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Patient Size–Specific Analysis of Dose Indexes From CT Lung Cancer Screening

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Abstract

OBJECTIVE.—The U.S. Centers for Medicare & Medicaid Services (CMS) recently approved the use of low-dose CT for lung cancer screening and described volumetric CT dose index ($CTDI_{vol}$) requirements. These were based on the National Lung Screening Trial, which used only fixed-tube-current techniques. The aim of this study was to evaluate dose index data from a lung cancer screening program using automatic exposure control (AEC) techniques to ensure compliance with requirements and to correlate dose index values with patient size.

MATERIALS AND METHODS.—$CTDI_{vol}$, dose-length product (DLP), and body mass index (BMI) data were collected for 563 lung cancer screening examinations performed with AEC between January 1, 2014, through August 31, 2015. $CTDI_{vol}$ and DLP were analyzed according to the patient's BMI classification. Results were compared with the CMS requirement that the $CTDI_{vol}$ for a standard-sized patient (height, 170 cm; weight, 70 kg) be 3.0 mGy or less, with adjustments for patients of different sizes. For a subset of patients, the average water-equivalent diameter and size-specific dose estimate were estimated.

RESULTS.—The average $CTDI_{vol}$ for a standard-sized patient was 1.8 mGy, which meets CMS requirements. $CTDI_{vol}$ values were lower for smaller patients and higher for larger patients. Overall, the mean $CTDI_{vol}$ and DLP were 2.1 mGy and 74 mGy·cm, respectively. The size-specific dose estimate for the average water-equivalent diameter (27.5 cm) of the patient subset was 2.6 mGy.

CONCLUSION.—The screening protocols using AEC resulted in $CTDI_{vol}$ values that were compliant with CMS requirements. $CTDI_{vol}$ values greater than 3.0 mGy were only observed for overweight or obese patients.

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Keywords

low-dose CT; lung cancer screening; volumetric CT dose index

The U.S. Centers for Medicare & Medicaid Services (CMS) recently issued its final decision to approve the use of low-dose CT for lung cancer screening for appropriate high-risk patients [1]. Before that decision, the U.S. Preventive Services Task Force issued its recommendation that lung cancer screening with low-dose CT should be supported [2]. In addition, the American College of Radiology (ACR) and the Society of Thoracic Radiology released a joint practice parameter for the performance and reporting of lung cancer screening thoracic CT in 2014 [3] that provides guidance on indications, contraindications, specifications, interpretation, and reporting of the examination; documentation and communication of findings; and equipment specifications. The ACR also launched several programs related to lung cancer screening, including the designated lung screening centers program [4, 5], the lung cancer screening resources pages [6], and the Lung Cancer Screening Practice Registry [7], which is part of the ACR suite of registries under the National Radiology Data Registry [8]. In technical support of these programs, the American Association of Physicists in Medicine (AAPM) published a set of reasonable lung cancer screening CT scanning protocols for 27 different scanners from six different manufacturers [9].

These activities will lead to the further increase in the number of lung cancer screening examinations using CT. The persons eligible for lung cancer screening under the CMS decision are asymptomatic adults 55–77 years old with a 30-pack-year history of smoking (a pack-year is the product of the number of packs of cigarettes smoked per day and the number of years spent smoking). Because this is a screening procedure for asymptomatic adults, radiation doses should be kept as low as possible.

The CMS's decision and ACR's designated lung screening centers program both describe several requirements, including performing low-dose CT with a volumetric CT dose index ($CTDI_{vol}$) of 3.0 mGy or less for standard-sized patients (height, 170 cm [5 feet 7 inches]; weight, 70 kg [155 lb]; body mass index [BMI; weight in kilograms divided by the square of height in meters], 24.3) with appropriate reductions in $CTDI_{vol}$ for smaller patients and appropriate increases in $CTDI_{vol}$ for larger patients [1, 4]. These values are consistent with the radiation dose estimates provided for subjects scanned in the National Lung Screening Trial [10, 11]. The National Lung Screening Trial only used fixed-tube-current scans [12] because when that trial started in 2002, most CT scanners were not equipped with automatic exposure control (AEC) systems, such as tube current modulation. In current practice, AEC methods are widely available, and many of the AAPM protocols [9] describe the use of these methods. In addition, scanners that are compliant with the MITA XR-29 standard [13, 14] have AEC capabilities, and this is now required for full CMS reimbursement of scans beginning in January 2016 [14].

Although the use of AEC methods has been shown to adjust the scanner output according to patient size [15, 16], it is difficult to predict a specific scanner output value (e.g., $CTDI_{vol}$) for a given set of protocol parameters and a specific-sized patient until the scan

is actually performed (or at least until a CT scan radiograph has been performed on an individual patient). This is especially true in complex anatomy such as the chest, which has a tremendous amount of variation in attenuation from the shoulders to the mid lungs and then again to the lung bases (as illustrated by Angel et al. [15]). This leads to a variation in tube current across the scan that often has a range of at least a factor of 2 and can easily be a factor of 5 or 10 in individual patients, thus making it difficult to predict $CTDI_{vol}$ values for patients of a specific size for a specific set of scan parameters. ACR and CMS requirements do not specify conditions for assuring compliance, though the ACR lists $CTDI_{vol}$, dose-length product (DLP), and patient height and weight as required data elements in its registry [17] so that retrospective analyses may be performed.

To further investigate the effects of patient size, two additional parameters were calculated for a subset of patients who underwent lung cancer screening. Although BMI is a general indicator of patient size, it takes into account the entire patient weight and height, without regard to body shape or composition. The average water-equivalent diameter [18] is a size metric that takes into account the patient's attenuation, which does take into account composition, especially in the thoracic region, which contains the air-filled lungs. In addition, this metric can be calculated for only the region being scanned and thus is more specific to the patient's thoracic anatomy. The size-specific dose estimate [19] is a dose metric that takes patient size into account.

Therefore, the motivations for this study were to investigate scanner output values ($CTDI_{vol}$) when AEC methods were used and to confirm that the parameter settings suggested by the current AAPM protocols do indeed result in scanner output values that are compliant with the ACR and CMS requirements. For this investigation, we examined the scanner output values from our low-dose lung cancer screening protocols, which also use AEC in the form of tube current modulation. The specific aims of this study were to evaluate CT dose indexes for the lung cancer screening program and to determine whether requirements were being met and to compare and correlate screening CT dose indexes against metrics that describe patient size.

Materials and Methods

Data Collection

Institutional review board approval was obtained from the University of California for the use of the retrospective collection of CT dose information from which identifying information had been removed. $CTDI_{vol}$ and DLP data and patient size (height and weight) data to calculate BMI were retrospectively collected for patients who underwent lung cancer screening examinations. These examinations were performed on one of six CT scanners (Sensation 64, Definition, Definition AS40, Definition AS64, Definition Flash, and Force, all from Siemens Healthcare) from January 1, 2014, through August 31, 2015, at our outpatient facilities. X-ray dose management software (Radimetrics, Bayer HealthCare) was used to mine the CT dose indexes and patient BMI data.

$CTDI_{vol}$ and DLP values were analyzed on the basis of the patient's BMI classification, as described in the AAPM protocols [9], in which the underweight group was BMI less

than 18.5, normal weight was BMI of 18.5–24.9, overweight was BMI of 25.0–29.9, and obese was BMI of 30.0 or more. All results were compared with the Medicare requirements ($CTDI_{vol} \leq 3.0$ mGy for a standard-sized patient, as described in the introduction, with appropriate reductions for smaller patients and increases for larger patients). This approach also allowed us to verify that reductions in $CTDI_{vol}$ occurred for smaller patients and that increases in $CTDI_{vol}$ occurred for larger patients.

To further investigate the effects of patient size, two additional parameters (water-equivalent diameter and size-specific dose estimate) were calculated for a subset of patients who underwent lung cancer screening on one of two CT scanners (Sensation 64 and Definition AS64). The average water-equivalent diameter for all slices within scan range was calculated from x-ray attenuation information contained in the DICOM header of the posterior-anterior CT localizer radiograph (topogram) performed for each patient before the CT scan; this information is extracted as described elsewhere [20]. The size-specific dose estimate was calculated by multiplying the recorded $CTDI_{vol}$ by a conversion factor based on the calculated average water-equivalent diameter [18, 19].

Scan Protocol

Lung cancer screening protocols for each CT scanner are shown in Table 1. All examinations used tube current modulation (Care Dose 4D, Siemens Healthcare) with the average strength setting. All scans performed on the Sensation 64 and Definition scanners used protocols consistent with those from the AAPM lung cancer screening guidelines [9], including an image quality reference parameter of 25 mAs along with 120 kV, 0.5-second rotation time, and pitch of 1.0. All examinations used a beam collimation of 64 × 0.6 mm except for the Definition AS40, which used 40 × 0.6 mm. All CT images were reconstructed with conventional filtered back projection kernels; iterative reconstruction methods were not used in these cases.

For the Definition Force scanner, the AAPM protocols were also followed and therefore the 100 kV with tin (Sn) filter was used with 150 Quality Reference mAs (Siemens Healthcare), 0.25-second rotation time, pitch of 1.0, and 192 × 0.6 mm collimation. All CT images were also reconstructed with filtered back projection. It should be noted that because of the lower kilovoltage and additional filtration capabilities offered by this scanner, the expected $CTDI_{vol}$ values for a standard-sized patient were substantially lower than the other scanners (0.5 mGy compared with approximately 2.0 mGy for other scanners).

Statistical Analysis

Statistical analysis was conducted using SPSS software (version 22.0, IBM SPSS). One-way ANOVA followed by the Tamhane T2 test was performed to indicate statistical significance in $CTDI_{vol}$ between BMI groups. A $p < 0.05$ was considered to indicate statistical significance.

Results

CT lung cancer screening examinations were performed for 563 patients during the study period. The patient size ranged from BMI of a minimum of 15 (underweight) to 55 (obese).

Figure 1 shows $CTDI_{vol}$ for the patients as a function of BMI. This figure shows that the $CTDI_{vol}$ for standard-sized patients (BMI of 24.3) was 1.8 mGy, which is well below the ACR and CMS limit of 3.0 mGy. The figure shows that the BMI where $CTDI_{vol}$ was greater than 3.0 mGy was 26.3. This figure also confirms that, as expected, there are reductions in $CTDI_{vol}$ for patients with lower BMIs and increases in $CTDI_{vol}$ for patients with larger BMIs. The mean (± SD) dose indexes for the entire dataset were $CTDI_{vol}$ of 2.1 ± 0.8 mGy (range, 0.5–6.0 mGy) and DLP of 74 ± 27 mGy·cm (range, 17–202 mGy·cm).

Figure 2 shows box plots of $CTDI_{vol}$ and DLP categorized according to patient's BMI. The $CTDI_{vol}$ values by BMI were 1.4 ± 0.2 mGy for underweight (BMI < 18.5; $n = 24$), 1.7 ± 0.4 mGy for normal weight (BMI, 18.5–24.9; $n = 219$), 2.1 ± 0.5 mGy for overweight (BMI, 25.0–29.9; $n = 185$), and 2.9 ± 0.8 mGy for obese (BMI ≥ 30.0; $n = 135$) patients. There were statistically significant differences in the $CTDI_{vol}$ between all groups ($p < 0.05$).

To further investigate the influence of patient size, we calculated the water-equivalent diameter in the thoracic region and then the corresponding size-specific dose estimate for a subset of 28 patients for whom these data were available. Figure 3A shows the $CTDI_{vol}$ value as a function of water-equivalent diameter for this subset of patients; this is similar to Figure 2 except that the *x*-axis uses a descriptor of patient size that is specific to the lung region and accounts for attenuation (water-equivalent diameter) rather than BMI, which is based on the entire body and is not specific to the thorax. Figure 3B extends this by showing the size-specific dose estimate as a function of water-equivalent diameter for that subset of patients. The average water-equivalent diameter for this patient subset was 27.5 cm, and the $CTDI_{vol}$ and size-specific dose estimate for the water-equivalent diameter were 1.9 mGy and 2.6 mGy, respectively. It should be noted that CMS did not specify $CTDI_{vol}$ as a function of water-equivalent diameter, so there is no specific $CTDI_{vol}$ limit for a given water-equivalent diameter value, nor is there a size-specific dose estimate limit.

Discussion

Similar to the ACR's designated lung screening center criteria [4], the CMS defines eligibility criteria for radiologic imaging facilities that perform lung cancer screening with low-dose CT, stating that the facility must perform low-dose CT with a $CTDI_{vol}$ of 3.0 mGy or less for standard-sized patients, with appropriate reductions in $CTDI_{vol}$ for smaller patients and appropriate increases in $CTDI_{vol}$ for larger patients [1]. These programs did not describe a method to ensure that the $CTDI_{vol}$ target values were being met for a standard-sized patient. Although this is straightforward for fixed-tube-current protocols, as used in the National Lung Screening Trial, it is not straightforward when AEC methods are used because the scanner output (i.e., $CTDI_{vol}$ value) is dependent on the protocol and patient anatomy. Although the AAPM protocols [9] represent a reasonable set of acquisition and reconstruction parameters for each scanner, to date and to our knowledge, there has been no verification that these protocols would meet the ACR and CMS criteria. The results of this study did show that, for the scanning parameters selected including the use of AEC, the $CTDI_{vol}$ for a standard-sized patient was 1.8 mGy, which is well below the threshold value. This study also showed that using a tube current modulation method such as Care Dose 4D

allowed the $CTDI_{vol}$ values to be reduced for smaller patients and to be increased for larger patients. It should be noted here that the $CTDI_{vol}$ values are not patient dose [21].

The results also show that a total of 49 patients (approximately 9% of collected data) had $CTDI_{vol}$ greater than 3.0 mGy; this only occurred for overweight and obese patients. In addition, the smallest BMI where $CTDI_{vol}$ was greater than 3.0 mGy was 26.3 kg/m^2. Patient size was strongly correlated with $CTDI_{vol}$, and the use of tube current modulation resulted in an increase in $CTDI_{vol}$ for patients with larger BMI, whereas patients with smaller BMI had a lower $CTDI_{vol}$.

Figure 1 shows some variation in the $CTDI_{vol}$ data, even for patients of the same size; further investigation revealed some interesting observations, which are described here. Figure 4 shows the same data as Figure 1 ($CTDI_{vol}$ vs patient BMI), but two specific groups are highlighted. The first highlighted group includes $CTDI_{vol}$ values from patients scanned on the Force using 100 kV with an Sn filter. These parameters were suggested by the AAPM protocols and were expected to yield lower $CTDI_{vol}$ values than other scanners because of the use of additional Sn filtration, which hardens the x-ray spectrum and eliminates lower-energy photons that would be completely absorbed by the patient's body. Figure 4 shows that the $CTDI_{vol}$ values were consistently lower than those of other scanners used in this study. Although a systematic study was not performed, the radiologists at our institution were asked to review the image quality from these scans, and they found it to be acceptable for lung cancer screening. One other case of interest is illustrated in Figure 4, which was a case performed on the Definition AS scanner and resulted in $CTDI_{vol}$ values much greater than those for other patients of a comparable patient size. On review of the image data, it was determined that the patient could not raise their arms over their head, so the scans were performed with the arms down, resulting in a substantial increase in the scanner output as reflected in the increased $CTDI_{vol}$ value. A very similar observation has been reported elsewhere by Angel et al. [15].

It should be noted that the ACR designated lung screening center program [4] provides technical specifications that includes some requirements (e.g., $CTDI_{vol} \leq 3.0$ mGy as consistent with CMS requirements) but also includes some recommendations on scanning parameters such as kilovoltage. Although the use of a particular kilovoltage value is not a requirement, the ACR recommends a range of kilovoltage values (100–140 kV) for a standard-sized patient. It also adds a comment in its technical specifications that the kilovoltage should be set in combination with the tube current–time product setting to meet the $CTDI_{vol}$ specifications. In our study, 120 kV was fixed for all scanners except for the Force (Table 1). For the Force, the kilovoltage used was the one recommended by the AAPM protocols (100 kV with the additional Sn filtration); in addition, tube current modulation (Care Dose 4D) was used with 150 Quality Reference mAs, and our results showed that this allowed our examinations to meet the $CTDI_{vol}$ requirements for a standard-sized patient. Therefore, the ACR and CMS requirements on $CTDI_{vol}$ were met with these kilovoltage and quality reference tube current–time product settings for the Force scanner. A few examples of lung cancer screening examinations from the Force for patients of different size are presented in Figure 5; these illustrate the level of image quality provided at the doses described.

Although size-specific dose estimate is not yet widely reported, some preliminary estimates of size-specific dose estimate values as a function of their water-equivalent diameter were explored and plotted in Figure 3B. As described earlier in this article, size-specific dose estimate takes into account the size of the patient and provides a more accurate reflection of dose to the center of the scan volume. For this subset of patients, the size-specific dose estimate for the average water-equivalent diameter of 27.5 cm for a subset of patients was 1.4 times larger than the $CTDI_{vol}$. Although the exact shape of the size-specific dose estimate curve versus the water-equivalent diameter curve is not the same as that for $CTDI_{vol}$ versus BMI, there are similarities in that both size-specific dose estimate and $CTDI_{vol}$ increase with patient size (though at different rates). Although size-specific dose estimate does take into account patient size, the shape of the size-specific dose estimate curve versus the water-equivalent diameter curve will be primarily governed by the AEC adjustment curve in the scanner itself. That is, the goal of any AEC scheme is not to produce a constant size-specific dose estimate across patient sizes, but rather to achieve a relatively constant image quality across patient size and attenuation (i.e., constant noise or some other description of image quality). Therefore, the shape of the size-specific dose estimate curve versus the water-equivalent diameter curve depends on the schematic goals of the AEC system as designed by the scanner manufacturer.

It should be noted that, although AAPM reports 220 and 204 [18, 19] have described water-equivalent diameter and size-specific dose estimate, respectively, and methods to calculate them, those values are not yet readily available on CT scanners. However, there are methods to estimate these values, and some dose-tracking software packages are including estimates of size-specific dose estimate. These values are reported here as a means of obtaining some experience for the future, when these parameters will be more readily available from the scanners and methods to calculate them will be reasonably well standardized.

There are a few limitations to our study. One is that this study was performed with CT scanners from one vendor only. Although it is very likely that AAPM-recommended settings will lead to similar results with systems from other vendors, it cannot be concluded from this study. Another is that this study focused on dose metrics in the screening program and did not systematically assess the image quality aspects of the protocols used. Although a review was conducted with our radiologists, and they concluded that the image quality was in general adequate for screening purposes, this review was limited and could be investigated further.

Conclusion

This study showed that the CT dose indexes values from a lung cancer screening program using protocol parameters based on the AAPM protocols and incorporating AEC techniques were able to meet the ACR and CMS requirements. This study also showed the effects of patient size on scanner output metrics, especially when AEC techniques were used. The patients with larger BMI receive higher $CTDI_{vol}$, but values greater than 3.0 mGy only occurred for a small subset (9% of total) of larger patients (overweight and obese by BMI definitions), as would be expected. $CTDI_{vol}$ categorized according to patient size, as well as

size-specific dose estimate, will provide more useful dose information for individual patients in the future.

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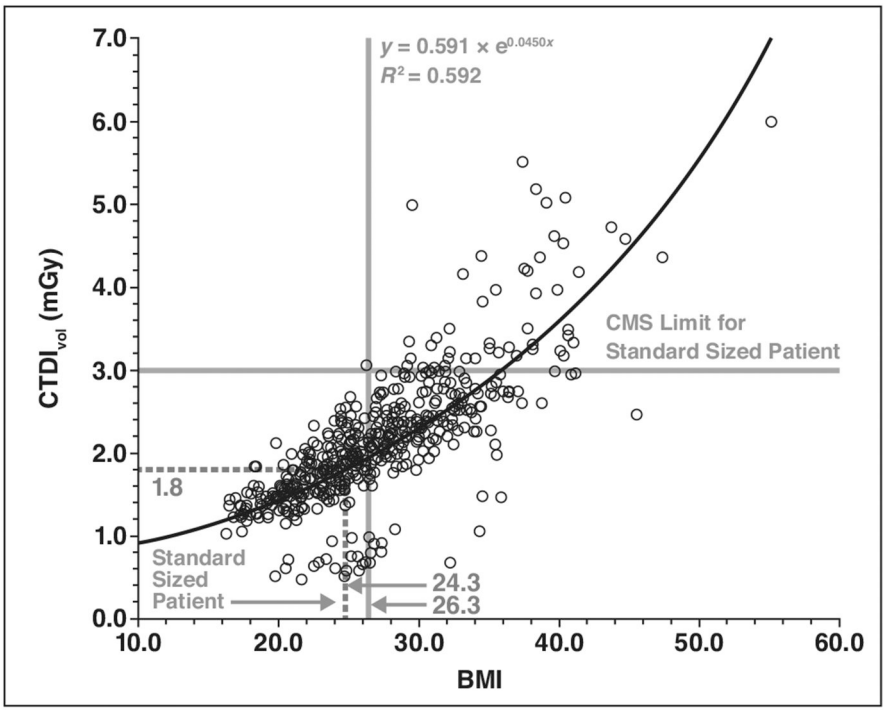

Fig. 1—.

Volumetric CT dose index ($CTDI_{vol}$) for patients as function of body mass index (BMI; weight in kilograms divided by square of height in meters). Centers for Medicare & Medicaid Services (CMS) limit is 3.0 mGy $CTDI_{vol}$ for standard-sized patient (height, 170 cm [5 feet 7 inches]; weight, 70 kg [155 lb]). Dashed line shows that, for standard-sized patient, BMI is 24.3 and average $CTDI_{vol}$ is 1.8 mGy (much lower than CMS limit). Vertical line shows BMI where $CTDI_{vol}$ was greater than 3.0 mGy, which was 26.3.

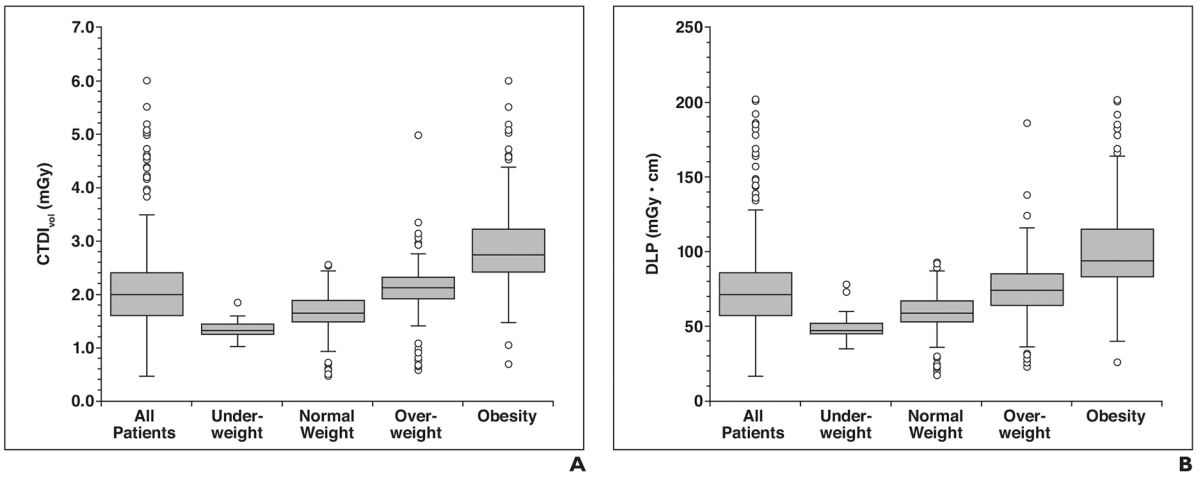

Fig. 2—. Volumetric CT dose index ($CTDI_{vol}$) and dose-length product (DLP) according to patient's body mass index (weight in kilograms divided by square of height in meters).

A and **B,** Box plots show $CTDI_{vol}$ (**A**) and DLP (**B**) by patient weight group. Outliers are shown as individual point (*circles*). Horizontal lines within boxes denote medians, and vertical lines and whiskers denote 95% CIs.

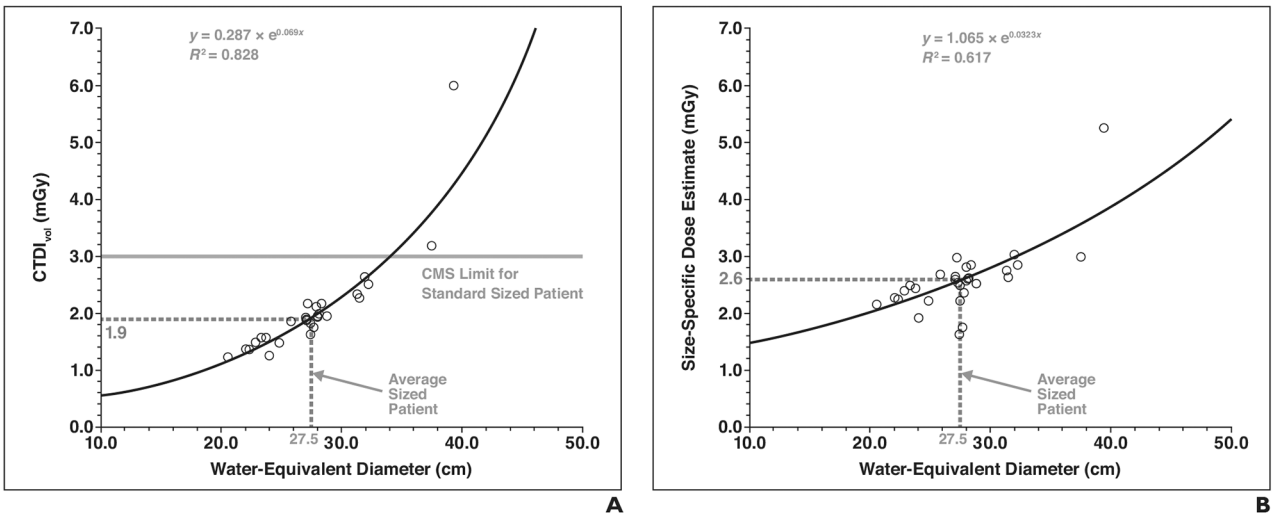

Fig. 3—. Volumetric CT dose index ($CTDI_{vol}$) and size-specific dose estimate as function of water-equivalent diameter.

A and **B,** Graphs show $CTDI_{vol}$ (**A**) and size-specific dose estimate (**B**). $CTDI_{vol}$ of 3.0 mGy is Centers for Medicare & Medicaid Services (CMS) limit for standard-sized patient (average water-equivalent diameter for subset is 27.5 cm).

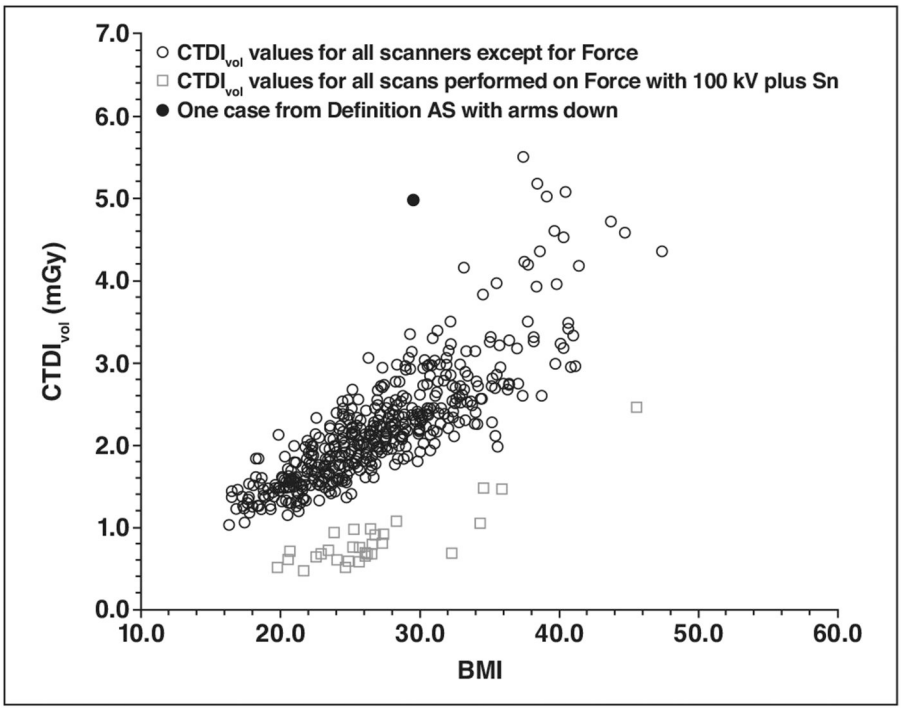

Fig. 4—.

Volumetric CT dose index ($CTDI_{vol}$) for patients as function of body mass index (BMI; weight in kilograms divided by square of height in meters). Open circles represent $CTDI_{vol}$ values for all scanners except for Force (Siemens Healthcare), and solid circle shows one case from Definition AS (Siemens Healthcare) with patient arms down. Squares represent $CTDI_{vol}$ values for all scans performed on Force scanner with 100 kV and tin (Sn) filtration.

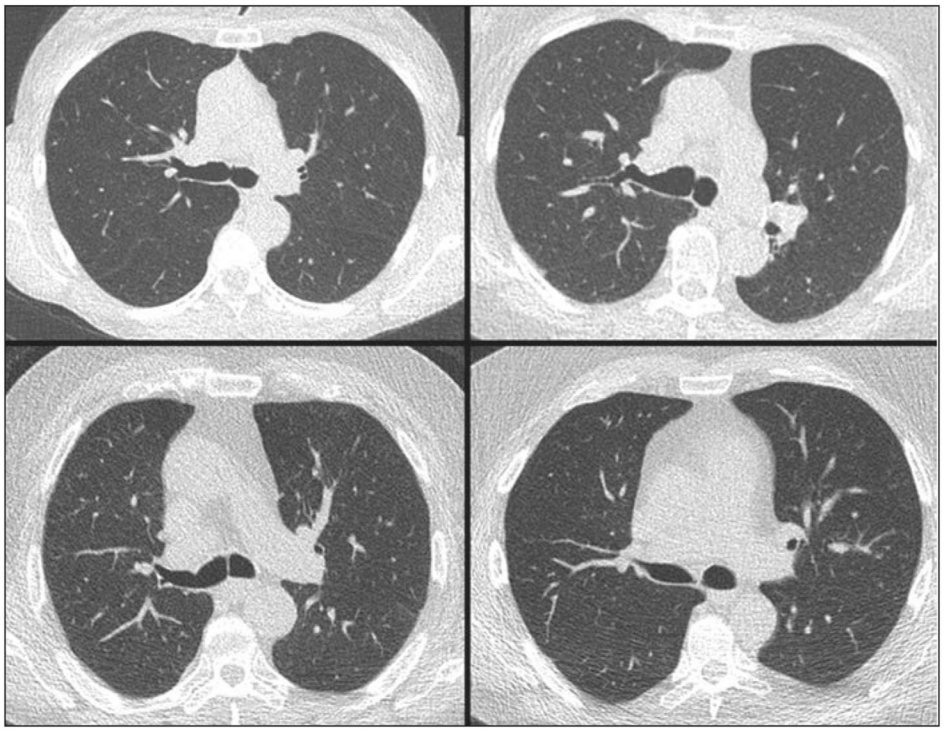

Fig. 5—.

Example images from CT lung cancer screening from Force scanner (Siemens Healthcare) using 100 kV with tin filtration and 150 Quality Reference mAs (Siemens Healthcare). Upper left shows patient with water-equivalent diameter of 28.4 cm (volumetric CT dose index [$CTDI_{vol}$], 0.59 mGy; dose-length product [DLP], 24.2 mGy·cm), upper right shows patient with water-equivalent diameter of 33.1 cm ($CTDI_{vol}$, 1.00 mGy; DLP, 37.7 mGy·cm), lower left shows patient with water-equivalent diameter of 36.4 cm ($CTDI_{vol}$, 1.22 mGy; DLP, 45.0 mGy·cm), and lower right shows patient with water-equivalent diameter of 38.4 cm ($CTDI_{vol}$, 2.1 mGy; DLP, 75.0 mGy·cm).

TABLE I:

Lung Cancer Screening Protocols for Various CT Scanners

Parameter	Sensation 64	Definition	Definition AS40	Definition AS64	Definition Flash	Force
Tube voltage (kV)	120	120	120	120	120	100 (with tin filtration)
Rotation time (s)	0.5	0.5	0.5	0.5	0.5	0.25
Pitch	1.0	1.0	1.0	1.0	1.0	1.0
Quality Reference mAs (Siemens Healthcare)	25	25	25	25	25	150
Detector configuration (mm)[a]	64 × 0.6	64 × 0.6	40 × 0.6	64 × 0.6	64 × 0.6	192 × 0.6
Nominal physical collimation (mm)	32 × 0.6	32 × 0.6	20 × 0.6	32 × 0.6	32 × 0.6	96 × 0.6

Note—All scanners were manufactured by Siemens Healthcare.

[a]On all scanners, a *z*-axis flying focal spot technique is used to obtain twice as many projections per rotation as detector rows.

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