Multivariate Analysis of Effective Dose and Size-Specific Dose Estimates for Thorax and Abdominal Computed Tomography

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Abstract

The study aimed to compute the effective dose (E) and size-specific dose estimate (SSDE) of routine adult patients undergoing thorax and abdominal computed tomography (CT) imaging and to present their multivariate analysis. All adult thorax and abdominal CT examinations conducted from March 2022 to June 2022 were prospectively included in this study. The Water Equivalent Diameter (D_w) and SSDE of all the examinations were computed from CT dose index volume ($CTDI_{vol}$) and Dose length product (DLP) displayed on the dose report in the CT console. The multivariate statistical analysis was performed to investigate the correlation of SSDE and E on $CTDI_{vol}$, D_w area of the region of interest (ROI) ($Area_{ROI}$), body mass index (BMI), conversion factor (f_{size}) and hounsfield (HU_{mean}) number in the ROI at 95% level of significance ($P < 0.05$). The linear regression analysis was performed to investigate the dependence of SSDE and E on other parameters for both abdominal and thorax patients. A total number of 135 (Abdomen = 61 and Thorax = 74) measurements were performed. The mean value of effective dose for abdomen and thorax patients was found to be 7.17 ± 3.94 and 4.89 ± 2.16 *mSv*, respectively. The SSDE was observed to be 13.24 ± 3.61 and 13.04 ± 3.61 *mGy* for thorax and abdomen respectively. The multivariate analysis suggests that SSDE for abdominal CT is found significantly dependent on $CTDI_{vol}$, D_w and f_{size} with $P < 0.05$ and E is found to be significantly dependent on DLP, $Area_{ROI}$, D_w and f_{size} at 95% level of confidence for abdominal CT imaging. SSDE for thorax CT was found significantly dependent on BMI, $CTDI_{vol}$, HU_{mean}, D_w and f_{size} at 95% level of confidence. Furthermore, E was observed dependent on DLP at $P < 0.05$. The linear regression analysis also shows that E is strongly correlated with DLP ($r = 1.0$) for both thorax and abdominal CT, further the SSDE was observed strongly correlated with $CTDI_{vol}$ with $r = 0.79$ and $r = 0.86$ for abdomen and thorax CT respectively. A strong correlation was observed between BMI and for D_w abdominal CT imaging ($r = 0.68$). The mean value of SSDE for thorax is slightly greater than abdomen. The average value of effective dose for abdomen and thorax measurements was found to be 7.17 ± 3.94 and 4.89 ± 2.16 *mSv* and , correspondingly. SSDE for both abdomen and thorax CT is significantly dependent on $CTDI_{vol}$, D_w and f_{size} at 95% level of confidence. The strong correlation was also observed E on DLP and SSDE on $CTDI_{vol}$ for both Abdomen and Thorax CT. The strong dependence of D_w on BMI ($r = 0.68$) is due to the excessive fat concentration around the stomach and abdomen.

Keywords: Dose length product, effective dose, size-specific dose estimate, water-equivalent diameter

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Introduction

The computed tomography (CT) technology was first introduced in healthcare science in 1972, to produce cross-sectional and nonsuperimposed images of the human body. It soon turned into one of the utmost popular noninvasive diagnostic modalities that many physicians all over the world rely on. Its use transfigured the science of diagnostic radiology, as it experienced swift scientific expansions (fast acquisition and reconstruction times, spiral acquisition mode, and multi-slice competence) and during the last two decades, its applicability has grown considerably. As a consequence, the figure of CT examinations has made a quantum jump to the extent that CT imaging has made a significant impact not only on patient care

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but also in patient and general public exposure from medical X-rays. The USA survey has suggested that CT imaging comprises approximately 10% of all X-ray examinations, the radiation dose constitutes about 70% of the collective dose from diagnostic radiology, and on average contributes half of all medical imaging exposure in the United States (US).[1-4] The fears about the high scan figures and the huge share to medical exposure have led to campaigns and strategies for developing guidelines for justification and optimization of image quality and dose in the radiological practice.[5]

At present, the parameters; Volume CT dose index volume ($CTDI_{vol}$, *mGy*)and dose length product (*DLP, mGy.cm*) are the two utmost vital parameters used to describe the radiation exposure from CT imaging.[6,7] $CTDI_{vol}$ is a calculated quantity which provides a standardized technique to compare radiation output levels between different CT units using a homogeneous calibration phantom of a specified size based on the CT parameter settings used during the scan. Since the $CTDI_{vol}$ does not take into consideration an individual patient's size or differential attenuation characteristics, thus is not a direct measurement of the absorbed dose delivered to the patient.[8] To overcome this drawback, the American Association of Physicists in Medicine (AAPM) came up with the term water-equivalent diameter (D_w), and its applications in defining patient radiation dose in 2014.[9] The aim of this Report (AAPM Task Group [TG] report 220)[9] is to provide a comprehensive metric for robotically estimating patient size that will take into consideration the differential patient attenuation and allow routine calculation of size-specific dose estimate (SSDE) for all patients, by slight operator intervention. The report developed size-specific conversions factors (f_{size}) for appropriate estimate of patient radiation absorption properties and SSDE.

The dosimetric quantity most appropriately meant for evaluating the risk of radiation-induced malignancy from CT is the "Effective dose (E)." The Effective dose (E) is the weighted sum of the doses to all irradiated organs, with the weighting incorporating the different radio-sensitivities of the various organs in the body.[10] Patient effective dose (E) is obtained from *DLP* (*mGy.cm*) by multiplying it age and site-corrected International Commission for Radiological Protection (ICRP) conversion factor (K). $CTDI_{vol}$ and *DLP* are the parameters relevant to the radiation dose from the CT system displayed after each CT examination in the form of a dose page. The present study was designed to compute the E and SSDE of routine adult patients undergoing thorax and abdominal CT imaging and to present the multivariate analysis of the SSDE and E.

Materials and Methods

Subject

A total of 135 adult patients (*Abdomen* = 61 *and Thorax* = 74) above the age of 18 years undergoing routine CT abdomen and thorax were included in this prospective study on GE Healthcare Revolution EVO CT installed in our department as per the standard protocol. The study was permitted by our Institutional Ethics Committee (Ref. No: IECJNMC/612, February 2022) and the written consent was waived off by the committee as the patients were already scheduled for a CT and were not exposed to an extra unnecessary scan from March 01, 2022 and June 30, 2022 for different clinical indications. The exclusion criteria were the following: (1) Patients below the age of 18 years, (2) patients with poor cooperation throughout the imaging (3) patients who were re-scanned owing to operational errors or patient's reasons (4) inferior or poor quality of imaging and (5) patients who had metal foreign or metal fixators bodies on the body surface.

Image acquisition

Altogether patients underwent a CT scan of the abdomen and thorax with a standard protocol using the following constraints: spine position with head first. The scanning range was from the lung apex to the pubic symphysis in abdomen imaging and from 7th cervical vertebra to diaphragm in the thorax examination. The CT examinations were performed with a WiproGE Healthcare Revolution EVO 3.68B MID BJG, 128-slice CT unit installed in our department. The preset imaging limits were as follows: tube voltage (kV_p:80 − 120), quality reference (*mAs*: 100), detector collimation (128 mm × 0.6 mm), acquisition matrix (512 × 512) , field-of-view [(314 mm × 314 mm)] , slice acquisition thickness (5 mm), inter-slice spacing , (1 mm) and the image reconstruction algorithm was CT unit was Filtered Back Projection Algorithm.

Effective dose

The effective dose (E) according to ICRP report-60[10] is defined as the weighted average of organ dose values (H_T) for a number of specified organs:

$$E = \sum_i w_i H_{t,i} \tag{1}$$

The unit of "E" is millisievert (*mSv*). How much a specific organ contributes to "E" depends on its relative sensitivity for radiation-induced effects, as represented by the tissue weighting factor (w_i) attributed to the organ. The "E" cannot be measured directly *in vivo*. The thermo-luminescent dosimeter-based measurements utilizing anthropomorphic phantom are very time-consuming and therefore are not well suited for the daily routine practice. Thus, "E" is derived from the product of the DLP and the age and site-corrected conversion factor (*K*). The value of "K" is 0.014 $mSv \times (mGy \times cm^{-1})$ and 0.015 $mSv \times (mGy \times cm^{-1})$ for adult thorax and abdomen, respectively.[11] Thus "E"

$$E = K \times DLP \tag{2}$$

The *DLP* is displayed after each CT imaging study in the form of a dose page and "E" is computed from the DLP.

Size-specific dose estimate

The $CTDI_{vol}$ and DLP values commonly used to express the radiation dose from a CT scan are limited to scanner output for a very specific standardized condition.[12] The actual dose received by the patient is a function of both patient dimensions and scanner output hence obtaining the exact patient dimensions is crucial to find the patient dose in CT.[13,14] AAPM report-204 described the usage of a size metric that involved the physical dimensions of the patient (anteroposterior, lateral [LAT] and anteroposterior or effective diameter), in conjunction with $CTDI_{vol}$ to compute SSDE from CT scan.[15] The report-204 task of estimating SSDE takes into consideration the geometric size of the patient but not the fundamental physical factors affecting the absorption of X-rays and is more vital than geometric size in determining the radiation dose absorbed by the patient. The concept of the use of water-equivalent diameter (D_w) was introduced by AAPM report-220, D_w into account the tissue attenuation in addition to patient geometric dimensions for estimation of SSDE is recommended. The SSDE is $CTDI_{vol}$ with multiplicative conversion factors (f_{size}) which rest on D_w as defined by the TG report-220. The D_w was determined by mid axial CT images. The $CTDI_{vol}$ and DLP are presented on the dose page of GE Advance Workstation software based on 32 cm Phantom in all the CT imaging studies. The SSDE and D_w was also computed by using the TG report-220 formalism from the following equations:[9]

$$D_w = 2\sqrt{\left(\frac{ROI_{mean}}{1000}+1\right)} \times \sqrt{\frac{A_{ROI}}{\pi}} \quad (3)$$

$$f_{size}^{32} = \alpha \times e^{-b \times D_w} \quad (4)$$

where a = 0.4378 and b = 0.043 are the normalized dose coefficients for the 32 cm polymethyl methacrylate phantom (PMMA) $CTDI_{vol}$ data as function of D_w. The normalized coefficients are the results of the three independent research groups, the curve fit shows excellent agreement across all data points, with a correlation coefficient of 0.967.

$$SSDE = f_{size}^{32} \times CTDI_{vol}^{32} \quad (5)$$

where region of interest (ROI) is the ROI covering the whole area of the body outline, ROI_{mean} is the mean hounsfield (HU) number in the ROI; A_{ROI} stands for the area of the ROI (cm^2); ROI_{mean} and A_{ROI} are automatically presented by team play (Syngo. via software Version VB40) according to the axial CT images and f_{size}^{32} are the conversion factors presented in the TG report. The D_w is estimated from the mean HU number in the ROI and area of the ROI ($Area_{ROI}$) (cm^2), automatically presented by team play according to the axial CT images.

Body mass index measurement

All the patients had weight and height measurements performed and their body mass index (BMI) was calculated immediately before the imaging using a dedicated calibrated device (Indosurgicals: Weight and height measuring instrument). The subcategories of the BMI data were used grouping the patients, where underweight mentioned to $BMI < 18.5\ kgm^{-2}$, normal weight referred to $18.5 \leq BMI \leq 24.9\ kgm^{-2}$, overweight stated to $25 \leq BMI \leq 29.9\ kgm^{-2}$, and obese referred to $BMI \geq 30\ kgm^{-2}$.

Statistical analysis

The statistical analysis was performed by Origin 6.0 (v6.1052 [B232] Origin Lab Corporation, Northampton, MA 01060 USA) software and statistical package for Social Sciences (SPSS), version 12.0 (SPSS Inc., Chicago, IL, USA) for all the data. The multivariate analysis was performed for E and SSDE to investigate their dependence on other quantities by using the SPSS software and the linear regression analysis was performed to find out the correlation between SSDE and $CTDI_{vol}$, SSDE and BMI, E and DLP, and E and BMI and BMI versus D_w with the help of Origin software.

Results

A total of 135 adult abdominal (male = 28, females = 33 and total = 61) and thorax (male = 45, females = 45 and total = 74) CT studies were obtained. The average age of the abdominal patients was found to be 45.39 ± 17.92 years with minimum age of 20 years and maximum age 86 years and the mean age of thorax patients was observed to be 46.34 ± 17.74 years with minimum age of 18 years and maximum age of 75 years. Approximately 57.2% of patients were having normal weight and height 12.9%, were overweight 23.4%, were underweight and only 6.51% were obese. The statistical values of $CTDI_{vol}$, DLP, E, D_w SSDE and BMI for the abdominal and thorax patients are presented in Tables 1 and 2, respectively, and the whole data and mathematical calculations can be seen in the supplementary file 1 (page 1 for abdomen and page 2 for thorax). The effective dose ranges from 2.8 to 21.99 *mSv* with the mean value of 7.17 *mSv* for abdominal CT patients and the

Table 1: Statistical results of abdomen computed tomography studies

Parameter	Mean	Minimum	Maximum	SD	SE	Range	95% CI
Age (years)	45.39	20.0	86.0	17.92	2.29	66.0	-
BMI (kgm^{-2})	20.82	13.3	36.26	4.43	0.56	22.96	-
DLP (mGy)	477.93	186.82	1466.2	262.94	33.67	1279.38	-
$CTDI_{vol}$ (mGy)	8.88	4.39	14.1	1.99	0.25	9.71	-
D_w (cm)	25.0	18.0	33.0	3.70	0.47	15.0	-
Effective dose (mSv)	7.17	2.8	21.99	3.94	0.50	19.19	7.17–7.17
SSDE (mGy)	13.04	7.04	22.23	2.54	0.32	15.19	13.15–12.95

SD: Standard deviation, SE: Standard error, CI: Confidence interval, BMI: Body mass index, DLP: Dose length product, $CTDI_{vol}$: Computed tomography dose index-volume, D_w: Water equivalent diameter, SSDE: Size specific dose estimate thorax CT studies the average E was found to be 4.89 *mSv* with maximum of 16.14 *mSv* as presented in the Tables 1 and 2. The water D_w was observed to range from 18.0 to 33.0 cm with mean value of 25.0 cm for abdominal CT images which is higher then D_w values of the thorax CT images. The mean value of estimates SSDE was found to be 13.04 *mGy* and 13.24 *mGy* for abdomen and thorax studies, respectively. We compared the results of the SSDE calculation of the present study with the literature published in international studies [Table 3] and it was observed that the mean SSDE values of our study are comparable with published literature for abdominal CT imaging. Further, in case of thorax CT imaging the mean SSDE value of our study is greater than the SSDE values presented in the literature.

The multivariate statistical analysis was performed to analyze the correlation of SSDE and E between BMI, $CTDI_{vol}$, DLP, HU_{mean}, $Area_{ROI}$, D_w, and size-based correction factor (f_{size}) for both abdomen and thorax CT imaging studies at 95% level of confidence significance ($P < 0.05$). The multivariate analysis tables for the abdomen and thorax CT is presented in Tables 4 and 5, respectively. As observed from the multivariate analysis in Table 4, the SSDE for abdominal CT imaging is found significantly dependent on $CTDI_{vol}$, D_w and f_{size} with $P < 0.05$ and E is found to be significantly dependent on DLP, $Area_{ROI}$, D_w and f_{size} at 95% level of confidence for abdominal CT imaging.

For thorax CT imaging the SSDE was found significantly dependent on BMI, $CTDI_{vol}$, HU_{mean}, D_w and f_{size} at 95% level of confidence. Furthermore, E was observed dependent on DLP at $P < 0.05$ as seen in Table 5. The vast difference in radiation doses is due to multiphase scans, the multiphase scans have higher E, DLP, and $CTDI_{vol}$.

The linear regression analysis between SSDE and $CTDI_{vol}$, SSDE and BMI, E and DLP, E and BMI [Figures 1-8]. The E shows very strong correlation with DLP for both abdomen and thorax CT studies with $r = 1.0$ as presented in Figures 3 and 7. The SSDE was also strongly correlated with also $CTDI_{vol}$ with $r = 0.79$ and $r = 0.86$ for abdomen and thorax patients respectively [Figures 1 and 5]. In order to investigate the dependence of D_w on BMI, the linear regression analysis performed for thorax and abdominal patients shows the strong correlation between BMI and D_w for abdominal CT imaging with $r = 0.68$ [Figure 9].

Discussion

The CT imaging involves relatively high dose to patients, the effective dose (E) from multiple CT procedures may range from 1.4 *mSv* to 12.7 *mSv*. There is sufficient scientific evidence that radiation injury to the deoxyribonucleic acid (DNA) in a solitary cell can be starting point to an altered cell that is still capable of undergoing cell division. Regardless of the body's

Table 2: Statistical results of thorax computed tomography studies

Parameter	Mean	Minimum	Maximum	SD	SE	Range	95% CI
Age (years)	46.34	16	75	17.74	2.06	59	-
BMI (kgm^{-2})	22.83	13.34	37.09	5.07	0.59	23.75	-
DLP (mGy)	349.31	206	1153	154.68	17.98	947	-
$CTDI_{vol}$ (mGy)	8.42	4.39	19.02	2.54	0.29	14.63	-
D_w (cm)	23.0	16.0	32.0	3.67	0.43	16.0	-
Effective dose (mSv)	4.89	2.88	16.14	2.17	0.25	13.26	4.81–4.81
SSDE (mGy)	13.24	7.99	36.33	3.61	0.42	28.34	13.34–13.11

SD: Standard deviation, SE: Standard error, CI: Confidence interval, BMI: Body mass index, DLP: Dose length product, $CTDI_{vol}$: Computed tomography dose index-volume, D_w: Water equivalent diameter, SSDE: Size specific dose estimate

Table 3: Comparison of mean value of size specific dose estimate in abdomen and thorax computed tomography imaging reported in the published literature

Anatomic Region	CT scanner	D_w (cm)	Mean $CTDI_{vol}$ (mGy)	Mean SSDE (mGy)	Reference
Thorax	SOMATOM definition flash scanner	15–20	2.10±0.25	3.78±0.44	[16]
		21–25	2.80±0.39	4.44±0.50	
		25–30	3.59±0.37	5.06±0.40	
		>30	4.89±0.39	5.86±0.31	
	40- and 128- slice	24.47±2.36	7.26±2.33	7.26±2.33	[16]
	40-slice	24.53±2.36	2.25±1.81	9.08±1.82	
	128-slice	24.42±2.35	8.02±2.38	11.84±2.73	
	WiproGE Rev. Evo 128-slice	16.0–36.0	8.42±2.54	13.24±3.61	Present study
Abdomen	40- and 128- slice	25.50±2.37	9.66±2.21	13.72±1.83	[7]
	40-slice	25.38±2.35	9.60±2.35	13.65±2.06	
	128-slice	26.61±2.38	9.71±2.22	13.77±1.65	
	WiproGE Rev. Evo 128-slice	18.0–33.0	13.04±2.54	13.04±2.54	Present study

CT: Computed tomography, $CTDI_{vol}$: CT dose index-volume, D_w: Water equivalent diameter, SSDE: Size specific dose estimate

Table 4: Multivariate analysis of abdomen computed tomography studies

Dependent variable	Independent variable	Mean square	*F*-statistics	*P*
SSDE (mGy)	BMI (kgm−2)	0.262	2.00	>0.05 (NS)
	$CTDI_{vol}$ (mGy)	115.54	885.66	<0.05 (significant)
	DLP (mGy)	0.023	0.17	>0.05 (NS)
	HU_{mean}	0.025	0.19	>0.05 (NS)
	$Area_{ROI}$	0.086	0.66	>0.05 (NS)
	D_w (cm)	0.982	7.53	<0.05 (significant)
	f_{size}	0.547	4.19	<0.05 (significant)
E (mSv)	BMI (kgm^{-2})	1.551E-006	0.21	>0.05 (NS)
	$CTDI_{vol}$ (mGy)	1.227E-006	0.16	>0.05 (NS)
	DLP (mGy)	724.99	97452223.38	<0.05 (significant)
	HU_{mean}	2.520E-005	3.39	>0.05 (NS)
	$Area_{ROI}$	3.011E-005	4.05	<0.05 (significant)
	D_w (cm)	5.048E-005	6.78	<0.05 (significant)
	f_{size}	3.997E-005	5.38	<0.05 (significant)

BMI: Body mass index, DLP: Dose length product, CT: Computed tomography, $CTDI_{vol}$: CT dose index-volume, D_w: Water equivalent diameter, SSDE: Size specific dose estimate, HU_{mean}: Mean hounsfield, $Area_{ROI}$: Area of the region of interest, f_{size}: Size-based correction, NS: Not significant

Table 5: Multivariate analysis of Thorax computed tomography studies

Dependent variable	Independent variable	Mean square	*F*-statistics	*P*
SSDE (mGy)	BMI (kgm^{-2})	1.20	4.02	<0.05 (significant)
	$CTDI_{vol}$ (mGy)	4.95.84	1664.50	<0.05 (significant)
	DLP (mGy)	0.24	0.82	>0.05 (NS)
	HU_{mean}	3.05	10.24	<0.05 (significant)
	$Area_{ROI}$	0.0	0.001	>0.05 (NS)
	D_w (cm)	9.03	30.33	<0.05 (significant)
	f_{size}	3.87	12.98	<0.05 (significant)
E (mSv)	BMI (kgm^{-2})	1.825E-006	0.211	>0.05 (NS)
	$CTDI_{vol}$ (mGy)	7285E-0070	0.08	>0.05 (NS)
	DLP (mGy)	0.244	16733029.62	<0.05 (significant)
	HU_{mean}	2.187E-006	0.25	>0.05 (significant)
	$Area_{ROI}$	5.358E-006	0.62	>0.05 (NS)
	D_w (cm)	5.911E-006	0.68	>0.05 (NS)
	f_{size}	6.06E-006	0.70	>0.05 (NS)

BMI: Body mass index, DLP: Dose length product, CT: Computed tomography, $CTDI_{vol}$: CT dose index-volume, D_w: Water equivalent diameter, SSDE: Size specific dose estimate, HU_{mean}: Mean hounsfield, $Area_{ROI}$: Area of the region of interest, f_{size}: Size-based correction, NS: Not significant

combating ability, which are generally very effective, there is a slight likelihood that this nature of radiobiological effect, exaggerated by the inspiration of other mediators not inevitably linked with the biological effect initiated by ionizing radiation may induce malignancy and if the primary impairment is to the germ cells in the gonads, genetic effects possibly will occur. The likelihood of stochastic effects attributable to the radiation rises with dose and is proportional to absorbed dose at low doses. At higher doses and dose rates, the probability often increases with dose than simple proportion. Even though a solitary scrutiny individual leads to a slight increase in the possibility of cancer initiation in a patient, in industrialized nations every member of population undertakes, on average, one such investigation every year; consequently, the collective risk increases precisely.[16-18] The rate of the CT examination is growing all over the globe and the types of clinical investigations by means of CT are correspondingly attracting further attention. Though, in disparity with the common trend in diagnostic radiology, the swift progress in tomography imaging could not develop in propose the methods to decrease of patient doses intended for any given imaging procedure. Therefore, the management of patient dose is crucial during CT imaging and the development of local diagnostic reference levels in the form of dose constraints is vital to ensure the radiation safety measures adequately followed.[19]

The aim of our study was compute the effective dose (E) and SSDE for adult thorax and Abdominal CT imaging in accordance AAPM TG Report 220. The AAPM TG Report 204[15] introduced the idea of SSDE. The SSDE is a patient size-corrected estimate of patient dose which uses a surrogate for the patient dose to scale the scanner reported $CTDI_{vol}$. The TG report 204 details the use of multiple size surrogates to normalize $CTDI_{vol}$ values to SSDE including: anterior-posterior (AP) dimensions, LAT

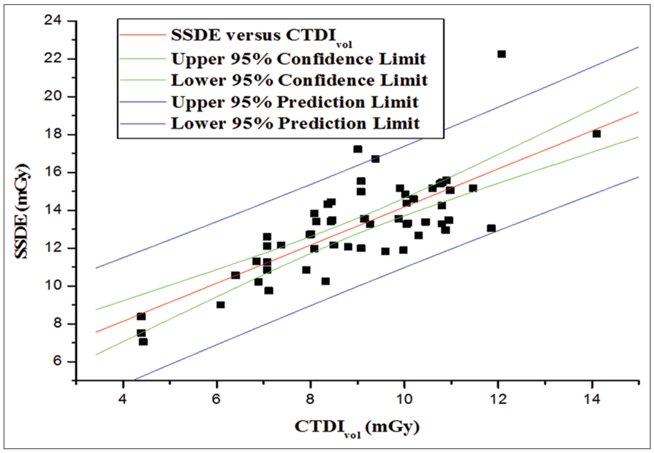

Figure 1: Linear regression analysis of SSDE (*mGy*) with $CTDI_{vol}$ (*mGy*) for abdomen CT imaging ($r = 0.79$). SSDE: Size-specific dose estimate, CT: Computed tomography, $CTDI_{vol}$: Computed tomography dose index-volume

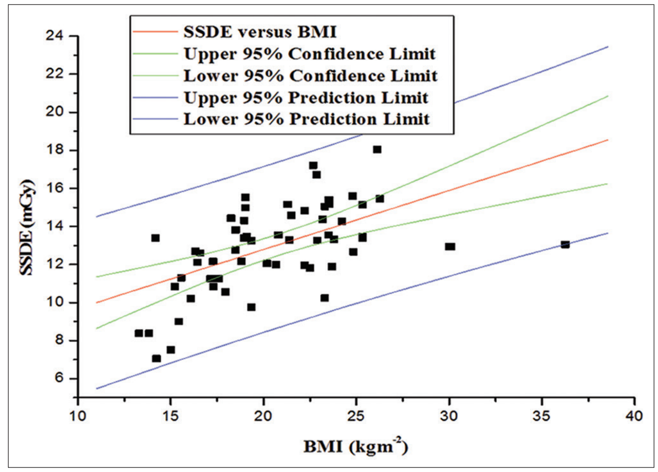

Figure 2: Linear regression analysis of SSDE (*mGy*) with BMI (*kgm*$^{-2}$) for abdomen CT imaging ($r = 0.54$). SSDE: Size-specific dose estimate, CT: Computed tomography, BMI: Body mass index

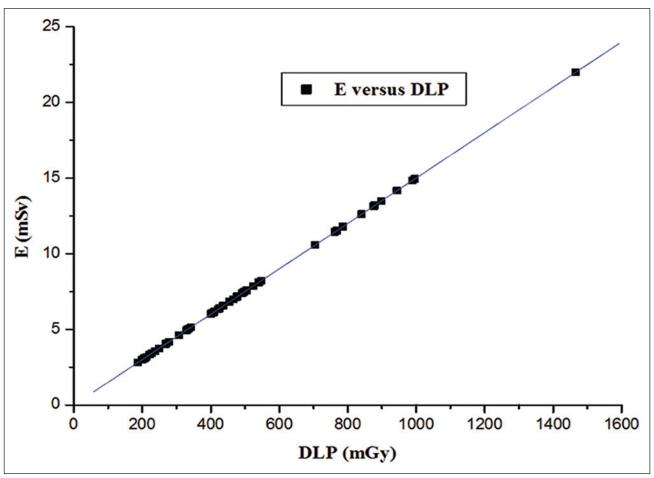

Figure 3: Linear regression analysis of E (*mSv*) with DLP (*mGy*) for abdomen CT imaging ($r = 1.0$). CT: Computed tomography. DLP: Dose length product

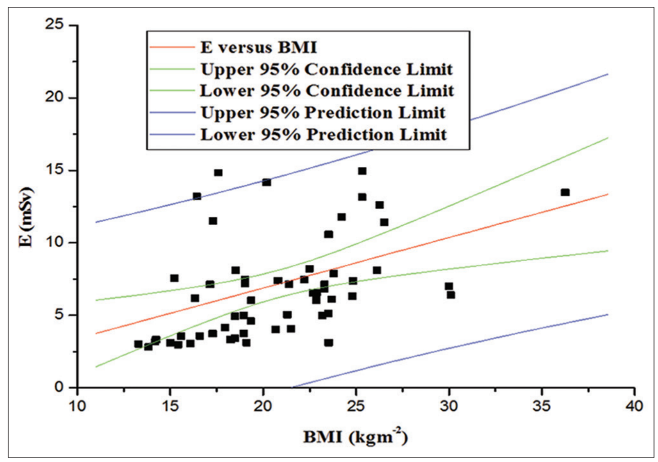

Figure 4: Linear regression analysis of E (*mSv*) with BMI (*kgm*$^{-2}$) for abdomen CT imaging ($r = 0.39$). CT: Computed tomography. BMI: Body mass index

dimensions, AP + LAT, circumference, and effective diameter $(AP \times LAT)^{\frac{1}{2}}$. The size surrogates of AAPM TG Report 204, however, are based only on patient geometry and do not take into consideration the differential attenuation offered by various tissue types within the body. This limitation was addressed in the AAPM TG Report 220[15] in detail, and introduced the concept of water-equivalent diameter (D_w), and its use in determining object radiation dose. The major goal of the TG Report 220 was to develop a sound metric for automatically estimating patient size that would account for patient attenuation and allow routine determination of SSDE for all patients, with minimal user intervention. The D_w represents the diameter of a cylinder of water that contains the same total X-ray attenuation as that contained within the patient's axial cross-section and depends on both the cross-sectional area of the patient and the attenuation of the contained tissues. The multivariate statistical analysis was performed to understand the relation of SSDE and E with all other parameters which influence the radiation dose received by the patient during CT examination. Multivariate analysis is a powerful statistical tool for evaluating multiple variables (more than two) to any association between them. It offers a more complex examination of data by looking at all possible independent variables and their relationship with one another.[20]

The SSDE was computed from the currently displayed radiation dose output ($CTDI_{vol}$) to and the water equivalent diameter (D_w) in accordance with the AAPM TG-220.[9] The effective dose (E) was derived from the DLP and by the multiplication of age and site corrected conversion factor (K) in accordance with the references of the ICRP report-60.[10] From the multivariate analysis tables [Tables 4 and 5], the SSDE is found significantly dependent on D_w, $CTDI_{vol}$ and f_{size}(AAPM conversion factor presented by TG-220) with $P < 0.05$ for both abdomen and thorax CT imaging. The D_w

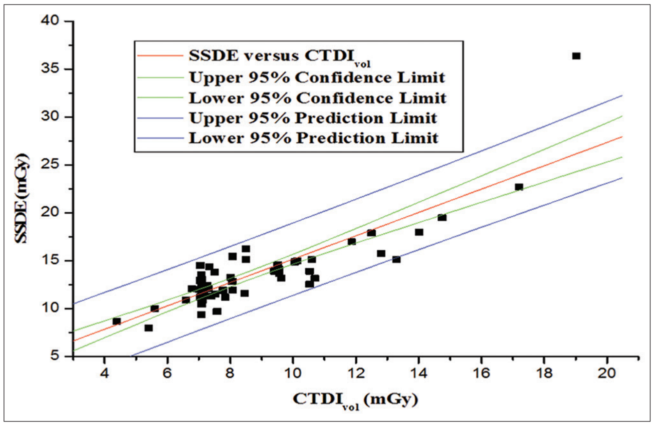

Figure 5: Linear regression analysis of SSDE (*mGy*) with $CTDI_{vol}$ (*mGy*) for thorax CT imaging (r = 0.86). SSDE: Size-specific dose estimate, CT: Computed tomography, $CTDI_{vol}$: Computed tomography dose index-volume

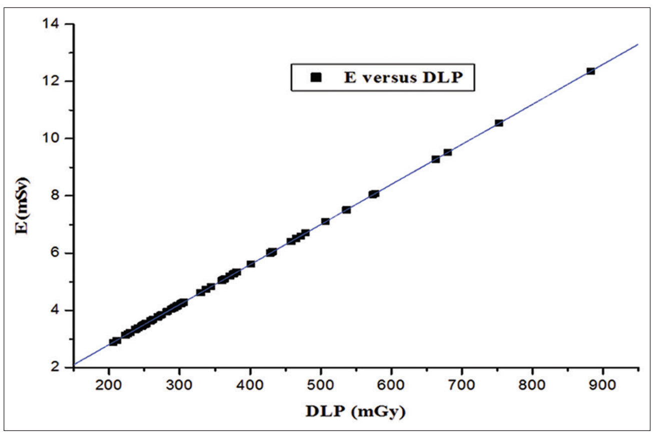

Figure 7: Linear regression analysis of E (*mSv*) with DLP (*mGy*) for thorax CT imaging (r = 1.0). CT: Computed tomography. DLP: Dose length product

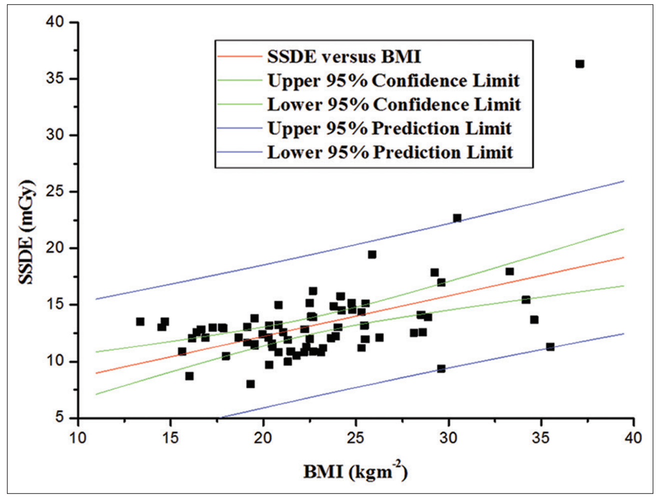

Figure 6: Linear regression analysis of SSDEE (*mGy*) with BMI (kgm^{-2}) for thorax CT imaging (r = 0.50). CT: Computed tomography. BMI: Body mass index

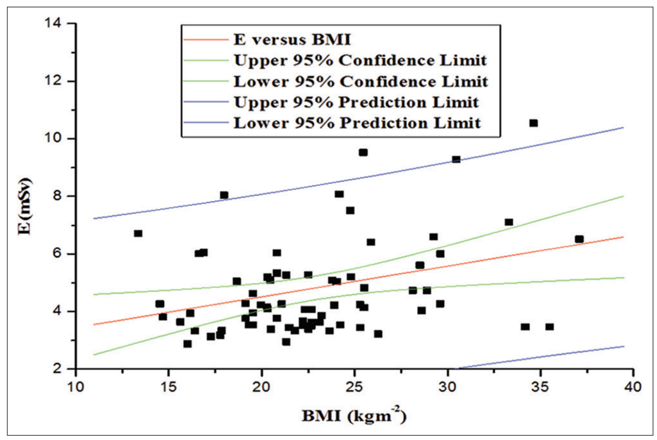

Figure 8: Linear regression analysis of E (*mSv*) with BMI (kgm^{-2}) for thorax CT imaging (r = 0.29). BMI: Body mass index, CT: Computed tomography

takes into consideration the differential attenuation due to various tissue densities in the body in addition to the patient geometric size and f_{size} presented in the Table 1D of the TG-220 provides the conversion factors based on the use of 32 cm diameter of PMMA for $CTDI_{vol}$ takes into account the geometric size and the differential attenuation of the different tissue in the scan area. Thus, the dependence of SSDE on D_w and f_{size} is obvious due to the geometric dimensions and differential attenuation because of various tissue densities in the body. The radiation dose output index ($CTDI_{vol}$) provides an estimate of average dose from multiple acquisitions when the CT table is incremented during the acquisition and is an indicator for measuring, comparing, and communicating radiation output of a CT unit. The accurate measurement of patient size is of vital importance for estimating the patient absorbed dose, as the radiation dose received by the patient during imaging is closely related to patient factors as well as the output of the CT scanner. Similar to previous studies,[21,22] we found that the actual patient sizes for chest and abdomen-pelvis were considerably <32 cm diameter standard AAPM phantom. Irrespective of inhomogeneous X-ray attenuation, a 32 cm diameter cannot accurately represent a realistic patient dimensions in terms of geometric dimensions. Hence, the radiation doses expressed via $CTDI_{vol}$ were underestimated compared to actual dose.[23,24] The $CTDI_{vol}$ displayed on the scanner console underestimates the dose to majority of the patients by 20% - 50% with the values for smaller patients being up to 50%. The discrepancies are due to the size of the standard Dosimetry phantom that was developed for European-North American Population is substantially larger than almost all the patients we are treating in our department. Our hospital is a central university medical college, which is a tertiary care referral center working as the apex center in western Uttar Pradesh, India, with the patients of all strata coming from a radius of 100 to 150 km. Furthermore, the patients of staff, students from different parts of India and many foreign students report for imaging. The majority of patients we are treating are lean and very few are of big size. Approximately, 81% of the patients we studied

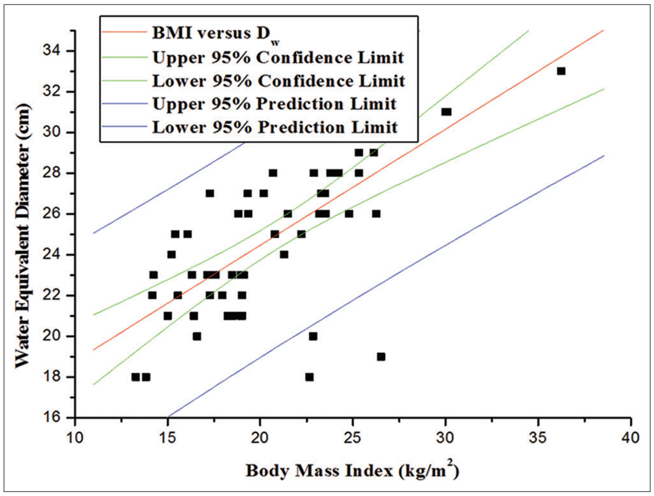

Figure 9: Linear regression analysis of BMI (*kgm*$^{-2}$) with D_w for abdomen CT imaging (r = 0.68). CT: Computed tomography. BMI: Body mass index

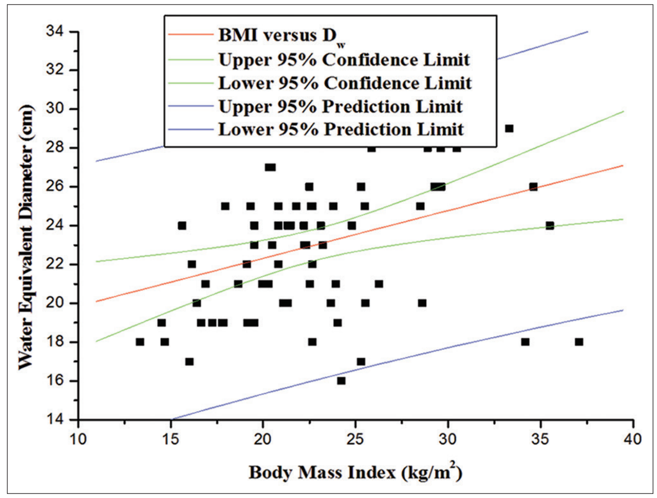

Figure 10: Linear regression analysis of BMI (*kgm*$^{-2}$) with D_w for thorax CT imaging (r = 0.34). CT: Computed tomography. BMI: Body mass index

were in the present study comprised of normal BMI and underweight (57.2% and 23.4% respectively) and 19% of the patients were overweight (12.9%) and obese (6.51%). The "E" is found to be significantly dependent on DLP for both the abdominal and thorax patients undergoing CT with $P < 0.05$. For thorax CT imaging the "E" is also observed significantly dependent on D_w, $Area_{ROI}$ and f_{size}, which suggests that the "E" is influenced by site which is scanned and the dimensions of the patient. All other parameters were found weakly correlated with the "E" and SSDE with $P < 0.05$.

The linear regression analysis between SSDE and $CTDI_{vol}$, SSDE and BMI, E and DLP and "E" and BMI for both the abdomen and thorax CT imaging patients verifies there is very strong useful relation between SSDE and $CTDI_{vol}$, E and DLP at 95% level of confidence. A weak correlation was observed between BMI and D_w for thorax CT imaging as seen in Figure 10 and contrary to this a strong correlation was observed between BMI and D_w for abdominal CT imaging [Figure 9]. The strong dependence of D_w on BMI is due to the excessive concentrations of visceral fat around the abdomen and stomach, suggests that BMI can be used as D_w surrogate for accurate patient size while accounting for geometric dimensions and X-ray attenuation characteristics. However, it is to be noted that manual calculation of D_w is cumbersome and time-consuming, therefore an automatic software program is required to calculate D_w, which must be verified before implementation of D_w surrogates are recommended in clinical practice.

There are some limitations to the study. First, the study was limited to single-scanner adult abdominal and thorax patients, brain and pediatric patients were not included. Second, multiphase and single-phase scans were not segregated. Third, the data of only adult patients were evaluated and majority of the patients were lean (small in size), representing a typical population group around the university. Finally, there might be a personal bias since all the measurements were made by one observer only.

Conclusion

The SSDE calculation from D_w according to the AAPM TG-220 is a robust, scientifically sound, and more realistic estimate of radiation dose for patients undergoing CT imaging and is less likely to under-or overestimate radiation dose compared to conventional $CTDI_{vol}$. The average values of SSDE calculated for thorax are slightly higher than the abdomen and the average value of E for abdomen is higher than thorax. The mean value of E for abdomen and thorax measurements was found to be 7.17 ± 3.94 and 4.89 ± 2.16 *mSv*, correspondingly. The average value SSDE was found to be 13.04 ± 2.54 and 13.24 ± 3.61 for both abdomen and thorax CT, respectively. The multivariate analysis suggests that SSDE for abdominal CT is found significantly dependent on $CTDI_{vol}$, D_w and f_{size} with $P < 0.05$ and E is found to be significantly dependent on DLP, $Area_{ROI}$, D_w and f_{size} at 95% level of confidence for abdominal CT imaging. SSDE for thorax CT was found significantly dependent on BMI, $CTDI_{vol}$, HU_{mean}, D_w and f_{size} at 95% level of confidence. The strong dependence of SSDE on D_w and f_{size} is due to the geometric dimensions and differential attenuation experienced by X-rays because of various tissue densities in the body. The strong dependence of D_w on BMI is due to the excessive concentrations of visceral fat around the abdomen and stomach. Therefore, we conclude that BMI can be used as D_w surrogate for accurate patient size while accounting for geometric dimensions and X-ray attenuation characteristics.

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Conflicts of interest

There are no conflicts of interest.

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