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Technical note

Effect of image quality on correlation modeling error using a fiducial marker in a gimbaled linear accelerator

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ABSTRACT

The purpose of this study was to investigate the effect of image quality under various imaging parameters (60, 70, 80, 90, 100, 110, and 120 kV at 200 mA and 10 ms/63, 80, 100, 160, 200, 250, and 320 mA at 120 kV and 10 ms) and the diameter of the fiducial marker (0.25, 0.50, 0.75, and 1.10 mm) on the correlation modeling error for dynamic tumor tracking (DTT) in the Vero4DRT system. Each fiducial marker was inserted into the center of the $30 \times 30 \times 10 \text{ cm}^3$ water-equivalent phantom. A programmable respiratory motion table was used to simulate breathing-induced organ motion, with an amplitude of $\pm 20 \text{ mm}$ and a breathing cycle of 4 s. The correlation modeling error was calculated from the absolute difference between the detected and predicted target positions in the cranio-caudal direction. The image contrast of the fiducial marker was enhanced with increasing kV and mA. Increasing the diameter of the fiducial marker also enhanced the image contrast. Correlation-modeling error does not depend on the image quality and fiducial marker diameter. A lower kV setting did not generate a 4D model due to poor image contrast. All fiducial marker diameters were identified as good candidates for DTT in the Vero4DRT system.

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1. Introduction

Respiratory motion is an important issue that may affect the radiation treatment of tumors located in the thoracic or upper abdominal regions. Various methods, such as forced shallow-breathing, breath holding, and respiratory gating, have been

proposed to reduce the impact of respiratory-induced tumor motion.¹ The most recent technique for respiratory-induced tumor motion compensation is real-time tumor tracking,² such as dynamic tumor tracking (DTT).^{3–6} The Vero4DRT™ system is a four-dimensional (4D) radiation therapy system, which uses a correlation model (4D modeling).

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Fig. 1 – Experimental setup. The Visicoil fiducial marker was inserted into the center of the tough water (TW) phantom, which was constructed using a bolus. An infrared (IR) marker phantom was placed on the table that moved in the vertical direction motion.

The 4D modeling function correlates the motions of the infrared (IR) markers on the abdominal wall and the motions of implanted fiducial markers in or near the target. 4D modeling error substantially increases with the increasing amplitude and decreasing period of the motion of the target.⁷ Two types of fiducials are available with the Vero4DRT system; one is a spherical marker, and the other is a cylindrical marker.

The 4D modeling process is achieved by detecting implanted fiducial markers in kilovoltage (kV) X-ray images acquired before treatment. Our experience with DTT suggests that an ambiguous image of a fiducial marker makes it difficult to create a 4D model. Fiducial markers must be clearly identified for the 4D modeling process, and image quality may have an effect on the 4D modeling error. Most of the published reports on the evaluation of fiducial markers for image-guided radiation therapy (IGRT) have not included their effects on a 4D model.^{8–10} The purpose of this study was to investigate the impact of image quality on the 4D modeling error and focus on the impact of the diameter of the fiducial marker.

2. Materials and methods

The Vero4DRT system (Mitsubishi Heavy Industries Ltd., Tokyo, Japan; BrainLAB AG, Feldkirchen, Germany) was used in this study. The characteristics of the Vero4DRT system have been described previously.^{3–7} The dual kV X-ray imaging subsystem is mounted on the O-ring-shaped gantry, and the IR camera system is attached to the ceiling in the treatment room. The dual orthogonal kV X-ray imaging subsystem is capable of simultaneously acquiring orthogonal radiographic images at arbitrary gantry angles. The Vero4DRT system provides patient positioning and 4D model functions by integrating the ExacTrac system, ver. 3.5.3 (BrainLAB AG).

The 4D modeling function was automatically established by the ExacTrac system after correlating the 4D motion of the target and the surrogate IR marker.

This study consisted of two parts: (1) an investigation of the image quality, and (2) determination of the 4D modeling error under various imaging parameters. We used VisicoilTM gold markers (IBA Dosimetry GmbH, Schwarzenbruck, Germany), with diameters of 0.25, 0.50, 0.75, and 1.10 mm and a length of 10 mm.

First, we evaluated the quantitative assessments of the visibility of each fiducial marker under various imaging parameters. Each fiducial marker was inserted into the center of the $30 \times 30 \times 10 \text{ cm}^3$ Tough Water (TW) phantom (Kyoto Kagaku Co., Ltd., Kyoto, Japan), which had been constructed using a 10-mm thick layer ($5 \text{ mm} \times 2$) of CLEARFIT bolus (Fujidenolo Co., Ltd., Nagoya, Japan). Images of the Tough Water (TW) phantom were taken using computed tomography (CT) (Optima CT 580W, GE Healthcare, Milwaukee, WI, USA). CT images were acquired according to our standardized treatment-planning body protocol with 120 kV, 400 mAs, 500-mm field of view (FOV), and 1.25 mm slice thickness. Transversal pixel resolution was 0.977 mm. An iPlan RT Dose treatment planning system, version 4.5.3 (BrainLAB AG) was used to plan the design. This plan was transferred to the Vero4DRT and ExacTrac systems (BrainLAB AG), and the implanted marker was defined by the planning CT on the ExacTrac system. The phantom system is shown in Fig. 1. The gantry angle was set to 0 degrees; thus, the X-ray tubes were set to 315 and 45 degrees. The phantom was then imaged under the following conditions:

- 1) Tube-voltage dependence: 60, 70, 80, 80, 90, 100, 110, and 120 kV at 200 mA and 10 ms.

Fig. 2 – kV X-ray imaging radiographs taken at 60 kV and 120 kV. Fiducial marker's diameters of (a) 0.25, (b) 0.50, (c) 0.75, and (d) 1.10 mm.

- 2) Tube-current dependence: 63, 80, 100, 160, 200, 250, and 320 mA at 120 kV and 10 ms.

Each image was extracted using ImageJ software v. 1.49 (National Institutes of Health, Bethesda, MD, USA). The statistical information of the fiducial marker and the background was used to calculate the image contrast, as follows:

$$(1) \text{image contrast} = \frac{I_{SM} - S_B}{I}$$

where S_M is the intensity produced by the fiducial markers and S_B is the background signal intensity.

The maximum signal intensity was used to ensure that the most visible part of each fiducial marker was recorded and analyzed. Exposure doses per shot were evaluated using a real-time air ionization chamber (AccuGold, Radcal, Monrovia, CA, USA) at the isocenter in the air.

Next, we evaluated the influence of the 4D modeling error of each fiducial marker under various image qualities. The programmable dynamic phantom (CIRS Inc., Norfolk, VA, USA), capable of producing motion based on an arbitrary input function, was used to simulate breathing-induced organ motion synchronously with a respiratory surrogate. Dobashi et al. reported that mean $\pm$ SD respiratory cycle averaged over all patients was 4.1 ± 1.3 s.¹¹ Therefore, the dynamic phantom was moved in the caudal–cranial (CC) direction in a 1D sinusoidal pattern, with an amplitude of ± 20 mm and a breathing cycle of 4 s, synchronously with the IR markers. The fiducial marker and the IR surrogate markers were simultaneously acquired to calculate the 4D modeling function. The motion of the surrogate was acquired from the IR markers attached to the phantom, which were monitored by the IR camera on the ceiling of the treatment room every 16.7 ms. The sampling interval of the kV X-ray images automatically changed to 640 ms when the velocity of the IR marker motion decreased. The acquisition times ranged from 20 to 40 s. The 4D model was created under the same image parameters as mentioned above. The 4D model was expressed as a quadratic equation involving IR marker positions and the speed of the IR marker motion.¹² The position of the fiducial marker during motion was defined as the detected target position. The

target position calculated by the 4D modeling function is defined as the predicted target position. The 4D modeling error was calculated from the absolute difference between the detected and predicted target position in the CC direction. The mean and standard deviations were displayed on the screen of the Vero4DRT system in the 4D modeling phase, and were utilized to investigate the 4D modeling error.

3. Results

Figs. 2 and 3 show the fiducial marker kV planar images at various kV and mA settings, respectively. All fiducial markers could be observed under various kV and mA settings. Fig. 4 shows the plot of the image contrast between the fiducial marker and the background as a function of kV and mA, respectively. The image contrast was enhanced with increasing kV and mA for the fiducial marker. In addition, increasing the fiducial marker's diameter resulted in enhanced image contrast. The average and standard deviation of the 4D modeling error are summarized in Tables 1 and 2. A low kV setting did not generate a 4D model. A 120-kV setting can generate a 4D model at any mA setting. 4D modeling error does not depend on a fiducial marker diameter or image quality, as long as a 4D model is created. Fig. 5 shows that the measured doses were highly linear as a function of kV and mA settings, with a coefficient of determination of $R^2 = 0.992$ and $R^2 = 0.9996$, respectively. Increasing the kV and mA settings resulted in an increased exposure dose.

4. Discussion

We investigated the effect of fiducial marker image quality on the 4D modeling error for DTT in the Vero4DRT system. Our study compared four different diameters of fiducial markers and demonstrated that the image contrast of fiducial markers significantly increased with an increase in kV and mA settings and improved visibility. Handsfield et al. reported that the image contrast increased with kV and mA values

Fig. 3 – kV X-ray imaging radiographs taken at 63 mA and 320 mA. Fiducial marker's diameters of (a) 0.25, (b) 0.50, (c) 0.75, and (d) 1.10 mm.

Fig. 4 – Change in image contrast with variation in (a) kV settings with 200 mA and 10 ms held constant and (b) mA settings with 120 kV and 10 ms held constant.

of gold, carbon, and polymer fiducial markers; gold was the most pronounced.⁹ X-ray image contrast is produced because X-ray penetration through an object differs from the penetration through adjacent background tissue. As kVp increases, more Compton interactions are involved between photons and materials. Materials with higher atomic numbers, such

as gold, absorb more photons and result in significant contrast enhancement. Therefore, a lower kV setting did not generate a 4D model due to a poor image contrast due to the small diameter. The phantom study suggested that the image contrast of the fiducial marker has a small effect on the 4D modeling error, except at lower voltage settings. In addition, a 120-kV setting

Table 1 – Mean and standard deviation of 4D modeling error at various kV settings.

kV	Fiducial marker diameter			
	0.25 mm	0.50 mm	0.75 mm	1.10 mm
60	NA	NA	NA	0.56 ± 0.42
70	NA	NA	0.65 ± 0.44	0.42 ± 0.31
80	NA	NA	0.35 ± 0.18	0.34 ± 0.19
90	0.52 ± 0.39	0.44 ± 0.36	0.35 ± 0.19	0.37 ± 0.29
100	0.50 ± 0.36	0.39 ± 0.30	0.37 ± 0.30	0.34 ± 0.19
110	0.62 ± 0.40	0.4 ± 0.37	0.35 ± 0.20	0.33 ± 0.25
120	0.48 ± 0.35	0.33 ± 0.22	0.37 ± 0.24	0.36 ± 0.17

NA: this parameter cannot create a 4D model.

Table 2 – Mean and standard deviation of 4D modeling errors at various mA settings.

mA	Fiducial marker diameter			
	0.25 mm	0.50 mm	0.75 mm	1.10 mm
63	0.54 ± 0.38	0.34 ± 0.20	0.35 ± 0.22	0.41 ± 0.36
80	0.32 ± 0.21	0.47 ± 0.36	0.33 ± 0.20	0.38 ± 0.29
100	0.36 ± 0.23	0.53 ± 0.38	0.34 ± 0.23	0.36 ± 0.20
160	0.41 ± 0.31	0.37 ± 0.32	0.40 ± 0.32	0.35 ± 0.19
200	0.48 ± 0.35	0.33 ± 0.22	0.40 ± 0.31	0.34 ± 0.23
250	0.45 ± 0.37	0.36 ± 0.32	0.34 ± 0.18	0.33 ± 0.20
320	0.36 ± 0.18	0.34 ± 0.24	0.37 ± 0.24	0.36 ± 0.17

Fig. 5 – Change in exposure dose with variations in (a) kV settings with 200 mA and 10 ms held constant and in (b) mA settings with 120 kV and 10 ms held constant.

can generate 4D modeling at any low mA setting. Therefore, the user can select any diameter of the fiducial marker for DTT in the Vero4DRT system. It should be selected according to CT scan protocols and magnetic resonance imaging (MRI) sequences for follow-up in order to reduce image artifacts and ensure the visibility of the markers.⁸ Smaller gold markers may be used to reduce artifacts when using kV imaging alone. Fiducial markers should be implanted close to the target volume to reduce variation in inter- and intra-fractional motions, and may influence the dose due to the high atomic number.¹³ Large gold fiducial markers result in extensive metal artifacts on the CT image and interfere with structure delineation and dose calculation. A larger fiducial marker also requires a larger-diameter needle to insert, and causes pain. However, a discussion of these topics is beyond the scope of this work.

In clinical practice, we monitored an implanted fiducial marker on orthogonal kV X-ray images during beam delivery. The predicted positions with arbitrary tolerance circles around the fiducial marker were displayed, and if the fiducial marker deviated from these tolerance circles, the radiation source should be shut down. Therefore, some visibility is necessary. High-kV and -mA settings showed benefits for clinical practice over low-kV and -mA settings. However, increasing the kV and mA also increased the exposure dose. Although the dose due to image guidance is small in the context of the uncertainty in therapy dose delivery, per standard radiation safety principles, any unnecessary exposure to radiation for patients should be minimized.

We selected a diameter of 0.75 mm for the first clinical application of treatment for a patient with liver cancer. Further studies will be reported as the results are obtained.

A limitation of this study was that it was performed under a 1D sinusoidal regulated moving target in the CC direction only. Further studies should investigate the relationship between image quality and the 4D modeling error under various breathing patterns. Another limitation is that the study was performed using kV tube angles of 315 and 45 degrees. The optimal X-ray monitoring angle to create a 4D model should be investigated in consideration of the intensity ratio of gold fiducial markers, which is decreased due to reduced radiation dose as it travels through tissues.¹⁴

5. Conclusions

In conclusion, we evaluated the influence of imaging qualities on a 4D modeling process in the Vero4DRT system using a fiducial marker. Imaging quality and variation in the diameter of the fiducial marker did not depend on the 4D modeling error, as long as the 4D model was created. A lower kV setting did not generate a 4D model due to a poor image contrast. All fiducial marker diameters were identified as good candidates for use in DTT, even those with small diameters.

Conflict of interest

None declared.

Financial disclosure

None declared.

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