ORIGINAL ARTICLE

Body-Mass Index-Based Effective Dose Determination in Commonly Performed Computed Tomography Examinations in Adults

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Abstract

Purpose: With the widespread application of ionizing radiation in medical practice, concerns have been increased regarding the hazardous effects of radiation. Studies have demonstrated that some variables such as body dimensions affect the absorbed radiation dose. In this study, the association between Body Mass Index (BMI) and absorbed dose in Computed Tomography (CT) is investigated.

Materials and Methods: A total of 550 adult patients (age ≥ 15 years) were included in the study. The height and weight of the patients were recorded for BMI calculation. Dosimetry data were acquired from digital imaging and communications in medicine dose reports. The patients were categorized into five groups according to their BMI, the categorized information was then imported into ImPACT Dose software for calculation of Size-Specific Dose Estimate (SSDE) and organ and effective doses. The relationship between patient BMI and the effective dose was also determined.

Results: A higher BMI contributed to increased radiation dose and SSDE in patients who had undergone chest or abdomen-pelvis CT examination ($p < 0.05$).

Conclusion: The radiation dose is related to a patient's BMI and rises with an increase in BMI. Accordingly, it is suggested that BMI and other variables, such as the type of scan and other body dimensions, which affect the radiation dose, can be used to estimate the radiation dose before performing CT. This estimation can be considered for the justification and optimization of CT examinations.

Keywords: Computed Tomography; Body Mass Index; Effective Dose; Size-Specific Dose Estimate.

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1. Introduction

The use of ionizing radiation in medical imaging, such as Computed Tomography (CT), can provide crucial diagnostic data that are useful for patient care [1]. The number of CT scan procedures performed increased by approximately 70% from the year 1998 to 2000 [2, 3]. Although the number of CT scans examinations is much lower than the radiological examination, due to their higher doses, they significantly affect the accumulated radiation dose received by the society.

CT examinations are included in 4% and 11% of all diagnostic examinations performed in Europe and America, respectively; however, the total dose received by people through this technique was 40% and 67%, respectively. This illustrates the crucial role of CT in population exposure to radiation [4-6]. The use of CT examinations and the amount of radiation employed to conduct particular examinations are now of concern for regulatory bodies, the medical imaging community, and the general public [7, 8].

Dose Length Product (DLP), volume Computed Tomography Dose Index (CTDIvol) and effective dose values are commonly used to determine radiation doses received from a CT device. However, these measures are used as surrogates for patient dose and provide data on the scanner output for only a few particular standardized situations [9]. Effective dose is a dosimetry parameter used to estimate the risks of ionizing radiation [10]. The effective dose is proportional to DLP, which measures the risk of radiation and is related to patient risk [11, 12].

CTDIvol indicates the amount of radiation delivered by a scanning device per slice for a specific CT examination. CTDIvol is evaluated in accordance with a homogenous and standardized phantom. It is a well-defined metric used in dosimetry protocols of all CT scanners and is a precise measure of the radiation output of scanning devices [9]. The increasing application of CT and concerns regarding radiation doses from medical imaging resulted in the need for imaging providers to promote precise evaluation of radiation doses that individual patients are exposed to. The Size-Specific Dose Estimate (SSDE), which is the product of the CT Dose Index (CTDI) and a patient size-related constant, is used to evaluate the mean dose to the center of the scan volume of an object with similar attenuation features to those of a patient. However, SSDE is not a direct measurement of the effective dose for a specific patient [13]. SSDE may vary by approximately 10-20% from the received dose, in dose evaluation and even at the time and it only allows evaluation of the average radiation dose to an individual in the clinical setting [14]. SSDE is a dose-related criterion that relates patient size to dose and it is calculated from CTDIvol by using a conversion factor. The conversion factor is determined from manually measured Anteroposterior (AP) and lateral skin-to-skin patient diameters at mid-slice levels on CT localizer images. This metric was recommended by the American Association of Physicists in Medicine (AAPM) Task Group number 204 for the report of patient radiation dose in CT and has since been widely used [14, 15].

Practically, the use of SSDE for the calculation of effective dose may be time-consuming resulting in interobserver variability in measurement [13]. Recent studies have focused on the evaluation of patient dose and image quality in CT by considering patient characteristics [16, 17]. In another method for quick calculation of effective dose in CT scanning, some coefficients are multiplied by the DLP to obtain a rough estimate of the effective dose [18]. However, the use of software for the calculation of organ dose and effective dose is time-consuming, and the use of converting coefficients results in rough estimates. The present study aims to provide a formula for the estimation of effective dose based on patient Body Mass Index (BMI) before performing CT that can be both accurate and specific for each patient.

2. Materials and Methods

In the present study, formulas were provided for estimation of effective dose based on patient BMI, which can be both accurate and specific for each patient. Additionally, the organ doses were calculated for different CT examination protocols. Finally, a simple and fast method was presented to estimate the effective dose received by patients by analyzing the type of scan and patient BMI before performing CT.

2.1. Characteristics of Patients

In this study, 550 adult patients who underwent two common CT examinations were randomly selected. Among these cases, 301 patients (158 men and 143 women) were referred for abdomen-pelvis CT, while 249 patients (131 men and 118 women) were referred for chest CT. The patients were then classified into five groups according to their BMI. The groups include the following groups. Group A: underweight with BMI < 20 kg/m^2; group B: normal weight with BMI 20-25 kg/m^2; group C: overweight with BMI 25-30 kg/m^2; group D: obese with BMI 30-35 kg/m^2; and group E: morbid obesity with BMI > 35 kg/m^2. The patients referred to the imaging center for CT examinations were assigned to their respective groups according to their BMI. Information about patients such as height, weight, and age were collected. Information about the radiation dosimetry such as CTDI and DLP were extracted and recorded as well. After collecting satisfactory patient data in each group, the data were imported into Micro Soft Excel software and then into ImPACT software (version 2.3) for calculation of effective dose and organ dose.

2.2. CT Scanner and Scanning Protocol

A 16-slice multidetector CT unit (Bright Speed model, manufactured by GE Company) was used to perform the examinations. Standard scan parameters, including a tube voltage of 120 kVp and 16 × 1.5 mm detector collimation in the spiral mode were used for chest and abdomen-pelvis CT examinations with the use of Automatic Exposure Control (AEC).

2.3. Data Collection

Information about AP and lateral imaging was extracted from the images using electronic measuring tools installed in the system. The central slices of the CT images were used for the measurement of the AP and lateral dimensions. Sample AP and lateral images of abdomen-pelvis and chest CT scans are shown in Figure 1. Information about effective mAs, kVp, rotation time, and pitch was recorded from digital imaging and communications in the medicine report header. Patient sex, age, type of CT scanning test, height, weight, scan length, DLP, and CTDIvol were recorded as well.

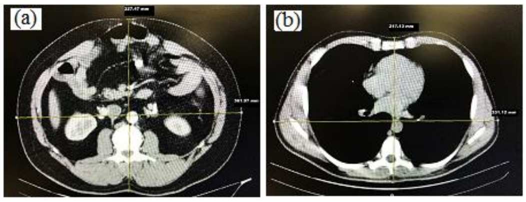

Figure 1. Example of AP and lateral dimensions measurement in abdomen-pelvis (a) and chest (b) CT scans

Patient dosimetry and effective dose determination were performed by ImPACT Dose software (version 2.3, Gm BH, Germany) [19, 20]. This software is a Monte Carlo-based pre-tabulated software that is widely used to calculate the radiation dose in CT scanning. ImPACT Dose software provides an acceptable standard for estimating the effective dose for a standard phantom associated with CT scanning protocols. The output data of the effective dose and its relationship with BMI was analyzed using Statistical Package for the Social Sciences (SPSS) software (version 16). Moreover, the relationship between BMI and the effective dose was investigated by curve estimation and regression analyses using MATLAB 2014 software.

3. Results

Among the total 550 total patients, 301 patients (including 158 men and 143 women) underwent abdomen-pelvis CT examinations. The mean and standard deviations of the effective doses in abdomen-pelvis CT examinations were 12.22 ± 1.84 mSv and 13.19 ± 1.52 mSv for men and women, respectively.

Among the total 500 participants, 249 patients (including 131 men and 118 women underwent chest CT examinations. The means and standard deviations of the effective doses in abdomen-pelvis CT examinations were 6.65 ± 1.25 mSv, and 6.37 ± 1.42 mSv for men and women, respectively. The means, ranges, and standard deviations of BMI, CTDIvol, DLP, effective dose, and SSDE in adult patients of both sexes underwent abdomen-pelvis and chest CT examinations are listed in Table 1.

Table 1. Mean, range and standard deviation of effective dose, $CTDI_{vol}$, DLP, SSDE for male and female patients in abdomen-pelvis and chest CT examinations

CT examination		BMI (kg/m^2)		$CTDI_{vol}$ (mGy)		DLP (mGy.cm)		Effective dose (mSv)		SSDE	
		Min-Max	Mean± SD	Min-Max	Mean± SD	Min-Max	Mean± SD	Min-Max	Mean± SD	Min-Max	Mean± SD
Abdomen-Pelvis	Male	17.3-38.1	26.4±5.2	8.6-34.2	15.3±6.1	427-1962	742±238	8.4-16.8	12.2±1.8	14.0-28.1	20.1±3.1
	Female	17.1-34-7	26.3±4.9	7.2-31.6	16.1±5.9	394-17.24	691±311	8.8-17.2	13.2±1.5		
Chest	Male	17.3-37.8	26.0±4.7	5.8-22.1	10.4±7.3	183-873	318±142	4.1-9.4	6.6±1.3	8.7-19.8	14.0±2.6
	Female	17.0-37.9	26.0±4.9	4.9-23.2	12.8-6.9	157.827	329±128	2.6-9.6	6.7±1.4		

The mean doses (mGy) for the organs that received the highest doses in abdomen-pelvis and chest CT examinations in men and women patients for different BMI categories are listed in Table 2. The values were calculated by ImPACT Dose software.

The AAPM Report 204 provides tables based on AP and lateral imaging which are used to find the size-dependent conversion factor (f size). When this factor is multiplied by CTDIvol, SSDE is yielded [21].

Scattergrams were plotted for the assessment of the relationships between effective dose (mSv) and patient BMI (kg/m^2) in adult male and female patients who underwent abdomen-pelvis CT examinations (Figure 2). The regression functions were calculated using MATLAB 2014 software and the following equations were obtained. Equations 1 and 2 show the relationships between the effective dose (mSv) and patient BMI (kg/m^2) in adult men and women patients undergoing abdomen-pelvis CT examinations, respectively.

$$\text{Effective dose} = 0.318\ \text{BMI} + 3.8327;\ R^2 = 0.80 \quad (1)$$

$$\text{Effective dose} = 0.2751\ \text{BMI} + 5.9492;\ R^2 = 0.78 \quad (2)$$

Equation 3 shows the relationship between SSDE (mGy) and patient BMI (kg/m^2) in adult patients undergoing abdomen-pelvis CT examinations.

$$\text{SSDE} = 0.531\ \text{BMI} + 6.4;\ R^2 = 0.80 \quad (3)$$

A scattergram was plotted for the assessment of the relationship between SSDE (mGy) and patient BMI (kg/m^2) in adult patients undergoing abdomen-pelvis CT examinations (Figure 3). The relation function was regressed using MATLAB 2014 software.

The relationships between the effective dose (mSv) and patient BMI (kg/m^2) in adult male and female patients undergoing chest CT examinations were regressed using MATLAB 2014 to produce the following equations. Equations 4 and 5 show the relationships between the effective dose (mSv) and patient BMI (kg/m^2) in adult male and female patients undergoing chest CT examinations, respectively.

$$\text{Effective dose} = 0.2388\ \text{BMI} + 0.4493;\ R^2 = 0.78 \quad (4)$$

$$\text{Effective dose} = 0.2579\ \text{BMI} + 0.0266;\ R^2 = 0.79 \quad (5)$$

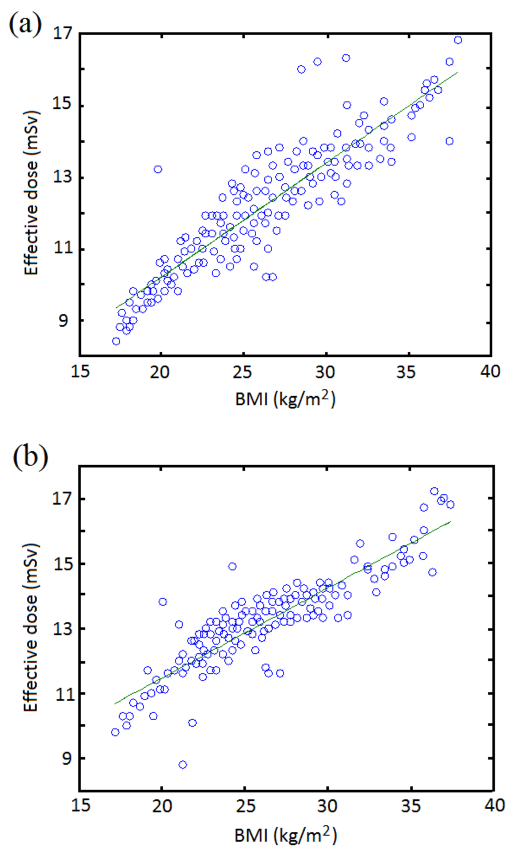

Figure 2. Scattergram and line regression for effective dose (mSv) versus BMI for adult men (a) and women (b) in abdomen-pelvis CT examinations

Table 2. Mean dose (mGy) for the organs with the highest dose in abdomen-pelvis and chest CT examinations for male and female patients with different BMI (kg/m^2), calculated by ImPACT Dose software

CT examination	Organ	Male					Female				
		BMI < 20	20 < BMI < 25	25 < BMI < 30	30 < BMI < 35	BMI > 35	BMI < 20	20 < BMI < 25	25 < BMI < 30	30 < BMI < 35	BMI > 35
Abdomen-Pelvis	Bladder	16.8	20.4	20.4	22.8	19.7	16.1	19.5	21.5	21.7	18.6
	Colon	13.9	16.9	16.9	19.4	17.3	8.1	9.8	10.8	11.0	9.5
	Gonads	13.4	17.9	18.0	29.6	37.2	8.3	9.9	10.7	10.3	8.1
	Lung	8.7	10.8	10.9	13.5	13.4	14.7	17.9	20.1	21.0	19.3
	Liver	14.4	17.7	17.7	21.2	20.0	14.0	16.9	18.5	18.4	15.4
Chest	Esophagus	8.4	10.8	12.5	12.1	10.5	8.3	10.6	12.1	11.5	9.1
	Liver	4.9	6.4	7.8	8.1	8.0	5.5	6.9	8.4	8.3	8.0
	Lung	10.2	13.5	16.3	17.1	17.1	10.3	13.7	16.7	15.6	14.5
	Thyroid	12.1	16.9	22.0	23.0	30.0	12.6	17.4	22.6	27.1	32.5
	Breast	-	-	-	-	-	8.3	10.8	12.9	13.2	12.3

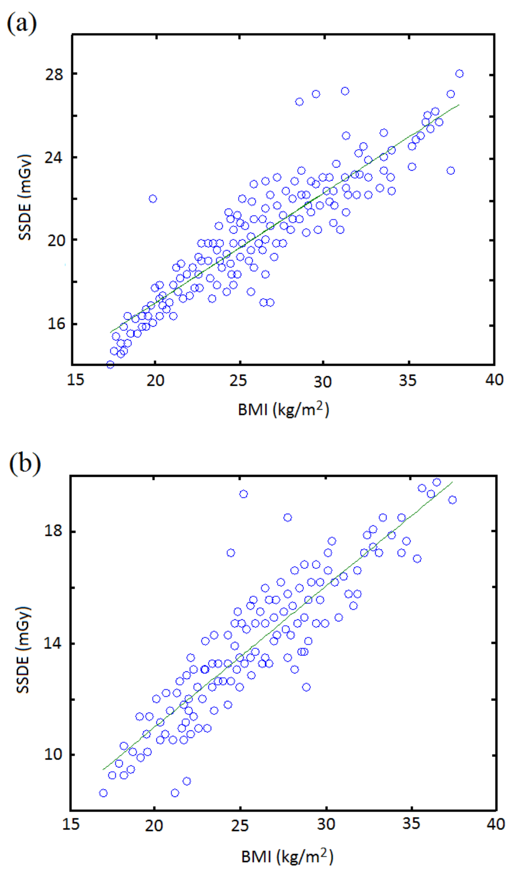

Figure 3. Scattergram and line regression for SSDE (mGy) versus BMI in abdomen-pelvis (a) and chest (b) CT examinations for both genders

A scattergram was plotted for assessment of the relationship between SSDE (mGy) and patient BMI (kg/m^2) in adult patients undergoing chest CT examinations (Figure 3). The relation function was regressed using MATLAB 2014 software. Equation 6 shows the relationship between the SSDE (mGy) and patient BMI (kg/m^2) in adult patients undergoing chest CT examinations.

$$\text{SSDE} = 0.5014\ \text{BMI} + 0.9435;\ R^2 = 0.79 \qquad (6)$$

4. Discussion

The results of the current study demonstrated that the changes in effective dose ranged from 14.03 to 28.05 mSv. Equation 1 was obtained for this variable, which shows the relationship between the effective dose and BMI in abdomen-pelvis CT examinations in adult men. In this regression, the coefficient of determination (R^2) is 0.8. Similarly, Equation 2 shows the relationship between the effective dose and BMI in adult women, with a coefficient of determination (R^2) of 0.78. An R^2 value close to 1.0 means a good correlation between the evaluated variables. In these Equations, R^2 ranges from 0.78 to 0.80 and this means a relatively good correlation between the effective dose and BMI. In addition, to estimate SSDE in abdomen-pelvis CT examinations, Equation 3 was obtained, which had a coefficient of determination of 0.80. In this regard, R^2 of 0.80 shows a relatively good correlation between the SSDE and BMI. Therefore, these three equations can be used to estimate the effective dose and SSDE in abdomen-pelvis CT examinations. The AAPM report recommends evaluating SSDE for each patient before performing CT scanning and using patient size and scan parameters to achieve diagnostic-quality CT images with the lowest possible radiation dose for patients [14, 15].

Khawaja *et al.* [22] reported that body weight is a more convenient and straightforward measure than the effective diameter for the estimation of SSDE for CT in pediatric patients. They further reported that evaluation of body diameters in clinical practice is inconvenient, time-consuming, and awkward. Moreover, especially without automated measurement methods, inter-observer variability was high. Since BMI is a composite measurement, which is obtained from both height and weight, it can also be used as a useful indicator of patient size parameters in place of effective diameter when estimating SSDE. Additionally, BMI, which is easily and routinely measured in clinical settings, is an objective measure with limited reported inter-observer variability or bias during the calculations [22]. Herein, for the first time in a population of more than 500 adult patients, relevant size metrics were evaluated and a strong correlation was observed between SSDE and effective diameter ($p < 0.001$) with BMI, demonstrating that BMI is an appropriate alternative to effective diameter for estimation of SSDE in abdomen-pelvis and chest CT examinations. A recent study by Alikhani *et al.* [23] demonstrated that fsize is significantly correlated with patient BMI in abdominal CT, and reported that exponential decreases in fsize values are associated with increasing BMI. The findings of the present study are consistent with these results in which BMI may be used as a surrogate for the evaluation of effective body diameter. The results of the present study indicated that effective dose and SSDE increase with increasing BMI in adult abdomen-pelvis CT examinations. The effective dose in women was always higher than that in men for the same scanning conditions and BMI. The effective dose increased from 8.8 to 17.2 mSv in women and from 8.4 to 16.8 mSv in men, and a nearly two-fold increase was observed in both groups with increasing

BMI. This finding is relatively consistent with that reported by Tahmasebi *et al.* who showed that effective dose increased with increasing BMI. However, in their study, the range of dose changes was lower and the doses themselves were in a lower range [24]. Nevertheless, the findings of the current study contradict those reported by Ware *et al.* [25]. In their study, the effective dose in the adult group remained nearly constant with increasing BMI.

To study the organ doses in abdomen-pelvis CT examinations, adult patients were classified into five categories according to the usual BMI classifications. Analysis with the ImPACT Dose software showed that doses to the organs at risk increased with increasing BMI in both men and women patients (Table 2). The ranges of radiation doses to the organs were consistent with those reported by Sadra and Sardary [20], who analyzed the results of direct dosimetry from a phantom. The increasing trend in accordance with increasing BMI was also consistent with the results reported by Israeli *et al.* [26], although the range of dose changes was higher than those in the current study. In other words, in that study, a wider dose range was observed compared to the results of this study.

The results of the current study showed increased calculated effective doses with increasing patient BMI. The doses increased from 4.1 to 9.4 mSv in the male group and from 2.6 to 9.6 mSv in the female group. Therefore, increased BMI showed an up to a 2.5-fold increase in effective dose. In this group of patients, with increasing BMI and effective dose, the SSDE also increased from 8.61 to 19.74 mGy. Equations 4-6 illustrate the relationship between the effective dose and SSDE with BMI. An R^2 value close to 1.0 means a good correlation between the evaluated variables. In these equations, R^2 ranges from 0.78 to 0.80 and this means a relatively good correlation between the effective dose and BMI and between the SSDE and BMI. By knowing the BMI, it is possible to estimate the effective dose and SSDE for chest CT examinations for male and female patients. The findings of the present study on the trend of increasing dose in proportion to increasing BMI are consistent with the results reported by Huda and Vance [27]. The dose values in their study which were obtained by using direct phantom dosimetry were lower than those calculated in this study. Based on the equations obtained from the dose calculations in equations number 4 and 5, there was a linear regression in the effective dose and BMI for men and women undergoing chest CT examinations. In Figure 3, the regression of a line on the data of SSDE versus BMI shows that equation number 6 also showed a relationship between SSDE and BMI in adult patients undergoing chest CT examinations.

The mean doses to the organs in chest CT examinations in adult men and women calculated for the five BMI categories using the ImPACT software showed an increasing trend with increased patient BMI (Table 2). This may be to the fact that with higher BMI, the amounts of primary and scattering radiations which are absorbed in the body organs are higher. This effect should be taken into account in the radiography of patients with higher BMI.

As a limitation in the present study, the number of adult patients with a high BMI was lower than that of patients with a lower BMI. This was due to the fact that the evaluated centers refused to perform imaging for patients with high BMI due to their device depreciation. Therefore, the number of samples in this BMI range was lower than that of patients with a lower BMI.

5. Conclusion

The results of the current study confirmed a relationship between the radiation dose to organs, SSDE, effective dose, and BMI of patients in CT. Therefore, since the evaluation of SSDE before performing CT is time-consuming and relatively difficult, this study reported equations including BMI for each of the correlations, which can be used to estimate the effective dose and SSDE based on the scan region and initial scan parameters.

Organs located in the scan region received higher radiation doses, while other organs received doses, which were associated with their distance from the scan region. In the abdomen-pelvis CT examination, the heart received a higher dose since it was close to the region of the beginning of the scanning.

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