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Original paper

Dosimetric impact of 4DCT artifact in carbon-ion scanning beam treatment: Worst case analysis in lung and liver treatments

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ABSTRACT

Introduction: We evaluated the impact of 4DCT artifacts on carbon-ion pencil beam scanning dose distributions in lung and liver treatment.
Methods & materials: 4DCT was performed in 20 liver and lung patients using area-detector CT (original 4DCT). 4DCT acquisition by multi-detector row CT was simulated using original 4DCT by selecting other phases randomly (plus/minus 20% phases). Since tumor position can move over the respiratory range in original 4DCT, mid-exhalation was set as reference phase. Total prescribed dose of 60 Gy (RBE) was delivered to the clinical target volume (CTV). Reference dose distribution was calculated with the original CT, and actual dose distributions were calculated with treatment planning parameters optimized using the simulated CT (simulated dose). Dose distribution was calculated by substituting these parameters into the original CT.
Results: For liver cases, CTV-D95 and CTV-Dmin values for the reference dose were 97.6 ± 0.5% and 89.8 ± 0.6% of prescribed dose, respectively. Values for the simulated dose were significantly degraded, to 88.6 ± 14.0% and 46.3 ± 26.7%, respectively. Dose assessment results for lung cases were 84.8 ± 12.8% and 58.0 ± 24.5% for the simulated dose, showing significant degradation over the reference dose of 95.1 ± 1.5% and 87.0 ± 2.2%, respectively.
Conclusions: 4DCT image quality should be closely checked to minimize degradation of dose conformation due to 4DCT artifacts. Medical staff should pay particular attention to checking the quality of 4DCT images as a function of respiratory phase, because it is difficult to recognize 4DCT artifact on a single phase in some cases

1. Introduction

Recent radiotherapy techniques in treatment planning and irradiation systems reduce excessive dose to healthy tissues and maintain high target dose conformation. Examples include intensity modulated radiation therapy (IMRT) [1,2], volumetric modulated arc therapy (VMAT) [3], and pencil beam scanning with intensity modulated proton/particle therapy (IMPT) [4]. These techniques provide good tumor control rates with less toxicity and improve quality of life. Moreover, treatment accuracy with these techniques can be further improved using an image guidance technique (image guided radiotherapy: IGRT) [5–7]. The main contribution of IGRT to radiotherapy is that it improves information on the visualization and quantification of organ and tumor geometry and positioning obtained with medical imaging systems. If geometrical/positional accuracy is low even though treatment planning and irradiation techniques provide high dose conformation, the treatment beam might miss the tumor. Geometrical/positional information, especially intrafractional motion, remains a major challenge to improved treatment accuracy in current radiotherapy.

The demand for treatment planning which incorporates intrafractional motion has increased, and four-dimensional computed tomography (4DCT) is already commercially available. The latest CT scanners utilize up to 320-row detectors (area-detector CT: ADCT) and acquire more than 16 cm in a single rotation. This represents a significant improvement over conventional multi-detector CT (MDCT), especially in cardiac imaging [8]. However, most treatment centers still use 64MDCT or fewer, which typically acquire a scan region of 40 mm or less. Thus, obtaining a sufficient scan region for treatment planning requires multiple CT scans in cine mode at respective couch positions. The resorting process in 4DCT is based on either respiratory phase or amplitude of motion. The former approach is most widely used despite the fact that respiratory motion is not strictly regular but varies in amplitude and

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period in respective respiratory cycles [9–11]. Tumor position is not always the same even in the same respiratory phase. This inconsistency between respiratory phase and tumor position could cause geometrical error (4DCT artifact). Indeed, one study reported tumor blurring, duplication, overlapping and incomplete imaging in 90% of all patients [12]. These artifacts hamper quantitative analysis, and it is questionable whether 4DCT images which include 4DCT artifact provide accurate dose distribution in actual situations. In particular, charged particle beams are highly sensitive to geometrical variations in water-equivalent pathlength.

Here, we evaluated the impact of the 4DCT artifacts on carbon-ion pencil beam scanning (C-PBS) dose distributions for lung and liver treatment.

2. Materials and methods

2.1. Patient and imaging

A total of 20 lung and liver cancer patients were randomly selected from patients at our institution (Table 1) and gave informed consent before participation. The study was approved by the Institutional Review Board of our institution. 4DCT image sets were acquired by a fast rotating ADCT under free-breathing conditions with monitoring of respiration using a respiratory sensing system [13]. Scan coverage along the longitudinal direction was approximately 13 cm in a single rotation with a rotation time of 0.5 s. Since ADCT obtains a wide scan region in a single rotation, absolute time is the same and neither sorting of image data nor respiratory signal errors occur across the scan coverage (Fig. 1b). A single 4DCT scan obtained sufficient scan region for lung treatment planning, but was insufficient to cover the whole liver, which required two 4DCT scans and sorted them as a function of respiratory phase. This sorting process is much simpler than that of using conventional MDCT. If necessary, medical staff remade the 4DCT to minimize the sorting error. Respiratory cycle and Euclidian distance of the center of mass of the clinical target volume (CTV) are summarized in Table 1. A single respiratory cycle in the 4DCT data set was subdivided into 10 phases (T00: peak inhalation, T50: around peak exhalation) using the respiratory signal.

2.2. Image processing

Generally, two types of 4DCT scan technique are available for clinical use, cine 4D [14] and helical 4D modes [15]. Cine 4D mode is performed by operating the CT scanner without couch movement using respiratory signals from the respiratory sensing system to obtain a single respiratory cycle at each couch position. The couch is then moved to the next adjacent position and sorts CT images at the same respiratory phase. In contrast, helical 4D mode is performed by helical CT scanning with a small helical pitch to obtain a single respiratory cycle at each couch position continuously. Temporal scans are sorted in sinogram space before reconstruction using the respiratory signal. Both 4D modes provide 4DCT images as a function of respiratory phase, but not in the same absolute time. Tumor position on the 4DCT might therefore differ under an irregular respiratory pattern even in the same respiratory phase (Fig. 1a and c). This may produce 4DCT artifacts on the 4DCT images, which degrade geometrical accuracy (Fig. 1c).

To simulate 4DCT imagery acquired by cine MDCT, we sorted 4DCT images at respective couch positions by selecting 4DCT images at other respiratory phases. The couch moving step was 20 mm. Our previous paper reported that intrafractional exhalation position varied by 7.5 ± 4.6% during treatment [16]. The external respiratory monitor does not obtain actual tumor position, but rather abdominal surface motion. Moreover, the 4DCT sets were subdivided based on respiratory phase, not amplitude. However, 10-phase 4DCT data sets were available, and respiratory amplitude variation could not be made to strictly corresponded to respiratory phase information. We approximated these assignments for the present study.

Generally, human respiratory pattern can be approximated to 4 s cycle, 1 cm amplitude and trigonometric function ($\cos^4$) [17]. When we considered two sigma statistical variation, exhalation positional variation could be 16.7%. 4DCT is expressed by respiratory phase not respiratory amplitude. Then the 4DCT respiratory phase at 16.7% position from peak exhalation was close to T30 and T70 (T50 ± 20%). Adopting a worst-case scenario, we randomly selected 4DCT images at plus/minus 20% respiratory phases from the reference phase. To satisfy the simulated 4DCT pattern statistically, we calculated 50 simulated 4DCT patterns for each patient.

Table 1
Patient characteristics. CTV displacement was defined as the Euclidian distance of the center of mass.

No.	Gender	Age (y)	Tumor size (mm) (LR × AP × SI)						Location	Pathology	Respiratory cycle (s)	CTV displacement (mm)
1	Female	78	37	×	36	×	44		S7	HCC	4.0	9.3
2	Female	80	27	×	20	×	27		S7	meta	3.8	21.6
3	Male	77	79	×	65	×	54		S4-8	HCC	5.1	8.3
4	Female	52	17	×	19	×	10		S8	meta	3.7	8.7
5	Female	58	75	×	91	×	61		S7-8	HCC	3.3	13.1
6	Male	55	70	×	66	×	53		S6-7	HCC	3.6	18.7
7	Male	80	86	×	75	×	61		S5-8	HCC	3.6	17.4
8	Male	73	61	×	58	×	83		S7	HCC	4.4	11.1
9	Male	71	17	×	17	×	16		S4	HCC	2.7	10.8
10	Male	78	64	×	50	×	51		S6-7	HCC	4.5	12.4
11	Male	75	34	×	32	×	17		LUL S4	ADC	4.1	2.9
12	Male	69	53	×	45	×	52		RLL S10	ADC	2.8	17.3
13	Male	76	25	×	26	×	25		RLL S6	meta	3.8	5.5
14	Female	48	13	×	13	×	24		LLL S10	meta	2.9	12.1
15	Male	65	50	×	59	×	39		RLL S9	SCC	4.3	13.4
16	Female	80	37	×	37	×	32		LUL S3	ADC	4.2	2.7
17	Female	81	14	×	11	×	12		LUL S3	meta	2.7	3.4
18	Female	65	27	×	30	×	28		RLL S7	meta	5.5	8.9
19	Male	61	27	×	25	×	17		RLLS8	ADC	3.6	7.7
20	Male	72	56	×	42	×	61		RLL S10	SCC	2.7	7.7

Abbreviations: CTV = clinical target volume. LR = left–right. AP = anterior-posterior. SI = superior-inferior.

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