Quantification of the kV X-ray imaging dose during real-time tumor tracking and from three- and four-dimensional cone-beam computed tomography in lung cancer patients using a Monte Carlo simulation

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ABSTRACT

Knowledge of the imaging doses delivered to patients and accurate dosimetry of the radiation to organs from various imaging procedures is becoming increasingly important for clinicians. The purposes of this study were to calculate imaging doses delivered to the organs of lung cancer patients during real-time tumor tracking (RTTT) with three-dimensional (3D), and four-dimensional (4D) cone-beam computed tomography (CBCT), using Monte Carlo techniques to simulate kV X-ray dose distributions delivered using the Vero4DRT. Imaging doses from RTTT, 3D-CBCT and 4D-CBCT were calculated with the planning CT images for nine lung cancer patients who underwent stereotactic body radiotherapy (SBRT) with RTTT. With RTTT, imaging doses from correlation modeling and from monitoring of imaging during beam delivery were calculated. With CBCT, doses from 3D-CBCT and 4D-CBCT were also simulated. The doses covering 2-cc volumes ($D_{2cc}$) in correlation modeling were up to 9.3 cGy for soft tissues and 48.4 cGy for bone. The values from correlation modeling and monitoring were up to 11.0 cGy for soft tissues and 59.8 cGy for bone. Imaging doses in correlation modeling were larger with RTTT. On a single 4D-CBCT, the skin and bone $D_{2cc}$ values were in the ranges of 7.4–10.5 cGy and 33.5–58.1 cGy, respectively. The $D_{2cc}$ from 4D-CBCT was approximately double that from 3D-CBCT. Clinicians should Figure that the imaging dose increases the cumulative doses to organs.

Keywords: real-time tumor tracking; 4D-CBCT; imaging dose; Monte Carlo simulation

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INTRODUCTION

Image-guided radiotherapy (IGRT) is a technology that enables localizing of a tumor with millimeter accuracy, by correcting intra- and interfraction geometric uncertainties. IGRT helps to maximize the potential of advanced radiation therapy techniques that are intended to spare healthy tissue as much as possible.

It is well known that respiratory motion can lead to uncertainty during beam delivery. IGRT shows advantages, especially when treating respiratory motion-susceptible tumors, such as lung, liver, and pancreatic cancers [1]. The American Association of Physicists in Medicine (AAPM) Task Group 76 suggested several motion management techniques, such as motion-encompassing, breath-holding, respiratory gating, and real-time tumor tracking (RTTT), to overcome the shortcomings due to respiratory motion [1].

Appropriate IGRT techniques differ for these various motion management techniques. Three-dimensional cone-beam computed tomography (3D-CBCT) finds the daily target position, enabling online correction of target position errors before treatment for motion-encompassing [2] and breath-holding techniques [3]. Four-dimensional (4D) CBCT has been used in clinical practice [4–6]. An advantage of 4D-CBCT over 3D-CBCT is that not only interfraction, but also intrafraction geometric uncertainties in the target position can be assessed before treatment [5, 6]. In addition to 3D-CBCT and 4D-CBCT, kV X-ray fluoroscopy is used clinically to monitor internal target motion, as in real-time tumor tracking (RTTT) systems [7] and kilovoltage intrafraction monitoring (KIM) [8].

Recently, RTTT has attracted much interest as a beam delivery technique for minimizing the impact of respiratory motion. RTTT can reposition the radiation beam according to target position, and is categorized into direct, indirect and hybrid approaches [9]. In direct RTTT, an internal target is used to reposition the radiation beams in real time. By contrast, in indirect RTTT, external surrogate features are used to estimate the location of the internal target. Hybrid RTTT combines direct and indirect RTTT. In any of these approaches, the patient is exposed continuously to kV X-rays to ensure tracking accuracy during beam delivery.

The Vero4DRT system (Mitsubishi Heavy Industries Ltd, Tokyo, Japan, and Brainlab AG, Feldkirchen, Germany) is equipped with gantry-mounted orthogonal kV X-ray imaging subsystems, consisting of two sets of kV X-ray tubes and flat-panel detectors. Using the subsystems, the Vero4DRT system is currently the unique unit enabling hybrid RTTT [10], 3D-CBCT [2] and 4D-CBCT [6].

Concern regarding an increased chance of secondary cancers due to high imaging doses has been recognized by the AAPM Task Group 75 [11]. Clearly, excessive imaging doses are not desirable from the perspective of the ‘as low as reasonably achievable’ principle, or the recommendations of the International Commission on Radiological Protection [12].

Recently, a review paper regarding imaging doses from 3D-CBCT was published by Alaei et al. [13]. Therein, several results of 3D-CBCT Monte Carlo dose calculations are summarized. Ng et al. quantified imaging doses from KIM and concluded that the total KIM dose at 1 Hz ranged from 2–10 mSv [14]. Depuydt et al. and Garibaldi et al. reported that the skin dose was ~0.08 mGy/image, with a source-to-skin distance (SSD) of 900 mm and kV exposure of 1 mAs, using the Vero4DRT system [15, 16]. To estimate imaging doses from these techniques is of clinical importance so as to be able to generate recommendations on how to minimize imaging doses due to such IGRT procedures.

Thus far, there is no published research investigating organ-specific imaging doses from RTTT, 3D-CBCT and 4D-CBCT using the Vero4DRT system. In this study, imaging doses to the organs of lung cancer patients were quantified during RTTT, 3D-CBCT and 4D-CBCT using a Monte Carlo technique.

MATERIALS AND METHODS

Description of the Vero4DRT system

The Vero4DRT system has several features that differ from those of other radiotherapy units. The system has an orthogonal kV X-ray imaging subsystem, an electronic portal imaging device system, and a gimbaled X-ray head with a compact 6 MV C-band klystron-based accelerator and a system-specific multileaf collimator (MLC) in an O-ring. The five-axis robotic treatment couch has high precision, of 0.1 mm and 0.1°, and an infrared (IR) camera is attached to the ceiling of the treatment room (Fig. 1). The gantry can be rotated by ±185° along an O-shaped guide lane at a nominal maximum speed of 7°/s, and the O-ring can be rotated by ±60° around its vertical axis at a nominal maximum speed of 3°/s [17]. The gimbaled X-ray head can swing along the two orthogonal gimbals (pan and tilt rotations) up to ±2.5°, with a maximum rotational speed of 9°/s.

The gantry-mounted orthogonal kV X-ray imaging subsystems consist of two sets of X-ray tubes (maximum tube voltage = 125 kV) and flat-panel detectors, with the ExacTrac system. The source-to-

Fig. 1. Photo of the Vero4DRT system. The system has an orthogonal kV X-ray imaging subsystem, an electronic portal imaging device system, and a gimbaled X-ray head with a compact 6 MV C-band klystron-based accelerator and a system-specific multileaf collimator in an O-ring. The five-axis robotic treatment couch has high precision, of 0.1 mm and 0.1°, and an infrared (IR) camera is attached to the ceiling of the treatment room. IR markers were placed on the abdomen of the patient.
Physical planning

Table 1. Patient characteristics and treatment planning

| Patient | Sex | Age (years) | Performance status | Tumor size (mm) | Side | Location | Maximum tumor motion (mm) | Prescribed dose at the isocenter (Gy) |
|---------|-----|-------------|--------------------|----------------|------|----------|--------------------------|--------------------------------------|
| 1       | F   | 85          | 1                  | 32             | Rt   | S6       | 16.1                     | 56                                   |
| 2       | F   | 86          | 1                  | 21             | Rt   | S9       | 25.9                     | 48                                   |
| 3       | M   | 84          | 0                  | 26             | Rt   | S6       | 16.1                     | 48                                   |
| 4       | M   | 71          | 1                  | 24             | Rt   | S5       | 14.1                     | 48                                   |
| 5       | M   | 85          | 0                  | 13             | Rt   | S9       | 32.3                     | 48                                   |
| 6       | F   | 85          | 0                  | 15             | Rt   | S9       | 30.7                     | 48                                   |
| 7       | F   | 80          | 1                  | 15             | Rt   | S10      | 46.1                     | 56                                   |
| 8       | M   | 87          | 1                  | 15             | Lt   | S6       | 10.4                     | 48                                   |
| 9       | M   | 84          | 1                  | 35             | Lt   | S4       | 14.5                     | 56                                   |

M = male, F = female, y = years, Rt = right, Lt = left, S = segment number.

Detector distance and source-to-isocenter distance are 1876 mm and 1000 mm, respectively. The maximum field size is 216 mm (in the O-ring plane) x 162 mm (perpendicular to the O-ring plane) at the isocenter level. Two kV X-ray imaging subsystems are attached to the O-ring at ±45° from the MV beam axis.

Patient characteristics

Nine lung cancer patients who underwent SBRT with RTTT were included (Table 1). There were five male and four female patients, with a median age of 85 (range, 71–87) years. The respiratory motion of the tumor exceeded 10 mm in all patients. Seven patients had tumors in the right lung and two in the left. The gross tumor volume (GTV) size was in the range of 2.8–31.6 cc. Four or five 1.5-mm-diameter spherical gold markers were implanted transbranially around the lung tumor as far peripherally as possible to minimize marker migration or dropout. The study was performed as a part of a set of institutional review board–approved studies.

Treatment planning

All patients were placed in the supine position on individualized vacuum pillows with both arms above the head. Ten respiratory phases in 4D-CT were acquired in axial cine mode using a 16-slice CT scanner (Light Speed RT16; GE Healthcare, Little Chalfont, UK) and a real-time positioning management system (Varian Medical Systems, Palo Alto, USA). Immediately after the 4D-CT, a breath-hold CT was also acquired at the end of exhalation. GTVs were delineated manually on the breath-hold CT and 10 phase images. An internal target volume for tracking (tITV) was defined as a composite of the 11 GTVs from the breath-hold CT and the 10 phase images from 4D-CT that were superimposed onto the breath-hold CT, with translation of the marker centroids to be matched [10]. At least 5 mm was added to the tITV for the planning target volume (PTV) [10]. The isocenter was located at the center of the PTV. A prescribed dose of 48 or 56 Gy was specified at the isocenter in four fractions. Treatment plans included seven or eight non-coplanar conformal fields, with a maximum dose rate of 500 MU/min (Table 2). The MLC was shaped to the PTV plus 5 mm. Dose distributions were calculated using the X-ray voxel Monte Carlo algorithm of the iPlan RT Dose software (ver. 4.5.1; Brainlab AG) on planning breath-hold exhalation CT images. The spatial resolution and mean statistical error were 2.5 mm and 2%, respectively. Details of the treatment plans have been reported elsewhere [10].

RTTT procedure

First, the patient was laid on a pre-formed vacuum pillow. Set-up error was corrected based on bony structures using the ExacTrac X-ray system. Then, the displacement of IR markers on the abdomen in the anterior–posterior direction and the 3D position of the tumor (as indicated by the implanted fiducial markers) were monitored for each fraction to build a correlation model, expressed using a quadratic function in terms of the position and velocity of the IR markers in the anterior–posterior direction [17]. The imaging parameters were 110 kV, 100 mA and 5 ms. The gantry and ring angle used to detect the implanted fiducial markers were determined as described in reference [18]. The sampling period was in the range of 20–40 s. This step was called ‘correlation modeling.’ During correlation modeling, the displacement of the IR markers on the abdomen in the anterior–posterior direction and the 3D positions of the implanted fiducial markers were monitored simultaneously using an IR camera at 16.7 ms intervals, with an orthogonal kV X-ray imaging subsystem at 80 or 160 ms. The sampling frequency was automatically switched depending on the velocity of IR marker motion.

During beam delivery, the implanted fiducial markers were monitored at 1 s via orthogonal kV X-ray imaging to ensure tracking accuracy. This step was called ‘monitoring.’ The initial imaging parameters for monitoring were nominally 110 kV, 100 mA and 5 ms, and were adjusted depending on the body thickness and tumor location.

Imaging dose during RTTT

To estimate imaging dose during RTTT, imaging doses from correlation modeling and monitoring were calculated. Additionally, imaging...
doses from correlation modeling and monitoring were evaluated separately. The current version of the ExacTrac X-ray system on the Vero4DRT platform updates the correlation model based on the monitoring images obtained during beam delivery. Thus, the imaging doses of the correlation modeling only immediately before beam delivery were calculated in this study.

The number of monitoring images per field was determined as $\text{MU} \times (\text{CF} / \text{maximum dose rate})$, where CF was a conversion factor for minutes to seconds (60 s/min) and the maximum dose rate was 500 MU/min. Table 3 shows details of the imaging protocols between correlation modeling and monitoring imaging.

3D-CBCT and 4D-CBCT imaging

To compare imaging doses during RTTT, those from single 3D-CBCT and 4D-CBCT were also calculated on the planning CT images for the nine patients. In clinical practice, 3D-CBCT is performed for all lung patients who undergo SBRT without RTTT. Additionally, although 4D-CBCT was not performed routinely, it was done for lung cancer patients enrolled in another institutional review board–approved trial.

Single- and dual-source kV X-ray tubes were used for the 3D-CBCT and 4D-CBCT imaging, respectively. The observed amplitude of the motion of the gold markers during respiration was used to sort each image into eight respiratory phase bins for 4D-CBCT imaging. The mechanical rotation center was set at the planned isocenter, and the CBCT datasets had a voxel size of $1 \times 1 \times 1 \text{mm}^3$. The maximum CBCT field of view was 200 mm in diameter and 150 mm in length, and the imaging parameters were 110 kV, 160 mA and 5 ms for both 3D-CBCT and 4D-CBCT imaging. These parameters were fixed for each patient.

For 3D-CBCT imaging, the rotational speed of the gantry was $7^\circ/s$, the gantry rotation time was 29 s, and the image acquisition interval was $0.5^\circ$, as used routinely in clinical practice. These parameters for 4D-CBCT imaging were $1.5^\circ/s$, 70 s and $0.3^\circ$, respectively, which were determined through prior 4D-CBCT scanning using an anthropomorphic phantom (Modus Medical Devices, London, ON, Canada). Table 4 shows details of the imaging protocols for 3D-CBCT and 4D-CBCT.

Monte Carlo simulation for kV X-ray images

The EGSnrc/BEAMnrc and EGSnrc/DOSXYZnrc packages [19, 20] were used to simulate kV X-ray dose distributions delivered by the Vero4DRT system. Details of the internal configurations were provided by Mitsubishi Heavy Industries. The photon cut-off energy was set to 1 keV, and the electron cut-off energy was set to 512 keV for all simulations. Due to the specification of the simulation code used in this study, the electron rest mass of 511 keV should be included in the electron cut-off energy. A library of phase space files representing the entire beam output for each kV X-ray field was built. The statistical uncertainty of the Monte Carlo calculation was <1% for all kV X-ray fields. The kV X-ray dose distributions are reported in the dose-to-medium format.

Previously, an in-house dose calibration protocol for the Monte Carlo simulation system, based on film and a chamber (DC 300; IBA/Scanditronix Wellhöfer, Schwarzenbruck, Germany), had been
established. First, half-value layers of 4.78, 5.10 and 5.70 mm (99.999% Al) were determined for kV X-ray energies of 100, 110 and 120 kV under an SSD of 1000 mm and imaging parameters of 100 mA and 28 ms using a kV tube at an angle of 0°. Then, the previous study confirmed that the calculated and measured percentage depth doses and profiles were in agreement, to within 3.5% and 2%, respectively, for kV X-ray energies of 100, 110 and 120 kV [21].

Additionally, the Monte Carlo simulations revealed a dose per image of 0.127 mGy/image at the water surface using an SSD of 900 mm and imaging parameters of 110 kV, 100 mA and 10 ms using a kV tube at an angle of 0°. From the results in previous validation tests, these values were comparable with the measured values obtained with multiple thermoluminescence dosimeters (TLD; MgSiO₄:Tb; diameter 2 mm and length 12 mm; TORECK, Kanagawa, Japan) at the phantom surface.

Data analysis
The kV X-ray dose distributions of correlation modeling, monitoring imaging, and 3D-CBCT and 4D-CBCT imaging were calculated based on the planning CT images with a dose calculation grid size of 2.5 × 2.5 × 2.5 mm. Then, the imaging dose distributions were exported to the MIM Maestro software (ver. 5.2; MIM Software, Cleveland, OH, USA), and evaluated by examining dose–volume histograms (DVHs) for the PTV, skin, ipsilateral lung, spinal cord, heart and bone. Bone included the ribs, vertebral bodies, and sternal bone. The skin was defined as the inner 5 mm of the body surface, with the exception of bone structures. Doses to the heart were also evaluated for two patients with left lung cancers.

RESULTS
Imaging doses from correlation modeling and monitoring for RTTT
A modeling period of 20 s was used for five patients and 40 s for four patients. The total numbers of images during single correlation modeling, extracted from the Record and Verify system, were in the range of 224–457 images per fraction. The calculated mean dose and the dose covering a 2-cc volume (D2cc, a surrogate for the maximum absorbed dose) for each organ undergoing RTTT are summarized in Fig. 2. Correlation modeling (left box plot in each structure) increased the mean dose by less than 3.5 cGy for soft tissues and 10.4 cGy for bone (Fig. 2a). The D2cc values upon correlation modeling over the specified sampling period were up to 9.3 cGy for soft tissues and 48.4 cGy for bone (Fig. 2b). When the correlation modeling used a 20-s sampling period, the D2cc values were up to 4.6 cGy for soft tissues and 25.0 cGy for bone.

In total, 132 kV X-ray fields were examined in the monitoring imaging for the nine patients (Table 2). The following imaging parameters were used: 110 kV, 100 mA and 5 ms for 122 fields, 110 kV, 160 mA and 5 ms for 2 fields, 110 kV, 200 mA and 5 ms for 6 fields, and 120 kV, 160 mA and 10 ms for 2 fields. The total numbers of monitoring images, extracted from the Record and Verify system, were in the range of 168–228 images per fraction. The mean doses from monitoring (middle box plot in each structure) were less than 2.6 cGy for soft tissues and 8.2 cGy for bone.

### Table 3. Comparison of the imaging protocols between correlation modeling and monitoring imaging

|                      | Correlation modeling | Monitoring imaging |
|----------------------|----------------------|--------------------|
| Source               | Dual                 | Dual               |
| Imaging parameters   | 110 kV, 100 mA, 5 ms | 110 kV, 160 mA, 5 ms (Nominally) Adjusted depending on the body thickness and tumor locations |
| Sampling period      | 20 to 40 s           | Depending on MU    |
| Image acquisition interval | 80 or 160 ms      | 1 s                |
| Number of images     | Depending on sampling period | Depending on MU    |
| Imaging angle        | ±45° from the MV beam axis | ±45° from the MV beam axis |

### Table 4. Comparison of the imaging protocols between 3D-CBCT and 4D-CBCT

|                      | 3D-CBCT | 4D-CBCT |
|----------------------|---------|---------|
| Source               | Single  | Dual    |
| Imaging parameters   | 110 kV, 160 mA, 5 ms | 110 kV, 160 mA, 5 ms |
| Gantry rotational speed | 7°/s     | 1.5°/s  |
| Gantry rotational time | 29 s     | 70 s    |
| Image acquisition interval | 0.5°     | 0.3°    |
| Number of images     | 391     | 702 (351 × 2) |
| Gantry rotation angle for patients with left lung cancer | 320–175° (CW) | 320–85° (CW) |
| for patients with right lung cancer | 40–185° (CCW) | 40–275° (CCW) |

3D = three-dimensional, 4D = four-dimensional, CBCT = cone-beam computed tomography, CW = clockwise, CCW = counter clockwise.
The D2cc from monitoring was up to 6.0 cGy for soft tissues and 18.3 cGy for bone. The skin and bone D2cc from monitoring were 0.3–0.9-fold smaller than those from correlation modeling due to the low sampling frequency (1 image/s; Fig. 2b).

The mean doses of both correlation modeling and monitoring (right box plot in each structure) were less than 5.3 cGy for soft tissues and 17.2 cGy for bone (Fig. 2a). The D2cc values were up to 11.0 cGy for soft tissues and 59.8 cGy for bone (Fig. 2b). Figure 3 shows representative DVHs with and without imaging doses via correlation modeling and monitoring for Patient #3, who had the highest bone D2cc in RTTT. The concomitant DVH for bone was slightly higher than the DVH without an imaging dose; however, the difference was not clinically significant.

Comparison of imaging doses from RTTT and 3D-CBCT and 4D-CBCT

The mean dose and the D2cc for each organ from RTTT and 3D-CBCT and 4D-CBCT are summarized in Fig. 4. The mean doses from both correlation modeling and monitoring are shown in the left box plot in each structure, which is the same as the right box plot in Fig. 2. The mean doses from a 3D-CBCT (middle box plot in each structure) were less than 3.3 cGy for soft tissues and 9.4 cGy for bone (Fig. 4a). The D2cc values were up to 6.0 cGy for soft tissues and 32.3 cGy for bone (Fig. 4b). Moreover, the mean doses from 4D-CBCT (right box plot in each structure) were less than 7.4 cGy for soft tissues and 22.3 cGy for bone (Fig. 4a). The D2cc values were up to 11.5 cGy for soft tissues and 58.1 cGy for bone (Fig. 4b), which were 1.7–2.3-fold greater than the values for 3D-CBCT. Imaging doses from RTTT were comparable with those from 4D-CBCT. Figure 5 shows representative kV X-ray dose distributions from RTTT and 3D-CBCT and 4D-CBCT images.

Linear correlation coefficients were calculated to investigate the relationship between the averaged body surface to the isocenter distance during CBCT, defined as 1000 minus the averaged SSD in mm, and skin D2cc and bone D2cc. It was found that linear correlation coefficients were −0.82 (with a slope of −0.20) for 3D-CBCT and −0.65 (with a slope of −0.17) for 4D-CBCT for skin D2cc, and −0.93 (with a slope of −0.14) for 3D-CBCT and −0.85 (with a slope of −0.17) for 4D-CBCT for bone D2cc (Fig. 6).

Fig. 2. Calculated (a) mean dose and (b) D2cc values for each organ. For each organ, the left box plot shows the imaging dose derived from correlation modeling, the middle box plot that from monitoring, and the right box plot that derived using both correlation modeling and monitoring. Correlation modeling (left box plot in each structure) increased the mean dose by less than 3.5 cGy for soft tissues and 10.4 cGy for bone. The mean imaging doses from monitoring (middle box plot in each structure) were less than 2.6 cGy for soft tissues and 8.2 cGy for bone. The D2cc values upon correlation modeling were up to 9.3 cGy for soft tissues, and 48.4 cGy for bone. The D2cc from monitoring was up to 6.0 cGy for soft tissues and 18.3 cGy for bone. The skin and bone D2cc from monitoring were 0.3–0.9-fold smaller than those from correlation modeling, due to the lower sampling frequency (1 image/s). In the box plot, the top of the rectangle indicates the third quartile, the horizontal line near the middle of the rectangle indicates the median, and the bottom of the rectangle indicates the first quartile. A vertical line extends from the top of the rectangle to indicate the maximum value, and another vertical line extends from the bottom of the rectangle to indicate the minimum value.

Fig. 3. Representative DVHs with and without imaging doses based on correlation modeling and monitoring for Patient #3, who had the highest bone D2cc in RTTT. Solid lines show DVHs without imaging doses, and broken lines show the concomitant DVHs with imaging doses. The concomitant DVHs with imaging doses from RTTT were almost identical to the DVHs without imaging doses, except for bone.
In the era of IGRT, kV X-ray imaging is used frequently during a course of radiation therapy to improve the precision and accuracy of the delivery of the treatment. Thus, knowledge of the imaging doses delivered to patients and accurate dosimetry of radiation to organs for each imaging procedure is becoming increasingly important for clinicians. In this work, imaging doses to organs from RTTT, 3D-CBCT and 4D-CBCT using the Vero4DRT system were calculated for nine lung cancer patients using Monte Carlo simulation. The current study revealed that imaging doses from RTTT were comparable with those from 4D-CBCT, and that those from RTTT and 4D-CBCT were approximately double those from 3D-CBCT.

Radiation-induced skin and bone toxicity are sometimes problematic. Especially, the dose to the bone was 2–6-fold greater than the dose to soft tissues because of the photoelectric effect. As shown in Fig. 3, presenting DVHs with and without an imaging dose for the patient with the highest bone D_{2cc} in RTTT, the concomitant DVHs with imaging doses were almost equivalent to the DVHs without imaging doses. The imaging doses from 4D-CBCT were equivalent to those from RTTT, and those from 3D-CBCT were less than those from RTTT (Fig. 4). In addition, note that the position where the hot spot appears differs between the therapeutic dose and imaging dose. From these results, the imaging doses from RTTT, 3D-CBCT and 4D-CBCT would be clinically negligible in lung SBRT cohorts. To minimize the radiation-induced skin and bone toxicities, the therapeutic doses to these structures should be reduced rather than the imaging doses.

**DISCUSSION**

In the era of IGRT, kV X-ray imaging is used frequently during a course of radiation therapy to improve the precision and accuracy of the delivery of the treatment. Thus, knowledge of the imaging doses delivered to patients and accurate dosimetry of radiation to organs for each imaging procedure is becoming increasingly important for clinicians. In this work, imaging doses to organs from RTTT, 3D-CBCT and 4D-CBCT using the Vero4DRT system were calculated for nine lung cancer patients using Monte Carlo simulation. The current study revealed that imaging doses from RTTT were comparable with those from 4D-CBCT, and that those from RTTT and 4D-CBCT were approximately double those from 3D-CBCT.

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**Imaging doses from RTTT in the Vero4DRT system**

Depuydt et al. reported that correlation modeling contributed to the imaging dose to the skin of ~8.8 mGy per build with 100 kV and 0.5 mAs, and a modeling period of 20 s for an SSD of 900 mm; however, despite the same mAs value and the similar dose per image with an SSD of 900 mm, these were ~4–5-fold lower than our results. The primary cause of the difference between doses to the skin would be whether the doses overlap at the skin surface. Depuydt et al. used a VISICOIL gold marker (IBA, Louvain-la-Neuve, Belgium) as a fiducial; thus, it is possible to reduce the kV X-ray fields to the minimum size required to detect the VISICOIL through RTTT. In this study, four or five spherical gold markers were implanted as far peripherally as possible. In addition, the relative position between the tumor and fiducial markers changes during respiration. Therefore, to detect all markers from various gantry and ring angles, it is difficult to reduce the kV X-ray fields, which resulted in overlapping at part of the skin surface. With such an overlap, the imaging doses would be larger.

Nakamura et al. demonstrated that the accuracies of correlation models derived using the shortest modeling period of 20 s were almost...
3D-CBCT imaging

Due to the superiority of 3D-CBCT imaging for patient positioning, there has been a rapid growth in the use of these systems in radiation therapy, which has helped to make IGRT a routine technique that is now used worldwide. However, the imaging dose delivered to patients from 3D-CBCT has become an issue of concern. Spezi et al. reported that the mean dose to the PTV varied from 2.5 to 5 cGy, and the lung and spinal cord received less than 4 and 5 cGy, respectively, in chest cases using the X-ray volume imaging unit mounted on an Elekta Synergy linear accelerator (Elekta, Crawley, UK) [29]. Differences between their imaging parameters (120 kV, 40 mA and 40 ms in the cited study) and ours indicate that these organs received slightly higher mean doses in the cited work. Ding et al. evaluated the imaging doses delivered to organs, using Varian 3D-CBCT devices [30, 31]. The D_{2cc} values to bone exceeded ~20 cGy, which was comparable with our results. The mean doses to soft tissues were in the range of 0.2–0.6 cGy [29], about half of our values with the use of a bow-tie filter. Differences in imaging parameters, the use of a bow-tie filter, and a newer image-processing algorithm, which was not implemented in the current version of Vero4DRT, may explain the differences between our results and theirs for 3D-CBCT.

4D-CBCT imaging

To our knowledge, this is the first reported study to assess imaging doses from 4D-CBCT. As shown in Fig. 4, the imaging doses from a 4D-CBCT were approximately double those of 3D-CBCT. Given a gantry rotational angle of 105° and the configuration of kV X-ray imaging subsystems, both kV X-ray fields overlapped on part of the skin surface. Additionally, interpatient variations in the skin D_{2cc} from 4D-CBCT was dependent on the SSD, as demonstrated by large negative correlation coefficients of −0.65 (Fig. 6). A short averaged body surface to isocenter distance indicates that the lung tumor was located adjacent to the anterior chest wall. In such cases, the overlapping areas of the skin surface increase, resulting in a larger skin D_{2cc}.

CONCLUSIONS

Imaging doses delivered by the Vero4DRT system for lung cancer patients were quantified. The mean imaging doses from both correlation modeling and monitoring were <5.3 cGy for soft tissues and <17.2 cGy for bone. The imaging doses derived from correlation modeling were greater than those derived from monitoring; thus, the use of a short modeling period is effective at reducing the imaging dose. The D_{2cc} from 4D-CBCT was up to 11.5 cGy for soft tissues and 58.1 cGy for bone, which were approximately double those from 3D-CBCT due to the presence of overlapping areas over part of the skin surface. Clinicians should Figure that the imaging dose increases the cumulative doses to organs.

CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest.
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