Evaluation of radiation dose in computed tomography simulator
การประเมินปริมาณรังสีในการตรวจเอกซเรย์คอมพิวเตอร์ สำหรับการจำลองการฉายรังสี

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Abstract

Background: Computed tomography (CT) simulator is the gold standard tool for radiotherapy treatment planning. In CT imaging the radiation dose must be as low as possible to minimize the patient's risk but still sufficiently high to obtain a satisfying image quality for diagnostic and treatment.

Objectives: To evaluate the radiation dose of patients who underwent a CT simulation for radiotherapy treatment planning at Sakon Nakhon Hospital and to compare the radiation dose with diagnostic reference levels (DRLs) and dose reference levels for radiotherapy CT simulation (DRLs of RT CT).

Materials and methods: Computed tomography dose index in air (CTDIair) and volume computed tomography dose index ($CTDI_{vol}$) were measured. The measured $CTDI_{vol}$ was then compared with the displayed CT scanner $CTDI_{vol}$. After that, 1-year $CTDI_{vol}$ and dose length product (DLP) were retrospectively collected from patient records between October 1st, 2020 and September 30th, 2021. The data included patients of the head and neck (H&N), thorax, and pelvis simulation protocols. The $CTDI_{vol}$ and DLP values obtained with parameters were compared with the DRLs and DRLs of RT CT.

Results: The CT scanner output was 0.20 mGy/mAs. The displayed CT scanner $CTDI_{vol}$ was higher than the measured $CTDI_{vol}$. The deviations between measured and reported $CTDI_{vol}$ of H&N, thorax, and pelvis protocols were 7.20%, 2.14% and 1.36%, respectively. The median values of $CTDI_{vol}$ and DLP were 15.97 mGy and 638.11 mGy.cm for the H&N protocol, 11.54 mGy and 487.64 mGy.cm for the thorax protocol, and 12.01 mGy and 541.25 mGy.cm for the pelvis protocol, respectively.

Conclusion: There were no CT simulation protocols in which the radiation doses exceeded the DRLs and dose reference levels for CT in radiation oncology. The radiation doses in computed tomography for radiotherapy treatment planning were properly optimized following the imaging guidelines.

Key words: computed tomography simulation, radiation dose, dose reference levels

บทคัดย่อ

หลักการและเหตุผล: เครื่องเอกซเรย์คอมพิวเตอร์จำลองการฉายรังสีเป็นเครื่องมือมาตรฐานสำหรับการวางแผนการรักษาในทางรังสีรักษา การสร้างภาพทางรังสีด้วยเครื่องเอกซเรย์คอมพิวเตอร์จึงควรใช้ปริมาณรังสีให้น้อยที่สุดเพื่อลดผลกระทบอันไม่พึงประสงค์ที่อาจเกิดขึ้นกับผู้ป่วย แต่ยังคงไว้ซึ่งคุณภาพที่เพียงพอต่อการวินิจฉัยและรักษา

วัตถุประสงค์: เพื่อประเมินปริมาณรังสีของผู้ป่วยที่เข้ารับการเอกซเรย์คอมพิวเตอร์ในการจำลองการฉายรังสีในหน่วยรังสีรักษา กลุ่มงานรังสีวิทยา โรงพยาบาลสกลนคร และเปรียบเทียบค่าระดับปริมาณรังสีอ้างอิงทางการวินิจฉัยและค่าระดับปริมาณรังสีอ้างอิงของเครื่องเอกซเรย์คอมพิวเตอร์จำลองการฉายรังสี

วัสดุและวิธีการ: วัดค่าปริมาณรังสีในอากาศ computed tomography dose index in air (CTDIair) และค่าปริมาณรังสีในแฟนทอม volume computed tomography dose index ($CTDI_{vol}$) จากนั้นนำค่า $CTDI_{vol}$ ที่ได้จากการวัดเปรียบเทียบกับค่า $CTDI_{vol}$ ที่แสดงบนหน้าจอของเครื่องเอกซเรย์คอมพิวเตอร์จำลองการฉายรังสี จากนั้นทำการศึกษาย้อนหลัง โดยเก็บค่าปริมาณรังสี $CTDI_{vol}$ และ dose length product (DLP) จากเอกซเรย์คอมพิวเตอร์จำลองการฉายรังสีบริเวณศีรษะและลำคอ ทรวงอก และเชิงกราน ในช่วงวันที่ 1 ตุลาคม 2563 ถึง 30 กันยายน 2564 แล้วนำค่า $CTDI_{vol}$ และ DLP เปรียบเทียบกับค่าระดับปริมาณรังสีอ้างอิงทางการวินิจฉัยและค่าระดับปริมาณรังสีอ้างอิงของเอกซเรย์คอมพิวเตอร์จำลองการฉายรังสี

ผลการศึกษา: ค่าปริมาณรังสีในอากาศมีค่า 0.20 mGy/mAs ปริมาณรังสี $CTDI_{vol}$ ที่แสดงบนหน้าจอมีค่ามากกว่าการวัด ความแตกต่างของค่า $CTDI_{vol}$ จากการวัดและที่แสดงบนหน้าจอของโปรโตคอลศีรษะและลำคอ ทรวงอก และเชิงกรานมีค่า 7.20%, 2.14% และ 1.36% ตามลำดับ ค่ามัธยฐานของ $CTDI_{vol}$ และ DLP ของการเอกซเรย์คอมพิวเตอร์จำลองการฉายรังสีบริเวณศีรษะและลำคอมีค่า 15.97 mGy และ 638.11 mGy.cm ทรวงอกมีค่า 11.54 mGy และ 487.64 mGy.cm และเชิงกรานมีค่า 12.01 mGy และ 541.25 mGy.cm ตามลำดับ

ข้อสรุป: ไม่มีโปรโตคอลของการตรวจเอกซเรย์คอมพิวเตอร์จำลองการฉายรังสีที่มีปริมาณรังสีเกินค่าระดับปริมาณรังสีอ้างอิงทางการวินิจฉัยและค่าระดับปริมาณรังสีอ้างอิงของเอกซเรย์คอมพิวเตอร์จำลองการฉายรังสี ปริมาณรังสีที่ใช้ในการสร้างภาพมีความเหมาะสมและเป็นไปตามมาตรฐาน

คำสำคัญ: เอกซเรย์คอมพิวเตอร์จำลองการฉายรังสี, ปริมาณรังสี, ค่าระดับปริมาณรังสีอ้างอิง

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Introduction

Computed tomography (CT) simulator is a CT scanner that comprises a wide gantry aperture, flat patient couch, external or room laser, and virtual simulation software. It is the gold standard modality in radiotherapy treatment planning.[1] It provides 3D imaging for targets and organs at risk localization and establishes a digitally reconstructed radiograph (DRR) for reference imaging of patient treatment verification. Moreover, the obtained Hounsfield units (HU) are converted to electron density for treatment planning and dose calculation.[2] The patient receives a relatively high radiation dose from a CT scan. The dose depends on several parameters, e.g., peak kilovoltage (kVp), tube current–time product (mAs), pitch, slice thickness, and scan range.[3-6]

Diagnostic reference levels (DRLs) of the used imaging procedure were reported by international organizations like the International Atomic Energy Agency (IAEA), the American College of Radiology (ACR) and the International Commission on Radiological Protection (ICRP). Likewise, national organizations such as the Ministry of Public Health and local institutes have published DRLs. DRLs were presented in terms of $CTDI_{vol}$ and dose length product (DLP). The ICRP recommended that the median values of the radiation doses in protocols were compared for national and international DRLs. If necessary, the dose of ionizing radiation in imaging procedures must be revised and optimized.[7-12] An excessive radiation dose may affect the health of the patient and increases the risk of radiation-induced malignancy.[13-15] On the other hand, a dose that is too low may result in image quality that is too poor for diagnosis or medical purposes.

Previous studies in Thailand reported that patients who underwent diagnostic CT in either brain, head and neck (H&N), or abdomen protocols received high radiation doses that exceeded international DRLs.[11, 16, 17] Moreover, several studies revealed that CT simulation doses were generally higher than CT diagnostic doses.[18, 19] To address this problem, estimation of the radiation dose and optimization of the radiation exposure are crucial for clinical protocol settings. The radiation dose used in the imaging modality should be optimized for patient safety and image quality. In this study, the CT scan dose in the treatment simulation procedure in our department was investigated. The objective was to determine and compare CT simulation radiation doses to the diagnostic and radiotherapy DRLs.

Materials and methods

Air kerma measurement

To verify output consistency, CT air kerma measurement or computed tomography dose index in air (CTDIair) was obtained by Optima 580, 16 slice CT scanner with an 80 cm bore diameter (GE Healthcare, Milwaukee, WI). CTDIair was performed in air at 120 kVp, 200 mAs, 1 s rotation time at 10 mm slice thickness with axial scan mode using a RaySafe X2 100 mm

CT ionization chamber (Unfors RaySafe AB, Billdal, Sweden). The ionization chamber and radiation base unit were calibrated by Secondary Standard Dosimetry Laboratory (SSDL). An ionization chamber was placed on the table couch by hanging it over the top of the couch as shown in **figure 1.** CTDIair was obtained using the following equation 1. Measurement data were collected in triplicate.

$$CTDI_{air} = \frac{1}{NT}\int_{-50}^{+50} K(z)\, dz \qquad (1)$$

Where, K(z) is radiation dose at Z direction over a length of 100 mm, N is the number of data slices, and T is the slice thickness.

The reliability of CT scanner dose report

The deviation between the measured radiation dose and the dose displayed by the CT scanner was determined prior to patient radiation dose analysis to validate the accuracy of the CT scanner dose report. The volume computed tomography dose index ($CTDI_{vol}$) dose reports of the head and neck (H&N), thorax, and pelvis protocols were compared with $CTDI_{vol}$ dose measurements. An ionization chamber was inserted in the center and peripheral holes of a phantom of 32 cm diameter to obtain the data for calculation of the weighted computed tomography dose index (CTDIw) as shown in **figure 1**. The measurement parameters were set to 120 kVp, varied mAs (H&N = 200 mAs, thorax = 275 mAs and pelvis = 250 mAs), 1 s rotation time at 10 mm slice thickness with axial scan mode. CTDIw and $CTDI_{vol}$ were calculated by following equations 2 and 3. Data were collected from three dose measurements.

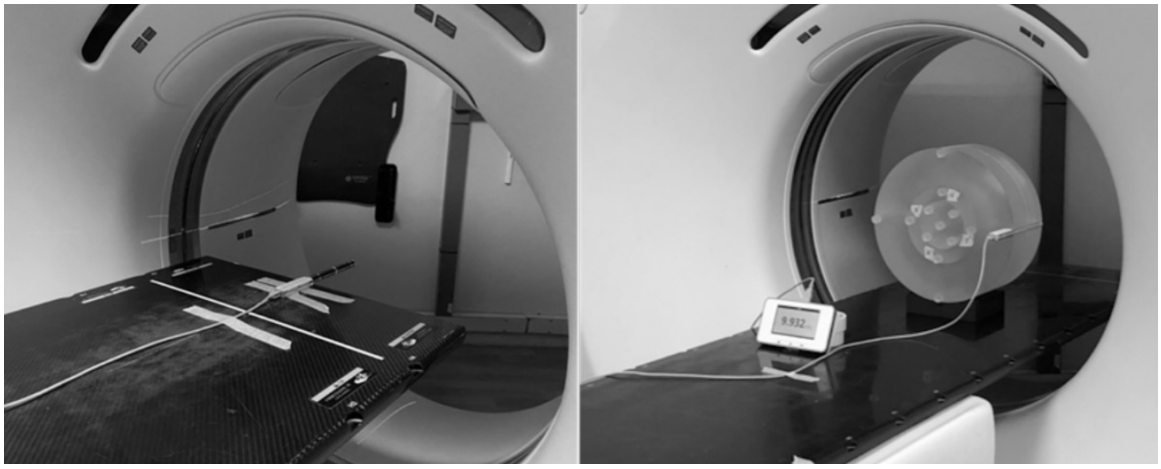


Figure 1. The setting of air kerma measurement (left), and CTDIw and CTDIvol measurements (right)

$$CTDI_w = 1/3\ CTDI_{100,\ center} + 2/3\ CTDI_{100,\ periphery} \quad (2)$$

Where $CTDI_w$ is the obtained value of $CTDI_{100,\ center}$ at the central hole of body phantom, and $CTDI_{100,\ periphery}$ is the average value of CTDI measured at 3, 6, 9, and 12 o'clock positions of body phantom.

$$CTDI_{vol} = CTDIw/pitch \quad (3)$$

The difference between the measured radiation dose and dose displayed by CT scanner was acceptable within ±20%.[7] The difference was calculated by following equation 4.

$$\text{The percentage difference} = \frac{\text{displayed } CTDI_{vol} - \text{measured } CTDI_{vol}}{\text{measured } CTDI_{vol}} \times 100 \quad (4)$$

Patient data collection

In this retrospective study, medical imaging data recorded on an Optima 580 CT scanner were collected. Data from a total of 817 adult patients (≥18 years old) were gathered from October 1st, 2020 to September 30th, 2021. The data sample sizes were calculated following by Taro Yamane Formula (Yamane, 1973). The three non-contrast media CT protocols (H&N, thorax, and pelvis) in our radiation therapy department were gathered. The selected patient data that fitted the three protocols comprised records from 89 patients of H&N protocol, 153 patients of thorax protocol, and 146 patients of pelvis protocol. The parameters used in the CT simulation protocols at the Radiation Therapy Unit, Radiology Department, Sakon Nakhon Hospital, Thailand are shown in **Table 1**. The research was approved by the Human Research Ethics Committee of Sakon Nakhon Hospital, SKHREC No.073/64.

CT simulation radiation dose analysis

The CT simulation doses were calculated and reported by the CT simulation scanner. All of $CTDI_{vol}$ reported for H&N, thorax and pelvis protocols were obtained using a reference phantom of 32 cm diameter. $CTDI_{vol}$ and DLP were displayed on the CT scanner monitor. The radiation doses were collected for data analysis.

Statistical analysis

Statistical analysis was performed in Microsoft Excel v. 16.90. The quantitative variable is shown as mean ± standard deviation, median, and 75th percentile. The dose deviation is shown in percentage difference. The median $CTDI_{vol}$ and DLP were compared with local, national and international DRLs and dose reference levels for CT in radiation oncology.

Results

Air kerma measurement

The CT scanner output was 0.20 mGy/mAs. The air kerma measurement revealed output consistency in comparison with the baseline (0.20 mGy/mAs).

The reliability of CT scanner dose report

The measured $CTDI_{vol}$ and displayed $CTDI_{vol}$ are shown in **Table 2**. The differences between the measured radiation dose and the reported

Table 1 The CT simulation protocols at the Radiation Therapy Unit, Radiology Department, Sakon Nakhon Hospital, Sakon Nakhon, Thailand.

Parameter	H&N	Thorax	Pelvis
kVp	120	120	120
Auto mA	Yes	Yes	Yes
Smart mA	Yes	Yes	Yes
mA range	100-300	200-350	100-400
Noise index	9.10	10.31	12.69
Slice thickness (mm)	2.5	2.5	2.5
Pitch	0.938	1.375	1.375
Collimator (mm)	10	20	20
Rotation time (sec)	1	0.6	0.8
Detector row	16	16	16
Dose reduction (%)	20	20	40
Image reconstruction	20% Iterative reconstruction 80% Back projection	20% Iterative reconstruction 80% Back projection	40% Iterative reconstruction 60% Back projection
Scan range	Vertex to laminar bifurcation	Chin tip to the 2nd of lumbar vertebrae	The 1st of lumbar vertebrae to greater trochanter

Table 2 The summary of measured CTDIvol, displayed CTDIvol and percentage deviation of dose for H&N, thoracic and pelvis simulation protocols.

Protocol	Displayed $CTDI_{vol}$ (mGy)	Measured $CTDI_{vol}$ (mGy)	Dose difference (%)
H&N	14.30	13.34	7.20
Thorax	12.89	12.62	2.14
Pelvis	15.63	15.42	1.36

dose by the CT scanner for H&N, thorax, and pelvis were 7.20%, 2.14% and 1.36%, respectively. The deviations were less than ±20% and acceptable. Therefore, the results revealed that the CT scan doses were accurate and reliable.

CT simulation radiation dose analysis

Patient data comprised 716 records from 360 males and 457 females. The median age of the patients was 57 years (age range 19–86 years). The radiation dose data showed normal distribution. The mean, median, 75th percentile, standard deviation values of $CTDI_{vol}$, patient scan length, and DLP for H&N, thoracic, and pelvis simulation protocols are shown in **Table 3**.

Table 4-5 show a comparison of radiation dose received by patients undergoing CT simulation with local DRLs (LDRLs) in Thai cancer hospitals, national, and international DRLs. For the H&N protocol, the $CTDI_{vol}$ was lower than in Thai cancer hospitals whereas the DLP value was slightly higher. For the thoracic protocol, our data showed that $CTDI_{vol}$ did not exceed Thai cancer hospitals, national, and international DRLs. Interestingly, our data revealed that the DLP value of the thoracic protocol was slightly higher than the national Thailand, ACR, and the UK whereas the DLP value was slightly lower than Thai cancer hospitals, and Japan.

Table 6-7 show a comparison of patient radiation doses with dose reference levels for CT in radiation oncology. All $CTDI_{vol}$ and DLP values from the three investigated CT simulation protocols in this study did not exceed dose reference levels for radiotherapy CT simulation (DRLs of RT CT).

Table 3 The data of CTDIvol, scan length and DLP for H&N, thoracic, and pelvis simulation protocols.

Protocol	H&N			Thorax			Pelvis		
	$CTDI_{vol}$ (mGy)	Scan length (mm)	DLP (mGy•cm)	$CTDI_{vol}$ (mGy)	Scan length (mm)	DLP (mGy•cm)	$CTDI_{vol}$ (mGy)	Scan length (mm)	DLP (mGy•cm)
Minimum	12.54	315.00	449.62	8.08	360.00	339.84	5.02	350.00	203.14
Maximum	21.68	415.00	934.69	13.90	460.00	632.28	21.33	485.00	964.84
Mean	16.08	375.75	632.05	11.18	406.63	485.89	12.04	422.31	546.80
Median	15.97	382.25	638.11	11.54	402.50	487.64	12.01	425.00	541.25
75th percentile	16.65	392.50	669.53	11.54	425.00	519.61	14.87	441.94	676.02
Standard deviation	1.60	24.26	80.61	0.94	25.45	51.04	3.54	28.28	166.16

Table 4 The comparison of CTDIvol with local, national, and international DRLs.

	$CTDI_{vol}$ (mGy)					
Protocol	**This study**	**Thai cancer hospitals (2021)[11]**	**Thailand (2021)[10]**	**Japan (2020)[12]**	**ACR (2018)[20]**	**UK (2022)[21]**
H&N	15.97	19.20	N/A	N/A	N/A	N/A
Thorax	11.54	24.30	18.00	13.00	12.00	8.50
Pelvis	12.04	N/A	N/A	N/A	N/A	N/A

N/A - Not Available

Table 5 The comparison of DLP with local, national, and international DRLs.

	DLP (mGy.cm)					
Protocol	**This study**	**Thai cancer hospitals (2021)[11]**	**Thailand (2021)[10]**	**Japan (2020)[12]**	**ACR (2018)[20]**	**UK (2022)[21]**
H&N	638.11	541.90	N/A	N/A	N/A	N/A
Thorax	487.64	771.84	417.00	510.00	443.00	290.00
Pelvis	541.25	N/A	N/A	N/A	N/A	N/A

N/A - Not Available

Table 6 The comparison of CTDIvol with DRLs of RT CT.

	$CTDI_{vol}$ (mGy)					
Protocol	**This study**	**RT India (2022)[22]**	**RT Croatia (2022)[23]**	**RT Slovenia (2020)[24]**	**RT Ireland (2018)[25]**	**RT UK (2018)[21]**
H&N	15.97	17.60	N/A	22.60	21.00	N/A
Thorax	11.54	N/A	17.00	19.20	N/A	14.00
Pelvis	12.04	17.60	20.00	17.90	N/A	N/A

N/A - Not Available

Table 7 The comparison of DLP with DRLs of RT CT.

	$CTDI_{vol}$ (mGy)					
Protocol	**This study**	**RT India (2022)[22]**	**RT Croatia (2022)[23]**	**RT Slovenia (2020)[24]**	**RT Ireland (2018)[25]**	**RT UK (2018)[21]**
H&N	638.11	790.65	N/A	969.20	882.00	N/A
Thorax	487.64	N/A	865.00	832.40	N/A	550.00
Pelvis	541.25	999.70	1,133.00	677.10	N/A	N/A

N/A - Not Available

Discussion

Nowadays, the CT simulator is the primary modality in radiotherapy simulation. The radiation dose of CT simulation must be investigated and properly optimized following imaging guidelines. This study investigated the radiation dose in CT simulation in three simulation protocols and compared the results with national, and international DRLs and the CT dose reference levels for treatment planning.

Prior to the CT simulation radiation dose study, this study performed CTDI in air to confirm CT output consistency because $CTDI_{vol}$ depends on machine output. The data confirmed consistent CT output as referenced by the user baseline and the standard government organization baseline of the Bureau of Radiation and Medical Devices, Department of Medical Sciences, Ministry of Public Health, Thailand. Forss et al.[26] suggested that the radiation dose display and the measured dose should be validated before radiation dose studies. The radiation dose report was validated to ensure the correctness of the radiation dose from the scanner. The result indicated that the reported scanner doses were slightly higher than the measured doses, as observed by other authors.[26, 27] The differences were acceptable and safe for the patients during the CT procedure. Regarding comparing our data with DRLs,[10-12, 20, 21] for the H&N protocol, the result could compare only the LDRLs in Thai cancer hospitals. Furthermore, it was not possible to do this for the pelvis protocol due to a lack of published $CTDI_{vol}$ and DLP values. For the thoracic protocol, the $CTDI_{vol}$ and DLP were slightly lower than the other protocols. The result showed that $CTDI_{vol}$ did not exceed local, national, and international DRLs except the UK. Interestingly, the DLP value of the thoracic protocol was slightly higher than the DLPs of Thailand, ACR, and the UK, whereas the DLP value was lower than Thai cancer hospitals and Japan. LDRLs in Thai cancer hospitals had the

highest $CTDI_{vol}$ and DLP among the published DRLs. DLP depends on $CTDI_{vol}$ and scan length. The radiation therapy scan length is generally greater than the diagnostic scan length. Approximately 10 cm must be acquired by extending 5 cm superior and inferior to the border of the treatment volume. The greater scan length was obtained for the accuracy of the calculation dose for treatment planning.[25]

CT diagnostic reference levels are not applicable in radiotherapy because radiotherapy CT doses are higher.[18, 19] Moreover, there are no international guidelines concerning DRLs for computed tomography in radiotherapy. There are a few differences between therapeutic and diagnostic CT modalities. The wide aperture of the CT scanner for the radiotherapy simulator provides a long source-to-patient distance. The scan parameters must be adjusted to combine a suitable radiation dose with a satisfying image quality.[28] In addition, extended target coverage and full scattering conditions create a high radiation dose technique in CT localization simulation.

Therefore, several studies published dose reference levels for radiotherapy CT simulation. Rao et al.[22] reported DRLs for H&N, and pelvis protocols in CT radiation therapy in India. CT images in treatment planning were obtained on a Philips 16 slice big bore CT scanner. All $CTDI_{vol}$ values in our study were lower than the reported by Rao et al. Moreover, the DLP value in our study was slightly lower in the H&N protocol and significantly lower in the pelvis protocol than the results from India. When comparing to European data from Croatia, Slovenia, Ireland, and the UK, all $CTDI_{vol}$ and DLP values in our study were lower than in those studies.[21-25] The differences in the doses were due to the greater mean weight and height of the European patients. These body parameters also led to different mAs and scan length settings. For the H&N protocol, this study could not compare with Croatia and the UK because of the different size of CT dosimetry phantom. Those data base on the 16 cm diameter phantom. On the other hand, our study indicated $CTDI_{vol}$ and DLP of H&N were based upon 32 cm diameter phantom. Croatia reported $CTDI_{vol}$ and DLP for the H&N were 35.0 mGy and 1,444.0 mGy•cm, respectively. The UK published $CTDI_{vol}$ and DLP for the H&N were 49.0 mGy and 2,150.0 mGy•cm, respectively.

This study had some limitations; for example, all data were manually gathered and there were no data on patient weight or BMI. Our study only focused on H&N, thorax, and pelvis CT simulation doses and did not investigate radiation doses for brain and abdomen. Furthermore, there was no data on the 4D gating CT simulation dose.

Conclusions

The median $CTDI_{vol}$ for the thoracic simulation protocol was lower than the local, national, and international DRLs. Moreover, the median $CTDI_{vol}$ and DLP values for all three non-contrast media simulation protocols did not exceed the DRLs of RT CT. The radiation doses in computed

tomography for radiotherapy treatment planning were properly optimized following the imaging guidelines.

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Conflict of interest

The authors declare no conflicts of interest in this research.

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