Original Article

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Evaluation of Head, Thorax and Abdomen-Pelvic Radiation Dosage from Computed Tomography with Dosimetry

Kuo-Ying Liu[1,2], Tai-Been Chen[3], Yung-Hui Huang[3], Chun-Chung Lui[1], Nan-Han Lu[4,5,]*

Objective: This study investigated the dosage of computed tomography (CT) ionizing radiation at institutions affiliated to this medical group, compared the technical performance of different manufacturers, discussed the performance of different device models, and calculated the ionizing radiation dose as precisely as possible without affecting clinical practices.

Methods: Of a patient population of 1,522 retrospectively analyzed for CT radiation dosage, 660 (43%) were female and 862 (57%) were male. We assessed three different CT modalities during the study period for the fulfillment of the eligibility criteria and recorded the CT dose index (CTDI) and calculated the size-specific dose estimate (SSDE) for each patient. Both imaging procedures and parameters have followed the recommendations and guidelines of the CT instrument. Regression analysis was applied to estimate the correlation between CTDI and SSDE. The index of offset dosage was determined with a regression equation.

Results: The R^2 and slopes of the regression model between CTDI and SSDE showed that the automatic exposure control (AEC) technique substantially fitted the participant's body size in CT examination and reduced the dosage of radiation exposure (i.e., $R^2 = 0.79 – 0.96$ and slope = 0.71 – 0.98 for thorax; $R^2 = 0.5 – 0.94$ and slope = 0.44 – 0.97 for abdomen-pelvic). Meanwhile, the results of regression analysis showed that the 640-row CT was associated with minimum offset dosages.

Conclusion: Our results demonstrated that the radiation dosage generated by 640-row CT was lower than that by the others, while the dosage of the 128-row equipment was higher than that of the 16-row. Therefore, the correlation between radiation exposure dosage and numbers of CT detectors was insignificant. Moreover, the minimum offset dosage (i.e., minimal difference between CTDI and SSDE) was associated with the 640-row CT. Hence, our analysis demonstrated that the 640-row CT could provide the most accurate radiation dosage for thoracic and abdomen-pelvic examination according to the patient's anthropometric parameters.

Key words: CT, CTDI, SSDE, AEC, minimum offset dosage

From the [1]Department of Radiology, Division of medical imaging, E-Da Cancer Hospital, I-Shou University; [2]Department of Information Engineering, [3]Department of Medical Imaging and Radiological Sciences and [4]School of Medicine, College of Medicine, I-Shou University; [5]Department of Radiology, E-Da Hospital, I-Shou University, Kaohsiung, Taiwan.

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* Address reprint request and correspondence to: Nan-Han Lu, Department of Radiology, E-Da Hospital, No.1, Yida Road, Jiaosu Village, Yanchao District, Kaohsiung City, 82445, Taiwan

Tel: +886-615-0011 ext. 6168, E-mail: ed102500@edah.org.tw

Introduction

There has been a growing interest in the study of computed tomography (CT) in recent years because of its excellent diagnostic capability.[1-5] However, CT involves a higher radiation dosage than that associated with more common conventional imaging procedures and it is also a common source of ionizing radiation. To comply with the international guidelines on ionizing radiation protection, professionals working with radiation have endeavored to reduce the ionizing radiation associated with CT examination.[6-9] Several organizations, including health supervision units in North America, American College of Radiology (ACR), Radiological Society of North America (RSNA), and various academic societies worldwide have developed standards for reducing the dosage of CT ionizing radiation to provide practical guidelines for related professionals to follow.[10-11] However, the complex interactions between different CT devices and various scanning techniques may contribute to the wide variations in CT ionizing radiation dosage reported from different medical institutions.[12-15,16] Previous studies have indicated that exposure to ionizing radiation at a younger age is related to a higher risk of cancer development.[17-19] Automatic exposure control (AEC) of the X-ray tube is a widely adopted technology to lower the ionizing radiation dosage. In particular, it has been proved empirically effective for decreasing ionizing radiation dosage in chest and abdomen examinations.[20-24] This study attempted to investigate the CT ionizing radiation dosage at institutions affiliated to this medical group, compare the technical performance of different manufacturers, evaluate the performance of different device models, and accurately calculate the ionizing radiation dosage without affecting clinical practices.

Materials and Methods

The current study retrospectively reviewed the Picture Archiving and Communication System (PACS) database to randomly collect information from adult patients (age > 18 years) who underwent thoracic or abdominal-pelvic CT examinations at three medical institutes affiliated to the E-Da Healthcare Group between January 2017 and December 2018. Patients who were less than 18 years old and those who failed to cooperate during CT examination were excluded from the present study. In addition, images acquired for special examinations were also excluded. The institutional review board of E-Da Hospital reviewed the study procedures and approved the waiving of informed consent for the current (EDAH IRB No. /Protocol No.: EMRP-106-074).

We assessed three different CT models during the study period for patients who fulfilled the eligibility criteria. CT examina-

Table 1. Acquisition parameters of three computed tomography scanners in three body regions

Item	Model	16-row	640-row	128-row
Year of introduction to E-Da Healthcare Group		2015	2015	2016
	kVp	130	120	120
Head	Rotation time	1.5 s/rot	0.75 s/rot	1 s/rot
	Detector row	1.2 × 12 mm	0.5 × 32 mm	0.625 × 32 mm
	kVp	130	120	120
Thorax	Rotation time	0.6 s/rot	0.275 s/rot	0.6 s/rot
	Detector row	1.2 × 16 mm	0.5 × 80 mm	0.625 × 64 mm
	kVp	130	120	120
Abdomen-pelvis	Rotation time	0.6 s/rot	0.5 s/rot	0.8 s/rot
	Detector row	1.2 × 16 mm	0.5 × 80 mm	0.625 × 64 mm

kVp: kilovoltage peak

tions were performed by using a 16-row CT (SOMATOM Emotion 2015 Siemens Medical Solutions, Germany), 640-row CT (Aquilion One ViSION Toshiba Medical Systems, Japan 2015) at the E-Da Cancer Hospital, and 128-row CT (Optima CT660; GE Healthcare, Milwaukee, Wis 2016) at the E-Da Dachang Hospital. The CT acquisition parameters are summarized in Table 1. The setting of each CT device was in accordance with the scan parameters recommended by their manufacturers for technical or clinical considerations.

Volume CT Dose Index (CTDIvol)

Since the early 1980s, the dosage of CT radiation exposure has been assessed with the CT dose index (CTDI)[25] that serves as a metric to quantify scanner output from multiple contiguous acquisitions and reflects the measured dose to the center of a scan volume.[25-27] Over the past three decades, the CTDI has been modified from its original definition to account for advances in CT technology. The Volumetric CTDI (CTDIvol), which is currently used for the assessment of ionizing radiation exposure, was specifically derived to address any gaps or overlaps between the collimation of X-ray tubes and the number of CT detectors. The dosages of X-ray beams from consecutive rotations of the X-ray tube that are displayed on the CT console are documented in the "Dose Report" of the CT examination. The CTDIvol is generally defined for two diameters of polymethylmethacrylate (PMMA) phantoms representing the head (16 cm in diameter, yielding CTDIvol[16]) and body (32 cm in diameter, yielding CTDIvol[32]). The computation of CTDIvol is as shown in formula (1 – 3).

The equation represented $CTDI_{100}$ measurements with a 100 mm ion chamber, where nT = the width of the X-ray beam; $CTDI_w$ = weighted average with $CTDI_{100}$ of the center and peripheral in the phantom to arrive at a single descriptor; D = distance that the bed moved at a pitch setting of 360 degrees of the X-ray tube rotation.

Size-Specific Dose Estimates (SSDE)

Although prior studies mainly relied on CTDIvol for assessing the need for changes in radiation doses from CT scanners according to patient size,[1-5] the parameter could not provide accurate information and may incorrectly estimate the radiation dose of a CT examination because of a lack of a detailed consideration of body anthropometrics. The American Association of Physicists in Medicine published Report 204[28] has proposed the use of CTDI with size-specific dose estimate (SSDE) conversion factors in computing a more accurate dose estimate for pediatric and adult body CT imaging.[29-31] Consistently, a previous study has demonstrated an improvement in the accuracy of dosage assessment by more than 10% when CTDI is coupled with estimates of patient size and a knowledge of the anatomy scanned.[32] SSDE conversion factors were created for two CTDI phantom diameters (i.e., 16 and 32 cm). The computation of SSDE is shown in formulae (4 – 7) and Figure 1.[27] The conversion of CTDIvol to SSDE is shown in formulae (8 & 9).

$$(1)\quad \mathrm{CTDI}_{100} = \frac{1}{nT}\int_{z=-50mm}^{+50mm} D(z)\,dz$$

$$(2)\quad \mathrm{CTDI}_{W} = \frac{1}{3}\,CTDI_{100}^{center} + \frac{2}{3}\,CTDI_{100}^{periphery}$$

$$(3)\quad CTDI_{vol} = \frac{CTDI_W}{pitch}$$

$$(4.1)\quad \mathrm{r}_1 = \frac{LAT}{2}$$

$$(4.2)\quad \mathrm{r}_2 = \frac{AP}{2}$$

$$(5)\quad A = \pi r_1 r_2$$

$$(6)\quad effective\_diameter = 2\sqrt{\frac{A}{\pi}} = \sqrt{AP \times LAT}$$

$$(7)\quad SSDE = CTDI_{vol} \times f_{size}$$

(8) $f_{size}^{32cm} = a \times e^{-b \times effective\_diameter}$

(9) $f_{size}^{16cm} = a \times e^{-b \times effective\_diameter}$

Recommendation on the calculation of SSDE by the Report 204[27] is shown in Formulae 8 and 9 as well as Figure 1, where a = 3.7 and b = 0.0367 for the formula (8); a = 1.87 and b = 0.0387 for the formula (9). Lateral diameter (LAT) and anterior-posterior diameter (AP) are defined in Figure 1.

The combined tube current modulation system from GE is AutomA 3D[33-35] consists of two parts: AutomA provides longitudinal AEC and Smart mA provides angular AEC, which can be used separately or in concert. The Siemens system uses a combined tube current modulation system called CARE Dose 4D[33-34,36] with automatic tube current modulation, according to the patient's size and attenuation changes. The real-time, online, controlled tube current modulations during each tube rotation are provided by the system. Toshiba uses a combined system called Sure Exposure 3D.[27,33-34] The system makes use of the frontal and lateral patient diameter, as well as the detector intensities to account for the oscillating tube current modulation during each gantry rotation.[38]

Using a quantitative complex-based SSDE method, we evaluated the accuracy of radiation dose distribution in the three different CT models in a cohort of study participants with reference to their anthropometric parameters.

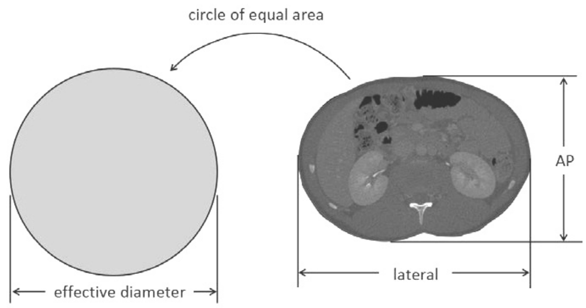

Fig. 1 Schematic diagram illustrating the mathematical conversion of anteroposterior (AP) and lateral diameters (LAT) diameters into a circle, in which the diameter (i.e., effective diameter) was used for the computation of size-specific dose estimates (SSDE) (Note: AP and LAT diameters representing maximum diameters on topograms).

Statistical analysis

All quantitative data are expressed as mean ± standard deviation. The data sets in this study were summarized by using descriptive statistical analysis. The Kruskal Wallis test was used to study the associations of CTDIvol, SSDE, and age with three different examination regions using three CT models, while the correlation coefficients (r) between CTDIvol and SSDE were estimated by the Pearson method. All comparison, linear regression, and correlation analyses were calculated by using Excel, version 2010 (Microsoft, Redmond, Wash) and SPSS (16/17, Chicago, IL, USA). A p value less than 0.05 was considered statistically significant.

Results

Of the 1,522 patients retrospectively reviewed for CT radiation exposure dosage analysis, 660 (43%) were female and 862 (57%) were male (Table 2). The basic characteristics of the study participants, their converted anthropometric parameter (i.e., effective diameter), the body region examined, the CT model used, and radiation dosage are summarized in Table 2. The results showed that 128-row CT had the highest radiation dose in the head, thorax, and abdomen-pelvis examinations. Dosage of CT radiation in the head was higher than that in the thorax and abdomen-pelvis from all three CT modalities.

Kruskal Wallis analysis demonstrated that both SSDE and age were significantly higher in the male group than those in their female counterpart when undergoing head studies regardless of the scanner chosen ($p < 0.001$).

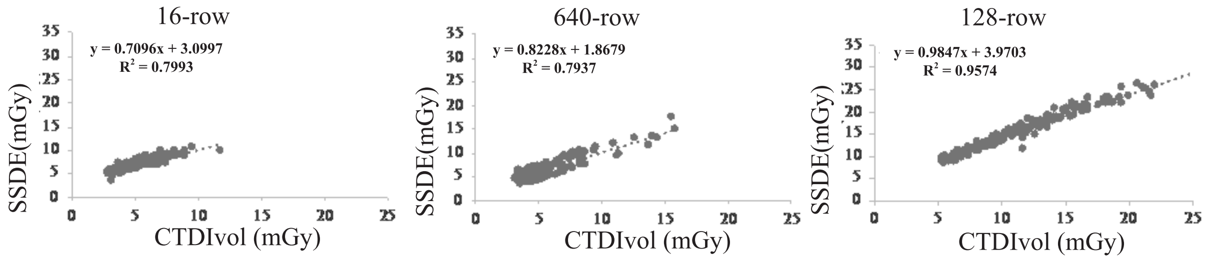

Fig. 2 Linear regression comparison of CTDIvol with SSDE using 16-row, 640-row, and 128-row computed tomography scanners in patients undergoing thoracic examination. CTDIvol: Volume CT Dose Index; SSDE: Size-Specific Dose Estimates.

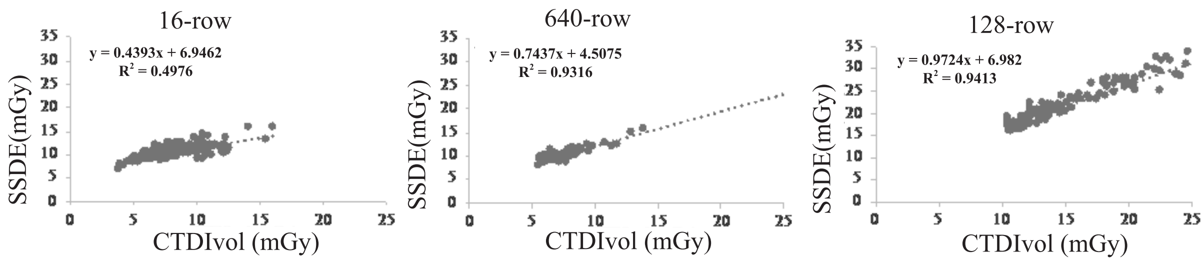

Fig. 3 Linear regression comparison of CTDIvol with SSDE for 16-row, 640-row, and 128-row scanners during abdomino-pelvic examination. CTDIvol: Volume CT Dose Index; SSDE: Size-Specific Dose Estimates.

Focusing on thoracic and abdomen-pelvic studies, CTDIvol, SSDE, and age were significantly higher in males than those in females ($p < 0.001$). The 128-row model was associated with the largest values of SSDE and CTDIvol compared with those in the other two models (Table 3).

For head examination, the correlation coefficient (r) between CTDIvol and SSDE was highest for the 640-row device and lowest for the 128-row model (0.72 and 0.178, respectively). In contrast, the highest and lowest correlation coefficient were associated with the 128-row and 640-row models (0.978 and 0.891, respectively) for patients undergoing thoracic examination. For patients receiving abdomen-pelvic examination, the 128-row and 16-row models showed the highest and lowest CC (0.97 and 0.705), respectively. When the whole body was considered, the 640-row scanner demonstrated the best correlation between CTDIvol and SSDE compared to that in the other two models. Although the correlation coefficient for thoracic examination associated with the 640-row scanner was lower (0.891) than that with the 128-row model (0.978), both showed a positive correlation ($r > 0.7$) (Table 4).

Linear regression analysis demonstrated a high correlation between CTDIvol and SSDE in patients receiving thoracic examination with all three scanners ($R^2 = 0.7993, 0.7937, 0.9574$ with the 16-, 640-, and 128-row scanners, respectively), while the correlation was low with the 16-row scanner (0.4976) and high for the 640-, and 128-row models (0.9316 and 0.9413, respectively) for abdomino-pelvic examination (Fig. 2 & 3). The 640-row scanner provided the minimum offset dosages for patients undergoing thoracic and abdomino-pelvic examinations (1.87 and 4.5, respectively) compared with those of the other two models.

Discussion

The comparatively diversified changes in CTDIvol and SSDE during the CT examinations may be attributable, at least in part, to the baseline heterogeneity in both AEC technique and sample size. The bony structure of the skull may contribute to the highest CTDIvol

Table 2. Patient population and results of radiation dosage analysis using three computed tomography scanners in three body regions

Item	Model	16-row	640-row	128-row	total
Head	No. of exam.	162	156	154	472
	Age (year)	58 ± 18.7 (20 – 96)	50 ± 9.4 (23 – 79)	60 ± 17 (20 – 91)	55.74 ± 16.4 (20 – 96)
	CTDIvol (mGy)	56.7 ± 0.7 (53.1 – 63.8)	57.4 ± 1.6 (52.4 – 57.9)	59.1 ± 0.5 (55.7 – 59.5)	57.7 ± 1.5 (52.4 – 63.8)
	SSDE (mGy)	43.3 ± 2.16 (36.4 – 48.5)	44.5 ± 2.6 (36.7 – 51)	45.9 ± 2.6 (37.5 – 52.3)	44.5 ± 2.7 (36.4 – 52.3)
	Difference	24%	22%	22%	23%
	Effective diameter	189.5 ± 10.3 (168 – 227)	186.3 ± 9.2 (162 – 208)	186.3 ± 12.1 (160 – 228)	187.4 ± 10.6 (160 – 228)
Thorax	No. of exam.	247	158	154	559
	Age (year)	61 ± 13 (20 – 88)	51 ± 10.3 (26 – 82)	52 ± 15.7 (20 – 86)	56.1 ± 14 (20 – 88)
	CTDIvol (mGy)	5.1 ± 1.3 (2.8 – 11.8)	5.8 ± 2.4 (3.2 – 15.8)	11.7 ± 5.2 (5.3 – 35.9)	7.1 ± 4.2 (2.8 – 35.9)
	SSDE (mGy)	6.7 ± 1.1 (3.4 – 10.3)	6.6 ± 2.2 (3.2 – 17.3)	15.4 ± 5.2 (8.3 – 33.8)	9.1 ± 5 (3.2 – 33.8)
	Difference	24%	12%	24%	22%
	Effective diameter	330.1 ± 34.7 (232 – 479)	368.5 ± 52.7 (233 – 506)	323.7 ± 30.4 (242 – 418)	339.2 ± 43.7 (232 – 506)
Abdomen-pelvis	No. of exam.	239	97	155	491
	Age (year)	59 ± 15.6 (20 – 93)	51 ± 11.6 (26 – 85)	55 ± 15 (20 – 97)	56.3 ± 15.1 (20 – 97)
	CTDIvol (mGy)	7.9 ± 1.9 (3.9 – 16)	7.5 ± 3 (5.5 – 32.3)	16.6 ± 6.2 (10.6 – 45.5)	10.6 ± 5.7 (3.9 – 45.5)
	SSDE (mGy)	10.4 ± 1.2 (6.6 – 15.8)	10.1 ± 2.3 (7.7 – 29.1)	23.1 ± 6.2 (15.8 – 50.6)	14.4 ± 7 (6.6 – 50.6)
	Difference	24%	26%	28%	26%
	Effective diameter	327.1 ± 45.6 (220 – 463)	323.4 ± 33.2 (257 – 430)	312.7 ± 29.8 (237 – 410)	321.8 ± 39.3 (220 – 463)

CTDIvol: Volume CT Dose Index; SSDE: Size-Specific Dose Estimates

and SSDE for head examination compared with the other two body regions regardless of the CT model chosen. When the whole body was considered, the 128-row scanner gave the highest CTDIvol independent of the patient's gender. Our results demonstrated no correlation between CTDIvol and the number of detectors in a scanner.

A potential risk of cancer development related to radiation exposure from CT examination hinders its liberal application.[17-19] Multi-detector CT scanner has been gaining popularity in current imaging examinations because of the advantage of a shortened examination time that enables higher spatial and temporal resolution.[1-5] However, several studies have shown an increase in radiation exposure of up to 27 – 36% associated with multi-detector CT

Table 3. Comparison of radiation exposure dosage associated with three computed tomography scanners in three body regions between men and women

Item	Gender	Index	16-row	640-row	128-row	*p*
Head	Women	N	80	54	91	225
		SSDE (mGy)	44.4 ± 1.9	46.3 ± 2.4	46.9 ± 2.3	< 0.001
		Age (year)	58.1 ± 19	51 ± 11.7	60.3 ± 17.3	< 0.001
	Men	N	82	102	63	247
		SSDE (mGy)	42.2 ± 1.9	43.6 ± 2.3	44.5 ± 2.3	< 0.001
		Age (year)	57 ± 18.5	49.3 ± 10.2	59.1 ± 16.6	< 0.001
Thorax	Women	N	111	38	86	235
		CTDIvol (mGy)	4.9 ± 1.4	4.6 ± 1.3	9.5 ± 3.9	< 0.001
		SSDE (mGy)	6.6 ± 1	5.8 ± 1.4	13.4 ± 4.4	< 0.001
		Age (year)	61 ± 12.8	54.2 ± 12.9	52.4 ± 15.6	< 0.001
	Men	N	136	120	68	324
		CTDIvol (mGy)	5.26 ± 1.28	6.2 ± 2.5	14.3 ± 5.4	< 0.001
		SSDE (mGy)	6.8 ± 1.1	6.9 ± 2.3	18.1 ± 4.9	< 0.001
		Age (year)	61.7 ± 13.2	50.6 ± 9.2	52.3 ± 15.9	< 0.001
Abdomen-pelvic	Women	N	106	24	70	200
		CTDIvol (mGy)	7.8 ± 1.9	7.5 ± 5.3	15.8 ± 6.7	< 0.001
		SSDE (mGy)	10.8 ± 1.3	10.4 ± 4.1	22.9 ± 6.5	< 0.001
		Age (year)	59.3 ± 17	55 ± 11.8	53.7 ± 15.1	0.014
	Men	N	133	73	85	291
		CTDIvol (mGy)	7.9 ± 2	7.6 ± 1.7	17.2 ± 5.8	< 0.001
		SSDE (mGy)	10.1 ± 1	10 ± 1.3	23.3 ± 6.1	< 0.001
		Age (year)	59.3 ± 14.6	49.1 ± 11.3	56.2 ± 14.9	< 0.001

CTDIvol: Volume CT Dose Index; SSDE: Size-Specific Dose Estimates

compared with single-detector CT.[39-41]

Our analysis provided an insight into the radiation dosage of three multi-detector scanners on examining different regions of the body. Our results revealed a lower radiation dose in the 16-row CT device when it was used in the thorax or the abdomen-pelvis compared to that of the 128-row scanner.

Our demonstration of no significant correlation between the number of detectors of a scanner and radiation dosage could eliminate the patient's concern when undergoing CT examination. The difference between CTDIvol and SSDE for the 640-row device was 12%, whereas that for the other two models was about 24%. The CTDIvol of a 640-row device was closer to SSDE, indicating that this model could better reflect the radiation dose for patients with diverse body shapes using the AEC technique.[33-34,37]

The risks of cancer and mortality due to medical examinations are mainly affected by low-level ionizing radiation dosage, age, and gender.[17,42] In thoracic examination, the dosage differences between males and females undergoing examinations with the 16-row, 640-row, and 128-row models were 6.8%, 25%, and 33%, respectively due to a gender difference in tissue density.

Our finding of a larger difference between CTDIvol and SSDE in the abdomino-pelvic examination (i.e., 26%) compared to that of head (i.e., 23%) and thorax (i.e., 22%) examinations was probably attributable to variations in abdomen-pelvic anatomy of the patients.

Although our results showed that the 128-row device generated a larger radiation dose than that from the other two models when it was used for abdominal scanning, there was a good correlation between CTDIvol and

SSDE scanning (r = 0.965). Therefore, our finding highlighted the advantage of its use for patients with different body shapes requiring an abdominal examination.

Despite the lack of a normal distribution in the values of SSDE in our participants because of a wide variation in body shape (i.e., extremely thin or obses), the 640-row scanner showed the highest overall correlation in head, thoracic, and abdomino-pelvic examinations compared to that of the other two models (i.e., lowest correlation in the 16-low scanner).

Estimated linear regression models demonstrated a better correlation between SSDE and CTDIvol associated with the use of the 640-row and 128-row scanners (R^2 = 0.79 – 0.95, slope = 0.74 – 0.98) for thoracic and abdomino-pelvic studies than that with the 16-row scanner (R^2 = 0.49). The findings were consistent with those of previous studies that reported more accurate radiation dosage assessment with the 128-row and 640-row models than that when the 16-row scanner was used.[35,37]

Regarding radiation dosage, linear regression analysis revealed a lower dosage associated with the 640-row scanner compared with that of the 128-row model for both thoracic (offset values: 1.86 vs. 3.97, respectively) and abdomen-pelvic (offset values: 4.9 vs. 6.73, respectively) examinations. Variations in the abdominal-pelvic region due to differences in body shape, operations, and bone material density remain a significant confounder in the assessment of AEC, and may contribute to a higher dosage (i.e., higher offset value) in the abdomino-pelvic examination than that in thoracic scanning.

Limitations

Our study had some limitations. First, because we did not have patients with a full range of body sizes for comparison, our findings cannot be extrapolated to those with an extreme body build (e.g., morbidly obsese or pediatric patients). Second, since we did not select patients based on their demographic or clinical characteristics, potential heterogeneity arising from differences in gender, underlying diseases, previous operations and implantations as well as bone marrow density may bias our findings.

Conclusion

The results of the current study demonstrated a minimal difference between CTDI and SSDE (i.e., offset dosage) associated with the 640-row CT scanner compared with that of the other two models, indicating the lowest radiation dosage generated by the 640-row CT scanner. Moreover, we showed no significant correlation between radiation exposure dosage and the number of CT detectors. Our finding of an accurate assessment of dosimetry-based assessment of radiation dosage using the 640-row CT scanner may highlight a lower risk of over- or under-estimating radiation dosage in patients with different body shapes compared to that when the other two models are used.

*Table 4. The correlation coefficient (r) between CTDIvol and SSDE analysis for men and women.**

Modality	Correlation coefficient	Head	Thorax			Abdomen-pelvis		
			Women	Men	total	Women	Men	total
16-row	Pearson	0.204	0.878	0.911	0.894	0.792	0.713	0.705
640-row	Pearson	0.720	0.751	0.901	0.891	0.985	0.918	0.965
128-row	Pearson	0.178	0.979	0.978	0.978	0.970	0.979	0.970

*Significance of difference determined with Pearson correlation analysis; CTDIvol: Volume CT Dose Index; SSDE: Size-Specific Dose Estimates

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