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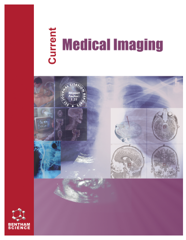

RESEARCH ARTICLE

Relationships between Size-specific Dose Estimate and Signal to Noise Ratio under Chest CT Examinations with Tube Current Modulation

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Abstract:

Purpose:

Exploring the relationship between the signal-to-noise ratio (SNR) of organs and size-specific dose estimate (SSDE) in tube current modulation (TCM) chest CT examination.

Methods:

Forty patients who received TCM chest CT scanning were retrospectively collected and divided into four groups according to the tube voltage and sexes. We chose to set up the region of interest (ROI) at the tracheal bifurcation and its upper and lower parts in slice images of the heart, aorta, lungs, paracranial muscles, and female breast, and the SNR of each organ was calculated. We also calculated the corresponding axial volume CT dose index (CTDIvolz) and axial size-specific dose estimate (SSDEz).

Results:

The correlation analysis showed that the correlation between the SNR of the slice images of most organs and SSDEz was more significant than 0.8, and that between the SNR and CTDIvol was more significant than 0.7. The simple linear regression analysis results showed that when the sex is the same, the SNR of the same organ at 100kVp was higher than 120kVp, except for the lung. In multiple regression analysis, the result indicated that the determination coefficients of the SNR and SSDEz of the four groups were 0.934, 0.971, 0.905, and 0.709, respectively.

Conclusion:

In chest CT examinations with TCM, the correlation between the SNR of each organ in slice images and SSDEz was better than that of CTDIvolz. And when the SSDEz was the same, the SNR at 100 kVp was better than that at 120 kVp.

Keywords: Chest computed tomography (CT), Size-specific dose estimate, Volume CT dose index, Automatic tube current modulation, Signal-to-noise ratio, ROI.

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1. INTRODUCTION

Medical radiation has become the most prominent artificial radiation source at present. Data showed that in 2016, the collective effective dose caused by CT examination in the United States accounted for 63% of the total effective dose, an increase of 13% over 2006 [1]. Therefore, the principle of radiation protection optimization should be strictly followed to reduce the radiation dose of CT scanning.

The volume CT dose index (CTDIvol) and dose length production (DLP), the most commonly used metrics for detecting CT radiation dose, only represents the radiation dose received by a standard dose body model of 16cm or 32 cm diameter, provide limited value in individualized radiation exposure detection in patients [2]. These metrics tend to underestimate slim patients and overestimate obese patients [3]. To address this limitation, the American Association of Physicists in Medical (AAPM) used the effective diameter (DE) and the water equivalent diameter (DW) to calculate the size-specific dose estimate (SSDE) [4, 5]. Related research showed SSDE was more suitable for patients' radiation dose

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than CTDIvol [6].

To minimize the patient's radiation exposure, tube current modulation (TCM) is almost exclusively available in modern CT scanners. This technique was used to adjust the tube current in each slice based on the attenuation of different patient positions to ensure image quality in different anatomical structures [7]. But it's worth noting that TCM will decrease tube current in lower attenuating regions. Literature showed that although lowering the tube current will reduce the radiation dose, at the same time, the image noise of the slice image will also increase [8]. Therefore, the radiation dose cannot be reduced blindly without regard to image quality [9].

Appropriate use of TCM can significantly reduce radiation dose, and previous studies have evaluated the relationship between radiation dose and image noise in patients with phantoms or patients of different sizes [10, 11]. However, these studies only considered CTDIvol as an indicator of a patient's radiation exposure, which has limitations. Subsequent scholars have considered SSDE, such as another study by Rajaraman *et al*., which considered the relationship between different patient sizes and SSDE as well as CTDIvol, and the results showed that patients' effective diameter correlated with SSDE more than with CTDIvol. And that using SSDE better characterizes the actual radiation dose received by the patient [12]. Barreto *et al*. compared the SSDE as well as the image noise of TCM and FTC, and the results showed that although TCM can slightly reduce CTDIvol, the image noise of TCM was higher than that of FTC when Dw was less than 28.4cm [13]. While filling this gap, the above studies still fail to quantitatively analyze and compare the relationship between radiation dose and the complex anatomy of the human body. With this in mind, Yurt *et al*. investigated the changes in image noise of the liver, fat, and aorta during dose reduction when applying the TCM technique in abdominal CT, correlating the image noise of organs within the slices images with the radiation dose. The results showed that while the use of TCM reduced the radiation dose by 10-35%, the noise in the liver increased by 9%, while the aorta was more sensitive, with an increase of 46% [14]. It was evident that the use of TCM technology reduces the radiation dose and increases the image noise while reducing the tube current value. Is it worthwhile to sacrifice image quality for radiation dose reduction? According to the study of Yurt *et al*., it can be found that the radiation dose sensitivity of the images of different organs is different. For example, when the radiation dose is reduced by half, the image noise of the liver barely meets the requirements of clinical diagnosis. Still, the noise of the aorta increases more, and it is not known if the image noise of this place meets the requirements of clinical diagnosis. To optimize the chest CT examination protocol with TCM, the relationship between radiation dose and organ image, SNR needs to be quantitatively analyzed. From there, it was observed how the noise of each organ in the slice image changes when the radiation dose is lowered and whether it affects the diagnosis of one of the organs. Therefore, it is inaccurate to describe the radiation dose during a patient's CT examination by using it [15].

As mentioned above, this study will investigate the correlation between the SNR of different organs and SSDE in the chest CT examination with TCM at different tube voltages and sexes.

2. MATERIALS AND METHODS

2.1. Patient information

A total of 40 patients who underwent chest CT scans in the First Affiliated Hospital of Bengbu Medical College from January 2021 to October 2022 were retrospectively collected. Inclusion criteria: no obvious artifacts and organic lesions in the slice images. According to the tube voltage and sexes, they were divided into four groups, with 10 patients in each group, namely, 100kVp male group, 100kVp female group, 120kVp male group, and 120kVp female group.

2.2. Study Protocol

The 256-row CT scanner (Revolution CT, GE Healthcare, USA) was used for chest CT scans. All patients were placed in a supine position. The parameters of chest CT scans of all patients are as follows: the scanning field of view was 500 mm, the matrix was 512×512, the scanning range was from the apex of the lung to the bottom of the diaphragm, and the beam collimation width was 80 mm; The reconstruction thickness of slice images was 5 mm, and the slice interval was 5 mm; The pitch was 0.992; When the tube voltage was 100kVp, the noise index (NI) was 10.2, and tube voltage was 120kVp, it was 10. The image reconstruction algorithm uses the AsiR algorithm with 40% intensity (Fig. **1**).

2.3. Image Quality

The SNR was used for objective assessments of the image quality of slice images. In order to reduce the influence of respiratory motion artifacts, three slices of tracheal bifurcation and upper and lower layers were selected from the slice images of the mediastinal window to depict the region of interest (ROI) [16]. Selected organs with uniform density to delineate ROI, ensure no calcification in the ROI range, and a similar organ surrounded the periphery to avoid the abnormal noise caused by uneven organ density and affect measurement accuracy. Finally, ROI was selected in the lung, the central area of the aorta, the mediastinum, the uniform muscle organ of the bilateral humerus, and the breast of the female. The tissues of the lung and female's breast are mixed, so the area of the ROI for the lung and breast should be appropriately small in order to ensure a uniform density of tissues in the ROI. In this experiment, the ROI of the lung was $50mm^2$, the ROI of the breast was $100mm^2$, and the ROI of other organs was $200mm^2$. Fig. (**2**) shows the selected parts and size of the ROI. Three ROI were delineated in each organ, the mean and standard deviation (SD) of CT values were measured, and the average was calculated to eliminate the inaccuracy of the data caused by sampling errors. Based on the data obtained, the SNR of each organ was calculated with the following Equation: $SNR=CT_{ROI}/SD_{ROI}$, where CT_{ROI} and SD_{ROI} were the mean CT value and CT standard deviation of the region of interest of each organ, respectively. The specific workflow is shown in Fig. (**1**).

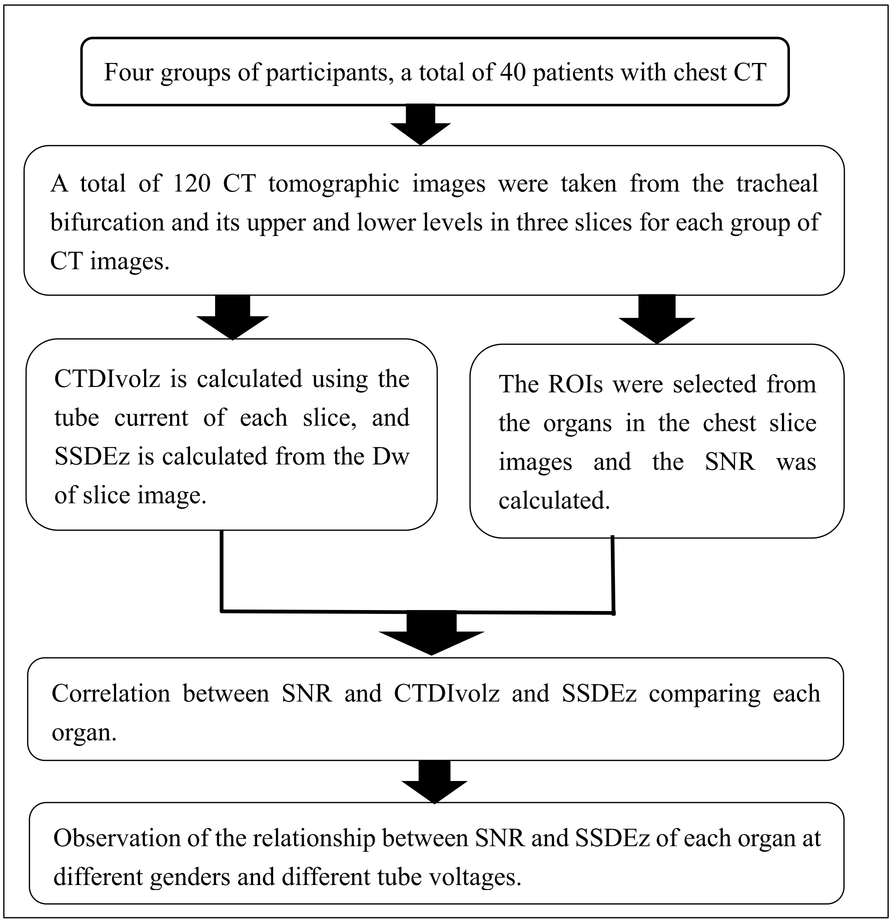

Fig. (1). Flowchart of each step used in this study.

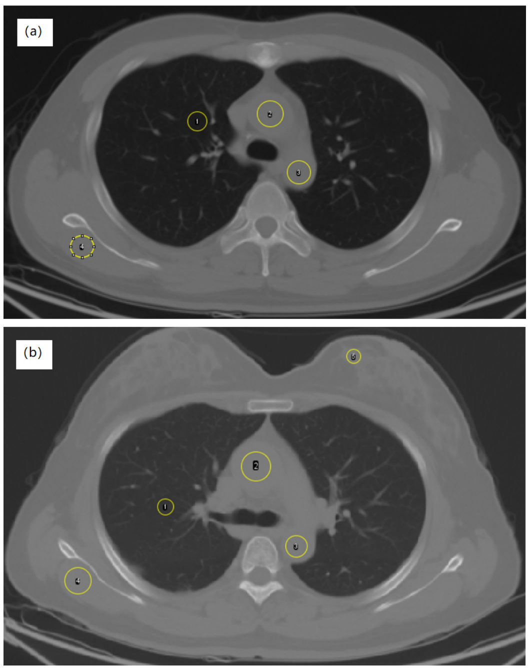

Fig. (2). Demonstration of ROI selection in chest CT for male (**a**) and female (**b**). The locations of ROIs 1-4 are the lungs, mediastinum, aorta, and muscles, respectively, and 5 represents the female breast.

2.4. Radiation Dose

Image J software was used to read and record the CTDIvol in the dose report of each patient and the tube current modulation profile in the slice images. AAPM Report 220 proposed a method to estimate the SSDE based on the patient's body size. First, the equivalent water diameter of each selected slice was calculated according to Equation (**1**), and the corresponding axial volume CT dose index (CTDIvolz) was calculated according to Equation (**2**). Finally, the related conversion factor *f* and the axial size-specific dose estimate (SSDEz) of each slice image were calculated according to Equations (**3**) and (**4**).

$$Dw = 2 \times \sqrt{\left(1+CT_{ROI}/1000\right)Area_{ROI}/\pi} \quad (1)$$

$$CTDIvolz = CTDIvol/mAs \times mAs(z) \quad (2)$$

$$f\left(Dw(z)\right) = 4.378094 \times e^{-0.04331124 \times Dw} \quad (3)$$

$$SSDEz = CTDIvolz \times f\left(Dw(z)\right) \quad (4)$$

2.5. Statistical Analyses

We used SPSS, version 27.0 for Windows, to process and analyze all statistical data. First, the radiation dose values and SNR of each organ in four groups of data were tested normally. Then, the independent samples t-test was used to examine the differences in radiation dose between males and females. The Pearson correlation test was used to analyze the relationships between the SNR of each organ and the radiation dose in the four groups. Then, the simple linear analysis was used to fit the relationship curve between SSDEz and SNR of each organ. Finally, the linear equations of SNR and SSDEz of all organs in the slice image were fitted by multiple regression analysis, which is used to observe how much the SNR of the images of each organ changes when the radiation dose changes. A p-value < 0.05(two tails) was considered statistically significant.

3. RESULTS

3.1. Comparison of Radiation doses for Men and Women

The results of the independent samples t-test showed that there was no significant difference in CTDIvolz between males and females. Still, SSDEz and Dw were significantly higher in females than in males, with p-values of 0.012 and 0.029, respectively (Table **1**).

Table 1. Comparison of SSDEz, CTDIvolz, and Dw for males and females.

-	Male	Female	P-value
	Mean(SD)	Mean(SD)	
CTDIvol	0.1473(0.04892)	0.1581(0.0517)	0.852
SSDEz	0.2195(0.06205)	0.2267(0.05059)	0.012
Dw	24.4788(1.94548)	25.1983(2.50448)	0.029

3.2. Correlation between SNR and SSDEz, CTDIvolz in Four Groups

As shown in Tables **2** and **3**, the SNR of each organ in each group was subjected to Pearson correlation analysis with SSDEz and CTDIvolz, respectively. The results showed that The SNR of organs was positively correlated with both SSDEz and CTDIvolz. The correlation coefficient of the SNR of most organs with SSDEz was more significant than 0.8, and the aorta in the 100kVp F group was less than 0.8, which was 0.685, but it is also significant. In most cases, the correlation coefficient between the SNR and CTDIvolz was more significant than 0.6 Except for mediastinum, lung, and breast in the 120kVp F group, the remained correlation coefficient between SNR and SSDEz was higher than that of CTDIvolz.

Table 2. Correlation between the SNR of each organ and SSDEz, CTDIvolz when the tube voltage was 100kVp.

Groups	Tissues	SSDEz	CTDIvolz
100kVp M	SNR_{aorta}	0.835	0.827
	$SNR_{mediastinum}$	0.855	0.847
	SNR_{muscle}	0.862	0.785
	SNR_{lung}	0.945	0.925
	SNR_{aorta}	0.685	0.684
100kVp F	$SNR_{mediastinum}$	0.814	0.812
	SNR_{muscle}	0.964	0.939
	SNR_{lung}	0.918	0.916
	SNR_{breast}	0.951	0.946

Table 3. Correlation between the SNR of each organ and SSDEz, CTDIvolz when the tube voltage was 120kVp.

Groups	Tissues	SSDEz	CTDIvolz
120kVp M	SNR_{aorta}	0.784	0.664
	$SNR_{mediastinum}$	0.826	0.715
	SNR_{muscle}	0.808	0.694
	SNR_{lung}	0.762	0.655
	SNR_{aorta}	0.875	0.829

(Table 3) contd.....

Groups	Tissues	SSDEz	CTDIvolz
120kVp F	SNR $_{mediastinum}$	0.929	0.962
	SNR $_{muscle}$	0.870	0.825
	SNR $_{lung}$	0.886	0.955
	SNR $_{breast}$	0.853	0. 869

3.3. Simple Linear Regression between the SNR of each Organ and SSDEz in the Slice Images

Fig. (**3**-**7**) represent the simple linear regression analysis results of SNR and SSDEz under different tube voltages and organs. The linear regression results indicated that the SNR of each organ was strongly dependent on SSDEz when the tube voltage was the same. Among the eighteen fitted curves, the R^2 of the lung in the 120 F group was the highest at 0.9119, while the R^2 of muscle in the 120 M group was the lowest at 0.37129. The remaining R^2 were between 0.6 and 0.9 in most relationships. Additionally, under the same sex, when SSDEz was closed, except for lungs, the SNR of each organ when the tube voltage was 100 kVp was generally higher than the tube voltage is 120 kVp. Finally, the slopes of the equations were greatest for the lungs and the breast, with the highest slopes of 286.71 for the lungs and 96.05 for the breast, while the slopes for the remaining organs ranged between 10 and 20 in most cases.

3.4. Multiple Regression Analysis between the Image SNR of each Organ and SSDEz

Multiple regression analysis was performed on the SNR of all organs and SSDEz in the four groups, and the linear regression equation for each parameter among the four groups was established, as shown below. The results showed that the R^2 of two groups of linear regression equations with 100 kVp and 120 kVp for females was better than that for males, with R^2 of 0.934 and 0.971, respectively, *P*<0.001. R^2 of the two groups of males under the tube voltage were 0.905 and 0.709, *P*<0.001.

(1) SSDEz120 M=0.029*SNRmuscle-0.001*SNRlung +0.025*SNRmediastinum-0.02*SNRaorta-0.011

(2) SSDEz120 F=0.037*SNRmuscle+0.001*SNRlung +0.003*SNRmediastinum+0.018*SNRorta+0.002 *SNRbreast-0.106

(3) SSDEz100 M=0.008*SNRmuscle+0.003*SNRlung -0.001*SNRmediastinum+0.007*SNRorta-0.023

(4) SSDEz100 F=0.017*SNRmuscle+0.001*SNRlung +0.011*SNRmediastinum-0.004*SNRorta+0.005 *SNRbreast-0.005

4. DISCUSSION

The results showed that the SNR of chest CT tomography was positively correlated with radiation dose; the higher the radiation dose, the better the SNR. The correlation between SNR and SSDEz in slice images was generally higher than that of CTDIvolz, with CTDIvolz having a higher correlation only in the mediastinum, lungs, and breasts of the 120F group compared to SSDEz. Previous studies have shown that CT image quality was highly correlated with radiation dose [17], which was consistent with our conclusion. Hiroki Kawashima *et al.* conducted a study on the equivalent material of the liver, and the results showed that the relationship between radiation dose and image quality was highly dependent on the patient's body size [18], which indicated that the absorbed dose and image quality of patients were closely related to the patient's body size. Usually, larger patients need to increase exposure to achieve the required image noise [5, 19, 20], so when exploring the relationship between SNR and radiation dose, it is necessary not to ignore the difference in body size. However, most of the existing dose descriptions were based on CTDIvol, which represents the radiation dose output by the CT scanner to the CT index dose phantom but not the actual dose absorbed by the patient [21]. The AAPM Report 220 put forward the SSDE calculation method based on the Dw calculation [22]. The difference between SSDEz and CTDIvolz is that it fully considers the patient's body size. The relevant study showed that if CTDIvol were used to characterize organ dose, it would obviously underestimate the absorbed dose of organs by approximately 30% - 48% [23]. At the same time, SSDE only overestimated the absorbed dose of organs by approximately 11% [24]. Compared to CTDIvol, SSDE is closer to the absorbed dose of various organs of the human body. It is more reliable to use SSDE to represent the radiation dose actually received by the patient, and its correlation with the quality of the slice images was higher.

When comparing the SNR of each organ in slice images under different tube voltages, we found that when the SSDEz was uniform, the image SNR of the organ under a tube voltage of 100kVp was higher than that of 120kVp in most cases. Previous research showed that when the tube voltage was constant, the higher the tube current, the better the image quality [25]. Our results are in good agreement with those of Kun Tang. *et al.* [26], who conducted a study on the effect of tube voltage on CNR found that when CTDIvol is the same, the CNR of 80kVp was higher than that of 120kVp. We speculated that the possible results are as follows: when the SSDEz was the same, the decrease in tube voltage from 120kVp to 100kVp was often accompanied by a significant increase in tube current. In CT imaging, the attenuation of X-rays that penetrate the human body is determined by the photoelectric effect and Compton scattering. The Compton effect is relatively independent of photon energy, and the change is not obvious with the change of the energy of X-ray photon. However the photoelectric effect strongly depends on the energy of X-rays, and the attenuation of the photoelectric effect is negatively correlated with the energy of X-rays. The lower the energy of X-ray photons, the stronger the photoelectric effect [27]. The increase in low-energy X-rays caused by the decrease in tube voltage in this experiment will ultimately increase the probability of photoelectric effects occurring. This sudden increase in the probability of low-energy X-ray photoelectric effect has a positive impact on SNR, which will offset the negative impact of tube voltage reduction on SNR, and the final SNR will even be better.

Observing the slopes of the equations for each organ in Fig. (**3-7**), we find that as SSDEz changes, the lungs have the largest slope, followed by the breasts, with little difference in the slopes of the aorta, mediastinum and muscles for the rest. These results suggested that the SNR of the lungs and the female breast decreased rapidly as the radiation dose was reduced, while the remaining organs' SNR was less affected. Yurt *et al*. have conducted a similar study and found that on abdominal CT examination, different organs showed different reductions in SNR with decreasing tube current, with the aorta showing the most severe decline. In comparison, our study observed this sex difference in SNR changes and expanded the range of organs selected for ROIs, making up for the shortcomings of Yurt *et al*. [14].

Pearson's correlation analysis results showed that the relationship between SNR and SSDEz was different between sexes when the tube voltage was the same. The correlation was generally better in females than in males. According to Table **1**, the mean value of SSDEz for females was 0.2267 mGy, significantly higher than that for males. This indicates that the radiation dose for female patients was significantly higher than that for males at the same tube voltage. We hypothesize that this is due to the fact that female patients tend to have higher attenuation due to the presence of the breast when acquiring an Antero-Posterior scout image of chest CT, which causes the CT scanner to up-regulate the tube current value at that location during TCM, thus resulting in a higher examined dose than in males. Dalah *et al*. retrospectively analyzed patients who had undergone CT coronary Computed Tomography Angiography. They showed that the mean mAs of female subjects was 146, which was significantly higher than 131.9 in males, according to the sex grouping [28]. This is similar to our conclusion.

The multiple regression analysis was used to fit the SNR of four organs in slice images of male patients and the SNR of five organs in slice images of female patients, and the linear regression equations of SSDEz and SNR were obtained with SSDEz at this level. This study showed that the determination coefficient of SNR and SSDEz was high, indicating that the organ SNR in the slice images has a high linear correlation with SSDEz. But these relationships were different between different sexes. The determination coefficient was more significant than 0.9 for females and slightly lower for males, but both were greater than 0.7 The difference in the determination coefficient between different sexes was mainly due to the influence of the number of fitting parameters. There were only four organ image SNRs in male chest sectional images, while there is a breast in female chest organs. Compared to males, more parameters were used to fit multiple regression, so the determination coefficient of female patients was better.

The limitations of this study are as follows: first, the data of this study is less, and we only considered the SNR, an objective image quality evaluation metric, as the parameter. Only chest CT examinations were collected in this experiment. We should consider incorporating CT of the abdomen and pelvis for follow-up exams. Second, the anatomical structure of the lung is complicated. The deviation of the noise measurement may be significant, and some extreme samples exist in some groups, so there may be sampling errors in the data obtained. Finally, the image quality evaluation index only uses the objective evaluation index SNR. Still, the slice image quality should also refer to the diagnostic index, so the combination of subjective and objective image quality evaluation should be chosen in the follow-up study.

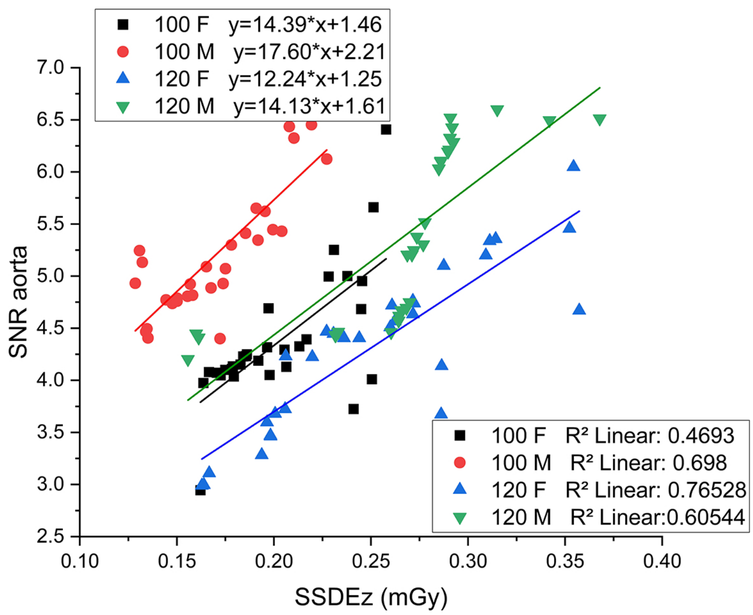

Fig. (3). Simple linear regression between the SNR of the aortic image and SSDEz under different tube voltages.

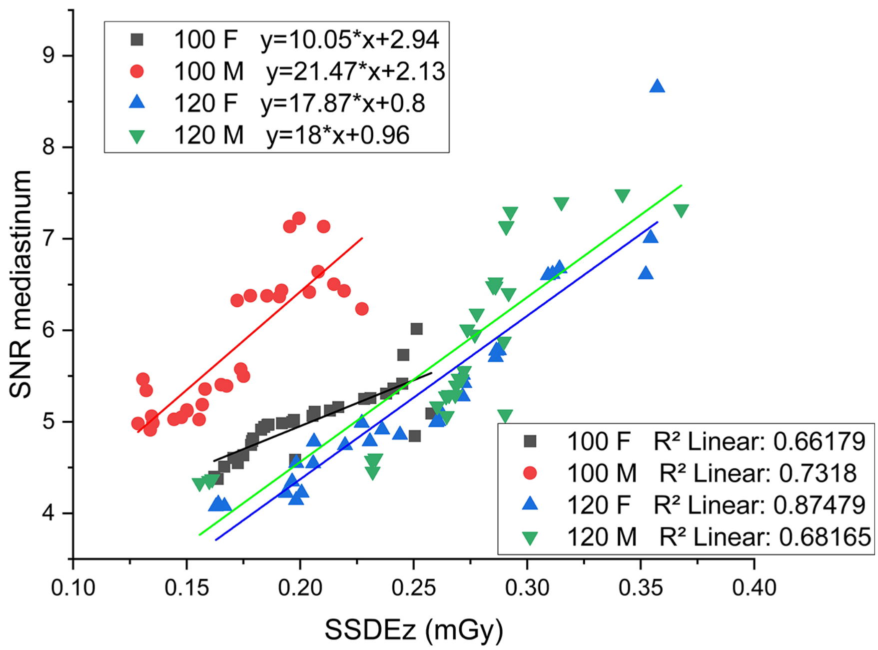

Fig. (4). Simple linear regression between the SNR of the mediastinal images and SSDEz under different tube voltages.

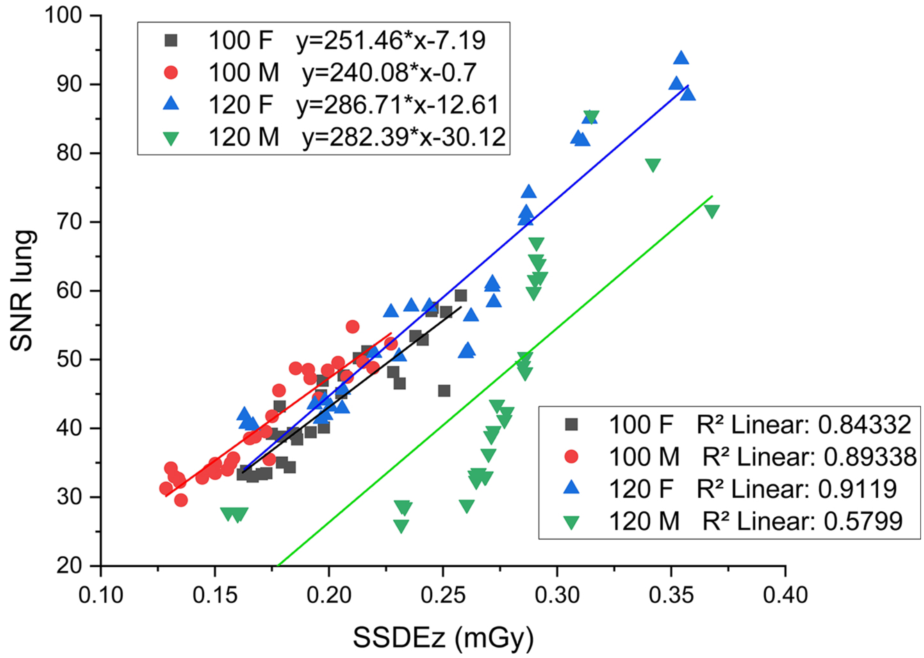

Fig. (5). Simple linear regression between the SNR of the lung images and SSDEz under different tube voltages.

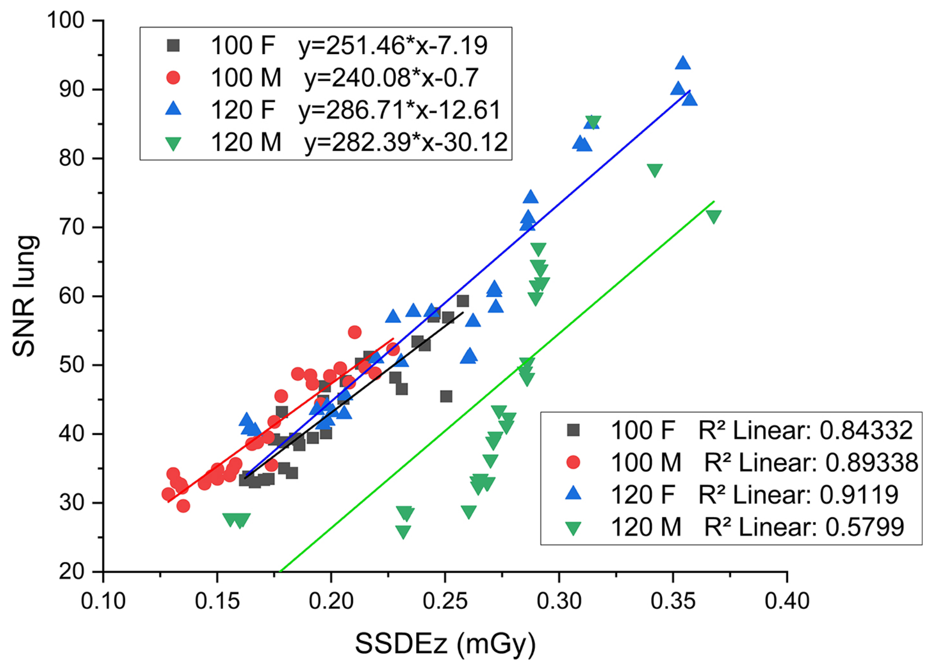

Fig. (6). Simple linear regression between the SNR of the muscle image and SSDEz under different tube voltages.

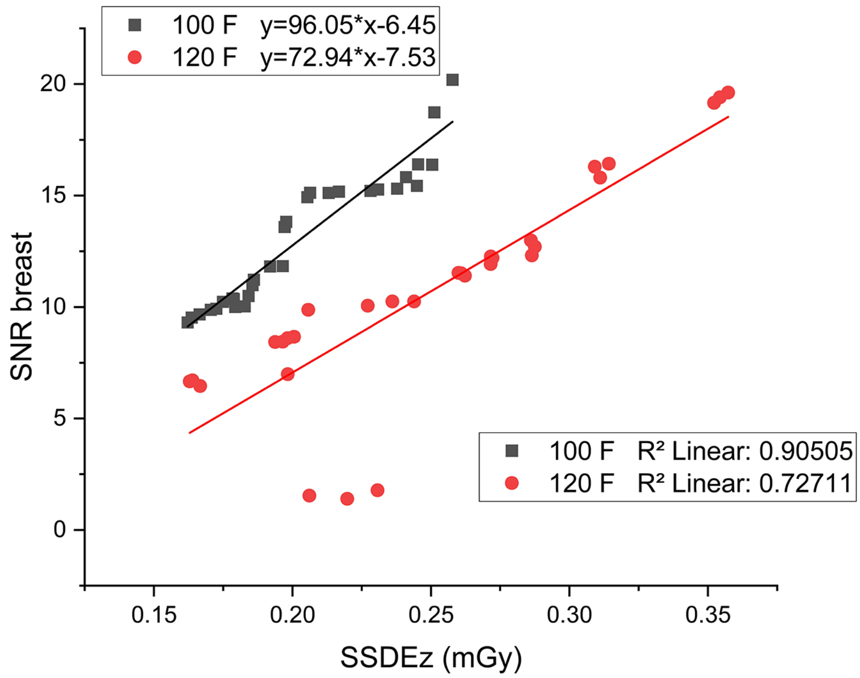

Fig. (7). Simple linear regression between the SNR of the breast image and SSDEz under different tube voltages.

CONCLUSION

In summary, there was a significant correlation between radiation dose and SNR in the TCM chest CT examination. The higher the radiation dose, the better the SNR. When SSDEz was the same, the quality of 100kVp slice images was generally higher than that of CTDIvolz, with CTDIvolz having a higher correlation only in the mediastinum, lungs, and breast of the 120F group compared to SSDEz. The determination coefficient of multiple regression analysis using organ SNR and SSDEz in slice images is excellent, and the image quality of various organs was associated with radiation dose. However, the radiation dose predicted with these SNRs of multiple organs was different, which is related to the tube voltage, sex, and the number of fitted organs.

LIST OF ABBRAVIATIONS

SSDE	=	Size-specific Dose Estimate
TCM	=	Tube Current Modulation
ROI	=	Region of Interest
SNR	=	Signal-to-Noise Ratio
CTDIvol	=	Volume of CT Dose Index
CT	=	Computed Tomography

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

This retrospective experiment involving human patients was approved by the Bengbu Medical College Ethics Committee (no.2021-292).

HUMAN AND ANIMAL RIGHTS

No animals were used for studies that are the basis of this research. All the used patients were in accordance with the ethical standards of the committee responsible for human experimentation (institutional and national) and with the Helsinki Declaration of 1975, as revised in 2013(http://ethics.iit.edu/ecodes/node/3931).

CONSENT FOR PUBLICATION

The need for consent for this experiment was waived by the ethics committee.

STANDARDS OF REPORTING

STROBE guidelines were followed.

AVAILABILITY OF DATA AND MATERIALS

The data presented in this study are available on request from the corresponding author [B.L].

FUNDING

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CONFLICT OF INTEREST

The authors declare no conflict of interest, financial or otherwise.

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Declared none.

REFERENCES

[1] Damilakis J, Dosimetry CT. CT Dosimetry. Invest Radiol 2021; 56(1): 62-8. [http://dx.doi.org/10.1097/RLI.0000000000000727] [PMID: 32932380]

[2] Shope TB, Gagne RM, Johnson GC. A method for describing the doses delivered by transmission x-ray computed tomography. Med Phys 1981; 8(4): 488-95. [http://dx.doi.org/10.1118/1.594995] [PMID: 7322067]

[3] Steiniger B, Klippel C, Teichgräber U, Reichenbach JR, Fiebich M. Can the size-specific dose estimate be derived from the body mass index? a feasibility study. Radiat Prot Dosimetry 2022; 198(6): 325-33. [http://dx.doi.org/10.1093/rpd/ncac038] [PMID: 35443046]

[4] Strauss K, Boone J, Cody D, McCollough C, McNitt-Gray M, Toth T. Size Specific Dose Estimates in Pediatric and Adult Body CT Examinations, AAPM Task Group 2014; 2011

[5] Boone JM, Strauss K, Cody DD. Size-specific dose estimates (SSDE) in pediatric and adult body CT examinations. In: (AAPM). College Park (MD): American Association of Physicists in Medicine 2011.

[6] Yuan Z. Comparison of different SSDE methods in evaluating the radiation dose in chest and abdomen CT scan. Chi J Radi and Prot 2016; 36(11): 852-6.

[7] McCollough CH, Bruesewitz MR, Kofler JM Jr. CT dose reduction and dose management tools: Overview of available options. Radiographics 2006; 26(2): 503-12. [http://dx.doi.org/10.1148/rg.262055138] [PMID: 16549613]

[8] Kwon JK, Chang IH, Moon YT, Lee JB, Park HJ, Park SB. Usefulness of low-dose nonenhanced computed tomography with iterative reconstruction for evaluation of urolithiasis: diagnostic performance and agreement between the urologist and the radiologist. Urology 2015; 85(3): 531-8. [http://dx.doi.org/10.1016/j.urology.2014.11.021] [PMID: 25733262]

[9] Larson DB. Optimizing CT radiation dose based on patient size and image quality: The size-specific dose estimate method. Pediatr Radiol 2014; 44(S3)(Suppl. 3): 501-5. [http://dx.doi.org/10.1007/s00247-014-3077-y] [PMID: 25304711]

[10] Khoramian D, Sistani S, Firouzjah RA. Assessment and comparison of radiation dose and image quality in multi-detector CT scanners in non-contrast head and neck examinations. Pol J Radiol 2019; 84: 61-7. [http://dx.doi.org/10.5114/pjr.2019.82743] [PMID: 31019596]

[11] Spampinato MV, Stalcup S, Matheus MG, *et al.* Radiation dose and image quality in pediatric head ct. Radiat Prot Dosimetry 2018; 182(3): 310-6. [http://dx.doi.org/10.1093/rpd/ncy066] [PMID: 30590841]

[12] Rajaraman V, Ponnusamy M, Halanaik D. Size specific dose estimate (SSDE) for estimating patient dose from CT used in myocardial perfusion SPECT/CT. Asia Ocean J Nucl Med Biol 2020; 8(1): 58-63. [PMID: 32064284]

[13] Barreto I, Verma N, Quails N, Olguin C, Correa N, Mohammed TL. Patient size matters: Effect of tube current modulation on size-specific dose estimates (SSDE) and image quality in low-dose lung cancer screening CT. J Appl Clin Med Phys 2020; 21(4): 87-94. [http://dx.doi.org/10.1002/acm2.12857] [PMID: 32250062]

[14] Yurt A, Özsoykal İ, Obuz F. Effects of the use of automatic tube current modulation on patient dose and image quality in computed tomography. Mol Imaging Radionucl Ther 2019; 28(3): 96-103. [http://dx.doi.org/10.4274/mirt.galenos.2019.83723] [PMID: 31507141]

[15] Larson DB, Malarik RJ, Hall SM, Podberesky DJ. System for verifiable CT radiation dose optimization based on image quality. part II. process control system. Radiology 2013; 269(1): 177-85. [http://dx.doi.org/10.1148/radiol.13122321] [PMID: 23784877]

[16] Braun FM, Johnson TRC, Sommer WH, Thierfelder KM, Meinel FG. Chest CT using spectral filtration: Radiation dose, image quality, and spectrum of clinical utility. Eur Radiol 2015; 25(6): 1598-606. [http://dx.doi.org/10.1007/s00330-014-3559-1] [PMID: 25515204]

[17] Shu Hongmin. Effects of different ASI□ levels and thickness of reconstructive layer on the quality of low-dose CT images of urinary calculi. Acta Universitatis Medicinalis Anhui 2019; 54(09): 1489-92.

[18] Kawashima H, Ichikawa K, Hanaoka S, Matsubara K, Takata T. Relationship between size-specific dose estimates and image quality in computed tomography depending on patient size. J Appl Clin Med Phys 2018; 19(4): 246-51. [http://dx.doi.org/10.1002/acm2.12340] [PMID: 29729075]

[19] Funama Y, Sugaya Y, Miyazaki O, Utsunomiya D, Yamashita Y, Awai K. Automatic exposure control at MDCT based on the contrast-to-noise ratio: Theoretical background and phantom study. Phys Med 2013; 29(1): 39-47. [http://dx.doi.org/10.1016/j.ejmp.2011.11.004] [PMID: 22182517]

[20] MacDougall RD, Kleinman PL, Callahan MJ. Size-based protocol optimization using automatic tube current modulation and automatic kV selection in computed tomography. J Appl Clin Med Phys 2016; 17(1): 328-41.

[http://dx.doi.org/10.1120/jacmp.v17i1.5756] [PMID: 26894344]

[21] McCollough CH, Leng S, Yu L, Cody DD, Boone JM, McNitt-Gray MF. CT dose index and patient dose: They are not the same thing. Radiology 2011; 259(2): 311-6.
[http://dx.doi.org/10.1148/radiol.11101800] [PMID: 21502387]

[22] Burton C, Szczykutowicz T. Evaluation of AAPM Reports 204 and 220: Estimation of effective diameter, water-equivalent diameter, and ellipticity ratios for chest, abdomen, pelvis, and head CT scans. J Appl Clin Med Phys 2017; 19.
[PMID: 29178549]

[23] Li X, Samei E, Segars WP, *et al.* Patient-specific radiation dose and cancer risk estimation in CT: Part II. Application to patients. Med Phys 2011; 38(1): 408-19.
[http://dx.doi.org/10.1118/1.3515864] [PMID: 21361209]

[24] Franck C, Vandevoorde C, Goethals I, *et al.* The role of size-specific dose estimate (SSDE) in patient-specific organ dose and cancer risk estimation in paediatric chest and abdominopelvic CT examinations. Eur Radiol 2016; 26(8): 2646-55.
[http://dx.doi.org/10.1007/s00330-015-4091-7] [PMID: 26670320]

[25] Ledenius K, Gustavsson M, Johansson S, Stålhammar F, Wiklund L-M, Thilander-KLANG A. Effect of tube current on diagnostic image quality in paediatric cerebral multidetector CT images. Br J Radiol 2009; 82(976): 313-20.
[http://dx.doi.org/10.1259/bjr/24404354] [PMID: 19188246]

[26] Tang K, Wang L, Li R, Lin J, Zheng X, Cao G. Effect of low tube voltage on image quality, radiation dose, and low-contrast detectability at abdominal multidetector CT: phantom study. J Biomed Biotechnol 2012; 2012: 1-6.
[http://dx.doi.org/10.1155/2012/130169] [PMID: 22619490]

[27] Hagspiel KD, Flors L, Housseini AM, *et al.* Pulmonary blood volume imaging with dual-energy computed tomography: Spectrum of findings. Clin Radiol 2012; 67(1): 69-77.
[http://dx.doi.org/10.1016/j.crad.2010.12.021] [PMID: 22070940]

[28] Dalah EZ, Obaideen A, Anam S, Alzimami K, Jambi LK, Bradley DA. Gender based lung cancer risks for symptomatic coronary artery disease patients undergone cardiac CT. PLoS One 2022; 17(4): e0265609.
[http://dx.doi.org/10.1371/journal.pone.0265609] [PMID: 35404962]