Automated Estimation of Abdominal Effective Diameter for Body Size Normalization of CT Dose

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Abstract Most CT dose data aggregation methods do not currently adjust dose values for patient size. This work proposes a simple heuristic for reliably computing an effective diameter of a patient from an abdominal CT image. Evaluation of this method on 106 patients scanned on Philips Brilliance 64 and Brilliance Big Bore scanners demonstrates close correspondence between computed and manually measured patient effective diameters, with a mean absolute error of 1.0 cm (error range +2.2 to −0.4 cm). This level of correspondence was also demonstrated for 60 patients on Siemens, General Electric, and Toshiba scanners. A calculated effective diameter in the middle slice of an abdominal CT study was found to be a close approximation of the mean calculated effective diameter for the study, with a mean absolute error of approximately 1.0 cm (error range +3.5 to −2.2 cm). Furthermore, the mean absolute error for an adjusted mean volume computed tomography dose index (CTDI_{vol}) using a mid-study calculated effective diameter, versus a mean per-slice adjusted CTDI_{vol} based on the calculated effective diameter of each slice, was 0.59 mGy (error range 1.64 to −3.12 mGy). These results are used to calculate approximate normalized dose length product values in an abdominal CT dose database of 12,506 studies.

Keywords Computed tomography · Radiation dose · Body imaging · Quality control · Image analysis

Introduction

Computed tomography (CT) has become one of the most common diagnostic modalities for evaluating disease processes in the abdomen. However, there has been increasing concern

regarding radiation dose levels from CT scans. As a result, there has been considerable interest in collecting and analyzing dose data reported from CT scanners. Several projects have focused on automated collection of CT dose information from the scanners or PACS to allow for detection of dose outliers and informed modification of imaging protocols [1–4].

However, CT dose is currently reported in terms of scanner radiation output related to energy imparted to a reference phantom, typically a 32-cm diameter phantom in adult body imaging [5]. As a result, CT dose to a small patient (i.e., a patient with an average diameter less than 32 cm) may be underestimated. In particular, without adjusting dose data for body size, excessive radiation dose in small patients may be difficult to detect in a large dose database.

In 2011, the American Association of Physicists in Medicine (AAPM) Task Group 204 described a method for adjusting volume computed tomography dose index (CTDI_{vol}) values based on the effective diameter of the patient, where effective diameter is defined as the diameter of the circle whose area is the same as the patient cross section [6]. Effective diameter can be calculated manually as the geometric mean of the lateral and anterior-posterior dimensions of the patient, assuming an elliptical patient cross section. However, manual measurement of these dimensions for each patient is laborious and not practically feasible for a large dose database.

In this report, we describe a method for automated calculation of effective diameter, based on reconstructed axial CT images. We also describe a process for approximating a dose length product normalized for body size using calculated effective diameters.

Materials and Methods

A simple algorithm for estimating the body size diameter on an axial CT slice was implemented in Python and C#. For a given image slice, we determined the number of pixels

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whose Hounsfield unit (HU) value exceeded a set threshold. This count was multiplied by the area of a single pixel to give an estimate of the area of the patient cross section. The effective diameter was then computed as the diameter of the circle whose area is the same as that of the cross section (Fig. 1). In particular, the estimated effective diameter D is given by the following equation:

$$D = 2 \cdot \sqrt{\frac{\sum_{\{HU(p) > t\}} p_x p_y}{\pi}} \quad (1)$$

where p_x and p_y are the x and y dimensions of a single pixel, and $\{HU(p) > t\}$ is the set of all pixels p where the Hounsfield unit value exceeds the threshold t . A preliminary evaluation demonstrated abdominal diameters calculated in this manner to be relatively constant for variations in the threshold t from -800 to -200 HU (Fig. 2). A threshold t of -500 HU was chosen for subsequent analysis.

Institutional Review Board approval was obtained for the data collection and analysis in this study. A retrospective test set of 106 consecutive patients receiving CT abdomen or CT abdomen and pelvis exams on either a Philips Brilliance 64 ($n=103$) or Philips Big Bore ($n=3$) scanner was studied. For each patient study, the middle slice of the longest image series (hereafter referred to as the “mid-study slice”) was selected as a representative cross section. The lateral and anterior-posterior dimensions of the cross section were measured manually on PACS by an abdominal radiologist; the effective diameter was computed from these measurements. This measurement was then compared to the results of the automated algorithm described above applied to the same image slice.

In order to evaluate the generalizability of Eq. 1 across different scanner manufacturers and couch types, we studied 60 additional patients who underwent CT abdomen or CT abdomen and pelvis exams on other scanners. These 60 patients were divided across three CT scanners (20 patients each): a Toshiba Aquilion 64 scanner, a Siemens Sensation 10 scanner, and General Electric LightSpeed 16 scanner. The calculated effective diameter of the mid-study slice was compared to manual measurements.

In order to evaluate variation of patient diameter along the length of the scan, the algorithm was applied to each slice of each of the 106 patients in the Philips data set, and the average of the measurements was compared to the manual measurement for the mid-study slice. In addition, manual measurements for all 106 patients were also performed at a fixed anatomic point, the origin of the superior

Fig. 1 Schematic illustration of the effective diameter calculation method. **a** Mid-study slice from a CT of the abdomen and pelvis. **b** Pixels in (a) exceeding threshold value of -500 HU are colored white, with remaining pixels colored black. **c** Circle with area equivalent to the total area of white pixels in (b). The estimated effective diameter is the diameter of this circle

mesenteric artery (SMA) from the aorta, or “SMA-effective diameter.”

For each study, we then computed an adjusted mean $CTDI_{vol}$ by multiplying each slice $CTDI_{vol}$ by a normalization dose coefficient derived from the calculated effective

Fig. 2 Variation of calculated effective diameters as a function of Hounsfield unit threshold on mid-study slices of three CT examinations of the abdomen and pelvis for representative large, medium, and small patients. Note the relatively flat plateau between -800 and -200 HU

diameter of that slice, using exponential Eq. A-1 in Appendix A of AAPM Report 204, i.e.:

$$y = a \cdot e^{-bx} \quad (2)$$

where y is a normalized dose coefficient; x is the effective diameter; $a=3.704$, and $b=0.03672$ [6]. We compared these values to an approximate mean CTDI_{vol} obtained by multiplying the mean CTDI_{vol} by a normalization dose coefficient derived from the calculated effective diameter of the mid-study slice. In all patients, CTDI_{vol} values reported by the scanner were with respect to a 32-cm diameter body phantom.

Finally, we performed the automated body size calculation on a set of 12,506 CT abdomen studies in our CT dose database, accumulated with our DoseRetriever system, using the middle image of the longest series of the study. We then multiplied the dose length product (DLP) of each study by the normalization dose coefficient derived from Eq. 2 above.

Results

The mean age for the main data set of 106 patients scanned on Philips Brilliance 64 or Brilliance Big Bore scanners was 61 years (range 21 to 93 years, standard deviation (SD)=14.9), and mean BMI was 26.2 kg/m^2 (range 12.5 to 48.6 kg/m^2 , $\text{SD}=6.0$). Of these patients, 29 had CT scans of the abdomen only, while 77 had CT scans of the abdomen and pelvis.

As noted above, the effective diameters were initially calculated using a Hounsfield unit threshold of -500 HU. However, to evaluate the variability of the calculated

effective diameter with respect to this chosen threshold, effective diameters for all 106 patients were also calculated using thresholds of -700 and -300 HU. The effective diameters calculated using a -700 HU threshold exceeded the effective diameters calculated using a -500 HU threshold by an average of 0.4 cm (maximum 0.9 cm). The effective diameters calculated using a -500 HU threshold, in turn, exceeded the effective diameters calculated using a -300 HU threshold by an average of 0.3 cm (maximum 0.5 cm). For the remainder of this work, a threshold value of -500 HU is used.

Correlation between the manual and automated measurements of effective diameter was very high. Comparing the measurements, the root mean square error was 1.1 cm , and the mean absolute error was 1.0 cm (error range $+2.2$ to -0.4 cm), with most automated measurements slightly higher than the manual measurements (Fig. 3).

The degree of correspondence between automated and manual measurements was preserved across scanner manufacturers. On evaluation of the 60 patients on Siemens Sensation 10, GE LightSpeed 16, and Toshiba Aquilion 64 scanners, the root mean square error of automated measurements compared to manual measurements was 0.83 cm , with a mean absolute error of 0.70 cm (error range $+1.5$ to -1.3 cm).

The deviation of the calculated effective diameter at the mid-study slice from the average calculated effective diameter over all the slices in the study is shown in Table 1. For comparison, we also computed the deviation of a measured effective diameter at a fixed anatomic level (the level of the superior mesenteric artery origin from the aorta) from the average calculated effective diameter over all the slices in the study, shown in Table 2.

Fig. 3 Comparison of calculated and measured effective diameters for mid-study slices of 106 CT examinations of the abdomen and pelvis. Line of identity is plotted

Table 1 Comparison of calculated diameter in mid-study slice versus mean calculated diameter for all slices

	RMSE (cm)	MAE (cm)	Error range (cm)
Abdomen and pelvis ($n=77$)	1.3	1.0	3.5 to -2.2
Abdomen only ($n=29$)	1.2	1.0	2.0 to -1.1
Total studies ($n=106$)	1.2	1.0	3.5 to -2.2

RMSE root mean square error, MAE mean absolute error

The root mean square error for an adjusted mean $CTDI_{vol}$ using a mid-study slice calculated effective diameter, versus the mean per-slice adjusted $CTDI_{vol}$ based on the calculated effective diameter of each slice, was 0.78 mGy, with a mean absolute error of 0.59 mGy (error range 1.64 to -3.12 mGy).

Finally, we performed the effective diameter calculation on the mid-study slice of each of 12,506 CT abdomen or CT abdomen and pelvis studies in our dose database. A normalized dose length product of each study was then computed (Fig. 4).

Discussion

Normalization of CT doses for body size is essential for detecting scan protocol deficiencies for small or pediatric patients. Patient age may provide a way to adjust dose measurements in children but does not account for variations in body habitus and does not address dose normalization in small adults. Although height and weight information provide information on body habitus [7], a nomogram is required to translate this information into an equivalent body size; furthermore, there is evidence to suggest that direct measurements of body size are more suitable for dose correction [8, 9].

The AAPM Task Group 204 addressed the problem of dose normalization using data from both physical phantoms and Monte Carlo-based measurements. For a single slice, a normalization coefficient can be derived from a table lookup of the measured effective diameter of the patient [6].

Prior to this work at our institution, our attempts to automatically normalize CT dose data by patient diameter used the reconstructed image diameter reported as a DICOM

Table 2 Comparison of measured diameter in SMA origin slice versus mean calculated diameter for all slices

	RMSE (cm)	MAE (cm)	Error range (cm)
Abdomen and pelvis ($n=77$)	1.4	1.0	3.4 to -3.6
Abdomen only ($n=29$)	1.2	0.9	1.2 to -3.8
Total studies ($n=106$)	1.3	1.0	3.4 to -3.8

RMSE root mean square error, MAE mean absolute error

Fig. 4 Estimation of a normalized dose length product. **a** Plot of DLP versus calculated effective diameter for 12,506 CT examinations of the abdomen and pelvis. There is a general trend of increasing DLP with calculated effective diameter. **b** Plot of normalized dose length product versus calculated effective diameter. Compared to DLP values in (a), the estimated normalized DLP values are increased for small patients and decreased for large patients

field, which provided an upper bound to patient diameter. This method proved unreliable, however, since the error of using the reconstructed image diameter can vary widely, depending upon the degree to which a CT technologist limits the reconstructed field of view.

The current work approximates patient effective diameter by a simple image-based heuristic, using a threshold of -500 HU for segmenting the image pixels (the variation of the calculated effective diameter with alternative Hounsfield unit thresholds of -700 and -300 HU was small). This method may be expected to underestimate the patient diameter based on the presence of bowel gas (Fig. 5) or inclusion of the lungs, or overestimate the patient diameter to the degree that the density of the scanner couch and overlying patient material or body parts exceeds the attenuation threshold. Overall, however, the effective diameter calculated in this manner

Fig. 5 Underestimation of measured effective diameter in a CT colonography study with the colon insuflated with air. The measured effective diameter is 30.9 cm, while the calculated effective diameter is 28.3 cm

corresponds closely with the measured effective diameter. This method also appears robust to attenuation artifacts from metal or contrast material (Fig. 6).

We compared manual and calculated effective diameters for a relatively small number (166) of patients. This number appears sufficient to demonstrate a high degree of accuracy of the calculation method for typical abdominal CT cases but may not be enough to estimate the range and frequency of outliers, such as may occur with additional body parts in the field of view. It is possible that additional image processing or segmentation techniques would improve the agreement of measured and effective diameters in outlier cases. Evaluation of such techniques is beyond the scope of

Fig. 6 Extensive beam hardening artifact from surgical clips does not significantly impair accuracy of calculated effective diameter. In this case, the measured effective diameter is 24.3 cm, while the calculated effective diameter is 25.5 cm

the current work. Furthermore, such techniques would necessarily entail increased complexity including additional assumptions about the images, and it is not clear that these would significantly improve accuracy of dose adjustments.

Although accuracy of calculated effective diameter is good for a single slice, the patient diameter varies over the length of the study. Furthermore, in most modern CT scanners, radiation output is modulated along the z-axis by the scanner using some varying measurement of patient diameter or cross-sectional area. Ideally, the $CTDI_{vol}$ for each slice should be normalized by the effective diameter at that slice; however, processing all of the slices for thousands of studies within a dose database could require a considerable amount of time.

As a first approximation, we have chosen to measure effective diameter at a single midpoint position of the study (the mid-study slice). Our results suggest that this diameter is a reasonable estimate of the average effective diameter, considering the expected magnitude of error involved in the normalization calculation. Furthermore, the numerical difference between a mean $CTDI_{vol}$ adjusted by a mid-study effective diameter versus the mean of adjusted per-slice $CTDI_{vol}$ in this study proved to be relatively small.

Of note, a more accurate model of size-specific CT dose adjustment may be possible using individual pixel Hounsfield unit values, as opposed to the thresholding method discussed in this paper. However, given the available experimental evidence, our goal has been to devise a method of automating measurement of effective diameter in a manner that produces results compatible with the manual technique validated in the AAPM Task Group 204 report. Furthermore, estimating body attenuation using pixel Hounsfield unit values may not be as robust to attenuation artifacts as the method described here.

It should be noted that several limitations prevent us from using a calculated normalized dose length product as an accurate method for estimating individual patient dose. We have used combined dose length products in the abdomen and the pelvis, though any attempt to convert such values to effective dose should require separate treatment of these anatomic regions. In particular, we have made no attempt to calculate organ-specific doses. In addition, we do not make special adjustments for doses in included portions of the chest (the lung bases); we would expect calculated effective diameters in the thorax to be less than measured effective diameters as defined by the AAPM report, due to pixels in the air-filled lungs below our Hounsfield unit threshold.

However, the limited goal of our diameter estimation method is to be able to organize estimated doses in a population by body size. Estimated dose instances that previously appeared elevated in large patients are slightly dampened, while estimated dose instances that previously appeared low for small patients become more conspicuous. Subsequent evaluation of doses in small patient CT

protocols can then more easily focus on a close examination of scans in the left upper quadrant of Fig. 4b, representing those scans involving a small patient diameter and a relatively high dose. In summary, we believe that automated calculation of effective diameter will improve our ability to evaluate the adequacy of our CT protocols tailored for body habitus.

Conclusion

Automated measurement of effective diameter on a CT abdominal image is accurate and may be useful to normalize CT dose data for body size.

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