

## Assessment of imaging radiation dose from tomotherapy systems

Pratchayakan Hompeng<sup>1,2</sup>, Wannapha Nobnop<sup>3</sup>, Tinnagorn Donmoon<sup>4</sup>, Komkrit Krongkietlearts<sup>5</sup>, Kananan Utitsarn<sup>5</sup>, Sumalee Yabsantia<sup>1,6</sup>, Thunyarat Chusin<sup>1,6\*</sup>

<sup>1</sup>Department of Radiological Technology, Faculty of Allied Health Sciences, Naresuan University, Phitsanulok Province, Thailand.

<sup>2</sup>Regional Medical Sciences Center 7 Khonkaen, Khonkaen Province, Thailand.

<sup>3</sup>Division of Radiation Oncology, Faculty of Medicine, Chiang Mai University, Chiang Mai Province, Thailand.

<sup>4</sup>Maha Vajiralongkorn Thanyaburi Hospital, Department of Medical Services, Ministry of Public Health, Pathum Thani Province, Thailand.

<sup>5</sup>Department of Radiotherapy, Lopburi Cancer Hospital, Lopburi Province, Thailand.

<sup>6</sup>Interdisciplinary Health and Data Sciences Research Unit, Faculty of Allied Health Sciences, Naresuan University, Phitsanulok Province, Thailand.

### ARTICLE INFO

#### Article history:

Received 19 October 2025

Accepted as revised 30 January 2026

Available online 10 February 2026

#### Keywords:

Tomotherapy systems, imaging radiation dose, kVCT, MVCT.

### ABSTRACT

**Background:** Tomotherapy systems employ image-guided radiotherapy (IGRT) using either megavoltage (MVCT) or kilovoltage (kVCT) computed tomography for daily patient positioning verification. However, these imaging procedures can deliver a non-negligible radiation dose to the patient. According to the American Association of Physicists in Medicine (AAPM) Task Group 180, this dose should be incorporated into the prescribed treatment dose if it exceeds 5%.

**Objectives:** This study aimed to assess IGRT imaging doses and determine whether the cumulative dose exceeded 5% of the prescribed treatment dose.

**Materials and methods:** Imaging doses from IGRT were evaluated under clinical scan protocols across four tomotherapy machines at three centers, including two MVCT systems and two kVCT systems. Doses were measured as Weighted Multiple Slice Average Dose (MSAD<sub>w</sub>) using a CTDI phantom. Cumulative imaging dose was calculated by multiplying MSAD<sub>w</sub> by the number of imaging sessions, then compared to the prescribed dose for each patient.

**Results:** The mean MSAD<sub>w</sub> values for MVCT ranged from 0.85 to 0.86 cGy per scan, while for kVCT it ranged from 0.19 to 2.65 cGy per scan. Over the treatment course, cumulative imaging doses accounted for 0.34-0.44% of the prescribed dose for MVCT and 0.28-0.87% for kVCT. Notable inter-center variations were observed, with differences of up to 51.16% in breast cancer cases and 35.71% in prostate cancer cases.

**Conclusion:** Cumulative imaging doses from both MVCT and kVCT across all centers remained below the 5% threshold, indicating no need to adjust the prescribed dose in clinical practice. Nevertheless, further studies are required to identify the causes of inter-center variations and to develop optimized imaging protocols aimed at minimizing patient dose while maintaining adequate image quality.

### Introduction

Image-guided radiation therapy (IGRT) is an advanced technique designed to improve treatment accuracy by using daily pre-treatment imaging to verify patient positioning. The acquired images are registered with the reference images through alignment of key anatomical landmarks, thereby ensuring precise patient setup and enhancing tumor localization.<sup>1</sup>

#### \* Corresponding contributor.

**Author's Address:** Department of Radiological Technology, Faculty of Allied Health Sciences, Naresuan University, Phitsanulok Province, Thailand.

**E-mail address:** thunyaratc@nu.ac.th

**doi:** 10.12982/JAMS.2026.048

**E-ISSN:** 2539-6056

Tomotherapy systems incorporate an IGRT platform capable of generating cross-sectional 3D images using either megavoltage computed tomography (MVCT) or kilovoltage computed tomography (kVCT) for daily position verification. Historically, MVCT was the standard modality. MVCT images are produced using the same X-ray source as the treatment beam, operated at a reduced energy of 3.5 MV. However, this approach is limited by relatively low image quality and prolonged acquisition times. To address these limitations, newer-generation tomotherapy units may be equipped with kVCT, which provides high-resolution images comparable to diagnostic CT and enables shorter scan times. Thus, the choice between MVCT and kVCT is determined by clinical requirements and system availability.<sup>2</sup>

Since cross-sectional images are used to verify and adjust patient positioning, sufficient image resolution is essential for visualizing target structures such as bone and soft tissue. Even though higher imaging doses can improve image quality, they also contribute additional radiation exposure. Therefore, imaging protocols should adhere to the As Low As Reasonably Achievable (ALARA) principle, ensuring adequate image quality for clinical purposes while minimizing unnecessary dose.<sup>3,4</sup> Although radiation therapy patients already receive high localized treatment doses, the additional exposure from imaging still carries risk and must be kept as low as reasonably possible.<sup>5</sup>

According to the American Association of Physicists in Medicine (AAPM) Task Group 180 report, the imaging dose should be included in the total prescribed dose if it exceeds 5% of the therapeutic dose.<sup>6</sup> This recommendation is supported by a study by Dische *et al.*,<sup>7</sup> which found that dose variations as small as 5%, based on clinical data from the continuous hyperfractionated accelerated radiotherapy (CHART) pilot study, may influence tumor control and increase patient morbidity.<sup>8,9</sup>

The AAPM Task Group 148 report recommends that radiation dose measurement for MVCT be defined using the Multiple Slice Average Dose (MSAD).<sup>10</sup> This dose is typically measured with a calibrated ionization chamber (e.g., Exradin A1SL) within a standard cylindrical phantom (e.g., the Cheese phantom). The scan range should cover the entire phantom. For imaging in normal mode, MSAD of approximately 1-3 cGy can be expected.<sup>10</sup> Although a Cheese phantom is commonly used in tomotherapy centers for radiation dose measurements, it has certain limitations when used to evaluate the MSAD. These limitations include a slight displacement of the phantom's designated center, which may not perfectly align with its actual midpoint. The phantom has a diameter of 30 cm, making it mismatch for head imaging dose assessments. It is also incompatible with pencil ionization chambers, which are required for measuring imaging doses from kVCT.

Several studies have investigated imaging doses associated with IGRT across different systems and protocols. Mege *et al.*<sup>11</sup> and Marco *et al.*<sup>12</sup> reported MVCT imaging doses of approximately 1-4 cGy per scan, depending on pitch settings and anatomical site, with higher pitch values generally associated with lower doses. Trivedi *et al.*<sup>13</sup> reported average CBCT imaging doses of 0.24 cGy for head and neck cancer and 0.76 cGy for pelvic cancer. Imaging was performed once weekly for head and neck cancer and on three consecutive days during the first week for pelvic cancer. Although cumulative doses were not directly measured and 2D imaging doses were excluded, the authors estimated total doses of 1.44 cGy and 5.32 cGy, both remaining below 5% of the prescribed dose. Additionally, Sakai *et al.*<sup>3</sup> reported imaging doses per kV-CBCT and per kVCT acquisition across nine machines at seven centers, with ranges of 0.09-0.66 cGy for head and 0.15-2.90 cGy for pelvic protocols. While imaging doses varied among machines and centers, the maximum dose difference was sevenfold in the head protocol and up to fourteenfold in the pelvic protocol, highlighting the need to establish standardized diagnostic reference levels (DRLs) in IGRT.

A review of existing literature shows that most studies assess imaging radiation doses using phantom measurements from a single scan. However, there is limited evaluation of the cumulative doses patients receive throughout the entire treatment course across different cancer types. Moreover, no published data from Thailand currently exist on patient imaging doses associated with IGRT using tomotherapy systems. Such data are essential not only for considering whether to include the imaging dose in the prescribed dose, but also for evaluating appropriate imaging protocols and optimizing patient dose in clinical practice, in alignment with the ALARA principle.

This study aimed to evaluate the radiation dose used for imaging with the IGRT system under clinical scan protocols for kVCT and MVCT at three radiotherapy centers. The dose was quantified as Weighted Multiple Slice Average Dose (MSAD<sub>w</sub>), measured in a Computed Tomography Dose Index (CTDI) phantom. The study also assessed whether the cumulative imaging dose received by patients throughout the course of treatment on tomotherapy systems exceeded 5% of the prescribed dose, according to AAPM Task Group 180 report.

## Materials and methods

### Tomotherapy system

This study evaluated the imaging dose across four tomotherapy machines at three centers. The MVCT systems included a Radixact X9 at Center A (MVCT 1) and a Radixact X5 at Center B (MVCT 2). The kVCT systems consisted of a Radixact X9 at Center A (kVCT 1) and a Radixact X5 at Center C (kVCT 2). All systems operated with software version 3.0.x (Accuray Inc., Madison, WI, USA).

**Megavoltage computed tomography (MVCT)**

MVCT uses the same linear accelerator source as the treatment beam but operates at a reduced energy level of approximately 3.5 MV for imaging purposes. MVCT generates cross-sectional images with a 400 mm field of view (FOV) and a matrix resolution of 512×512 pixels. The jaw width is fixed at the J1 setting, corresponding to a nominal beam width of approximately 4 mm at the isocenter. The pitch setting in MVCT controls the couch movement per gantry

rotation, influencing image resolution. Fine, Normal, and Coarse modes correspond to couch speeds of 4, 8, and 12 mm per rotation and reconstructed slice thicknesses of 2, 4, and 6 mm, respectively.<sup>1,14</sup> The scan time depends on the selected pitch; the Coarse mode requires approximately one-third of the scan time and delivers about one-third of the radiation dose compared to the Fine mode. In this study, the clinical scan protocols for MVCT typically used in all centers are detailed in Table 1.

**Table 1.** Clinical scan protocols for MVCT used in this study.

| Mode   | Voltage (MV) | Slice thickness (mm) | Pitch | FOV (mm) |
|--------|--------------|----------------------|-------|----------|
| Coarse | 3.5          | 6                    | 3     | 400      |

**Kilovoltage computed tomography (kVCT)**

The kV X-ray tube is mounted at 267.5 degrees relative to the treatment beam position. A CsI:TI flat-panel detector is installed directly opposite the X-ray source, with a source-to-detector distance of 155 cm. Imaging parameters for kVCT are not manually adjustable by users. Instead, predefined scan protocols are selected based on the anatomical region and patient body size. The selected anatomical region determines the tube voltage (kVp), reconstructed slice interval, and slice

thickness, while body size determines the tube current per view (mA/view). The mode selection determines the longitudinal beam width, couch speed, views per rotation, scan time, and pitch. The pitch is fixed for 440 mm and 500 mm fields of view (FOV), but adjustable for a 270 mm FOV. FOV selection also determines the type of filtration: a 0.5 mm copper filter is used for 270 mm FOV, while a bowtie filter is used for 440 mm and 500 mm FOVs.<sup>1,14</sup> These clinical scan protocols for kVCT used in this study are detailed in Table 2.

**Table 2.** Clinical scan protocols for kVCT were used in this study.

| Protocol | Voltage (kVp) | Body size | mAs | Slice interval (mm) | Slice thickness (mm) | Mode   | Pitch | FOV (mm) |      |
|----------|---------------|-----------|-----|---------------------|----------------------|--------|-------|----------|------|
| Head     | 100           | Small     | 240 | 1.2                 | 2.4                  | Fine   | 0.86  | 270      |      |
|          |               | Medium    | 375 |                     |                      |        |       |          |      |
|          |               | Small     | 192 |                     |                      | Normal | 1     |          |      |
|          |               | Medium    | 300 |                     |                      |        |       |          |      |
|          |               | Small     | 144 |                     |                      | Coarse | 1.4   |          |      |
|          |               | Medium    | 225 |                     |                      |        |       |          |      |
| Thorax   | 120           | Small     | 240 | 1.8                 | 3.6                  | Fine   | 0.75  | 440      |      |
|          |               | Medium    | 375 |                     |                      |        |       |          |      |
|          |               | Large     | 480 |                     |                      |        |       |          |      |
|          |               | Small     | 192 |                     |                      | Normal |       |          | 0.75 |
|          |               | Medium    | 300 |                     |                      |        |       |          |      |
|          |               | Large     | 384 |                     |                      |        |       |          |      |
|          |               | Small     | 144 |                     |                      | Coarse |       |          |      |
|          |               | Medium    | 225 |                     |                      |        |       |          |      |
|          |               | Large     | 288 |                     |                      |        |       |          |      |

**Table 2.** Clinical scan protocols for kVCT were used in this study (continued).

| Protocol | Voltage (kVp) | Body size | mAs | Slice interval (mm) | Slice thickness (mm) | Mode   | Pitch | FOV (mm) |
|----------|---------------|-----------|-----|---------------------|----------------------|--------|-------|----------|
| Pelvis   | 140           | Small     | 240 | 1.8                 | 3.6                  | Fine   | 0.75  | 440      |
|          |               | Medium    | 375 |                     |                      |        |       |          |
|          |               | Large     | 480 |                     |                      |        |       |          |
|          |               | Small     | 192 |                     |                      | Normal |       |          |
|          |               | Medium    | 300 |                     |                      |        |       |          |
|          |               | Large     | 384 |                     |                      |        |       |          |
|          |               | Small     | 144 |                     |                      | Coarse |       |          |
|          |               | Medium    | 225 |                     |                      |        |       |          |
|          |               | Large     | 288 |                     |                      |        |       |          |

**MSAD measurement****Dose assessment of MVCT imaging**

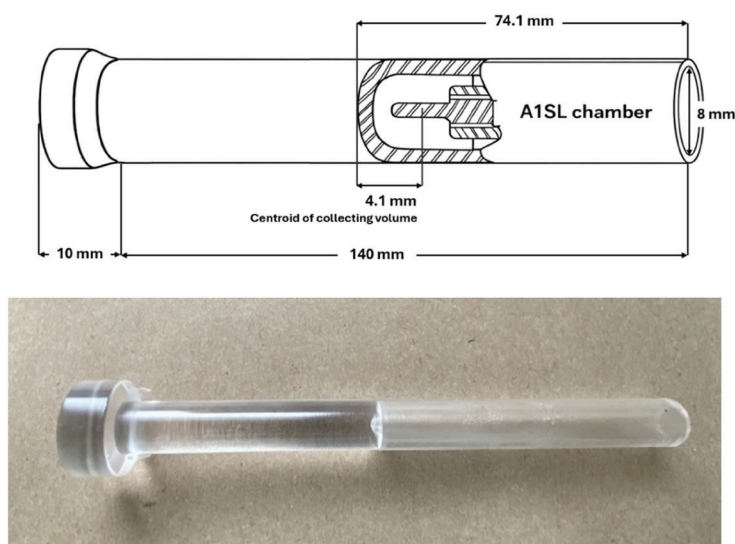
The AAPM Task Group 148 report recommends that radiation dose measurements for MVCT be defined using the MSAD, which is measured with a calibrated ionization chamber placed within a standard cylindrical phantom. The report specifies that the scan range should cover the entire length of the phantom to ensure accurate integration of dose contributions from multiple slices.<sup>10</sup>

The Exradin A1SL ionization chamber (Standard Imaging Inc., Middleton, WI, USA) was used for dose measurements at both Center A and Center B. The chamber used at Center A was calibrated in water by the Bureau of Radiation and Medical Devices, Department of Medical Sciences, in November 2022, while the chamber used at Center B was calibrated in water by the Department of Medical Physics, University of Wisconsin-Madison, in February 2022. Dose measurements were performed with the chamber positioned in a CTDI phantom (GAMMEX Inc., Middleton, WI, USA). Both chambers were calibrated within a two-

year interval, which is considered acceptable under national dosimetry practice, provided that calibration is traceable to a national standards laboratory and detector stability is maintained.

The Exradin A1SL ionization chamber has a sensitive volume of 0.053 cm<sup>3</sup> and an outer diameter of 6.35 mm. The sensitive (collecting) volume has an axial length of approximately 4.4 mm. Because the chamber diameter is smaller than the standard CTDI phantom insert hole, a custom-designed PMMA rod was fabricated to ensure a secure fit, as illustrated in Figure 1.

The custom-designed PMMA rod has an effective length of 140 mm, excluding the 10-mm head portion, and contains a central hole with a length of 74.1 mm. This hole length was determined as the sum of the distance from the rod end to the center of the phantom (70 mm) and the distance from the center of the centroid of the collecting volume to the end of the A1SL chamber wall (4.1 mm), thereby ensuring accurate centering of the sensitive volume within the CTDI phantom.

**Figure 1.** Custom-designed PMMA rod for holding the Exradin A1SL ionization chamber.

The CTDI phantom measured 16 cm in diameter was used for the head scan protocol and 32 cm for the body scan protocol, with a uniform length of 15 cm.

The phantom was placed on the table, with its center aligned to the isocenter of the tomotherapy machines as shown in Figure 2.

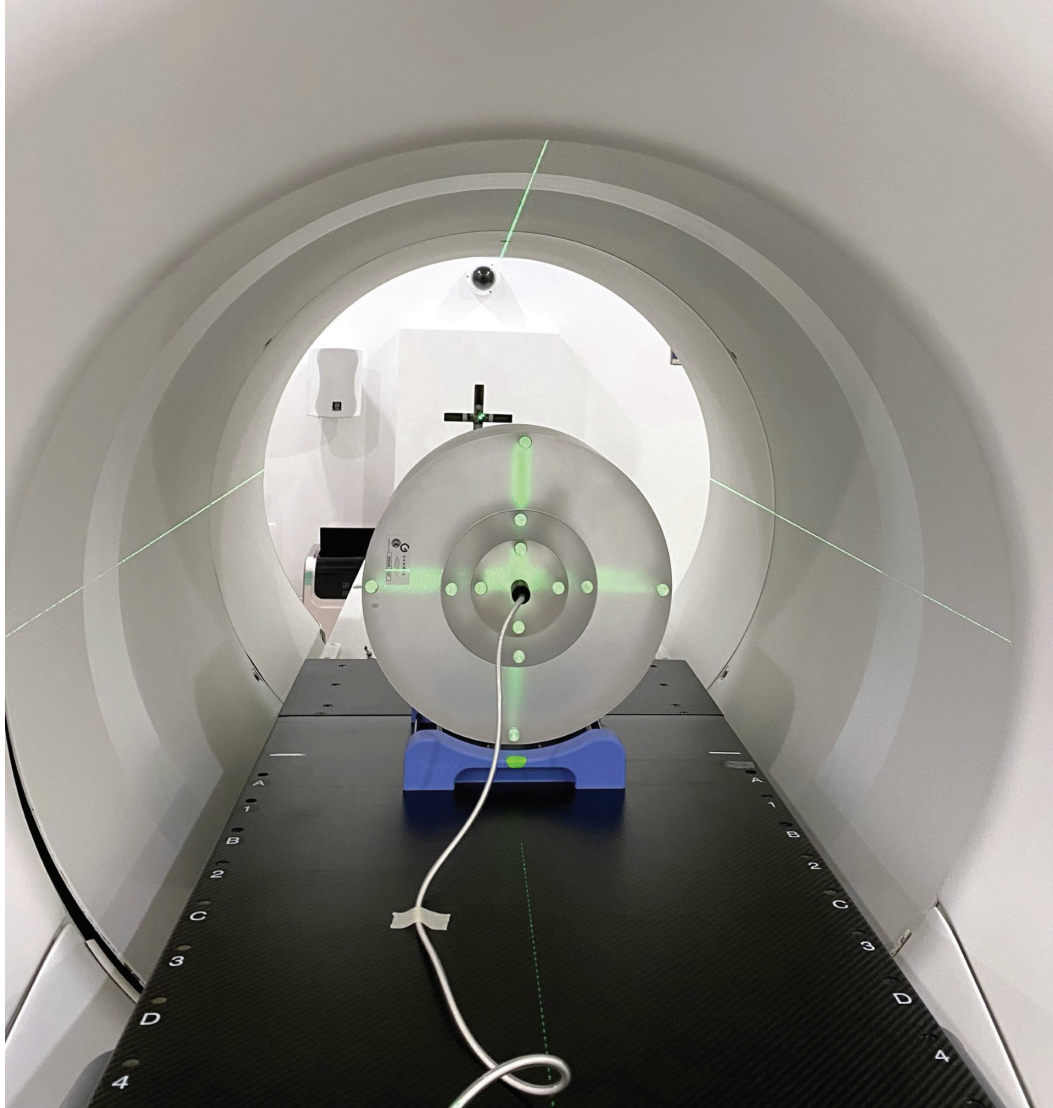


**Figure 2.** The equipment setup for body CTDI phantom dose measurement.

All scans were performed in Coarse mode using a 3.5 MV beam, with a pitch of 3 and a slice thickness of 6 mm (Table 1). A scan length of 15 cm was selected to cover the entire phantom. Each measurement was repeated twice. The MSAD and per scan were calculated according to Equations (1) and (2), respectively.

$$\text{MSAD} = M \times N_{D,w,Q_0} \quad (1)$$

where  $M$  is the meter reading (nC), and  $N_{D,w,Q_0}$  is the absorbed dose-to-water calibration factor (cGy/nC). The values of  $N_{D,w,Q_0}$  were 59.58 cGy/nC for Center A (MVCT 1) and 57.87 cGy/nC for Center B (MVCT 2).

$$\text{MSAD}_w^{\text{MVCT}} = \frac{1}{3} \text{MSAD}_{\text{center}} + \frac{2}{3} \text{MSAD}_{\text{periphery}} \quad (2)$$

where  $\text{MSAD}_{\text{center}}$  is the dose measured at the center of the phantom, and  $\text{MSAD}_{\text{periphery}}$  is the average dose measured at the four peripheral positions. Further details of the calculation can be found in the AAPM Task Group 75 report.<sup>15</sup>

Dose measurements were performed according to the recommendations of AAPM Task Group 148 report. Accordingly, no correction was applied for spectral differences between imaging and treatment beams. Pitch correction was also unnecessary, as meter readings were acquired using the clinical pitch settings.<sup>16</sup>

#### **Dose assessment of kVCT imaging**

Since axial scanning is unavailable for kVCT imaging on the Radixact system, an MSAD-based methodology consistent with MVCT was used, reflecting the similar helical acquisition principles of both modalities.<sup>17</sup>

A 100-mm pencil ionization chamber (RaySafe X2 CT, Unfors RaySafe AB, Billdal, Sweden) was employed for dose measurements. The chamber was calibrated in air by the Bureau of Radiation and Medical Devices, Department of Medical Sciences, in April 2024. All scans followed the clinical protocols summarized in Table 2, with a fixed scan length of 10 cm, as described by Leon et al.<sup>16</sup> MSAD per scan were calculated using Equations (3) and (4), respectively.

$$\text{MSAD} = M \times N_{K,Q_0} \times f \quad (3)$$

where M is the meter reading,  $N_{K,Q_0}$  is the air kerma calibration factor, and f is a correction factor of 1.06 used to convert air kerma to absorbed dose in tissue for typical diagnostic CT beam qualities, corresponding to an effective photon energy of approximately 70 keV (~120 kVp).<sup>18</sup> Although the air-to-tissue conversion factor can exhibit some energy dependence, variations across the kVp range used in this study are expected to be small, on the order of approximately 2% across 100-140 kVp. The values of  $N_{K,Q_0}$  were 0.994, 0.995, and 0.997 for beam qualities of 100 kVp, 120 kVp, and 140 kVp, respectively, for both Center A and Center C.

$$\text{MSAD}_w^{\text{kVCT}} = \frac{1}{3} \text{MSAD}_{\text{center}} + \frac{2}{3} \text{MSAD}_{\text{periphery}} \quad (4)$$

### Patient data

The study was approved by the Ethics Committee of Naresuan University, Thailand (IRB No. P1-0127/2024; approval date: 3 September 2024). Patient data were retrospectively collected between July 2023 and September 2024 from those who underwent IGRT for positioning verification. Inclusion criteria included patients aged  $\geq 18$  years with a body weight of  $60 \pm 15$  kg during treatment, representing the standard Thai adult population in accordance with the National Diagnostic Reference Levels in Thailand 2023.<sup>19</sup> These criteria were applied to ensure consistency in patient anatomy and imaging protocols and to minimize body size-related bias. Patients were also required to have completed the full prescribed treatment course and to have received IGRT scans encompassing the planning target volume (PTV). Patient data were categorized into four categories: 1) sex, age, and body weight, 2) prescribed radiation dose, 3) imaging protocol, and 4) number of imaging sessions. For each type of cancer, 30 patients were randomly selected.<sup>20</sup> If fewer patients

were available, all eligible cases from July 2023 to September 2024 were included.

At Center A, MVCT 1 was used for breast, prostate, and cervical cancer patients, while kVCT 1 was used for brain, head and neck, breast, prostate, and cervical cancer patients. Centers B and C contributed to breast and prostate cancer patients.

### Cumulative dose

To estimate the cumulative imaging dose, the  $\text{MSAD}_w$  measured in a phantom for each scan protocol was multiplied by the total number of imaging sessions (n) each patient received during treatment. The calculation methods for MVCT and kVCT are shown in Equations (5) and (6).

$$\text{Cumulative imaging dose}_{\text{MVCT}} = \text{MSAD}_w^{\text{MVCT}} \times n \quad (5)$$

$$\text{Cumulative imaging dose}_{\text{kVCT}} = \text{MSAD}_w^{\text{kVCT}} \times n \quad (6)$$

The cumulative imaging dose throughout the treatment course was expressed as a percentage of the mean prescribed dose, as shown in Equation (7).

$$\% \text{Imaging dose} = \left( \frac{\text{Cumulative imaging dose throughout the treatment}}{\text{Mean prescribed dose}} \right) \times 100 \quad (7)$$

The percentage of imaging dose throughout the treatment course was used to determine the proportion of patients whose cumulative imaging dose exceeded the 5% threshold, according to AAPM Task Group 180 report.<sup>6</sup>

### Data analysis

An MSAD value was obtained for each measurement condition at each center based on twice-repeated phantom measurements. Owing to the limited number of independent MSAD values, inter-center comparisons were performed using descriptive metrics, specifically percentage differences, rather than formal statistical testing.

## Results

### Imaging dose measurement in the CTDI phantom MVCT imaging

The mean  $\text{MSAD}_w^{\text{MVCT}}$  values were  $0.85 \pm 0.01$  cGy at Center A and  $0.86 \pm 0.00$  cGy at Center B. The percentage difference between the two centers was 1.17%, as shown in Figure 3.

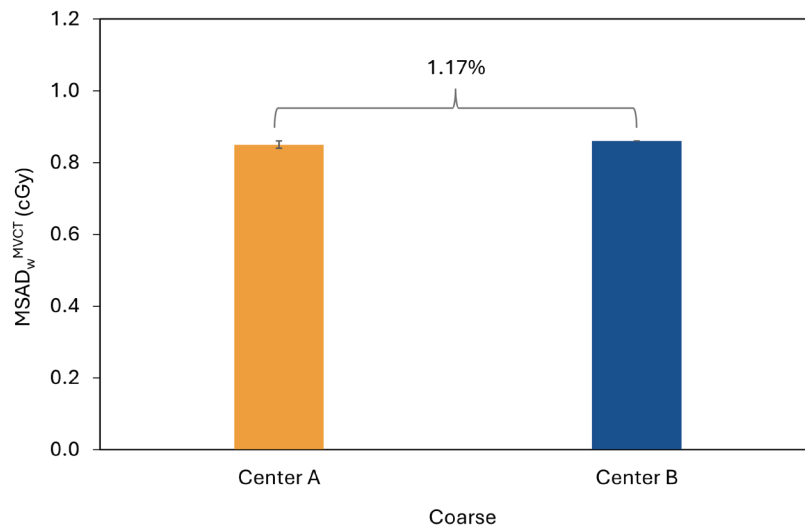


**Figure 3.** The  $MSAD_w^{MVCT}$  values for Coarse mode obtained from Center A and Center B.

### ***kVCT imaging***

Overall, the  $MSAD_w^{kVCT}$  values demonstrate notable variations across different scan modes and body sizes. The Fine mode yielded the highest  $MSAD_w^{kVCT}$  values, whereas the Coarse mode resulted in the lowest values.  $MSAD_w^{kVCT}$  values increased by a range of 1.5-1.7 fold when comparing small to medium body sizes.

The mean  $MSAD_w^{kVCT}$  values for the head protocol at Center A across the three modes (fine, normal, and

coarse) ranged from  $0.19 \pm 0.01$  to  $0.49 \pm 0.00$  cGy and  $0.26 \pm 0.02$  to  $0.82 \pm 0.00$  cGy for small and medium body sizes, respectively. At Center C, the corresponding ranges were  $0.22 \pm 0.01$  to  $0.47 \pm 0.01$  and  $0.33 \pm 0.00$  to  $0.83 \pm 0.01$  cGy, respectively. The percentage difference between the two centers was within 20% for all modes, except for the Coarse mode with the medium body size, which showed a difference of 23.73%, as shown in Figure 4.

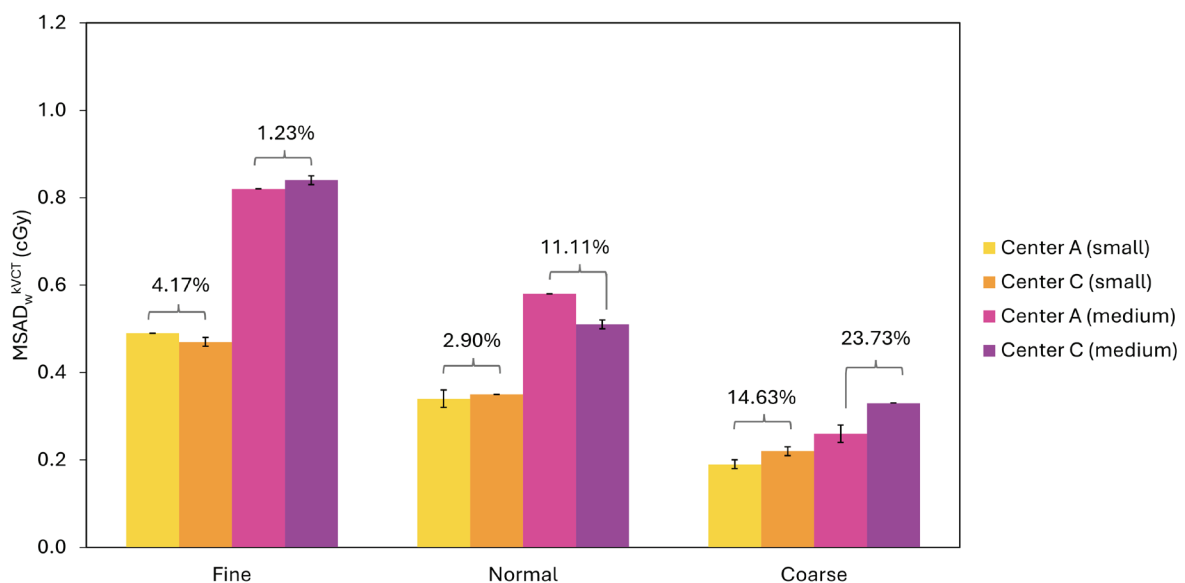


**Figure 4.** The  $MSAD_w^{kVCT}$  values for head protocol obtained from Center A and Center C.

The mean  $MSAD_w^{kVCT}$  values for the thorax protocol at Center A across the three modes (fine, normal coarse) ranged from  $0.49 \pm 0.02$  to  $0.86 \pm 0.00$  cGy,  $0.78 \pm 0.03$  to  $1.31 \pm 0.01$  cGy, and  $1.11 \pm 0.01$  to  $1.68 \pm 0.00$  cGy for small, medium, and large body sizes, respectively. At Center C, the corresponding ranges were  $0.55 \pm 0.01$

to  $0.97 \pm 0.06$  cGy,  $0.83 \pm 0.02$  to  $1.46 \pm 0.01$  cGy, and  $1.12 \pm 0.05$  to  $1.96 \pm 0.04$  cGy, respectively. The percentage difference between the two centers was within 20% for all modes, except for the Normal mode with small body size, which showed a difference of 21.33%, as shown in Figure 5.

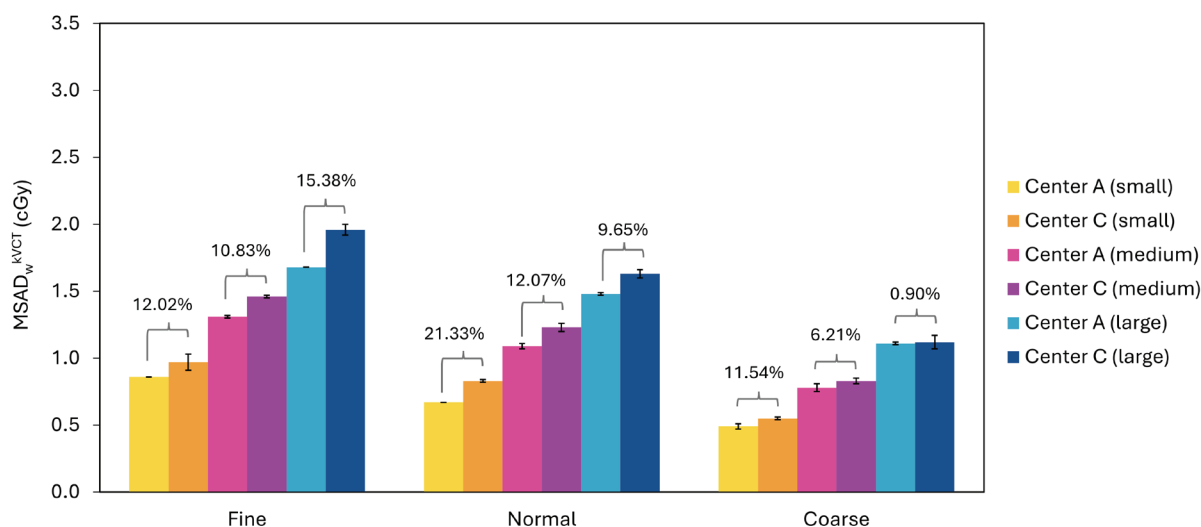


**Figure 5.** The MSAD<sub>w</sub><sup>kVCT</sup> values measured using the thorax protocol from Center A and Center C.

The mean MSAD<sub>w</sub><sup>kVCT</sup> values for the pelvis protocol at Center A across the three modes (fine, normal, and coarse) ranged from 0.74±0.01 to 1.19±0.00 cGy, 1.13±0.00 to 1.93±0.06 cGy, and 1.53±0.02 to 2.65±0.05 cGy for small, medium, and large body sizes, respectively. At Center C, the corresponding ranges were 0.79 ± 0.01

to 1.42±0.02 cGy, 1.27±0.01 to 2.22±0.02 cGy, and 1.58±0.05 to 2.61±0.04 cGy, respectively. The percentage difference between the two centers was within 20% for all modes, except for the Normal mode with the small body size, which showed a difference of 21.00%, as shown in Figure 6.

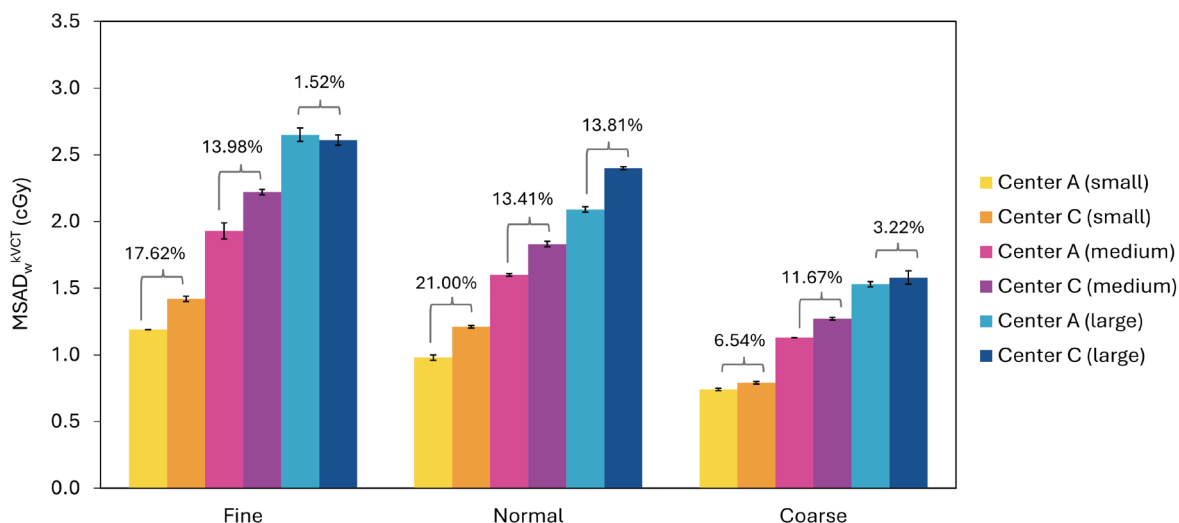


**Figure 6.** The MSAD<sub>w</sub><sup>kVCT</sup> values measured using the pelvis protocol from Center A and Center C.

### **The cumulative imaging dose received by the patient throughout the treatment course**

#### **MVCT imaging**

Patient data were collected from MVCT imaging throughout the treatment course at Center A (MVCT 1) for patients with breast, prostate, and cervical cancers

and at Center B (MVCT 2) for patients with breast and prostate cancers, as summarized in Table 3. The mean age differences between centers were 3.88% for breast cancer and 2.59% for prostate cancer patients. Mean body weight differences for the same groups were 0.30% and 6.78%, respectively.

**Table 3.** Patient data from MVCT imaging at Centers A and B.

| Center     | Cancer type | Sex    | Number | Age (years) | Weight (kg) |
|------------|-------------|--------|--------|-------------|-------------|
| A (MVCT 1) | Breast      | Female | 30     | 53.57±11.60 | 60.20±9.81  |
|            | Prostate    | Male   | 30     | 72.73±6.83  | 69.87±13.42 |
|            | Cervix      | Female | 30     | 53.53±13.29 | 56.37±8.74  |
| B (MVCT 2) | Breast      | Female | 30     | 51.53±11.87 | 60.38±10.25 |
|            | Prostate    | Male   | 30     | 70.87±7.63  | 65.29±9.62  |

**Note:** data presented as Mean±SD

Prescribed dose data collected from MVCT imaging are summarized in Table 4. The mean prescribed dose for breast cancer patients at Center A was 3.06% higher than at Center B. In contrast, for prostate cancer patients, the mean prescribed dose of Center B was

1.21% higher than that at Center A. Additionally, the average number of fractions at Center B was 31.58% higher for breast cancer patients and 3.92% higher for prostate cancer patients compared to Center A.

**Table 4.** Prescribed dose data from MVCT imaging at Centers A and B.

| Center     | Cancer type | Prescribed dose (PD)                        | PD (cGy)     | Fraction |
|------------|-------------|---------------------------------------------|--------------|----------|
| A (MVCT 1) | Breast      | 4,240 cGy/16 fraction-4,960 cGy/16 fraction | 4,840±272.92 | 16±0.00  |
|            | Prostate    | 5,500 cGy/20 fraction-7,560 cGy/28 fraction | 6,564±589.40 | 25±4.12  |
|            | Cervix      | 4,600 cGy/23 fraction-5,700 cGy/25 fraction | 4,852±399.46 | 23±0.81  |
| B (MVCT 2) | Breast      | 4,256 cGy/16 fraction-5,000 cGy/25 fraction | 4,694±366.58 | 22±4.61  |
|            | Prostate    | 6,000 cGy/20 fraction-7,600 cGy/38 fraction | 6,644±624.78 | 26±6.70  |

**Note:** data presented as Mean±SD

The average number of MVCT imaging sessions per patient throughout the treatment course was 13.95% higher at Center B than at Center A for breast cancer. For prostate cancer patients, both centers reported

the same average number of sessions, as shown in Table 5. Additionally, most patients at both centers received one MVCT scan per treatment fraction.

**Table 5.** Number of MVCT imaging sessions per patient throughout the treatment course.

| Cancer type | Center A          | Center B          |
|-------------|-------------------|-------------------|
|             | MVCT 1 (sessions) | MVCT 2 (sessions) |
| Breast      | 20±4.9 (16-30 )   | 23±4.6 (16-28)    |
| Prostate    | 27±5.0 (20-37)    | 27±6.7 (20-40)    |
| Cervix      | 25±2.5 (23-34)    | -                 |

**Note:** data presented as Mean±SD

The cumulative MVCT imaging dose throughout the treatment course at Center A was 17.40±4.15 cGy for breast cancer, 22.61±4.26 cGy for prostate cancer, and 21.34±2.12 cGy for cervical cancer patients. At Center B, doses were 20.56±4.68 cGy for breast cancer

and 24.02±6.85 cGy for prostate cancer, as shown in Figure 7. The mean dose at Center B was 16.65% higher than at Center A for breast cancer and 6.05% higher for prostate cancer.

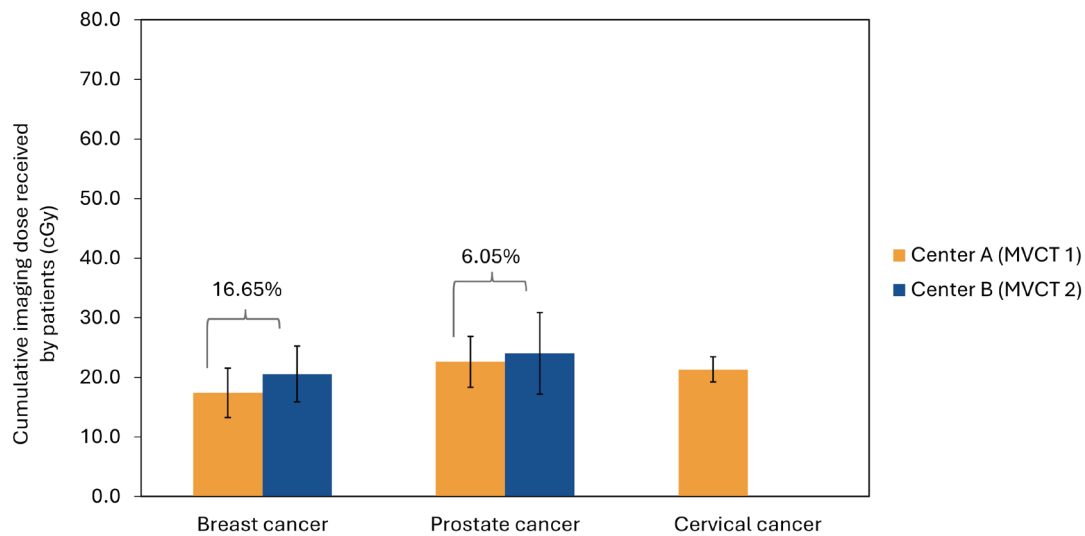


**Figure 7.** Cumulative MVCT imaging dose received by patients throughout the treatment course.

The percentage of cumulative MVCT imaging dose relative to the prescribed dose at Center A was  $0.36 \pm 0.11$  for breast cancer,  $0.34 \pm 0.04$  for prostate cancer, and  $0.44 \pm 0.03$  for cervical cancer. At Center B, the corresponding values were  $0.43 \pm 0.08$  for breast cancer and  $0.36 \pm 0.07$  for prostate cancer. Nevertheless, the cumulative imaging dose remained below 5% of the prescribed dose for all cancer types at both centers.

#### kVCT imaging

Patient data were collected from kVCT imaging throughout the treatment course at Center A (kVCT 1) for patients with brain, head and neck, breast,

prostate, and cervical cancers and at Center C (kVCT 2) for patients with breast and prostate cancers, as summarized in Table 6. The mean age differences between centers were 7.03% for breast cancer and 0.50% for prostate cancer patients. Mean body weight differences for the same groups were 6.36% and 0.55%, respectively.

Center A included a wider variety of cancer types because the kVCT 1 system was used across multiple disease sites, while some brain and head and neck cancer patients were treated with other radiotherapy machines. In contrast, the kVCT 2 system at Center C was used exclusively for breast and prostate cancer patients.

**Table 6.** Patient data from kVCT imaging at Centers A and Center C.

| Center     | Cancer type   | Sex    | Number | Age (years)       | Weight (kg)       |
|------------|---------------|--------|--------|-------------------|-------------------|
| A (kVCT 1) | Brain         | Male   | 5      | 45.56 $\pm$ 17.62 | 60.88 $\pm$ 12.99 |
|            |               | Female | 11     |                   |                   |
|            | Head and neck | Male   | 17     | 60.20 $\pm$ 10.69 | 53.60 $\pm$ 8.24  |
|            |               | Female | 13     |                   |                   |
|            | Breast        | Female | 30     | 56.97 $\pm$ 10.69 | 60.52 $\pm$ 12.30 |
|            | Prostate      | Male   | 30     | 69.97 $\pm$ 5.40  | 67.00 $\pm$ 13.23 |
| C (kVCT 2) | Cervix        | Female | 30     | 52.40 $\pm$ 13.28 | 59.69 $\pm$ 11.82 |
|            | Breast        | Female | 30     | 61.12 $\pm$ 11.13 | 56.79 $\pm$ 9.37  |
|            | Prostate      | Male   | 30     | 69.62 $\pm$ 6.25  | 67.37 $\pm$ 13.06 |

**Note:** data presented as Mean $\pm$ SD

Prescribed dose data collected from kVCT imaging are summarized in Table 7. The prescribed dose for breast cancer patients at Center A was 2.44% higher than at Center C. In contrast, for prostate cancer patients, the prescribed dose of Center C was 1.61%

higher than that at Center A. Additionally, the average number of fractions at Center A was 6.06% higher for breast cancer patients and 4.44% higher for prostate cancer patients compared to Center C.

**Table 7.** Prescribed dose data from kVCT imaging at Centers A and Center C.

| Center     | Cancer type   | Prescribed dose (PD)                         | PD (cGy)       | Fraction  |
|------------|---------------|----------------------------------------------|----------------|-----------|
| A kVCT 1)  | Brain         | 5,400 cGy/27 fraction -7,000 cGy/33 fraction | 5,925±640.31   | 30±1.90   |
|            | Head and neck | 6,000 cGy/30 fraction -7,000 cGy/33 fraction | 6,880±275.93   | 33±0.76   |
|            | Breast        | 4,240cGy/16 fraction -5,000 cGy/25 fraction  | 4,558±350.58   | 17±1.72   |
|            | Prostate      | 5,240 cGy/20 fraction -7,000 cGy/28 fraction | 6,049±727.12   | 23 ± 3.84 |
|            | Cervix        | 4,600 cGy/23 fraction -5,500 cGy/25 fraction | 4,848 ± 392.14 | 23±0.37   |
| C (kVCT 2) | Breast        | 4,240 cGy/16 fraction -5,000 cGy/25 fraction | 4,448±426.26   | 16±2.63   |
|            | Prostate      | 6,000 cGy/20 fraction -7,800 cGy/39 fraction | 6,147±406.39   | 22±5.33   |

**Note:** data presented as Mean±SD

The average number of kVCT imaging sessions per patient throughout the treatment course at Center C was 28.57% higher than at Center A for breast cancer

and 21.43% higher for prostate cancer, as shown in Table 8.

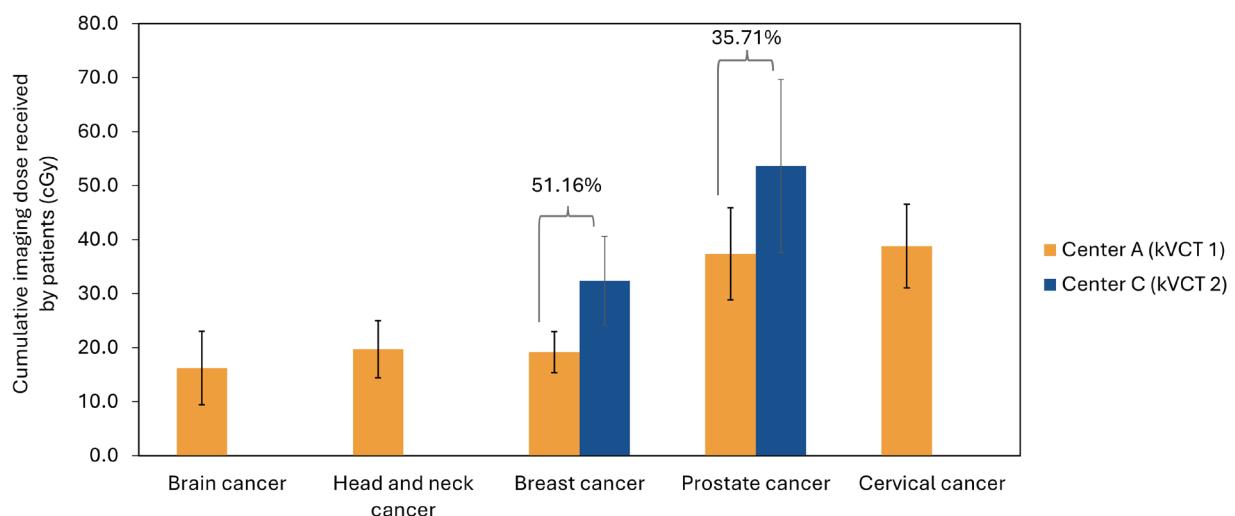
**Table 8.** Number of kVCT imaging sessions per patient throughout the treatment course.

| Cancer type     | Center A<br>kVCT 1 (sessions) | Center C<br>kVCT 2 (sessions) |
|-----------------|-------------------------------|-------------------------------|
| Brain cancer    | 32±2.8 (27-38)                | -                             |
| Head and neck   | 37±3.5 (31-45)                | -                             |
| Breast cancer   | 21±3.8 (17-32)                | 28±6.5 (15-45)                |
| Prostate cancer | 25±4.9 (20-34)                | 31±7.4 (23-58)                |
| Cervical cancer | 25±3.1(23-38)                 | -                             |

**Note:** data presented as Mean±SD

The cumulative kVCT imaging dose delivered over the treatment course at Center A was 16.20±6.82 cGy for brain cancer, 19.73±5.29 cGy for head and neck cancer, 19.17±3.79 cGy for breast cancer, 37.38±8.53 cGy for prostate cancer, and 38.80±7.72 cGy for cervical cancer. In comparison, at Center C, the corresponding

doses were 32.35±8.23 cGy for breast cancer and 53.63±16.02 cGy for prostate cancer, as illustrated in Figure 8. Notably, the mean dose at Center C was 51.16% higher than at Center A for breast cancer, and 35.71% higher for prostate cancer.

**Figure 8.** Cumulative kVCT imaging dose received by patients throughout the treatment course.

The percentage of cumulative kVCT imaging dose relative to the prescribed dose at Center A was  $0.28 \pm 0.12$  for brain cancer,  $0.29 \pm 0.08$  for head and neck cancer,  $0.42 \pm 0.10$  for breast cancer,  $0.62 \pm 0.10$  for prostate cancer, and  $0.80 \pm 0.16$  for cervical cancer. At Center C, the corresponding values were  $0.73 \pm 0.19$  for breast cancer and  $0.87 \pm 0.26$  for prostate cancer.

Nevertheless, the cumulative imaging dose remained below 5% of the prescribed dose for all cancer types at both centers.

In all centers and for all cancer types, the cumulative imaging doses from both MVCT and kVCT did not exceed 5% of the prescribed dose, as summarized in Table 9.

**Table 9.** The percentage of cumulative MVCT and kVCT imaging dose relative to the prescribed dose.

| Imaging type | Center | Cancer type   | %Cumulative imaging dose |
|--------------|--------|---------------|--------------------------|
| MVCT         | A      | Breast        | $0.36 \pm 0.11$          |
|              |        | Prostate      | $0.34 \pm 0.04$          |
|              |        | Cervix        | $0.44 \pm 0.03$          |
|              | B      | Breast        | $0.43 \pm 0.08$          |
|              |        | Prostate      | $0.36 \pm 0.07$          |
| kVCT         | A      | Brain         | $0.28 \pm 0.12$          |
|              |        | Head and neck | $0.29 \pm 0.08$          |
|              |        | Breast        | $0.42 \pm 0.10$          |
|              |        | Prostate      | $0.62 \pm 0.10$          |
|              |        | Cervix        | $0.80 \pm 0.16$          |
|              | C      | Breast        | $0.73 \pm 0.19$          |
|              |        | Prostate      | $0.87 \pm 0.26$          |

**Note:** data presented as Mean $\pm$ SD

## Discussion

This study evaluated the radiation dose associated with imaging using the IGRT system under clinically scanned protocols. The dose was quantified as the  $MSAD_w$ , measured in a CTDI phantom. Additionally, the study assessed whether the cumulative imaging dose received by patients throughout the treatment course with tomotherapy systems exceeded 5% of the prescribed therapeutic dose.

The measured  $MSAD_w^{MVCT}$  in the CTDI phantom with a 15 cm scan length was 0.85 cGy at Center A and 0.86 cGy at Center B. These values are consistent with previous findings by Devi R *et al.*<sup>21</sup> (0.82 cGy) and the value reported in the manufacturer's manual<sup>14</sup> (0.84 cGy), both of which were obtained using a Cheese phantom with an 18 cm scan length provided by the manufacturer. The dose differences between the method used in this study and that described in the manufacturer's manual were within 5%. Importantly, all measured values remained below the 1 cGy threshold specified by the manufacturer for MVCT imaging in Coarse mode.<sup>14</sup> The  $MSAD_w^{MVCT}$  was evaluated only in Coarse mode, as this scan mode is preferred at both Center A and Center B due to its shorter acquisition time compared with the Fine and Normal modes.

An evaluation of kVCT imaging doses revealed that radiation exposure generally increased with the

anatomical region being scanned, reflecting the tube potential (kVp) applied. Additionally, dose levels also rose with patient body size, corresponding to the tube current–time product (mAs). Imaging dose also varied depending on the imaging mode, which is influenced by pitch settings. Lower pitch values yielded higher image quality but were associated with increased radiation doses. Among the modes, Fine provided the highest image quality, followed by Normal and Coarse.<sup>14</sup> When pelvic and thoracic imaging were compared using the same FOV size (440 mm), pelvic protocols consistently resulted in higher radiation doses across all imaging modes and body sizes. This difference was primarily attributable to the higher tube potential used for pelvic imaging (140 kVp) compared to thoracic imaging (120 kVp).

A study by Ehler *et al.*<sup>17</sup> reported kVCT imaging doses measured using an 18 cm scan length without applying a correction factor to convert air kerma to absorbed dose in tissue (f factor), with reported dose ranges of 0.18–0.91 cGy (head), 0.45–1.67 cGy (thorax), and 0.65–2.38 cGy (pelvis), and percentage differences between measured doses and displayed  $CTDI_{vol}$  of -3.25% to 12.50%. In comparison, the present study observed comparable dose ranges when doses were calculated without applying the f factor, with reported dose ranges of 0.18–0.79 cGy (head), 0.46–

1.85 cGy (thorax), and 0.70-2.51 cGy (pelvis), and percentage differences between measured doses and displayed  $CTDI_{vol}$  of -8.00% to 16.67%. Additional context is provided by the study of Leon *et al.*<sup>16</sup> which evaluated imaging dose in diagnostic CT systems using a 10 cm scan length and a measurement methodology comparable to that employed in the present study. Leon *et al.*<sup>16</sup> reported percentage differences between measured and displayed  $CTDI_{vol}$  ranging from -9.3% to 8.2%. It is acknowledged that the use of a 10 cm scan length with a 100-mm pencil ionization chamber may underestimate the absolute kVCT dose due to incomplete integration of scatter. However, despite this potential underestimation, the thorax and pelvis dose ranges were comparable to, and in some cases higher than, those reported by Ehler *et al.*<sup>17</sup> using a longer scan length (18 cm), indicating that scan length alone does not fully explain the observed differences. The remaining discrepancies are likely due to methodological differences and system-specific factors, including variations in hardware configuration, detector design, and system optimization that can influence mAs requirements and effective imaging output.

This study found that Center A used kVCT imaging protocols (Normal and Coarse modes) that delivered lower radiation doses compared to Center C (Fine and Normal modes). For breast cancer, Normal medium (50.72%) and Coarse small (30.72%) modes were most common at Center A, while Center C used a higher proportion of Fine medium (71.55%) and Normal medium (1.42%). A similar trend was seen for prostate cancer imaging, where Center A used mainly Normal medium (72.67%) and Coarse medium (10.28%), while Center C used more Fine small (5.54%), Fine medium (14.02%), and Normal medium (59.89%). As a result, cumulative imaging doses differed by 51.16% for breast cancer and 35.71% for prostate cancer.

The cumulative imaging dose delivered to breast and prostate cancer patients was higher with kVCT (19.17-53.63 cGy) compared to MVCT (17.40-24.02 cGy). This was primarily due to the greater number of imaging sessions and the use of higher-dose imaging protocols in kVCT. Center C showed a 28.57% higher imaging session count for breast cancer and 21.43% for prostate cancer compared to Center A. This increase may be attributed to differences in patient setup practices, with Center C using support devices rather than rigid immobilization systems, leading to more positional variability. When target alignment could not be corrected by couch shifts alone, patient repositioning was required, resulting in repeated IGRT acquisitions.

Patient size can influence imaging dose estimates derived from phantom-based  $MSAD_w$ , as standardized PMMA phantoms may not fully represent individual patient anatomy. Smaller patients may receive higher absorbed doses due to reduced x-ray attenuation,

whereas larger patients may receive lower doses as a result of increased attenuation and scatter. To more accurately evaluate the impact of patient size on dose estimation, size-specific dose estimates (SSDE) can be used, as they account for differences between patient dimensions and standardized phantom sizes and enable more patient-specific dose assessment.

In this study, the cumulative imaging dose throughout the treatment course did not exceed 5% of the prescribed dose for any cancer type at any center, remaining within clinically acceptable limits. Where clinically feasible, the use of lower-dose imaging protocols, such as the Coarse mode instead of Fine or Normal modes, may further reduce cumulative radiation exposure without compromising image quality. This is supported by Marco *et al.*,<sup>12</sup> who reported negligible differences in image quality among Fine, Normal, and Coarse modes, with no clinically relevant impact on IGRT patient positioning. These findings support dose optimization strategies and may inform the development of institutional policies for tomotherapy-based IGRT. Furthermore, AAPM Task Group 142 report recommends performing annual evaluations of imaging doses, as well as reassessments after any replacement of imaging-related equipment, to ensure that patient doses remain within safe and clinically acceptable limits.<sup>22</sup>

### Limitations

This study has several limitations. Firstly, dose measurements were performed twice for each imaging condition, which may underestimate random uncertainty; additional repetitions would be required for a more robust characterization of measurement variability and for supporting statistically significant analysis. Secondly, kVCT doses were measured using a fixed 10 cm scan length with a 100 mm pencil ionization chamber, which may underestimate the absolute dose due to incomplete scatter integration. Thirdly, the imaging protocols evaluated were limited to those used at three centers, which may not fully represent the range of clinical practices. Fourthly, dose measurements were based on a phantom-derived  $MSAD_w$ , which may not reflect patient-specific scan lengths and body sizes in clinical practice, affecting dose estimations. Finally, all measurements were performed at the isocenter, which may not accurately reflect patient positioning in clinical settings and could lead to variations in delivered dose.

### Conclusion

The mean  $MSAD_w^{MVCT}$  values per scan at Center A and B were  $0.85 \pm 0.01$  cGy and  $0.86 \pm 0.00$  cGy, respectively, with a percentage difference of 1.17%. The mean  $MSAD_w^{kVCT}$  values per scan at Center A and C ranged from 0.19-0.83 cGy, 0.49-1.96 cGy, and 0.74-2.65 cGy for the head, thorax, and pelvis protocols, respectively. The imaging doses between the two centers differed by less than 20% in most cases, except for the head protocol

in Coarse mode for medium size (23.73%), the thorax protocol in Normal mode for small size (21.33%), and the pelvis protocol in Normal mode for small size (21.00%). The cumulative imaging doses from MVCT and kVCT over the treatment course accounted for 0.34-0.44% and 0.28-0.87% of the prescribed dose, respectively. In all centers and for all cancer types, the cumulative imaging dose did not exceed 5% of the prescribed dose. However, a substantial variation in cumulative imaging dose was observed between centers, with differences of 51.16% in breast cancer cases and 35.71% in prostate cancer cases. These findings highlight the need to investigate the underlying causes of this variation and to establish optimized imaging protocols in future study.

### Ethical approval

This research was approved by the ethics committee of Naresuan University, Thailand (IRB No. P1-0127/2024).

### Funding

This work was supported by Naresuan University (NU), and National Science, Research and Innovation Fund (NSRF) [Grant number R2569B107].

### Conflict of interest

The authors declare no potential conflicts of interest.

### CRedit authorship contribution statement

**Wannapha Nobnop, Sumalee Yabsantia, and Thunyarat Chusin:** supervision; **Pratchayakan Hompeng:** manuscript drafting; **all authors:** study conception, design, material preparation, data collection, and analysis, writing: reviewed and approved the final version.

### Acknowledgements

The authors gratefully acknowledge the medical physicists at the Radiation Therapy Departments of Maharaj Nakorn Chiang Mai Hospital, Lopburi Cancer Hospital, and Maha Vajiralongkorn Thanyaburi Hospital for their kind cooperation, technical assistance, and facilitation during data collection.

### References

- [1] Tegtmeier RC, Ferris WS, Bayouth JE, Miller JR, Culbertson WS. Characterization of imaging performance of a novel helical kVCT for use in image-guided and adaptive radiotherapy. *J Appl Clin Med Phys.* 2022; 23: e13648. doi.org/10.1002/acm2.13648.
- [2] Yang B, Geng H, Chang TYA, Tse MY, Lam WW, Huang CY, et al. Clinical implementation of kVCT-guided tomotherapy with ClearRT. *Phys Eng Sci Med.* 2022; 45: 915-24. doi.org/10.1007/s13246-022-01162-y.
- [3] Sakai Y, Monzen H, Takei Y, Kosaka H, Nakamura K, Yanagi Y, et al. Evaluation of in-room volumetric imaging doses for image-guided radiotherapy: A multi-institutional study. *J Med Phys.* 2023; 48: 189-94. doi.org/10.4103/jmp.jmp\_109\_22.
- [4] Tomita T, Isobe T, Furuyama Y, Takei H, Kobayashi D, Mori Y, et al. Evaluation of dose distribution and normal tissue complication probability of a combined dose of cone-beam computed tomography imaging with treatment in prostate intensity-modulated radiation therapy. *J Med Phys.* 2020; 45: 78-87. doi.org/10.4103/jmp.JMP\_4\_20.
- [5] Brenner DJ. Induced second cancers after prostate-cancer radiotherapy: No cause for concern? *Int J Radiat Oncol Biol Phys.* 2006; 65: 637-9. doi.org/10.1016/j.ijrobp.2006.02.044.
- [6] Ding GX, Alaei P, Curran B, Flynn R, Gossman M, Mackie TR, et al. Image guidance doses delivered during radiotherapy: Quantification, management, and reduction: Report of the AAPM Therapy Physics Committee Task Group 180. *Med Phys.* 2018; 45: e84-9. doi.org/10.1002/mp.12824.
- [7] Dische S, Saunders MI, Williams C, Hopkins A, Aird E. Precision in reporting the dose given in a course of radiotherapy. *Rad Onc.* 1993; 29: 287-93. doi.org/10.1016/0167-8140(93)90146-Y.
- [8] Saunders MI, Dische S, Grosch EJ, Fermont DC, Ashford RFU, Maher EJ, et al. Experience with CHART. *Int J Radiat Oncol Biol Phys.* 1991; 21: 871-8. doi.org/10.1016/0360-3016(91)90722-G.
- [9] Morgan-Fletcher SL. Prescribing, Recording and Reporting Photon Beam Therapy (Supplement to ICRU Report 50), ICRU Report 62. ICRU, pp. ix+52, 1999 (ICRU Bethesda, MD) \$65.00 ISBN 0-913394-61-0. *Br J Radiol.* 2001; 74: 294. doi.org/10.1259/bjr.74.879.740294.
- [10] Langen KM, Papanikolaou N, Balog J, Crilly R, Followill D, Goddu SM, et al. QA for helical tomotherapy: Report of the AAPM Task Group 148. *Med Phys.* 2010; 37: 4817-53. doi.org/10.1118/1.3462971.
- [11] Mege JP, Wenzhao S, Veres A, Auzac G, Diallo I, Lefkopoulos D. Evaluation of MVCT imaging dose levels during helical IGRT: Comparison between ion chamber, TLD, and EBT3 films. *J Appl Clin Med Phys.* 2016; 17: 143-57. doi.org/10.1120/jacmp.v17i1.5774.
- [12] De Marco P, Abdi Osman I, Castellini F, Ricotti R, Leonardi MC, Miglietta E, et al. Image quality and dose evaluation of MVCT Tomotherapy acquisitions: A phantom study. *Physica Medica.* 2019; 57: 200-6. doi.org/10.1016/j.ejmp.2019.01.009.
- [13] Trivedi G, Dixit C, Oinam A, Kapoor R, Bahl A. Kilovoltage cone-beam computed tomography imaging dose estimation and optimization: Need of daily cone-beam computed tomography. *J Cancer Res Ther.* 2019; 15: 470-4. doi.org/10.4103/jcrt.JCRT\_949\_17.
- [14] Radixact physics essentials guide., Version 3.0.x ed.

Published online: Accuray Incorporated; 2023.

- [15] Murphy MJ, Balter J, Balter S, Bencomo JA, Das IJ, Jiang SB, et al. The management of imaging dose during image-guided radiotherapy: Report of the AAPM Task Group 75. *Med Phys*. 2007; 34:4041-63. doi.org/10.1118/1.2775667.
- [16] Leon SM, Kobistek RJ, Olguin EA, Zhang Z, Barreto IL, Schwarz BC. The helically-acquired CTDI<sub>vol</sub> as an alternative to traditional methodology. *J Appl Clin Med Phys*. 2020; 21: 263-71. doi.org/10.1002/acm2.12944.
- [17] Ehler ED, Alaei P. Imaging dose and image quality of kilovoltage imaging implemented on a helical tomotherapy unit. *Z Med Phys*. 2025.; in press. doi.org/10.1016/j.zemedi.2024.12.003.
- [18] McCollough CH, Cody D, Edyvean S, Geise R, Gould B, Keat N, et al. The measurement, reporting, and management of radiation dose in CT. College Park, MD, USA: AAPM. 2008; Report No. 96: pp 1-68. doi.org/10.37206/97
- [19] Department of Medical Sciences, Ministry of Public Health. National diagnostic reference levels in Thailand 2023. Nonthaburi: Department of Medical Sciences, Ministry of Public Health; 2023: pp 42, ISBN 978-616-11-5048-8.
- [20] Vañó E, Miller DL, Martin CJ, Rehani MM, Kang K, Rosenstein M, et al. ICRP Publication 135: Diagnostic reference levels in medical imaging. *Ann ICRP*. 2017; 46(1): 1-144. doi:10.1177/0146645317717209.
- [21] Devi R, Singh B, Basandrai D, Passi K, Singh V. Estimation of weighted computed tomography dose index (CTDI<sub>w</sub>) in megavoltage computed tomography (MVCT). *Egypt J Radiol Nucl Med*. 2024; 55:205:1- 8. doi:10.1186/s43055-024-01374-0.
- [22] Klein EE, Hanley J, Bayouth J, Yin FF, Simon W, Dresser S, et al. Task group 142 report: Quality assurance of medical accelerators. *Med Phys*. 2009; 36: 4197-212. doi.org/10.1118/1.3190392.