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Target motion trajectories

The accuracy of extracted target motion trajectories in four-dimensional cone-beam computed tomography for lung cancer patients ☆

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ABSTRACT

Purpose: To quantify the accuracy of extracted target motion trajectories in dual-source four-dimensional cone-beam computed tomography (4D-CBCT) by comparison with the actual three-dimensional (3D) target motion acquired simultaneously during 4D-CBCT scan.

Materials and methods: 4D-CBCT scans were performed for 19 different sinusoidal-like patterns and 13 lung cancer patients with implanted markers. Internal (In) or external (Ex) surrogates with amplitude (Amp)- or phase (Ph)-based sorting were used for the reconstructions. The targets were a pseudo-tumor and implanted marker for the phantom and clinical studies, respectively. The accuracy was evaluated by determining the maximum error ($MaxE_i$) between the 3D target position extracted from 4D-CBCT and the actual 3D target position detected by fluoroscopy in each ith phase ($0 \leqslant i \leqslant 7$).

Results: Median peak-to-peak target displacements in the superior–inferior (SI) direction were 20.6 and 20.6 mm in the phantom and clinical studies, respectively. In the phantom and clinical studies, the maximum of median $MaxE_i$s in the SI direction was 4.6 and 9.2 mm in the In_Ph reconstruction. In the clinical study, the maximum of median $MaxE_i$s was observed during the end-inhalation phase among all reconstruction approaches.

Conclusions: This study showed the magnitude of underestimation toward the inferior direction of target motion in clinical 4D-CBCT.

Management of respiratory motion so that the delivered dose is limited to the target while sparing the surrounding normal tissue has become increasingly important in the area of high-precision external radiotherapy. The roles and various techniques of respiratory motion management have been reported by the American Association of Physicists in Medicine [1].

Fluoroscopy- and computed tomography (CT)-based methods have been developed to verify respiratory-induced tumor motion. In the CT-based method, four-dimensional (4D)-CT or 4D cone-beam CT (CBCT) techniques can be used to extract the three-dimensional (3D) target position in each respiratory phase during imaging.

One of the best methods to confirm intra- and inter-fraction variation in the target position before beam delivery is 4D-CBCT imaging using an on-board imager mounted on a linac. Various authors have evaluated the accuracy of extracted target motion trajectories in 4D-CBCT. Lee et al. used a motion phantom to evaluate the accuracy of various sinusoidal wave patterns and found them to be within 2 mm using an Elekta machine (Elekta, Crawley, UK) [2]. However, the authors compared the 3D target positions on 4D-CBCT images with 4D-CT images acquired asynchronously. Dang et al. evaluated the accuracy in four lung cancer patients by comparing down-sampled 4D-CBCT with full-sampled 4D-CBCT images on a Varian machine (Varian Medical System, Palo Alto, CA, USA) [3]. However, the actual 3D target positions were not depicted, even for full-sampled cases. These studies only compared target positions on 4D-CBCT images or down-sampled cases with non-simultaneously acquired target positions on 4D-CT images or full-sampled 4D-CBCT images, respectively. Single-source 4D-CBCT can only obtain target motion along the gantry rotation axis direction on projections. Thus, no studies have defined the actual

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3D position acquired simultaneously from CBCT projections during 4D-CBCT scans as the ground truth target position.

In this study, we developed a dual-source 4D-CBCT subsystem mounted on a Vero4DRT (Mitsubishi Heavy Industries, Tokyo, Japan, and Brainlab AG, Feldkirchen, Germany), which allowed us to extract the actual 3D target position during the 4D-CBCT scan. This was because the subsystem simultaneously projected the object's actual 3D position onto two orthogonal projections. The aim of this study was to quantify differences between actual and 4D-CBCT-reconstructed target motion trajectories in both a phantom study and clinical lung stereotactic body radiotherapy (SBRT). This is the first study to quantify the accuracy of extracted target motion trajectories using various wave patterns as well as the accuracy in clinical practice.

Materials and methods

We first performed the phantom study using 19 different sinusoidal-like wave patterns. Details are provided in the Supplementary materials section.

Patient characteristics

We performed 4D-CBCT scans of 13 consecutive lung cancer patients who underwent SBRT with implantation of two to four 1.5-mm-diameter gold markers (GMs) (Olympus, Tokyo, Japan) (Table 1). The patients were enrolled in the Institutional Review Board-approval trial and selected under the following eligibility criteria: (1) a performance status of 0 or 1; (2) undergoing SBRT for early-stage lung cancer (T1a–T2aN0M0) or ⩽3 lung metastatic cancers; (3) an identifiable tumor on 4D-CBCT; and (4) completion of a written informed consent form.

4D-CBCT data acquisition and reconstruction process

To determine abdominal motion in the anterior–posterior (AP) direction, infrared (IR) markers placed on the patient's abdomen were captured by a movable Polaris Spectra camera (Northern Digital Inc., Ontario, Canada) located close to the patient, which was independent from the Vero4DRT system. More details on data acquisition are described in the Supplementary materials section. Three consecutive 4D-CBCT scans were performed for each patient, except for Patient 10 who underwent two consecutive scans. A second round of scans for all patients except Patient 10 were performed for a different purpose and were not used in this study.

Surrogate respiratory signals acquired simultaneously with the projections were converted to eight phase bins using retrospective sorting methods such as amplitude (Amp)- or phase (Ph)-based sorting. In these sorting techniques, the displacement or motion cycle of the signal was equally divided into eight phases. We defined end-exhalation and end-inhalation to be the 0th and 4th phases, respectively. The Feldkamp–Davis–Kress algorithm was employed for each grouped projection to reconstruct the 3D-CBCT image corresponding to each phase [4]. In this study, the motion in the superior–inferior (SI) direction of the implanted GM located closest to the tumor was defined as the internal (In) surrogate signal, and both sorting methods were employed for image reconstruction (In_Amp and In_Ph). Additionally, in the clinical study, the AP motion of the IR marker was used as the external (Ex) surrogate signal and was sorted by amplitude (Ex_Amp). Other studies reported that amplitude-based sorting was superior to phase one in extracting target motion trajectory [5,6]. In addition, external surrogates may not always accurately show internal target motion, especially with irregular breathing [7]. Thus, the external surrogate with phase-based sorting was not evaluated.

Three-dimensional target position and target motion trajectory

All GMs were semi-automatically detected on each projection, as described in the Supplementary materials section. The target was defined as the GM that exhibited the worst correlation coefficient (CC) with the internal surrogate. The estimated uncertainty associated with detecting GMs from X-ray fluoroscopy was 0.08 mm (with coverage factor of $k = 1$). This uncertainty was considering the size of GM and the pixel size of 0.22 mm at the isocenter level. The uncertainty of the size of GMs was estimated by measuring the sizes of four GMs 40 times on projections. To calculate the actual 3D position from the two orthogonal projections obtained simultaneously, the two-dimensional (2D) positional data were converted to 3D positional data by a transformation matrix with a predefined calibration parameter [8].

On reconstructed 4D-CBCT images, targets were manually contoured in all phases with MIM Maestro (ver. 6.5; MIM software, Cleveland, OH, USA). The centroid position of the contour was defined as the target position. Target motion trajectories in In_Amp, In_Ph, and Ex_Amp on 4D-CBCT images were evaluated with the root-mean-square error (RMSE) and maximum error (MaxE) in each phase. RMSE of the ith phase ($0 \leqslant i \leqslant 7$) ($\mathrm{RMSE}_i$) was defined as:

$$\mathrm{RMSE}_i = \sqrt{\frac{1}{N_i}\sum_{j=1}^{N_i}\left\{s_{\text{4D-CBCT},i} - s_{\text{truth},i}(j)\right\}^2}, \quad (1)$$

where N_i is the number of all ground truth positions in the ith phase and $s_{\text{4D-CBCT},i}$ or $s_{\text{truth},i}(j)$ is the 4D-CBCT position in the ith phase or ground truth target positions sorted in the ith phase, respectively.

Table 1
Patient characteristics.

Patient			Tumor			No. of gold markers	TMD [mm]
No.	Age (y.o.)	Sex	Stage	Side	Size [mm]		
1	85	F	T2a	Rt	37	2	28.8
2	75	M	T1a	Rt	12	4	16.0
3	81	M	T1a	Rt	10	4	28.6
4	83	M	T1a	Rt	18	4	25.6
5	75	M	T1a	Rt	19	2	27.3
6	77	F	T1a	Rt	18	4	18.6
7	86	M	T1b	Rt	22	3	14.9
8	87	M	T1b	Rt	23	3	11.7
9	79	F	T1a	Rt	11	4	12.4
10	88	M	T1a	Rt	17	3	12.8
11	90	F	T1a	Lt	18	3	38.9
12	85	M	T2a	Lt	42	2	45.7
13	82	M	T1b	Lt	25	3	13.2

Abbreviations: F, female; M, male; Rt, right lobe; Lt, left lobe; TMD, distance between centroid of tumor and internal surrogate marker.