Patient-specific radiation dose and cancer risk estimate in Computed Tomography Pulmonary Angiography Examinations based on lung effective diameter.

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Abstract: Computed Tomography (CT) scan examinations has greater demands especially in CT Pulmonary Angiography (CTPA) owing to the public and radiology personnel worries towards CT radiation exposure and risks. The aim of present study is to evaluate the comprehensive radiation exposure in computed tomography pulmonary angiography (CTPA) and its cancer risk. The records of 100 patients who had undergone CTPA were retrieved. The radiation dose exposure, scanning acquisition protocol as well as patient characteristics were noted. Radiation exposure were presented as Volume Computed Tomography Dose Index (CTDIvol), Size-Specific Dose Estimate (SSDE), Dose-Length Product (DLP), and effective dose (E) and organ dose. Effective cancer risk per million procedure was calculated by referring to the International Commission on Radiological Protection Publication 103. The $CTDI_{vol}$, SSDE, DLP were comparable within different effective diameter groups. The average effective dose received by a patient was 8.68 mSv. The organ dose and effective cancer risk attained for breast, lung and liver were 17.05 ± 10.40 mGy (194 per one million procedure), 17.55 ± 10.86 mGy (192 per one million procedure) and 15.04 ± 9.75 mGy (53 per one million procedure), respectively. In conclusion, CTDIvol was undervalued and SSDE was more accurate in describing radiation dose exposure. The lungs and breast of

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subjects with large effective diameter were higher risk of developing cancer as they received the highest exposure. Therefore, extra safety measures should be considered for large-sized patients undergoing CTPA.Purpose: This study evaluates the comprehensive radiation exposure in computed tomography pulmonary angiography (CTPA) and its cancer risk.

Keywords: Computed Tomography; radiation dose; radiation cancer risk; CT Pulmonary Angiography; effective diameter

1. Introduction

Computed tomography (CT) is a vital tool for screening, diagnosing and managing patient care. It has become the preferred imaging method, and its use is significantly increasing. most preferable tools in diagnostic imaging where the number of examinations using this technique is significantly growing. However in 2001, the International Commission on Radiological Protection (ICRP) has expressed concern over the high use of CT in medicine after it was reported that the radiation exposure was greater compared to other imaging modalities [1].

CT Pulmonary Angiography (CTPA) allows the visualization of pulmonary arteries to facilitate diagnosis and treatment of pulmonary embolism (PE). Despite having high accuracy, CTPA has been observed to expose patients and medical personnel to ionizing radiation doses of more than 10 mSv, which epidemiological data suggest may increase the risk of cancer [2].

The radiation dose produced by CT scanners can basically be calculated as the the calculation of volumetric Computed Tomography Dose Index ($CTDI_{vol}$). It is based on CT parameters used during the scanning of a standard phantom as a surrogate patient [3]. However, $CTDI_{vol}$ estimates based on a phantom have many potential errors as they do not consider the size of the body, which is varies between patients, especially children.

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To overcome this, the size-specific dose estimates (SSDEs), which incorporates individual patient factors into the $CTDI_{vol}$ calculation, was introduced by the American Physicians Association (AAPM) in 2011. Instead of basing dose calculation solely on a phantom, SSDE requires the input of individual patient size in the CT scanner [3]. AAPM also published a specific size conversion factor to accurately estimate the absorption properties of various body sizes and their doses. These conversion factor is multiplied with $CTDI_{vol}$ to obtain the SSDE [4].

Previous studies were published the estimation of SSDE by method introduced by AAPM. It is found that the ratio of SSDE with $CTDI_{vol}$ is inversely proportional with the size of the patient. When the size of the patient increases, the ratio become decreases [5]. For CTPA there are several studies that focused on CT dose and its optimization techniques [2,6–8]. However, there is no known comprehensive study regarding radiation dose exposure in CTPA, specifically on SSDE.

The most promising assessment is estimating the organ dose and effective cancer risk according to the patient's body habitus. Both assessments varied in different conditions, dependency on age, sex and population studied [9]. The limitation of radiation dose estimation may be overcome by these assessments which are tailored to an individual patient exposure rather than a general population.

The 7^{th} report on Biological Effects of Ionizing Radiation (BEIR VII Phase 2) by the United States National Academy of Sciences is popularly cited in estimating the effective cancer risk based in radiological scans. Most studies reported that detrimental effects of radiation exposure are higher in susceptible patient populations, especially young women and children [10] As such, it is important to calculate an accurate organ-equivalent dose before obtaining an estimation of cancer risk. However, there was no study that evaluated the organ dose and effective cancer risk specifically in CTPA examination based on previous study elsewhere [2,7,8,11]. This study aims to evaluate radiation dose in current CTPA practice examination correspond to SSDE and to estimate the effective cancer risk for each scan and organ.

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2. Materials and methods

2.1. Study subjects

The research protocol was approved by the ethics committee of Ministry of Health (Malaysia) which waived patient consent form for the retrospective analysis with an approval ID: NMRR-18-3088-44138. The records of 100 adults who underwent CTPA were retrieved from a Hospital Kuala Lumpur, Malaysia. The subjects were above age 18 and they underwent the procedure between September 2018 to February 2019. All subjects were scanned using a Philips Brilliance 128 multi-detector CT (MDCT) scanner and the images were reconstructed using the DICOM software.

2.2. CT parameters

A systematic survey form was drafted. Scan parameters and data, such as subjects' gender, antero-posterior (AP) and lateral (LAT) body lengths, tube voltage (kV), tube current(mA), rotation time, pitch factor, $CTDI_{vol}$ and dose-length-product (DLP) were recorded from scanner console. The AP and LAT lengths of each subjects' image were measured using digital calipers on the scanner console, at mid-slice location of the transverse CT images. Only the scan data of pulmonary embolism scan were included, while cases with incomplete details and modified protocols were excluded.

CTPA was performed using 40 to 70 ml of iodinated contrast medium, followed by 50 ml saline chaser which were intravenously injected into the subjects at a flow rate of 5 ml/s. The bolus tracker technique was performed by placing the region of interest (ROI) on the main pulmonary trunk. The scan was started after 3 to 14 seconds with a threshold of 70 HU. The z-dom modulation was activated prior each scan. Images were reconstructed with 1 mm slice thickness and 512 x 512 matrix size. To enhance the image quality, the iDose^4 level 4 iterative reconstructive technique was used for post-processing of images. The radiographers performing the scan were well experienced in this protocol at least 3 years.

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2.3. Radiation dose calculation

$CTDI_{vol}$, AP and LAT lengths obtained from the scanner console were used to calculate SSDE based on the American Association of Physicists in Medicine (AAPM) Report 204. For comparison purposes, the $CTDI_{vol}$, and SSDE were also estimated using CT-EXPO Ver 2.3.1 (SASCRAD, Bucholz, der Norheide, Germany) and Monte Carlo simulation based on data from systematic survey.

Derivation of SSDE according to AAPM report 204 began with the calculation of the effective diameter of the subjects' body as stated in Equation 1.

$$Effective\ Diameter\ (cm) = \sqrt{AP\ x\ LAT} \qquad \text{(Equation 1)}$$

The effective diameters (body size) were normalized to the tabulated body size-dependent conversion factor (f-size) stated in the AAPM report 204. SSDE was calculated by multiplying the normalized f-size with the $CTDI_{vol}$ displayed on the scanner console as in equation 2.

$$SSDE = normalised\ f - size\ \ x\ CTDIvol \qquad \text{(Equation 2)}$$

The effective dose (E) and organ dose are standard health risk indicators for organ and tissues exposed to ionizing radiation. The equation of E is as follow:

$$E\ \approx k\ x\ DLP \qquad \text{(Equation 3)}$$

where the conversion factor of a representative thorax region (k) obtained from the International Commission on Radiological Protection (ICRP) Publication 103 (2007) (ICRP 2007) are multiply with DLP. The E and organ dose were estimated only by CT-EXPO software in this study.

2.4. Risk Assessment

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The effective cancer risk for subjects' breast, lung and liver exposed to the CPTA primary beam was estimated using equation 4:

$$R = \sum r_T . H_T \qquad \text{(Equation 4)}$$

where r_T is the nominal risk factor attained from the International Commission on Radiological Protection (ICRP) Publication 103 (ICRP 2007) and the H_T is the organ-specific equivalent dose obtained by CT-EXPO in breast, lung and liver respectively. The effective cancer risk (R) per procedure was estimated by multiplying the organ dose with the risk factor (r_T). Then the sum the cancer probability risk (R) for each organ was estimated by equation 4.

2.5. Statistical Analysis

Descriptive statistics are reported in this study as fraction and means with standard deviations. All data were entered SPSS V17.0 (SPSS, version 17.0 for Windows, Chicago, Illinois, USA) for statistical analysis. A p-value of <0.05 was considered to indicate statistically significant differences. Since the data was normal the independent t-test and one-way ANOVA test used in this study. The value involved from the protocol were presented in the tables and boxplots.

3. Results

3.1. Patient characteristic and Radiation Dose

Table 1 shows the mean baseline characteristics of study subjects compromising 42 men and 58 women. The range age for men was 23 – 71, whereas it was 18 – 77 for women. The effective diameters ranged from 20.14 to 37.48 cm in males and 19.71 – 32.25 in females.

Table 2 states the scanning parameters of this study. The tube voltage was set at 100 or 120 kV depending on the subject's habitus. The tube current and scan range were adjusted depending on body size.

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The calculation of $CTDI_{vol}$, SSDE, DLP and the ratio of SSDE to $CTDI_{vol}$ were grouped according to effective diameters and in total as stated in Table 3. Overall, the $CTDI_{vol}$, SSDE, DLP and the ratio of SSDE and $CTDI_{vol}$ obtained for both methods was 11.06 ± 7.17 vs 11.40 ± 7.36, 14.62 ± 8.41 vs 15.37 ± 9.67, 400.38 ± 259.10 vs 437.68 ± 277.35 and 1.41 vs 1.36 respectively. All SSDE values were higher than $CTDI_{vol}$ for each patients' effective diameters group. The details of the observation as shown in Table 3 and Figure 1.

Table 4 is a complication of scan parameters and dose results of other CTPA studies that used CT-Scanners by various manufactures. All the studies produced different SSDE and $CTDI_{vol}$, DLP and effective dose results because of the different pitch, tube current and beam collimation employed in their scans. The results of this study were similar to Sabel et al. (2016) but we measured the highest value of $CTDI_{vol}$ compared with other studies. The SSDE value reported by Sabel et al. (2016) was the highest, around one-third more than this study. This was likely because of our subjects' size, which were mostly larger compared with this study. The highest values of the DLP and effective dose is this study and the lowest is a study done by Laqmani et al. (2016).

3.2. Organ Dose and Effective Cancer Risk

Table 5 states the individual and total organ dose for breast (females only), lung and liver. Table 6 states the effective cancer risk in a million procedures. The breast seemed to receive the highest organ dose in total, hence resulting in the cancer risk per million procedures. However, in the largest effective diameter, the lung had slightly higher dose exposure with similarly high cancer risk than the breast. The liver had the least dose exposure even though the values increased with effective diameter. But its risk factor was extremely low- more than three times lower compared to the breast and lung. This breakdown of results between gender is also provided. Table 7 shows that the effective dose, organ doses and effective cancer risk were all higher in females than males, but only the effective dose was significant ($P = 0.04$). Figure 1 shows the mean radiation doses and effective cancer risk.

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4. Discussion

The patient size varied along the Z-axis of the scan due to changes in the thickness and composition of the subjects' habitus. As expected, the variation of the subjects' effective diameter was contributed to the SSDE in line with a previous study [8]. Hence, the $CTDI_{vol}$ calculated from the console and CT-EXPO software was observed to be undervalued compared to SSDE especially in small-sized subjects.

The small variations in SSDE to $CTDI_{vol}$ ratio generated by CT-EXPO method in different subject sizes group was expected since the software's calculations were based on mathematical phantom [9]. However, the ratio generated by the AAPM report method was wider in small-sized group compare to bigger-sized as the f-size increased in decreasing subjects' body size. A previous study had observed that when the automated exposure control (AEC) system was deployed, both $CTDI_{vol}$ and SSDE values were higher in large-sized subjects than those who were standard-sized. When the AEC system was turned off, there seems to be no significant difference between the radiation doses in different subject sizes [12]. This observation was aligned with in this study where the AEC was deployed.

The variation in $CTDI_{vol}$ and SSDE were highly dependent on the scanning parameters. The use of low tube voltage had been reported as the most effective way to reduce the radiation dose exposure in CT examination especially CTPA [11,13,14]. A previous study had demonstrated that by lowering the tube voltage to 80 kV, it could reduce the $CTDI_{vol}$ to about 70% in contrast to this study [7]. However, the low tube had to be applied cautiously without affecting image quality. Another study reported that reducing the tube voltage in CT examination involve contrast media could maximize the photoelectric effect, as the applied voltage was closer to the k-edge of iodine (33.2 keV). It could enhanced performance of image quality as well as to reduce the radiation dose [6].

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The tube current indicated in Table 4 showed similar trend in various studies. Most studies applied the AEC system to modulate the tube current and reduce unnecessary radiation exposure to their subjects. However, the variation in pitch factor and beam collimation showed different approaches taken by different institutions in utilizing their CT-Scanner.

Theoretically, the scanning is controlled by increasing or decreasing the pitch factor, where the radiation dose received by patients would be reduced by increasing the pitch factor, but at the expense of image quality [15]. Modern scanners were developed to cover a wider beam collimation range per rotation of the CT X-ray tube. This would reduce the scanning time and radiation dose received by the patient [16].

The DLP value and effective diameter were dependent on the scan length and range as stated in other studies [2,6,8,17]. However, there was limited information on the scan parameters. As the $CTDI_{vol}$ and SSDE values in this study were high, the DLP and effective dose could be expected to follow suit as in Table 4. The dose calculation was highly dependent on the scan length and patient habitus, especially for DLP [18,19]. A previous study which also calculated the radiation dose exposure using AAPM Report 204 and CT-EXPO software, reported that the two methods had a deviation of around five per cent, which was similarly observed in this study [20].

It is clearly shown that the breast and lungs received the highest radiation dose exposure as these organs cover all in primary beam. Both also had equally high risk of developing cancer. On the other hand, the liver attained the lowest values in organ dose and effective cancer risk. This was mainly because in a CTPA procedure, the liver would only be partially scanned as it was not fully within the region of interest.

This observation was in line with the BEIR VII report, which stated the dose exposure and cancer risk were dependent on the location of the organ from primary beam, as well as their sensitivity to radiation. The higher tube current required to scan subjects with increasing body effective diameter was the main factor that caused the significant differences in organ doses and their cancer risk as observed in Table 5 and

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6. The AEC system automatically modulated the tube current according to patient size and habitus [21]. Thus, subjects with large body sizes were at higher risk when undergoing CTPA.

Unfortunately, the risk estimation in this study was not comparable with other studies, which were presented with various methodologies and different cases [22–24]. Although not significant, the result of this study supported a previous research that found a higher effective cancer risk in females. The overall lethality risk for females was approximately 35 % higher in comparison with males as illustrated in Table 7 [9].

There were some limitations in this study. Firstly, the subjects in this study not involved with pediatrics and adolescents hence further investigation needed to evaluate the radiation dose and selected organ risk between these group of ages. Secondly, the SSDE values derived using CT-EXPO software was not normalized to the effective diameters of each patient. Thus, the values were not accurately estimated since the CT-EXPO software only utilized a fixed size mathematical phantom. However, this study overcome this limitation with another evaluation by AAPM report 204 method. Lastly no alternative dose descriptor software beside CT-EXPO used in this study to calculate the effective dose, organ dose and effective cancer risk. No comprehensive comparison of the value of these variables had been done in this study. Further study could focus on another group ages of subjects scan and additional of dose descriptor software to compare the results with CT-EXPO software.

5. Conclusions

The radiation dose exposure of CTPA depended on various factors and would significantly increase with the subjects' effective diameter. The $CTDI_{vol}$, SSDE, effective dose, organ dose and cancer risk were significantly different between effective diameters. Only the effective dose was significantly different between gender.

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Table

Table 1. Data on baseline characteristic based on gender

Baseline Characteristic	Values		
	Male	**Female**	**TOTAL**
Age*	49.26 ± 14.57	48.60 ± 19.12	48.88 ± 17.28
AP (cm)*	21.68 ± 3.68	21.88 ± 2.71	21.80 ± 3.14
LAT (cm)*	33.46 ± 4.17	32.85 ± 3.53	33.10 ± 3.80
Effective Diameter (cm)*	26.89 ± 3.71	26.76 ± 2.64	26.82 ± 3.12

*(mean ±SD)

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Table 2. Data on scanning acquisition in CTPA examination

Scanning Parameter	**Values**
Tube Voltage (Kv)	100 and 120 kV
Tube Current (mAs)*	184.50 ± 81.87
Scan Range (mm)*	277.44 ± 88.03
Pitch Factor	0.798
Beam Collimation (mm)	0.625 x 40
Rotation Time (s)	0.50

*(mean ±SD)

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Table 3. Dose descriptors values of CTPA examination for both method

Effective Diameter (cm)	Method	Dose Descriptors			
		$CTDI_{vol}$ (mGy)*	SSDE (mGy)*	SSDE/ $CTDI_{vol}$	DLP (mGy.cm)*
19 - 25	Console/AAPM report 204	6.44 ± 2.63	9.93 ± 3.89	1.54	239.59 ± 97.36
	CT-EXPO	6.69 ± 2.75	9.01 ± 3.78	1.30	262.94 ± 106.15
25 - 28	Console/AAPM report 204	9.86 ± 6.46	13.70 ± 9.04	1.42	351.85 ± 231.85
	CT-EXPO	9.98 ± 5.74	13.41 ± 7.74	1.34	379.07 ± 203.58
28 - 38	Console/AAPM report 204	17.42 ± 6.90	239.59 ± 97.36	1.28	631.46 ± 274.43
	CT-EXPO	18.17 ± 7.22	239.59 ± 97.36	1.38	697.28 ± 305.68
TOTAL	Console/AAPM report 204	11.06 ± 7.17	14.62 ± 8.41	1.41	400.38 ± 259.10
	CT-EXPO	11.40 ± 7.36	15.37 ± 9.67	1.36	437.68 ± 277.35

*(mean ±SD)

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Table 4. Radiation dose comparison between this study (CT-EXPO method) with other studies in CTPA examination

Study	Brand	Scanning Parameter						Dose Descriptors			
		Tube Voltage (Kv)	Effective tube current (mAs)*	Pitch factor	Beam Collimation (mm)	Scan Range (mm)*	Scan Length (mm)*	$CTDI_{vol}$ (mGy)*	SSDE (mGy)*	DLP (mGy.cm)*	Effective Dose (mSv)*
This Study	Brilliance iCT; Philips	100 and 120	184.50 ± 81.87	0.798	64 x 0.625	277.44 ± 88.03	363.91 ± 43.09	11.40 ± 7.36	15.37 ± 9.67	437.68 ± 277.35	8.68 ± 5.47
Sauter et al. 2018	Brilliance iCT; Philips	100 and 120	105 (49–368)	0.900	12 x 0.625	n/a	n/a	n/a	n/a	190 (72-695)	4.6 ± 2.27
Sabel et al. 2016	Siemens Somatom Force	80,100 and 130	236 (134–328)	1.900	192 x 0.600	n/a	n/a	8.10 (median)	16.2 (14.7-17.6)	226 (205-259)	3.3 (3.00-3.80)
Laqmani et al. 2016	256 slice Brilliant iCT; Philips	80	130 (references tube current)	0.915	128 x 0.625	n/a	249 ± 61	1.9±0.6	n/a	66 ± 27	0.9 ± 0.4
Laqmani et al. 2014	256 slice Brilliant iCT; Philips	80	189 (references tube current)	0.758	128 x 0.625	n/a	n/a	2.3±0.8	n/a	73.1 ± 26.7	1.24 ± 0.45

*(mean ±SD)/mean (range: min to max)

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Table 5: Effective Dose and Organ Equivalent Dose Comparison in by CTPA examination

Effective Diameter (cm)	Effective Dose (mSv)*	Organ Dose (mSv)*		
		Breast	Lung	Liver
19 - 25	5.19 ± 2.50	10.94 ± 4.62	10.62 ± 4.12	9.15 ± 4.23
25 - 28	7.47 ± 4.11	15.48 ± 7.93	15.55 ± 8.39	13.48 ± 6.99
28 - 38	13.90 ± 5.66	23.81 ± 12.17	27.39 ± 11.87	23.19 ± 11.76
p - value	0.0001	0.0001	0.0001	0.0001
TOTAL	8.68 ± 5.47	17.05 ± 10.40	17.55 ± 10.86	15.04 ± 9.75

*(mean ±SD)

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Table 6. Estimation of cancer probability risk according to the CTPA examination in million procedures

Effective Diameter (cm)		Cancer Probability Risk (in million procedures) *		
		Breast	Lung	Liver
	Nominal Risk Factor (r_T)$10^{-4}Sv^{-1}$	112.10	114.20	30.30
19 - 25		118.67 ± 54.45	114.14 ± 47.03	31.55 ± 12.88
25 - 28		174.38 ± 94.26	167.06 ± 91.60	46.59 ± 25.63
28 - 38		278.63 ± 118.27	305.67 ± 120.17	84.39 ± 33.77
p - value		0.0001	0.0001	0.0001
TOTAL		194.00 ± 113.84	191.91 ± 118.36	53.19 ± 32.90

*(mean ±SD)

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Table 7. Comparison based on different gender according to the CTPA examination

Variable		Gender		P - value
		Male	Female	
Effective Dose (mSv)*		7.47 ± 4.11	9.53 ± 5.68	0.04
Organ Dose (mSv)*	Breast	n/a	17.05 ± 10.40	n/a
	Lung	15.55 ± 8.39	17.63 ± 10.41	0.31
	Liver	13.48 ± 6.99	14.58 ± 9.28	0.84
Cancer Probability Risk (per one million population) *	Brest	n/a	194.00 ± 113.84	n/a
	Lung	185.54 ± 124.36	196.53 ± 114.70	0.16
	Liver	52.35 ± 35.31	53.79 ± 31.34	0.16

*(mean ±SD)

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Figure

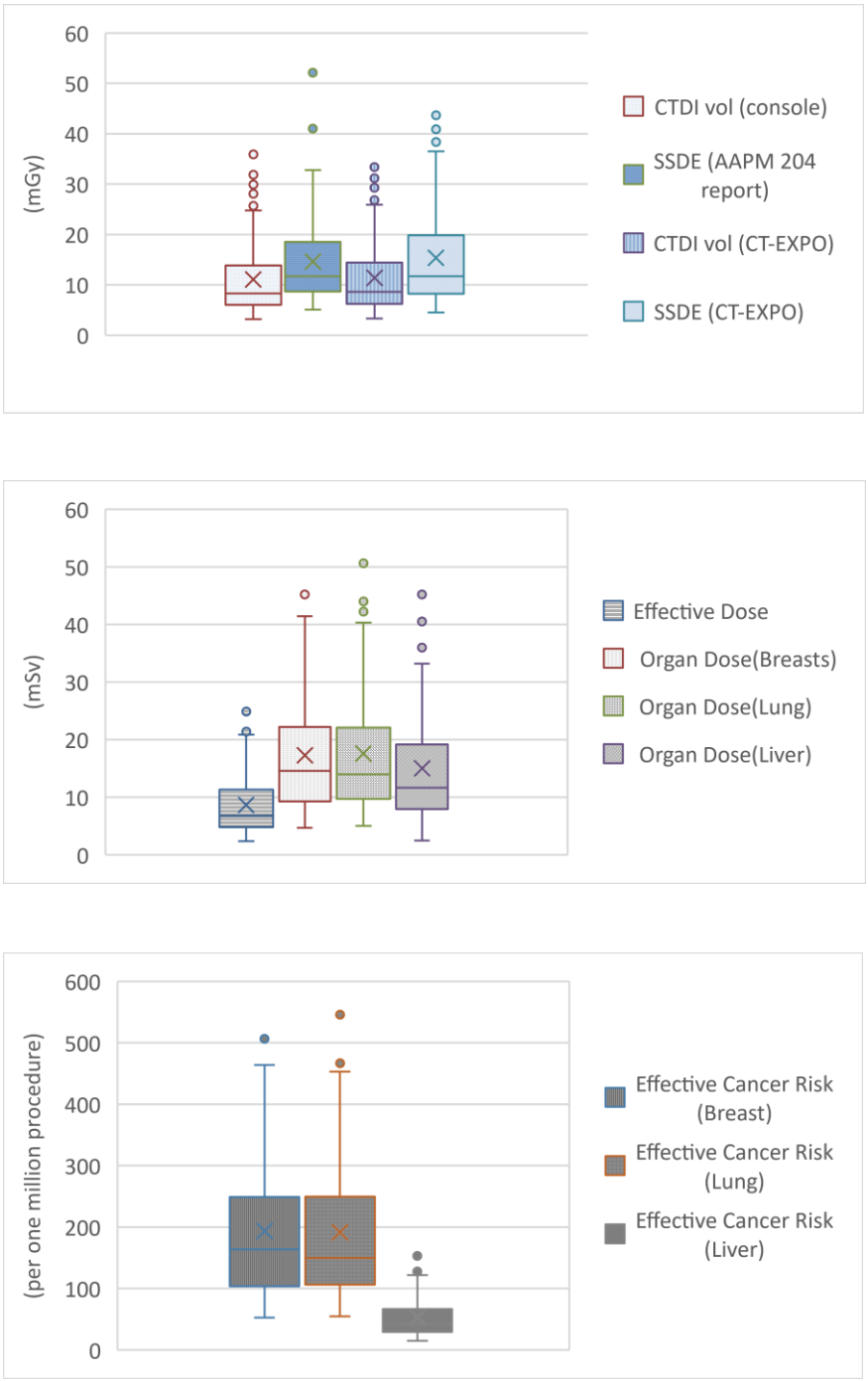

Figure 1. The distribution of radiation dose and cancer probability risk value in CTPA examination: **(A)** $CTDI_{vol}$ vs SSDE **(B)** Effective Dose and Organ Dose **(C)** Effective Cancer Risk.