Size-specific Dose Estimates for Adult Patients at CT of the Torso[1]

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Purpose: To determine relationships among patient size, scanner radiation output, and size-specific dose estimates (SSDEs) for adults who underwent computed tomography (CT) of the torso.

Materials and Methods: Informed consent was waived for this institutional review board–approved study of existing data from 545 adult patients (322 men, 223 women) who underwent clinically indicated CT of the torso between April 1, 2007, and May 13, 2007. Automatic exposure control was used to adjust scanner output for each patient according to the measured CT attenuation. The volume CT dose index ($CTDI_{vol}$) was used with measurements of patient size (anteroposterior plus lateral dimensions) and the conversion factors from the American Association of Physicists in Medicine Report 204 to determine SSDE. Linear regression models were used to assess the dependence of $CTDI_{vol}$ and SSDE on patient size.

Results: Patient sizes ranged from 42 to 84 cm. In this range, $CTDI_{vol}$ was significantly correlated with size (slope = 0.34 mGy/cm; 95% confidence interval [CI]: 0.31, 0.37 mGy/cm; $R^2 = 0.48$; $P < .001$), but SSDE was independent of size (slope = 0.02 mGy/cm; 95% CI: −0.02, 0.07 mGy/cm; $R^2 = 0.003$; $P = .3$). These R^2 values indicated that patient size explained 48% of the observed variability in $CTDI_{vol}$ but less than 1% of the observed variability in SSDE. The regression of $CTDI_{vol}$ versus patient size demonstrated that, in the 42–84-cm range, $CTDI_{vol}$ varied from 12 to 26 mGy. However, use of the evaluated automatic exposure control system to adjust scanner output for patient size resulted in SSDE values that were independent of size.

Conclusion: For the evaluated automatic exposure control system, $CTDI_{vol}$ (scanner output) increased linearly with patient size; however, patient dose (as indicated by SSDE) was independent of size.

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Larger patients require the use of more x-ray photons than do smaller patients to achieve similar levels of image quality in x-ray imaging modalities such as computed tomography (CT). Therefore, CT scanner manufacturers have implemented a variety of automatic exposure control (AEC) systems that adjust scanner output levels for individual patients (1–6). The amount of radiation a CT scanner delivers during an examination (ie, the radiation output) can be quantified by using the volume CT dose index ($CTDI_{vol}$), which allows measurement of the dose in an acrylic cylinder for a very specific set of conditions (7–10). $CTDI_{vol}$ is an internationally standardized measurement (11–13) and is displayed on the scanner console both before and after a scan is performed (11). $CTDI_{vol}$ is sensitive to changes in scan parameters, including tube potential, tube current, x-ray beam filtration, pitch, and gantry rotation time. Hence, $CTDI_{vol}$ can be used to compare the radiation output of different CT scanners and different scan protocols (9,10,14,15). However, because $CTDI_{vol}$ is a measurement only of scanner output, it does not include information about patient size and does not represent patient dose (10, 16)

Turner et al (17) showed that organ doses could be estimated from $CTDI_{vol}$ by multiplying $CTDI_{vol}$ by a size-dependent, scanner-independent factor. As an expansion of this work, a method to estimate patient dose that accounts for patient size was introduced in the American Association of Physicists in Medicine (AAPM) Report 204 in collaboration with the International Commission on Radiation Units and Measurements and the Image Gently campaign of the Alliance for Radiation Safety in Pediatric Imaging (16). By using multiple CT scanner models and including the four major CT manufacturers, four independent research groups evaluated dose as a function of size by using four different methods: measurements in tissue-equivalent torso-shaped phantoms or polymethyl-methacrylate cylindrical phantoms and Monte Carlo simulations in cylinders or voxelized patient models. Data for absorbed dose in the center of the scan region were normalized to $CTDI_{vol}$, combined among the four research groups, and fit to an exponential relationship as a function of size. Use of the tabulated size-dependent conversion factors (f_{size}), combined with a measurement of patient size, allows conversion from $CTDI_{vol}$ to the size-specific dose estimate (SSDE) (16) (Fig 1).

Patient dimensions such as anteroposterior (AP) thickness at the midline and lateral (LAT) width can be determined from the CT radiograph before the scan or from CT images after the scan. Once the patient size is determined, f_{size} can be found from the appropriate table in the AAPM Report 204 or computed from a mathematical equation (16).

The purpose of this retrospective study was to determine the relationships among patient size, scanner radiation output, and SSDE for adults who underwent CT of the torso at our institution.

Advances in Knowledge

- For CT examinations of the torso in 545 adults, 48% of the variation in the volume CT dose index ($CTDI_{vol}$) was due to patient size; the sum of anterioposterior plus lateral dimensions increased from 42 to 84 cm and the $CTDI_{vol}$ increased from 12 to 26 mGy.
- The mean size-specific dose estimate (SSDE), which considered patient size and scanner output ($CTDI_{vol}$), was 22 mGy ± 3 and did not depend on patient size; however, use of other automatic exposure control systems or settings may lead to a size dependence for SSDE.

Implications for Patient Care

- Both scanner output and patient size must be considered in the estimation of patient dose.
- In larger patients, increasing the scanner output to maintain adequate image quality does not necessarily increase the mean absorbed dose, relative to that of smaller patients scanned with lower scanner output levels.

Materials and Methods

Sample Selection

This institutional review board–approved, retrospective study was performed by using routine CT examinations of the torso performed in adults for clinical indications with patient waiver of informed consent. Data were retrieved from our institutional archive of examinations performed between April 1, 2007, and May 13, 2007.

Data included were from the first examinations performed each day, with a limit of three examinations per day for each examination type on each scanner. Under Minnesota state law, patients can prohibit the use of medical information for research purposes. Examinations were not included in this study for any such patients. Scans were of the entire torso (chest, abdomen, and pelvis) or the following subregions: chest and abdomen, abdomen, abdomen and pelvis, or pelvis.

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Abbreviations:
AAPM = American Association of Physicists in Medicine
AEC = automatic exposure control
AP = anteroposterior
CI = confidence interval
$CTDI_{vol}$ = volume CT dose index
f_{size} = size-dependent conversion factor
LAT = lateral
SSDE = size-specific dose estimate

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Conflicts of interest are listed at the end of this article.

See also the article by Brady and Kaufman and the editorial by Brink and Morin in this issue.

Figure 1

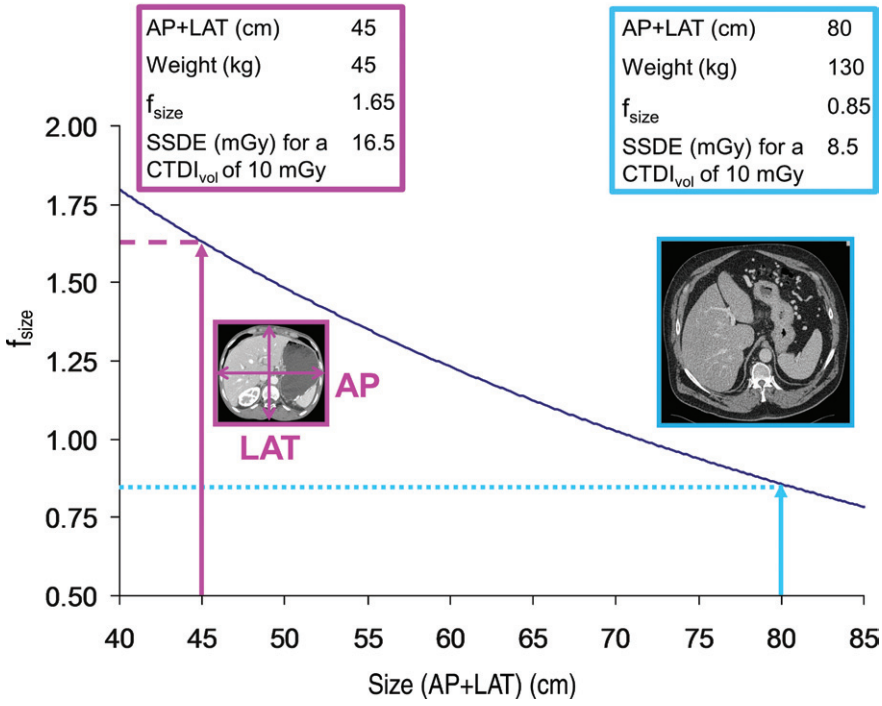

Figure 1: Graph shows how f_{size} was used to convert $CTDI_{vol}$ to SSDE, according to method in AAPM Report 204 (16). Size was determined by summing AP and LAT dimensions at the midline (AP+LAT), measured from transverse CT images at the mid-liver level. Sample calculations of SSDE from f_{size}, $CTDI_{vol}$, and AP+LAT are shown for small and large patients.

CT Scanners and Scan Parameters

Data were obtained from 11 CT scanners: Sensation 16 (n = 3), Sensation 64 (n = 6), and Definition (n = 2) (Siemens Healthcare, Forchheim, Germany). The scan protocols were all based on the manufacturer's routine abdomen protocol, and all used the same AEC system (CareDose 4D; Siemens Healthcare, Forchheim, Germany), which modulated tube current in the longitudinal and angular directions to adjust scanner output according to the attenuation for each patient at different tube positions (1–6). For this AEC system, the user specifies two parameters. The first is the effective tube current–time product (effective mAs) required to achieve the desired level of image quality for the specific diagnostic task in a reference patient (adults who weigh 70-80 kg). This value is called the quality reference effective mAs, where effective mAs is defined as the tube current–time product (mAs) divided by the pitch. The quality reference effective mAs values were either 240 or 250 for the studied examinations. The second user-specified parameter for the AEC system is the strength with which the tube current was adjusted as a function of patient size: weak, average, or strong (5,6). The same strength setting was programmed into each of the scanners and was used for all protocols. We used the average setting.

Data Collection and SSDE Determination

$CTDI_{vol}$ was calculated by the scanner by using the average tube current throughout the entire scan and was recorded for each scan series. For each patient, AP and LAT dimensions at the mid-liver level were measured from axial CT images by using digital calipers on the scanner console. These values were summed to obtain a single metric to represent patient size (AP+LAT). The AAPM Report 204 provides tables based on AP+LAT that are used to find the f_{size} that, when multiplied by $CTDI_{vol}$, yields SSDE. Alternatively, analytic expressions can be used to compute effective diameter and f_{size}:

$$\text{effective diameter} = \sqrt{(AP \cdot LAT)}, \quad (1)$$

$$f_{size} = a \cdot e^{-b \cdot (\text{effective diameter})}, \quad (2)$$

where a = 3.70 and b = 0.0367 (16). This approach was followed to compute f_{size} and SSDE according to equations 2 and 3 (16),

$$\text{SSDE} = f_{size} \cdot CTDI_{vol}. \quad (3)$$

Statistical Analysis

Mean, standard deviation, range, and fifth and 95th quantiles were computed for patient age, patient age by sex, AP+LAT, $CTDI_{vol}$, f_{size}, effective diameter, and SSDE. Means and standard deviations were also computed separately for AP and LAT. To characterize the patient population having f_{size} of approximately 1 (ie, 0.995–1.004), the means and standard deviations for AP, LAT, AP+LAT, effective diameter, and $CTDI_{vol}$ were calculated separately for this group.

Linear regression models were used to estimate separately the relationship of AP+LAT (independent variable) with both $CTDI_{vol}$ and SSDE (dependent variables). Each regression model was evaluated for fit by using standard residual diagnostics (ie, normal distribution and standardized residual predictor plots, graphical constant variance, partial linearity, leverage, and Cook's D). For SSDE as a function of size, we also used localized smoothing of the regression model by using the SAS procedure for localized estimation.

To account for heteroscedasticity (nonconstant variance of the residuals over the observed data range), the robust variance estimator (commonly called a "sandwich estimator," and using the HC_0 model) was used to provide heteroscedasticity-consistent estimates

of the model parameter standard errors (18).

For each model, the slope of the fitted line, along with its standard error (model-based for $CTDI_{vol}$ and robust for SSDE) and 95% confidence interval (CI) for the fit and for single observations, were estimated and graphed. To assess the magnitude of association, the squared coefficients of determination (R^2) were computed. A P value of less than .05 was considered to indicate a statistically significant difference. Statistical analyses were conducted by using SAS version 9.3 and JMP 9.0.1 (SAS Institute, Cary, NC).

Descriptive Statistics for Patients, CT Scanner Output, and SSDE

Statistic	Age (y)	Age of Women (y)	Age of Men (y)	AP+LAT (cm)	$CTDI_{vol}$ (mGy)	SSDE (mGy)
Mean	62	60	64	61.2	18.1	21.8
Standard deviation	15	16	14	7.4	3.7	3.4
Minimum	18	18	20	41.8	5.9	10.2
Maximum	98	93	98	84.2	26.7	31.1
Fifth quantile	33	28	35	48.3	11.5	15.6
95th quantile	84	83	85	72.4	23.5	27.2

Note.—Total number of patients was 545, with 223 women and 322 men.

Results

Population

For 545 adults, 322 men and 223 women (Table), the mean age was 62 years ± 15 (range, 18–98 years). AP+LAT was 61.2 cm ± 7.4 (range, 24–84 cm; AP, 27.0 cm ± 4.0; LAT, 34.2 cm ± 3.8) corresponded with a range of f_{size} of 1.74–0.80. The mean scanner output as indicated by $CTDI_{vol}$ was 18.1 mGy ± 3.7 and the mean SSDE was 21.8 mGy ± 3.4. There were 13 patients with an f_{size} of approximately 1.00 (range, 0.995–1.004). These patients had APs of 32.6 cm ± 1.3, LATs of 39.1 cm ± 1.6, AP+LATs of 71.7 cm ± 0.4, effective diameter of 35.7 cm ± 0.1; and equivalent $CTDI_{vol}$ and SSDE values (20.1 mGy ± 3.2).

Dependence on Patient Size

No significant deviations from regression assumptions were observed when modeling $CTDI_{vol}$ as the dependent variable. However, the modeling of SSDE as a linear function of patient size was somewhat less than optimal. Localized smoothing of the regression model suggested a piecewise linear model with points of inflection around 50 and 70 cm. Approximately 90% of the data were between these values, and the simple linear regression model and smoothed curve were essentially coincident in this range. For values outside this range, the linear model overestimated SSDE because the observed SSDEs for the extreme values were lower than those of the majority of observed values. The smoothed curve was within the 95% CI for the mean of the linear regression model throughout the entire range of observed values. Hence, the linear regression model, although not optimal in the entire range of the data, was chosen to model SSDE as a function of patient size.

Scanner output as indicated by $CTDI_{vol}$ was strongly dependent on patient size, but SSDE was not dependent on size (Fig 2). When $CTDI_{vol}$ was the dependent variable, a model consisting of only patient size had a slope of 0.34 mGy/cm (95% CI: 0.31, 0.37 mGy/cm; $P < .001$) and explained 48% of the variation in $CTDI_{vol}$ ($R^2 = 0.48$). SSDE did not statistically vary as a function of patient size (the linear regression model fit parameters were 0.02 mGy/cm; 95% CI: −0.14, 0.06 mGy/cm; $P = .2$). Patient size explained less than 1% of the variation in SSDE ($R^2 = 0.003$), supporting the conclusion that SSDE was independent of size.

Discussion

With the use of the AEC system and parameter settings used at our institution, patient size was strongly correlated with $CTDI_{vol}$. Thus, if $CTDI_{vol}$ was used as a surrogate for patient dose (rather than as a measure of scanner output), larger patients could appear to receive higher doses than smaller patients. However, $CTDI_{vol}$ alone does not measure patient dose; patient size must be taken into account (10,16). After patient sizes were considered and $CTDI_{vol}$ values were converted to estimates of patient dose (SSDE), the correlation between patient dose and patient size was eliminated.

These results are expected to be strongly dependent on the AEC system and settings used to adjust scanner output for patients of different sizes. For example, if scanner output were more aggressively increased with increased patient size (eg, to achieve lower levels of image noise in large patients than for the studied AEC system and settings), a positive correlation between SSDE and patient size might be observed. Previously, Israel et al (19) studied the relationship between $CTDI_{vol}$, dose, and patient size (weight) for a clinical population, but by using a different AEC system (smart mA, GE Healthcare, Milwaukee, Wis) with the user-selectable parameter noise index set to 11.5. Their results differed markedly from those of our study. They observed a stronger, essentially linear relationship between $CTDI_{vol}$ and size (slope = 0.66 mGy/kg; $R^2 = 0.82$). They also found that dose to the liver increased with an essentially linear relationship (slope = 1.2 mGy/kg; $R^2 = 0.66$), ranging from a dose of about 5 mGy for a 45-kg patient to about 40 mGy for a 130-kg patient. Thus, their estimate of patient dose was dependent on patient size. In a phantom study, Schindera et al (20), by using an AEC system similar to that of Israel et al, with a noise index of 12.5 and 15, observed that $CTDI_{vol}$ increased approximately 10 times, and dose at the position of the liver increased about five times when the phantom cross-section

Figure 2

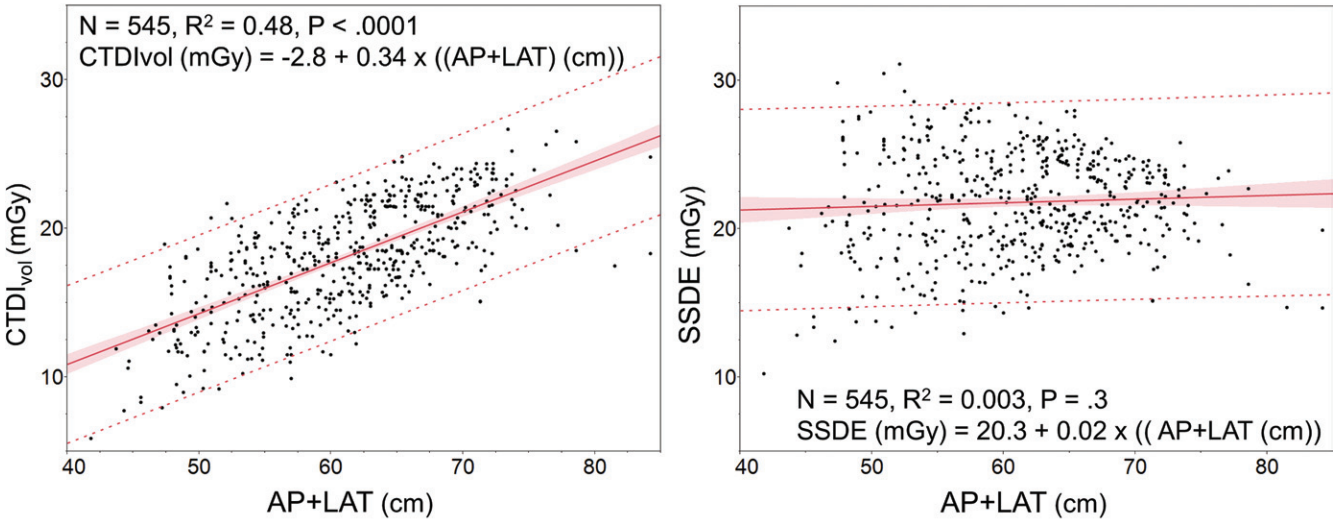

Figure 2: Scatterplots show **(a)** CT scanner output, as indicated by $CTDI_{vol}$, and **(b)** SSDE as function of patient size, which is indicated by sum of AP thickness and LAT width (AP+LAT). Data were from 545 adult patients who underwent CT scans of torso. All scans were performed by using the same AEC system and settings to adapt scanner output to changes in patient size. Simple linear regression models were used to fit each data set (solid line). 95% CIs are shown for fitted line (shaded region) and for individual values (dashed lines). Slope of line regressing $CTDI_{vol}$ against AP+LAT had 95% CI of 0.31 to 0.37 mGy/cm. Slope of line regressing SSDE against AP+LAT (which used robust variance estimator) had 95% CI of −0.02 to 0.07 mGy/cm.

was increased from small (18 × 22 cm) to oversized (34 × 38 cm). The increases both groups observed in organ dose as a function of patient or phantom size was determined by the behavior of the AEC system they studied, which attempts to maintain constant image noise for all patient sizes (2–4). This differs from the AEC used in our study, which, relative to adult patient size, requires lower noise values in children and allows higher noise values in obese adults (4,5,21).

The strength of the adjustment of scanner output for a change in patient size should be established by the user for the specific diagnostic task. Constant dose in all patient sizes is neither predicted nor demanded from the fundamental principles of x-ray attenuation and Poisson statistics, which underlie the relationships between the amount of x-rays required to form an image and the statistical variations of CT numbers observed in the image. Rather, acceptable diagnostic quality with the lowest reasonable dose for all patient sizes is required. Although our study did not explicitly determine diagnostic quality, on the basis of a decade of clinical experience with the AEC used in this study, we assumed that the criterion of acceptable diagnostic performance in different patient sizes was met. This assumption is one potential limitation to this study.

Variability in $CTDI_{vol}$ (variability in y) for a given patient size (specific x value) was observed because of the expected variability in patient body habitus and selected scan range. For a CT scan of the abdomen, if the scan range is extended in either the superior or inferior directions, additional tissues such as the lung or pelvic bones would be included in the scan. Including either type of tissue would change the $CTDI_{vol}$ value of the scan because the reported $CTDI_{vol}$ value is averaged throughout the entire scan length. Inclusion of more lung tissue would tend to decrease the reported $CTDI_{vol}$, whereas inclusion of the pelvis would tend to increase the reported $CTDI_{vol}$. Patient-to-patient variations are also expected because of differences in body habitus, for example, variations in the proportion of muscle to adipose tissue and the spatial distribution of body fat. Hence, for a properly functioning AEC system, $CTDI_{vol}$ is expected to differ, even for patients of the same AP+LAT dimension at the level of the mid liver, if the anatomy is thicker or thinner, or of different density or effective atomic number at other levels. After multiplying different $CTDI_{vol}$ values by the same f_{size}, the corresponding SSDE would also vary.

For a given patient size, the absolute variability of SSDE will not, in general, be the same as the variability of $CTDI_{vol}$ because f_{size} is a function of patient size. For patients with AP+LAT less than 72 cm, multiplying $CTDI_{vol}$ by an f_{size} greater than 1 will cause the variability in $CTDI_{vol}$ to be magnified for SSDE. For example, when AP+LAT is 50 cm, f_{size} is 1.5, so a difference in $CTDI_{vol}$ would be magnified by 50% after conversion to SSDE. Conversely, for large patient sizes, where f_{size} is less than 1, the variability in $CTDI_{vol}$ would be diminished after conversion to SSDE. As a result, for smaller-sized patients, converting to

SSDE appeared to increase rather than decrease variability compared with $CTDI_{vol}$. For data sets where the variability in y depends on the value of x, a property called heteroscedasticity, linear regression analysis could give misleading results because the assumption of uniform variation is violated. For this reason, the robust variance estimator, which is designed to account for nonuniform variance, was used to fit SSDE as a function of size. The parameter estimates (intercept and slope), R^2, and the analysis of variance table are the same when the robust variance estimator is used as when the simple linear regression model is used. The key change is for the standard error of the slope and intercept, which influence the CIs. For the fit of SSDE as a function of AP+LAT, when heteroscedasticity was appropriately accounted for, the 95% CI of the slope was −0.020 to 0.069 mGy/cm, which was slightly larger than if heteroscedasticity were ignored (95% CI: −0.014, 0.063 mGy/cm). If a greater range of patient sizes were studied (eg, from children to large adults), the influence of heteroscedasticity would correspondingly increase.

The purpose of this study was not to evaluate the SSDE metric, which has already been validated by the data reported in AAPM Report 204. The report states that, because patient size is included in the calculation of SSDE, SSDE gives a more meaningful estimate of patient dose, and therefore patient risk, than the value of $CTDI_{vol}$, which is currently saved in patient records. For a given value of $CTDI_{vol}$, SSDE is an estimate of the mean dose to the center of the scan volume for an object having similar attenuation characteristics as a given patient; it is not a direct measurement of dose to a specific patient. By implementing an automated measurement of patient size on scanners, SSDE could be automatically determined for each CT examination. An AAPM task group is currently developing a standardized technique to accomplish this.

Limitations of this study were that only adult patients were included, and only scanners from one manufacturer, and hence, only one AEC system, were evaluated. The diagnostic suitability of the images throughout different patient sizes was assumed, but not explicitly demonstrated. For some of the largest patients, the $CTDI_{vol}$ values may have been limited by the x-ray tube, and hence, may have been lower than those prescribed by the AEC algorithm. Neither risk nor organ doses were determined in this work. This is, in part, because uncertainties in available data make it difficult to estimate the risk associated with effective doses or organ doses below 100 mSv (22–24). SSDE provides an estimate of the average dose in the scan volume for a patient of a specific size and is a reasonable and simple way to estimate organ dose for relatively large organs located in the scan volume (16,17). However, for very small organs and organs only partially included in or located outside of the scan volume, SSDE will not provide a reasonable estimate of organ dose.

In summary, use of an AEC system to adjust scanner output for patient size in CT examinations of the torso resulted in a linear relationship between patient size and scanner output. After $CTDI_{vol}$ was converted to SSDE, dependence on patient size was no longer observed. For 545 adult patients who received CT examinations of the torso and who varied in size by a factor of two, the AEC system that was used increased $CTDI_{vol}$ from 12 to 26 mGy, but the average estimated patient dose (SSDE) was 22 ± 3 mGy, independent of size. This indicated that increasing the scanner output for larger patients will not necessarily increase the mean absorbed dose to these patients.

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