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Original paper

Influence of the correlation modeling period on the prediction accuracy of infrared marker-based dynamic tumor tracking using a gimbaled X-ray head

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ABSTRACT

Purpose: To assess the utility of 10 s and 20 s modeling periods, rather than the 40 s currently used, in the clinical construction of practical correlation models (CMs) in dynamic tumor tracking irradiation using the Vero4DRT.

Methods: The CMs with five independent parameters (CM parameters) were analyzed retrospectively for 10 consecutive lung cancer patients. CM remodeling was performed two or three times per treatment session. Three different CMs trained over modeling periods of 10, 20, and 40 s were built from a single, original CM log file. The predicted target positions were calculated from the CM parameters and the vertical displacement of infrared markers on the abdomen (P_{IR}) during the modeling. We assessed how the CM parameters obtained over modeling periods of T s ($T = 10$, 20, and 40 s) were robust to changes in respiratory patterns after several minutes. The mimic-predicted target positions after several minutes were computed based on the previous CM parameters and P_{IR} during the next modeling. The 95th percentiles of the differences between mimic-predicted and detected target positions over 40 s ($E95_{robust,T}$: $T = 10$, 20, and 40 s) were then calculated.

Results: Strong correlations greater than 0.92 were observed between the $E95_{robust,20}$ and $E95_{robust,40}$ values. Meanwhile, irregular respiratory patterns with inconsistent amplitudes of motion created differences between the $E95_{robust,10}$ and $E95_{robust,40}$ values of $\geq$10 mm.

Conclusions: The accuracies of CMs derived using 20 s were almost identical to those obtained over 40 s, and superior to those obtained over 10 s.

Introduction

Respiratory motion creates uncertainty during beam delivery. If such motion is not managed, large margins should be added to clinical target volumes [1]. Several investigators have reported that use of large target volumes increased complications in normal tissues in lung and pancreatic cancer patients [2,3]. Management of respiratory motion is effective in reducing beam delivery to normal tissue, in turn, making it possible to escalate the dose to the tumor.

Respiration-synchronized beam delivery techniques that are used clinically to reduce the impact of respiratory motion can be separated broadly into three categories: breath-holding, respiratory gating, and dynamic tumor tracking (DTT) [4,5]. Of these, recent interest has focused on the DTT technique, which can be used to reposition the radiation beam dynamically with reference to the target position. Compared with breath-holding and respiratory gating, DTT can minimize the internal margins while maintaining a 100% duty cycle. This delivers the beam efficiently without the need for patients to hold their breath.

We have applied infrared (IR) marker-based DTT irradiation (IR Tracking) clinically using the Vero4DRT (Mitsubishi Heavy Industries [MHI], Ltd., Tokyo, Japan, and Brainlab AG, Feldkirchen, Germany) in treating lung cancer patients since September 2011

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[6–10]. IR Tracking is categorized as a hybrid DTT method that combines direct localization methods with an indirect DTT method [11]. IR Tracking observes external surrogate features and determines localization of the internal target using a correlation model (CM) derived from both one-dimensional (1D) surrogate data and 3D internal target data. A key issue in IR Tracking is the accuracy of the CM used [4,11]. A CM affected by poor precision will increase localization error. Before starting IR Tracking at each fraction, the vertical displacement of IR markers on the abdomen and the 3D position of a tumor, as indicated by implanted fiducial markers (detected target positions), are monitored for 20, 30, or 40 s to build a CM (Fig. 1). Vero4DRT users can select the training periods. We have used a modeling period of 40 s to acquire as much information as possible on the respiratory pattern. The 3D-predicted target position is then calculated during treatment, based on 1D surrogate data and the CM.

There are several reports on the tracking accuracy of IR Tracking. Mukumoto et al. [9] found that the 95th percentiles of overall targeting errors were up to 4.1 mm when a modeling period of 40 s was used. Depuydt et al. [12] typically used a modeling period of 20 s in a patient simulation study. However, these studies did not address the influence of different modeling periods on tracking accuracy. Also, our group has previously concluded that changes in breathing patterns, including baseline drift, reduced the correlation between internal target and external IR marker positions [8]. As a next step, based on those previous results, we believed that the modeling period could greatly influence the tracking accuracy.

The purpose of the present study was to compare the prediction accuracy using modeling periods of 10 and 20 s, rather than the 40 s currently used in the clinical construction of practical CMs in IR Tracking.

Materials and methods

Patients

We analyzed CMs retrospectively over a modeling period of 40 s for 10 consecutive lung cancer patients who underwent IR Tracking. Five patients were treated at Kyoto University Hospital and five at the Institute of Biomedical Research and Innovation. There were eight male patients and two females, with a median age of 85 (range, 60–87) years. Lung tumors were located in the right middle lobe (one patient), in the right lower lobe (six), and in the left lower lobe (three). Four or five fiducial markers, 1.5 mm in diameter, were implanted transbronchially around the lung tumor. An individualized vacuum pillow (Kyoto University Hospital: Bodyfix; Medical Intelligence, Schwabmünchen, Germany; Institute of Biomedical Research and Innovation: ESFORM Engineering System, Matsumoto, Japan) was made for each patient with both arms raised. Five IR markers were attached to the abdominal wall to allow monitoring of external respiratory signals. A CM remodeling was performed two or three times per treatment session to improve the prediction accuracy, and the median elapsed time prior to remodeling was 12 (range, 2–33) min.

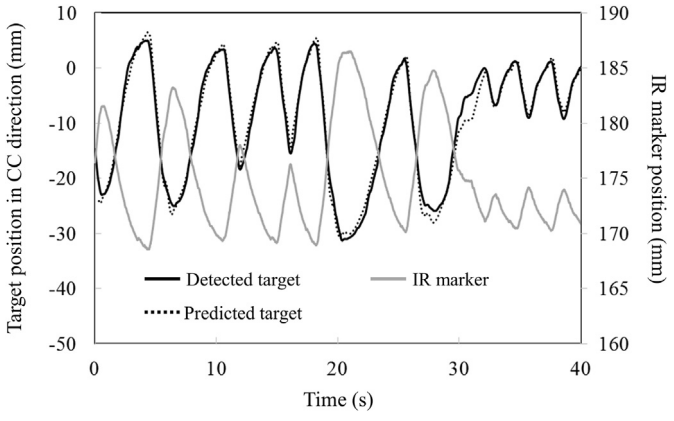

Figure 1. An example of a representative CM. The detected and predicted target positions in the CC direction and IR marker positions are shown.

In clinical practice, we monitored the implanted fiducial markers at a minimum monitoring interval of 1 s during beam delivery via orthogonal kV X-ray imaging. Circles with user-defined radii (3 mm at our hospital), placed around the predicted positions of the fiducial markers (tolerance circles), were displayed on monitor images to serve as benchmarks for CM remodeling. Vero4DRT does not support an auto CM updating function; thus, additional correlation modeling was needed to improve prediction accuracy during each treatment session if any systematic deviation between the positions of the fiducial markers and the tolerance circles was observed [8,9].

Calculating the predicted target position

Immediately after correction of any initial setup error caused by bony anatomy, an ExacTrac subsystem integrated into the Vero4DRT platform constructed a CM over a modeling period of 40 s. During the modeling period, the vertical displacement of IR markers on the abdomen (P_{IR}) values and the implanted fiducial markers were monitored simultaneously with an IR camera at 60 Hz and with an orthogonal kV X-ray imaging subsystem at 6.25 or 12.5 Hz. The sampling frequency changed automatically from 12.5 to 6.25 Hz when the velocity of IR marker motion (v_{IR}) decreased. The monitoring interval of 1 s remains the same, independent of the sampling frequency. The gantry and ring angle used for monitoring of implanted fiducial markers were determined with reference to the findings of our previous study [6]. In total, ~500-kV X-ray fluoroscopic image sets were acquired during a single correlation modeling session over 40 s. The imaging parameters were 110 kV, 100 mA, and 5 or 10 ms. These settings are the minima required to detect implanted fiducials in lung cancer cases. The CM was expressed using a quadratic function in terms of P_{IR} and v_{IR}, as follows:

$$F(P_{IR}, v_{IR}) = aP_{IR}^2 + bP_{IR} + c + dv_{IR}^2 + ev_{IR} \quad (1)$$

Three different CMs with modeling periods of 10, 20, and 40 s were constructed retrospectively from original CM log files using software developed in-house. The 10- and 20-s modeling periods were extracted from the beginning of the 40-s modeling period.

Based on available information from the vendor, the CM was built as following 1–4:

1. The predicted P_{IR} after 25 ms $[P'_{IR,k}(t+25)]$ was calculated from the previous multiple consecutive positions of the kth IR marker ($P_{IR,k}$; $1 \le k \le 5$) before time t, using an approximate linear equation derived using the weighted least-squares method. A time of 25 ms was required to compensate for the sub-system latency of IR marker position acquisition. Depuydt et al. [13] mentioned sub-system latencies in terms of the IR marker position acquisition of 25 ms. We were also informed of the latency of IR marker position acquisition by MHI and Brainlab AG. Details of the construction and the stability of the weighted least-squares model cannot be disclosed because of a provision in our contract with MHI and Brainlab AG.