 1: compensating boli were designed for the CT data set CT_0 without couch rotation ($\phi = 0$). Treatment beam was calculated for the target with a beam angle of $\pm 20^\circ$ with CT_0 . (b) Plan 2: compensating boli were designed for the CT data set without couch rotation ($\phi = 0$). Treatment beam was calculated for the target with couch rotation $CT_{\pm 20}$. (c) Plan 3: compensating boli were designed for $CT_{\pm 20}$. Treatment beam was delivered to the target with $CT_{\pm 20}$.

using the boli designed in Plan 1. The accumulated dose distribution was calculated by registering dose distributions generated from the $CT_{\pm 20}$ to the CT_0 position by applying B-spline-based DIR.⁹

Plan 3

In Plan 3, treatment planning and dose calculations were generated using the second and third CT data sets with couch rotation ($CT_{\pm 20}$) including patient morphological variations (Figure 1c, the first and second columns). The accumulated dose was calculated by registering dose distributions on the $CT_{\pm 20}$ to the CT_0 position by applying DIR in order to evaluate the effect of morphological variation with treatment couch rotation using boli designed to account for the rotation.

Dose assessment

Accumulated dose assessments were performed using the reference CT data set (CT_0) for the three treatment plans. We evaluated the

minimum dose received by a volume $\geq 95\%$ (D_{95}); maximum dose (D_{max}); minimum dose (D_{min}) to the GTV and PTV; maximum dose (D_{max}) to the spinal cord; and lung volume (total lung volume minus the PTV) receiving ≥ 20 Gy (RBE) (V_{20}). Mean and standard deviation values of all metrics were calculated instead of any statistical tests (pair-wise comparison etc.) because of the limited number of patients.

To evaluate DIR accuracy, the reference image of CT_0 and its DIR-generated counterpart [$CT_{\pm 20}$ images to CT_0 image (warped CT_0)] were registered and the vector field between them was calculated. If there was no registration error, the original CT_0 and warped CT_0 were the same. The DIR accuracy was derived from the magnitude of the vector field differences (three-dimensional Euclidean distance) around the respective beam fields. The mean DIR accuracy between CT_0 and $CT_{\pm 20}$ was calculated to be 1.1 ± 1.2 mm (Table 1).

Figure 2. Accumulated carbon-ion dose distributions for (a) Plan 1, (b) Plan 2 and (c) Plan 3 (patient number 10). These were overlaid on the CT image without rotation. Beam angles were 20°, 70°, 110° and 340°. Yellow lines show the planning target volume. Pink, red, green, light blue and blue lines show the 95%, 90%, 80%, 50% and 30% isodose lines, respectively. The arrow indicates an underdosage to the planning target volume in Plan 2. For colour images please see online.

All calculations were performed using in-house software, as previously described in detail.¹⁰

RESULTS

An example of a carbon-ion beam dose distribution simulation with the respective plans (patient number 10) are shown in Figure 2. The accumulated dose distributions to the GTV and PTV were decreased in Plan 2 (GTV – D_{95} : 96.2%, PTV – D_{95} : 90.0%) compared with Plan 1 (GTV – D_{95} : 97.1%, PTV – D_{95} : 97.1%). Beam angles of 20° and 110° in Plan 2 were calculated using CT₋₂₀. The other beam angles of 70° and 340° were calculated using CT₂₀. Each imaging plane was selected to include

the centre of the target. The dose distribution (GTV – D_{95} : 97.1%, PTV – D_{95} : 96.9%) in Plan 3 was similar to that in Plan 1 (GTV – D_{95} : 97.1%, PTV – D_{95} : 97.1%). The treatment beam parameters were optimized to cover the PTVs at each couch angle. The accumulated dose also covered the PTV. V_{20} for lung was 2.3%, 2.0% and 2.3% for Plans 1, 2 and 3, respectively. D_{max} to the cord was 1.2 Gy (RBE) for all plans.

To clearly understand the above results, we portrayed the subtracted dose distributions in Figure 3. The subtracted images show the variations in organ morphology with couch rotation (lower panel in Figure 3). Underdosage/overdosage was observed

Figure 3. Carbon-ion beam dose distributions (upper panel, left to right: Plan 1, Plan 2 and Plan 3) and dose differences (lower panel) (patient number 10). Beam angle was 70°. Yellow lines show the planning target volume (PTV). Pink, red, green, light blue and blue lines show the 95%, 90%, 80%, 50% and 30% dose limits, respectively. The white arrow indicates an underdosage to the PTV in Plan 2. The dose distribution of Plan 1 was subtracted from the dose distributions of Plans 2 and 3. The lower panel shows Δ dose overlaid on the CT subtraction images between CT₀ and CT₂₀ (registered rigidly to match gross tumour volume contour). For colour images please see online.

on the distal/proximal side of the PTV (Figures 2 and 3, white arrows) and the lateral side of the beam field. As a result, beam range varied owing to the patient surface positional changes of 4 mm with couch rotation. In addition, the spread-out Bragg peak (SOBP) position was shifted towards the proximal side. The magnitude of the dose variation was greater to regions with more surface position variation with changing rotation angle. In Plan 3, the dose distribution to the target was similar to the dose distribution of Plan 1, but the dose to the normal tissues, such as the patient surface and muscle, was different.

For all patients, D_{95} values to the PTV were $\geq 94.6\%$ of the prescribed dose in Plans 1 and 3 (Table 2). In Plan 2, the mean

D_{95} value was 92.7% of the prescribed dose. PTV – $D_{\min}$ was significantly different with each plan, with values of 53.9, 43.7 and 51.4 Gy (RBE) in Plans 1, 2 and 3, respectively. Since Plan 1 represents the ideal dose distribution with error-free DIR registration, and dosimetric errors may result from its application to Plans 2 and 3, the dose to the target tended to be higher. In Plan 3, taking the angles of rotation into account, the dose was close to that of Plan 1. V_{20} values for the lung were 3.4–3.5% in all plans averaged over all patient data sets. $D_{\max}$ values to the spinal cord were 6.1–6.3 Gy (RBE) in all plans. The range of cord – $D_{\max}$ values observed [0–28.2 Gy (RBE)] was owing to variations in the distance from the tumour to the cord.

Table 2. Dose assessment [D_{95} , $D_{\max}$ and $D_{\min}$ for the gross tumour volume (GTV) and planning target volume (PTV), V_{20} for the lung, $D_{\max}$ to the spinal cord] averaged over all patients in three treatment plans

Metrics	Plan number	Mean	Minimum	Maximum	Standard deviation
GTV					
D_{95} (%)	1	97.1	97.0	97.2	0.1
	2	96.8	95.1	97.3	0.7
	3	97.1	96.7	97.2	0.2
$D_{\max}$ [Gy (RBE)]	1	52.4	52.3	52.8	0.2
	2	52.3	52.3	52.3	0.0
	3	52.4	52.3	52.8	0.2
$D_{\min}$ [Gy (RBE)]	1	50.5	48.1	51.2	1.1
	2	48.4	43.8	51.2	2.2
	3	50.6	48.6	51.2	1.0
PTV					
D_{95} (%)	1	96.8	95.8	97.1	0.5
	2	92.7	90.0	94.5	1.4
	3	96.2	94.6	97.0	0.8
$D_{\max}$ [Gy (RBE)]	1	52.4	52.3	52.8	0.3
	2	52.3	52.3	52.8	0.2
	3	52.4	52.3	52.8	0.2
$D_{\min}$ [Gy (RBE)]	1	47.4	44.9	49.1	1.6
	2	38.5	32.2	41.7	3.2
	3	45.3	40.7	48.1	2.1
Lung					
V_{20} (%)	1	3.4	1.6	6.5	1.7
	2	3.5	1.6	7.0	1.8
	3	3.5	1.6	6.6	1.7
Cord					
$D_{\max}$ [Gy (RBE)]	1	5.3	0.0	24.3	8.3
	2	5.4	0.0	24.8	8.4
	3	5.5	0.0	24.8	8.3

D_{95} , minimum dose received by a volume $\geq 95\%$; $D_{\max}$, maximum dose; $D_{\min}$, minimum dose; RBE, relative biological effectiveness; V_{20} , volume receiving ≥ 20 Gy (RBE).

DISCUSSION

We evaluated dose variation owing to morphological changes in the thoracic region with couch rotation for the purpose of irradiating at an oblique beam angle with a fixed beam port. Underdosage to the target occurred with the accumulated dose calculation in Plan 2. This result indicates that treatment planning with multiple CT data sets with couch rotation needs to account for morphological variations and needs DIR to calculate the accumulated dose. In Plan 2, underdosage was observed at the distal side of the target. This is owing to the patient surface positional variation, as described above. As a result, the SOBP position was shifted towards the proximal side.

We are currently developing the rotating gantry port and adapting it for a moving target.^{11–13} However, a rotating gantry entails large construction and maintenance costs. Using a conventional fixed beam port for treatment is feasible, provided that

interfractional position changes are kept to a minimum by using immobilization. However, the patient morphological changes with treatment couch rotation still remain. Although accumulated dose calculations using the DIR technique (Plan 3) lengthen treatment-planning time, they are nevertheless necessary for evaluation of the organ at risk as well as the target, particularly in conformal treatments such as particle beam therapy. Using DIR, accumulated dose planning can be tailored to the morphological changes with rotation.

CONCLUSION

We evaluated the dose variations occurring with couch rotation using DIR. The PTV coverage was improved by accounting for anatomical deformation. Rotation significantly affected dose distribution to patients' body surface/lung regions. It is necessary to consider the morphological changes induced by couch rotation.

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