Development of a video image-based QA system for the positional accuracy of dynamic tumor tracking irradiation in the Vero4DRT system

Kazuyu Ebe, Satoru Sugimoto, Satoru Utsunomiya, Hiroshi Kagamu, and Hidefumi Aoyama
Joetsu General Hospital, 616 Daido-Fukuda, Joetsu-shi, Niigata 943-8507, Japan
Satoru Utsunomiya, Hiroshi Kagamu, and Hidefumi Aoyama
Graduate School of Medical and Dental Sciences, Niigata University, Niigata 951-8510, Japan
Laurence Court
The University of Texas MD Anderson Cancer Center, Houston, Texas 77030-4009
Katsuichi Tokuyama, Ryuta Baba, Yoshisada Oghara, Kosuke Ichikawa, and Joji Toyama
Joetsu General Hospital, 616 Daido-Fukuda, Joetsu-shi, Niigata 943-8507, Japan

(Received 3 October 2014; revised 15 June 2015; accepted for publication 30 June 2015; published 21 July 2015)

Purpose: To develop and evaluate a new video image-based QA system, including in-house software, that can display a tracking state visually and quantify the positional accuracy of dynamic tumor tracking irradiation in the Vero4DRT system.

Methods: Sixteen trajectories in six patients with pulmonary cancer were obtained with the ExacTrac in the Vero4DRT system. Motion data in the cranio-caudal direction (Y direction) were used as the input for a programmable motion table (Quasar). A target phantom was placed on the motion table, which was placed on the 2D ionization chamber array (MatriXX). Then, the 4D modeling procedure was performed on the target phantom during a reproduction of the patient’s tumor motion. A substitute target with the patient’s tumor motion was irradiated with 6-MV x-rays under the surrogate infrared system. The 2D dose images obtained from the MatriXX (33 frames/s; 40 s) were exported to in-house video-image analyzing software. The absolute differences in the Y direction between the center of the exposed target and the center of the exposed field were calculated. Positional errors were observed. The authors’ QA results were compared to 4D modeling function errors and gimbal motion errors obtained from log analyses in the ExacTrac to verify the accuracy of their QA system. The patients’ tumor motions were evaluated in the wave forms, and the peak-to-peak distances were also measured to verify their reproducibility.

Results: Thirteen of sixteen trajectories (81.3%) were successfully reproduced with Quasar. The peak-to-peak distances ranged from 2.7 to 29.0 mm. Three trajectories (18.7%) were not successfully reproduced due to the limited motions of the Quasar. Thus, 13 of 16 trajectories were summarized. The mean number of video images used for analysis was 1156. The positional errors (absolute mean difference + 2 standard deviation) ranged from 0.54 to 1.55 mm. The error values differed by less than 1 mm from 4D modeling function errors and gimbal motion errors in the ExacTrac log analyses (n = 13).

Conclusions: The newly developed video image-based QA system, including in-house software, can analyze more than a thousand images (33 frames/s). Positional errors are approximately equivalent to those in ExacTrac log analyses. This system is useful for the visual illustration of the progress of the tracking state and for the quantification of positional accuracy during dynamic tumor tracking irradiation in the Vero4DRT system. © 2015 American Association of Physicists in Medicine. [http://dx.doi.org/10.1118/1.4926779]

Key words: dynamic tumor tracking irradiation, Vero4DRT, video image-based quality assurance

1. INTRODUCTION

In radiation therapy for thoracic and abdominal tumors, monitoring and managing respiratory motion is important to reduce positional and dosimetric uncertainty during beam delivery.1,2 A dynamic tumor tracking technique, the Vero4DRT system, has been reported as a promising approach to improve delivery accuracy.3–5 This technique provides continuous irradiation and enables rapid treatment. A Vero4DRT system (MHI-TM2000 Ver3.0.0; Mitsubishi Heavy Industries, Ltd., Tokyo, Japan, and Brainlab, Feldkirchen, Germany)6,7 was installed at Joetsu General Hospital in 2012. The Vero4DRT
system monitors the motion of passive infrared (IR) markers on the patient’s abdominal wall using the IR cameras of the ExacTrac system. The IR markers are used as surrogates to identify real-time target positions. A 4D modeling function correlates the motions of the IR markers and the motions of embedded fiducial markers. A pair of 4D data points (position and time) for the IR markers and internal fiducial gold markers are simultaneously acquired to establish a 4D modeling function before tracking irradiation. A gimbaled mechanism is used to swing the Linac toward the predicted target positions. This mechanism enables automatic tracking of the Linac axis with the moving object. This system performs continuous irradiation with megavoltage (MV) x-rays of the target under the surrogate IR system.

Respiratory wave forms differ depending on the individual patient and physiological conditions. The verification of the positional accuracy of the dynamic tumor tracking irradiation based on the patients’ trajectories provides clinical assurance for the Vero4DRT system. The reported positional accuracy of the Vero4DRT is quite high using a beam field light as well as film dosimetry.

The newly developed QA system mainly comprises a 2D ionization chamber (IC) array, a programmable motion table, and in-house video-image analyzing software. Distances in the cranio–caudal direction (Y direction) between the center of a moving object and the center of an exposed area were measured on each 30-ms image (33 frames/s). In this paper, we demonstrate that this video image-based QA system is useful in visually presenting the progression of a tracking state and evaluating positional errors during continuous irradiation with the Vero4DRT.

2. MATERIALS AND METHODS

2.A. Patients

Forty-second-long 4D data for sixteen target trajectories were obtained from six lung cancer patients treated between 2012 and 2013. 2D data (time and position in the cranio–caudal direction: Y direction) were used for phantom studies. The patient profiles are presented in Table I. Four patients were enrolled in preclinical studies (Joetsu IRB #55; the patients’ 4D data were acquired using treatment beams that were not irradiated), and two patients were enrolled in clinical practice (Joetsu IRB #76; treatment beams were irradiated).

Sphere gold markers with a diameter of 1.5 mm were inserted into the peripheral bronchi and embedded in pulmonary tissues so that the markers were adjacent to the tumor under bronchoscopy (BF 260, Olympus, Tokyo, Japan). The total number of implanted fiducial markers was more than three. Three is the minimum number of markers for dynamic tracking in the Vero4DRT system. Several days after implantation, the patient was set up in a treatment room using a pair of orthogonal kV images. After positioning the patient, a 4D modeling process was performed as follows: A pair of motion data points for the gold markers in the lung and motion IR markers on the abdominal wall were simultaneously acquired. The positions of the gold markers were calculated using the orthogonal kV images acquired every 80–160 ms, and the intervals depended on the velocity of the markers. The acquisition times ranged from 20 to 40 s. The gravity centers of the plural markers during motion were designated as “detected target positions” in the ExacTrac. The motions of the abdominal wall were acquired from the IR motion array attached to the patient’s abdominal wall. The array was composed of five passive IR markers placed on a resin plate whose motion was monitored by the IR camera on the ceiling of the treatment room every 15–20 ms. The 4D modeling function was automatically established by the ExacTrac system after correlating the 4D motion data of the target and the abdominal wall. Then, predicted target positions were calculated using the 4D modeling function in the ExacTrac system. After the 4D modeling process, dynamic tumor tracking irradiations were performed. The beam axis, regulated by the gimbal mechanism, was directed to the “predicted target positions” automatically calculated in ExacTrac using the established 4D modeling function. The function worked continuously at the rate of 50 times/s using the data from real-time IR marker positions (surrogate IR system).

In the treatment planning system (iPlan, Brainlab), the target position was set in the center of the planning target volume (PTV) on CT images in the breath-holding expiratory

| Case | Clinical condition | Age | Gender | Diagnosis | Site | TV (cm³) | Diameter (cm) | Fiducial markers | traj. (peak-to-peak: mm) | Total traj. |
|------|-------------------|-----|--------|-----------|------|---------|-------------|----------------|----------------------|-------------|
| 1    | Preclinical       | 86  | Male   | Primary LC | rt_lung_S8 | 4.11    | 2.0         | 4             | 25.20 32.60 25.30 3 | 3           |
| 2    | Preclinical       | 65  | Male   | Primary LC | rt_lung_S3 | 3.84    | 1.9         | 3             | 4.60 7.50 4.60 3 | 3           |
| 3    | Preclinical       | 64  | Male   | Metastatic LC | lt_lung_S1+2 | 1.53   | 1.4         | 3             | 4.20 4.40 4.30 3 | 3           |
| 4    | Preclinical       | 86  | Female | Primary LC | rt_lung_S6 | 25.79   | 3.7         | 4             | 29.00 23.50 31.90 3 | 3           |
| 5    | Practical        | 83  | Male   | Primary LC | lt_lung_S1+2 | 23.75   | 3.6         | 5, 3          | 2.70 0.80 None 2 | 2           |
| 6    | Practical        | 73  | Male   | Metastatic LC | rt_lung_S9 | 0.38    | 0.9         | 5, 4          | 15.00 26.80 None 2 | 2           |

Note: LC = lung cancer; TV = tumor volume; traj. = trajectory.

Medical Physics, Vol. 42, No. 8, August 2015
The PTV margin accounted for some factors such as tumor locations in the ten-phase 4DCT images, an estimated migration of plural markers, 4D modeling function errors, gimbals motion errors, and the estimated drift of the patient’s abdominal wall.

2.B. Composite phantom system

The entire phantom system is presented in Fig. 1. It mainly comprised three components: (1) a 2D IC array (MatriXX, IBA Dosimetry GmbH, Schwarzenbruck, Germany), (2) a programmable motion table (Quasar, Modus Medical Devices Inc., Ontario, Canada), and (3) two target phantoms: a cubic phantom for procedures of 4D modeling and an aperture lead block for MV x-ray irradiation.

The 2D IC array (MatriXX) was placed on a patient couch. The array contained 1020 ICs, and the volume of each IC was 0.08 cm³. The physical distance between ICs was 7.62 mm. A water-equivalent phantom (30 × 30 × 2 cm³ in size) was inserted between the MatriXX and the Quasar to maintain the horizontal level of the latter.

The programmable respiratory motion table (Quasar) was used to simulate pulmonary target motions. The motion table had two tables, one moved in the horizontal direction and the other in the vertical direction. The motion of the former table was synchronized with that of the latter one. For example, when the former began to move in the cranio direction (+Y direction), the latter moved in the posterior direction (−Z direction). The horizontal motion table was directed to move according to a programmed wave form. A motion IR marker array was placed on the vertical motion table.

The measured patient trajectories were used to drive the phantom motion. Those input files were automatically converted to Quasar respiratory motion (QRM) files. Approximately 10 s of constant data, as a baseline control, was added in front of the actual patient motion data. The amplitude level of these data was determined to avoid abrupt movement of the table. The horizontal motion table remained at the initial position of the patient motion data for 10 s. In this way, 16 patterns of motion in the Y direction in six patients were programmed.

A cubic phantom (5 × 5 × 5 cm³ in size) was prepared from cork containing a target of a metal ball of 1 cm in diameter embedded in its center. Four small metal balls as fiducial markers (1.4 mm in diameter, Suremark, Civco, Orange City) were attached to the cork surfaces. The cubic phantom was placed on a water-equivalent phantom (30 × 30 × 5 cm³ in size, 4.65 kg in weight) that was placed on the horizontal motion table of the Quasar. The center of the cubic phantom was set up at the isocenter.

The centers of the MatriXX IC region, Quasar horizontal motion table, and a cork phantom were aligned to the vertical axis in stationary conditions. All QA-components, including the two water-equivalent phantoms, consisted of five layers. The cubic phantom was moved according to a programmed file in the Y direction.

2.C. Dynamic tumor-tracking irradiation

A 4D modeling procedure was performed on the moving cork phantom for 40 s to establish the 4D modeling function [Fig. 1(a)]. A pair of orthogonal kV x-ray cameras were rotated at gantry angles of 45° and 315° to detect plural fiducial markers and avoid interruption by the metal target ball. The orthogonal kV images and the positional data of the motion IR markers were acquired at the same rate as in the patient study. A radiation dose was continuously administered to the MatriXX. The delivered dose was recorded by the MatriXX every 30 ms. The total number of dose data was 33/s × 40 s = 1320. Digital imaging and communication in medicine (DICOM) files were exported to the newly developed in-house video-image analyzing software named MHI-QA, which is based on the DD-System (R-Tech Inc., Tokyo, Japan; Fig. 2).

On a frame of the video images, two exposed fields of a square and a circle were identified using the threshold algo-
2. E. Scale evaluation for the MatriXX/DD-System

The motion distances detected by the MatriXX/DD-System were compared to those detected by the IR positioning system. The IR system was used as a control. Measurements were obtained as follows: An aperture lead block with attached passive IR markers was shifted from the origin to the desired 13 positions ranging from −10 to +10 mm in the Y direction with the aid of the Quasar driving system. Digital values of the IR positioning system were recorded before and after each shift. Any value shift in the Y direction was correlated to an IR scale. The aperture block was irradiated with 6-MV x-rays twice, once at the original position and second at the shifted position. The difference between the original position and the shifted position of an exposed circular field was obtained with the MatriXX/DD-System and assumed to be a scale in this QA system. A Linac head was directed at the isocenter of the Vero4DRT system and remained stationary. The x-ray field was 15 × 15 cm² in size.

2.F. Integration of six data sets

Figure 3 presents the integration process for the six data sets in the Y direction: (1) log data of detected target positions of a patient in the ExacTrac [patient’s tumor trajectory Fig. 3(a)]; (2) log data of programmed “QRM” [Fig. 3(b)]; (3) log data of detected target positions of a cubic phantom in the ExacTrac [cub motion, Fig. 3(c)]; (4) log data of the circular center motion in the DD-System [Fig. 3(d)]; (5) log data of the square center motion in the DD-System [Fig. 3(e)]; and (6) gimbal motion [Fig. 3(f), described in Sec. 2.H]. The three motion curves of (2)–(4) [Figs. 3(b)–3(d)] were translationally shifted to the original patient’s trajectory curve of (1) [Fig. 3(a)] and superimposed on it using digital values in spreadsheet software. The wave form and the peak-to-peak distance of the patient’s tumor trajectory were visually evaluated to verify reproducibility by QRM, by the cube motion detected with the Vero4DRT system, and by the circular center motion detected with the MatriXX/DD-System (reproducibility). Furthermore, the square center motion of (5) [Fig. 3(e)] and the gimbal motion of (6) [Fig. 3(f)] were superimposed on the patient’s tumor trajectory to verify the tracking state. Finally, five motion curves were superimposed on the patient’s tumor trajectory [Fig. 3(g)]. The time range when six wave forms appeared in the same form was determined and then designated as the “analyzed interval.” The log data in the Y direction during an analyzed interval were used for the QA analysis.
Integration of six $Y$ data sets in trajectory #1 as an example. Five waves [(b:2)–(f:6)] were superimposed on the patient’s trajectory (a:1) after translational shifts. The time interval when all six waves existed was determined for an analysis (g). In this case, patient tumor motion was reproduced by the Quasar [(b:2)–(d:4)], and the tracking irradiation by the Vero4DRT followed the Quasar motion during the analyzed interval of 35.7 s (from 0 to 35.7 s) [(c:5) and (f:6)].

2.G. Accuracy of the 4D modeling function

4D modeling function errors (predicted errors) were studied in a patient [Fig. 4(a)] and a phantom [Fig. 4(b)]. The positional data for the detected target positions and predicted target positions were recorded in the ExacTrac log file. The 4D modeling function errors in the $Y$ direction were defined as the absolute differences between the detected target positions and the predicted target positions in the $Y$ direction. The 4D modeling function errors were included in the positional errors during MV x-ray irradiation.

2.H. Accuracy of gimbal motion

Gimbal motion errors (mechanical errors) were studied [Fig. 4(d)]. The beam axis was directed to the predicted target positions using the gimbal mechanism. The actual gimbal angles (a tilt angle and a pan angle) and the predicted target positions were recorded in the ExacTrac log file. The gimbal axis was assumed to be the beam axis. The minimum distance between the gimbal axis and a predicted target position was geometrically calculated as follows: the gimbal axis was orthogonal to another axis that passed through the point of a predicted target position. The point of intersection on the gimbal axis was designated as the “gimbal position.” The gimbal motion error in the $Y$ direction was defined as the absolute value of the $Y$-component of the vector from the predicted target position to the gimbal position. The gimbal motion errors were included in the positional errors during MV x-ray irradiation as well as 4D modeling function errors.

2.I. Absolute differences

Figure 4 shows four types of absolute differences in the $Y$ direction: (1) 4D modeling function errors in the patient study [Fig. 4(a)]; (2) 4D modeling function errors in the phantom study [Fig. 4(b)]; (3) positional errors during tracking irradiation evaluated with the DD-System [Fig. 4(c)]; and (4) gimbal motion errors in the phantom study [Fig. 4(d)]. Absolute mean $\triangle Y$ (abs $m \triangle Y$) was defined as follows: $||\triangle Y1|| + ||\triangle Y2|| + \cdots + ||\triangle Yn||/n$ (n: number of $\triangle Y$). The analyzed intervals were the same as those described in Sec. 2.F.

Type (3) was compared to types (2) and (4) to verify the accuracy of our video image QA system. Type (1) was compared to type (2) to reveal the differences between the in vivo and in vitro predicted errors.

3. RESULTS

3.A. Scale evaluation for the MatriXX/DD-system

The MatriXX/DD-System scale was compared to an IR scale. A linear correlation was observed (correlation coefficient, $R = 0.9996$). The differences between the two scales were less than 1 mm at all 13 positions (motion range: ±10 mm).
Four types of absolute di-
motion of 30 mm.

Table III presents comparisons of the peak-to-peak
distances of the 13 patient trajectories and those of 5 types of
motions: (1) QRM motion vs patient trajectory in column (a);
(2) cube motion vs patient trajectory in column (b); (3) circular
center motion vs patient trajectory in column (c); (4) square
center motion vs patient trajectory in column (d); (5) gimbal
motion vs patient trajectory in column (e); and (6) square
center motion vs gimbal motion in column (f).

The differences in (1) [column (a) in Table III] ranged
from −0.04 to 0.40 mm (mean: 0.03 mm). The peak-to-peak
distances obtained from the QRM files were approximately
equivalent to those of the patients. A maximum difference of
0.40 mm was observed for trajectory #01. In this case, the
patient’s motion data were intermittent and were therefore
interpolated in the QRM file.

The differences in (2) [column (b)] and (3) [column (c)]
ranged from −0.90 to −0.30 mm (mean: −0.71 mm) and from
−1.13 to −0.02 mm (mean: −0.51 mm), respectively. The results for [(1)−(3)] demonstrated that the patients’ trajectories were reproduced by the Quasar with slightly smaller motions.

The differences in (4) [column (d)] and (5) [column (e)]
ranged from −1.17 to 0.69 mm (mean: −0.13 mm) and from
−0.89 to 0.91 mm (mean: −0.16 mm), respectively. The differences in (6) [column (f)] ranged from −0.59 to 0.46 mm (mean:
0.03 mm). The results for [(4)−(6)] indicated that the dynamic
tracking irradiation followed the patients’ trajectories with
small errors.

Thus, the peak-to-peak distances of the circular center
motions and square center motions analyzed in our video-image
analyzing system were approximately equivalent to the pa-
tients’ trajectories as well as those of the cube motions and
gimbal motions.

The statistical values of the positional errors obtained from
our QA system are presented in column (9), Table IV. The
absolute mean difference, sd, and “absolute mean difference
+ 2 sd” ranged from 0.22 to 0.70, 0.16 to 0.43, and 0.54 to
1.55, respectively (n = 13).

3.C. 4D modeling function errors

4D modeling function errors in the phantom study are pre-
sented in column (8), Table IV. The absolute mean difference,
sd, and absolute mean difference + 2 sd ranged from 0.08 to
0.32 mm, 0.06 to 0.28 mm, and 0.20 to 0.85 mm, respectively
(n = 13). These values were all less than 1 mm.

In the patient study, the error values of absolute mean
difference + 2 sd ranged from 0.36 to 4.77 mm [n = 13, column
(7), Table II]. These error values are all larger than those in
the phantom study [column (7) vs column (8)]. Differences of
greater than 1 mm were observed in case 1 (trajectories #01
and #03) and case 4 (trajectories #10 and #11).

3.D. Gimbal motion errors

Gimbal motion errors are presented in column (10), Ta-
bble IV. The absolute mean difference, sd, and absolute mean
difference + 2 sd ranged from 0.04 to 0.25 mm, 0.03 to
0.23 mm, and 0.09 to 0.70 mm, respectively (n = 13). These
values were all less than 1 mm.

Fig. 4. Four types of absolute differences in the Y direction (abs ΔY’s, magenta) are shown in trajectory #11 as an example. (a:7) Abs ΔY’s of the 4D modeling function as function errors (predicted errors) in the patient study [detected target positions (blue) vs predicted target positions (orange)] (n = 379); (b:8) abs ΔY’s of the 4D modeling function as function errors (predicted errors) in the phantom study [detected target positions (blue) vs predicted target positions (orange)] (n = 384); (c:9) abs ΔY’s of the exposed two fields analyzed with in-house video-image analyzing software as positional errors [circular center motion (blue) vs square center motion (orange)] (n = 1192); (d:10) abs ΔY’s of the gimbal motion as gimbal motion errors (mechanical errors) in the phantom study [predicted target positions (orange) vs gimbal positions (light orange)] (n = 1881). The analyzed interval was 35.7 s, equivalent to that in Fig. 3(g) (n: the total number of the analyzed log data for 35.7 s).

3.B. Video image analysis

The sixteen Y motions in six patients are presented in Fig. 5.
Each figure contains six waves as described in Sec. 2.F. The
summarized data are presented in Table II.

The mean number of analyzed video images was 1156.3
during the analyzed mean interval of 34.7 s (n = 13). The pixel
size values ranged from 1.69 to 1.74 mm [mean: 1.70, standard
deviation (sd): 0.05, n = 16].

The peak-to-peak distances ranged from 0.80 to 32.60 mm
in the data from the six patients (n = 16, Table II). Thirteen
of sixteen trajectories (81.3%) were successfully reproduced.
The distances of the reproduced trajectories ranged from 2.7
to 29.0 mm. Three (18.7%) were not successfully reproduced.
One (trajectory #14) had too little motion, 0.80 mm, to move
the Quasar motion table. The motion of the other two (trajec-
tories #02 and #12) was greater than the Quasar maximum
motion of 30 mm.
Fig. 5. Y motion curves superimposed on sixteen patients’ trajectories. Each figure contains six motion curves as shown in Fig. 3. An analyzed interval is shown in each figure. Thirteen of 16 patients’ trajectories were successfully reproduced. Three trajectories (#02, #12, and #14) were not successfully reproduced due to the limited motion of the Quasar.

3.E. Comparison of the function errors, gimbal motion errors, and QA results

Table IV presents the statistical values of the 4D modeling function errors in column (8), the QA results for the positional errors in column (9), and the gimbal motion errors in column (10). The statistical error values for the QA results were compared to the 4D modeling function errors and those of the gimbal motion errors. The values of the positional errors were all greater than those of the 4D modeling function errors and those of the gimbal motion errors in absolute mean difference, sd, and absolute mean difference + 2 sd, respectively. However, the maximum difference was 1 mm. The gimbal motion errors were smaller than the 4D modeling function errors, with the exception of the values of sd in trajectories #01 and #10.

4. DISCUSSION

Uncertainties in the dynamic tumor tracking irradiation system include several known factors: (1) the 4D modeling function errors, (2) the gimbal motion errors, (3) the migration of the fiducial markers,12,13 and (4) the migration of the surrogate IR markers during irradiation.14 In the ExacTrac log analyses, factors (1) and (2) were less than 1 mm. Mechanical errors [factor (2)] smaller than the predicted errors [factor (1)] have been reported previously,5 similar to our results. Factors
Table II. Peak-to-peak distances of six motion curves, 4D modeling function errors \((in vivo and in vitro)\), QA results for positional errors, gimbal motion errors, the total number of analyzed video images, the analyzed interval, and reproducibility are summarized for 16 patient trajectories. Each column presents the following: (1) the original patient trajectory \((detected target positions in the ExacTrac)\), denoted PT; (2) the programmed QRM file, denoted QRM; (3) the cube phantom trajectory \((detected target positions in the ExacTrac)\), denoted CU; (4) \("circular center positions" in the DD-System\), denoted DDI; (5) \("square center positions" in the DD-System\), denoted DDO; and (6) gimbal positions, denoted GB. Statistical values of \("abs m.Y + 2 sd"\) are presented in columns (7)–(10): (7) function errors in the patient \((detected target positions vs predicted target positions)\), denoted PFE; (8) function errors in the cube phantom \((detected target positions vs predicted target positions)\), denoted CFE; (9) positional errors in the DD-System \((circular center positions vs square center positions)\), denoted DDE; and (10) gimbal motion errors \((predicted target positions vs gimbal positions)\), denoted GBE. The number of analyzed images ranged from 1111 to 1247 \((n = 13)\). The analyzed intervals ranged from 33.3 to 37.4 s \((n = 13)\). The total number of the log data during the analyzed interval is shown as \(n^*\). Reproducibility was confirmed for 13 of 16 trajectories (81.3%). Three trajectories were not successfully reproduced \((**\)\). Column numbers (1)–(10) correspond to those in Figs. 3 and 4. Note that the error values in column (7) are all larger than those in column (8) \((n = 13)\).

| No. | traj. | Case | PT | QRM | CU | DDI | DDO | GB | PFE | CFE | DDE | GBE |
|-----|-------|------|----|-----|----|-----|-----|----|-----|-----|------|-----|
| 01  | Case1 | 1    | 25.20 | 25.60 | 24.90 | 24.51 | 25.89 | 26.11 | 2.13 | 0.66 | 1.55 | 0.65 | Yes |
| 02  | Case1 | 2    | 32.60 | 30.00 | 29.30 | 29.32 | 30.51 | 30.41 | 6.61 | 1.19 | 1.90 | 0.94 | No (**)
| 03  | Case1 | 3    | 25.30 | 25.26 | 24.50 | 24.17 | 25.71 | 25.56 | 3.56 | 0.83 | 1.50 | 0.62 | Yes |
| 04  | Case2 | 1    | 4.50 | 4.50 | 3.70 | 4.33 | 4.27 | 4.07 | 0.73 | 0.27 | 0.63 | 0.13 | Yes |
| 05  | Case2 | 2    | 7.50 | 7.49 | 6.80 | 6.96 | 7.25 | 7.10 | 1.18 | 0.28 | 0.97 | 0.16 | Yes |
| 06  | Case2 | 3    | 4.60 | 4.60 | 3.80 | 4.30 | 4.12 | 4.27 | 0.94 | 0.28 | 0.54 | 0.14 | Yes |
| 07  | Case3 | 1    | 4.20 | 4.20 | 3.50 | 4.18 | 3.63 | 3.62 | 1.16 | 0.20 | 0.68 | 0.11 | Yes |
| 08  | Case3 | 2    | 3.63 | 3337 | 209 | 1111 | 1114 | 1759 | 363 | 209 | 1111 | 1754 | 1111 |
| 09  | Case3 | 3    | 376 | 3740 | 234 | 1247 | 1247 | 1969 | 376 | 234 | 1247 | 1969 | 1247 |
| 10  | Case4 | 1    | 29.00 | 29.00 | 28.40 | 28.28 | 29.38 | 28.92 | 4.77 | 0.71 | 1.32 | 0.70 | Yes |
| 11  | Case4 | 2    | 349 | 3571 | 335 | 1191 | 1191 | 1880 | 349 | 335 | 1191 | 1880 | 1191 |
| 12  | Case4 | 3    | 23.50 | 23.50 | 22.90 | 22.64 | 23.29 | 23.88 | 6.11 | 0.34 | 1.33 | 0.65 | Yes |
| 13  | Case4 | 4    | 379 | 3554 | 384 | 1192 | 1192 | 1881 | 379 | 384 | 1192 | 1881 | 1192 |
| 14  | Case5 | 1    | 31.90 | 30.00 | 29.40 | 28.91 | 30.54 | 30.20 | 4.58 | 0.95 | 1.83 | 0.77 | No (**)
| 15  | Case5 | 2    | 322 | 3270 | 322 | 1091 | 1091 | 1722 | 322 | 322 | 1091 | 1722 | 1091 |
| 16  | Case5 | 3    | 2.70 | 2.71 | 1.90 | 2.38 | 2.05 | 1.81 | 0.38 | 0.20 | 0.82 | 0.12 | Yes |
| 17  | Case6 | 1    | 392 | 3410 | 214 | 1127 | 1127 | 1796 | 392 | 214 | 1127 | 1796 | 1127 |
| 18  | Case6 | 2    | 417 | 3451 | 217 | 1151 | 1151 | 1817 | 417 | 217 | 1151 | 1817 | 1151 |
| 19  | Case6 | 3    | 406 | 3440 | 215 | 1146 | 1146 | 1812 | 406 | 215 | 1146 | 1812 | 1146 |
| 20  | Case6 | 4    | 317 | 3550 | 343 | 1180 | 1180 | 1870 | 317 | 343 | 1180 | 1870 | 1180 |
| 21  | Case6 | 5    | 26.80 | 26.80 | 26.00 | 25.86 | 27.43 | 27.12 | 1.69 | 0.85 | 1.04 | 0.63 | Yes |
| 22  | Case6 | 6    | 0.96 | 0.96 | 0.96 | 0.96 | 0.96 | 0.96 | 0.96 | 0.96 | 0.96 | 0.96 | Yes |

Mean 13.62 13.65 12.91 13.10 13.48 13.45 — — — — 1156.3 34.7 (** not successful)
Sd 10.24 10.26 10.94 10.71 10.66 — — — — 39.8 1.2 successful
Maximum 29.00 29.00 28.40 28.28 29.38 28.92 4.77 0.85 1.55 0.70 1247 37.4 noises
Minimum 2.70 2.71 1.90 2.38 2.05 1.81 0.36 0.20 0.54 0.09 1111 33.3

(3) and (4) were not significant because fiducial markers and IR markers were fixed in our QA system. The positional error values \((absolute mean.Y + 2 sd)\) analyzed with the DD-System ranged from 0.54 to 1.55 mm during continuous irradiation. These error values were compared to factor (1) and factor (2) in 13 trajectories. The differences were less than 1 mm at maximum. Our QA results were approximately equivalent to those in the ExacTrac log analyses.

In this study, 13 of 16 patient trajectories were reproduced using Quasar, whose peak-to-peak distances ranged from 2.7 to 29.0 mm. Three were not successfully reproduced due to limited motion of the Quasar. Quasar motions detected with
### Table III. Comparisons of the peak-to-peak distances of the 13 patient trajectories and those of five types of motions in columns [(1)–(6)], Table II. Each column presents the following: (a) $\Delta_{QRM}$ motion vs patient trajectory; (b) $\Delta_{cube}$ motion vs patient trajectory; (c) $\Delta_{s}$ circular center motion vs patient trajectory; (d) $\Delta_{square}$ square center motion vs patient trajectory; and (e) $\Delta_{gimb}$ gimbal motion vs patient trajectory. The peak-to-peak distances of the circular center motions and square center motions obtained with our video-image analyzing system were approximately equivalent to those of the patient trajectories [(c) and (d)]. Note that columns (b) and (c) are all negative values showing slightly smaller motion of the patient trajectories. Column (f) was added to present the differences between the square center motions and gimbal motions. Abbreviations are the same as in Table II.

| No. traj. | Case          | $\Delta_{(2)QRM}$ vs (1)PT | $\Delta_{(3)CU}$ vs (1)PT | $\Delta_{(4)DDI}$ vs (1)PT | $\Delta_{(5)DDO}$ vs (1)PT | $\Delta_{(6)GB}$ vs (1)PT | $\Delta_{(5)DDO}$ vs (6)GB |
|----------|---------------|-----------------------------|---------------------------|-----------------------------|---------------------------|---------------------------|-----------------------------|
| 01       | Case1_1       | 0.40                        | -0.30                     | -0.69                       | 0.69                      | 0.91                      | -0.22                      |
| 03       | Case1_3       | -0.04                       | -0.80                     | -1.13                       | 0.41                      | 0.26                      | 0.15                       |
| 04       | Case2_1       | 0.00                        | -0.80                     | -0.17                       | -0.23                     | -0.43                     | 0.19                       |
| 05       | Case2_2       | -0.01                       | -0.70                     | -0.54                       | -0.25                     | -0.40                     | 0.15                       |
| 06       | Case2_3       | 0.00                        | -0.80                     | -0.30                       | -0.48                     | -0.33                     | -0.16                      |
| 07       | Case3_1       | 0.00                        | -0.70                     | -0.02                       | -0.57                     | -0.58                     | 0.01                       |
| 08       | Case3_2       | 0.08                        | -0.60                     | -0.23                       | -1.17                     | -0.68                     | -0.49                      |
| 09       | Case3_3       | 0.00                        | -0.80                     | -0.17                       | -0.63                     | -0.58                     | -0.05                      |
| 10       | Case4_1       | 0.00                        | -0.60                     | -0.72                       | 0.38                      | -0.08                     | 0.46                       |
| 11       | Case4_2       | 0.00                        | -0.60                     | -0.86                       | -0.21                     | 0.38                      | -0.59                      |
| 13       | Case5_1       | 0.01                        | -0.80                     | -0.32                       | -0.65                     | -0.89                     | 0.24                       |
| 15       | Case6_1       | 0.00                        | -0.90                     | -0.53                       | 0.34                      | -0.05                     | 0.38                       |
| 16       | Case6_2       | 0.00                        | -0.80                     | -0.94                       | 0.63                      | 0.32                      | 0.31                       |

| Mean     | 0.03          | -0.71                      | -0.51                     | -0.13                       | -0.16                     | 0.03                      |
| Sd       | 0.11          | 0.15                       | 0.33                      | 0.55                       | 0.49                      | 0.31                       |
| Maximum  | 0.40          | -0.30                      | -0.02                     | 0.69                       | 0.91                      | 0.46                       |
| Minimum  | -0.04         | -0.90                     | -1.13                     | -1.17                     | -0.89                     | -0.59                     |
| $n$      | 13            | 13                        | 13                       | 13                        | 13                       | 13                        |

Table IV. Comparisons of statistical error values in the phantom QA study. The 4D modeling functions in the phantom studies were more accurate than those in the patient studies [column (7) vs column (8) in Table II]. In the Quasar phantom, the motions of the target (target signals) and the IR markers (external signals) synchronized perfectly. Thus, the correlation between placement of a heavy phantom on the Quasar motion table reduced its stroke.

| No. traj. | Case          | Abs mean $\Delta Y$ (mm) | Sd (mm) | Abs mean $\Delta Y + 2$ sd (mm) |
|-----------|---------------|--------------------------|---------|---------------------------------|
| 01        | Case1_1       | 0.28                     | 0.69    | 0.25                            | 0.19                      | 0.43                       | 0.20                      | 0.66                      | 1.55                      | 0.65                       |
| 03        | Case1_3       | 0.29                     | 0.70    | 0.20                            | 0.27                      | 0.40                       | 0.21                      | 0.83                      | 1.50                      | 0.62                       |
| 04        | Case2_1       | 0.12                     | 0.26    | 0.05                            | 0.07                      | 0.19                       | 0.04                      | 0.27                      | 0.63                      | 0.13                       |
| 05        | Case2_2       | 0.12                     | 0.44    | 0.06                            | 0.08                      | 0.26                       | 0.05                      | 0.28                      | 0.97                      | 0.16                       |
| 06        | Case2_3       | 0.13                     | 0.22    | 0.05                            | 0.07                      | 0.16                       | 0.04                      | 0.28                      | 0.54                      | 0.14                       |
| 07        | Case3_1       | 0.08                     | 0.30    | 0.04                            | 0.06                      | 0.19                       | 0.03                      | 0.20                      | 0.68                      | 0.11                       |
| 08        | Case3_2       | 0.10                     | 0.47    | 0.04                            | 0.07                      | 0.24                       | 0.03                      | 0.24                      | 0.96                      | 0.11                       |
| 09        | Case3_3       | 0.09                     | 0.25    | 0.05                            | 0.06                      | 0.18                       | 0.04                      | 0.22                      | 0.60                      | 0.12                       |
| 10        | Case4_1       | 0.26                     | 0.59    | 0.24                            | 0.22                      | 0.36                       | 0.23                      | 0.71                      | 1.32                      | 0.70                       |
| 11        | Case4_2       | 0.32                     | 0.57    | 0.24                            | 0.24                      | 0.38                       | 0.21                      | 0.81                      | 1.33                      | 0.65                       |
| 13        | Case5_1       | 0.08                     | 0.35    | 0.04                            | 0.06                      | 0.23                       | 0.03                      | 0.20                      | 0.82                      | 0.09                       |
| 15        | Case6_1       | 0.17                     | 0.62    | 0.14                            | 0.15                      | 0.37                       | 0.11                      | 0.47                      | 1.36*                     | 0.36**                     |
| 16        | Case6_2       | 0.29                     | 0.36    | 0.19                            | 0.28                      | 0.34                       | 0.22                      | 0.85                      | 1.04                      | 0.63                       |

| Maximum      | 0.32                     | 0.70                     | 0.25                      | 0.28                      | 0.43                       | 0.23                      | 0.85                      | 1.55                      | 0.70                       |
| Minimum      | 0.08                     | 0.22                     | 0.04                      | 0.06                      | 0.16                       | 0.03                      | 0.20                      | 0.54                      | 0.09                       |
| $n$          | 13                       | 13                       | 13                       | 13                       | 13                       | 13                       | 13                       | 13                       | 13                       |
ACKNOWLEDGMENTS

The authors are deeply grateful for Professor Masahiro Hiraoka and Professor Keisuke Sasai for their encouragement and Dr. Mitsuhiro Nakamura for his useful comments. The authors thank R-Tech Inc., Tokyo, Japan, for their assistance in developing the in-house video-image analyzing software. The authors thank Becky Agatsuma, Miyoko Shibata, and Carole Quas for preparing the paper. The authors have no conflicts of interest to declare.

Author to whom correspondence should be addressed. Electronic mail: nr24490@nifty.com; Telephone: +81-25-524-3000; Fax: +81-25-524-3002.

1. P. J. Keall, G. S. Mageras, J. M. Balter, R. S. Emery, K. M. Forster, S. B. Jiang, J. M. Kapatoes, D. A. Low, M. J. Murphy, B. R. Murray, C. R. Ramsey, M. B. Van Herk, S. S. Vedam, J. W. Wong, and E. Yorke, “The management of respiratory motion in radiation oncology report of AAPM Task Group 76,” Med. Phys. 33, 3874–3900 (2006).

2. S. H. Benedict, K. M. Yenice, D. Followill, J. M. Galvin, W. Hinson, B. Kavanagh, P. Keall, M. Lovelock, S. Meeks, L. Papiez, T. Purdie, R. Sadagopan, M. C. Schell, B. Salter, D. J. Schlesinger, A. S. Shiu, T. Solberg, D. Y. Song, V. Stieber, and R. Timmerman, “Stereotactic body radiation therapy: The report of AAPM Task Group 101,” Med. Phys. 37, 4078–4101 (2010).

3. T. Depuydt, D. Verellen, O. Haas, T. Gevaert, N. Linthout, M. Duchateau, K. Tournel, T. Reyniers, K. Leysen, M. Hoogeman, G. Storme, and M. De Ridder, “Geometric accuracy of a novel gimbals based radiation therapy tumor tracking system,” Radiother. Oncol. 98, 365–372 (2011).

4. T. Depuydt, K. Poels, D. Verellen, B. Engels, C. Collen, C. Haerbeke, T. Gevaert, N. Buls, G. Van Gompel, T. Reyniers, M. Duchateau, K. Tournel, M. Boussaert, F. Steenbeke, F. Vandenbroucke, and M. De Ridder, “Initial assessment of tumor tracking with a gimballed Linac system in clinical circumstances: A patient simulation study,” Radiother. Oncol. 106, 236–240 (2013).

5. N. Mukumoto, M. Nakamura, A. Sawada, Y. Suzuki, K. Takahashi, Y. Miyabe, S. Kaneko, T. Mizowaki, M. Kokubo, and M. Hiraoka, “Accuracy verification of infrared marker-based dynamic tumor-tracking irradiation using the gimbaled x-ray head of the Vero4DRT (MHI-TM2000),” Med. Phys. 40, 041706 (pp.) (2013).

6. Y. Kamino, K. Takayama, M. Kokubo, Y. Narita, E. Hirai, N. Kawawada, T. Mizowaki, Y. Nagata, T. Nishidai, and M. Hiraoka, “Development of a four-dimensional image-guided radiotherapy system with a gimbaled x-ray head,” Int. J. Radiat. Oncol., Biol., Phys. 66, 271–278 (2006).

7. Y. Kamino, S. Miura, M. Kokubo, I. Yamashita, E. Hirai, M. Hiraoka, and J. Ishikawa, “Development of an ultrasmall C-band linear accelerator guide for a four-dimensional image-guided radiotherapy system with a gimbaled x-ray head,” Med. Phys. 34, 1797–1808 (2007).

8. L. T. Wang, T. D. Solberg, P. M. Medin, and R. Boone, “Infrared patient positioning for stereotactic radiosurgery of extracranial tumors,” Comput. Biol. Med. 31, 101–111 (2001).

9. K.-H. Cheong, S.-K. Kang, M. Lee, S. S. Kim, S. Park, T. J. Hwang, K. J. Kim, D. H. Oh, H. Bae, and T. S. Suh, “Evaluation of delivered monitor unit accuracy of gated step-and-shoot IMRT using a two-dimensional detector array,” Med. Phys. 37, 1146–1151 (2010).

10. C. Ong, W. F. Verbakel, J. P. Cuijpers, B. J. Slotman, and S. Senan, “Dosiometric impact of interplay effect on RapidArc lung stereotactic treatment delivery,” Int. J. Radiat. Oncol., Biol., Phys. 79, 305–311 (2011).

11. C. W. Hurkmans, M. van Lieshout, D. Schuring, M. J. van Heumen, J. P. Cuijpers, F. J. Lagerwaard, J. Widder, U. A. van der Heide, and S. Senan, “Quality assurance of 4D-CT scan techniques in multicenter phase III trial of surgery versus stereotactic radiosurgery (radiosurgery or surgery for operable early stage (stage 1A) non-small-cell lung cancer (ROSEL) study),” Int. J. Radiat. Oncol., Biol., Phys. 80, 918–927 (2011).

12. M. Imura, K. Yamazaki, H. Shirato, R. Onimaru, M. Fujino, S. Shimizu, T. Harada, S. Ogura, H. Dosaka-Akita, K. Miyasaka, and M. Nishimura, “Insertion and fixation of fiducial markers for setup and tracking of lung tumors in radiotherapy,” Int. J. Radiat. Oncol., Biol., Phys. 63, 1442–1447 (2005).

13. K. Taguchi, K. Ebe, A. Hiyama, K. Tsukamoto, H. Sasai, Y. Nakashima, S. Yamatogi, R. Kanzaki, T. Matsumoto, and N. Matsunaga, “Changes in the distance between an internal fiducial marker and a motion tumor on fluoroscopic real-time tumor-tracking system evaluated with an in-room CT system,” Int. J. Radiat. Oncol., Biol., Phys. 66, S612 (2006).

14. M. Akimoto, M. Nakamura, N. Mukumoto, H. Tanabe, M. Yamada, Y. Matsu, H. Mouzen, T. Mizowaki, M. Kokubo, and M. Hiraoka, “Predictive uncertainty in infrared marker-based dynamic tumor tracking with Vero4DRT,” Med. Phys. 40, 091705 (8pp.) (2013).