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SHORT COMMUNICATION

Assessment of radiation dose from abdominal quantitative CT with short scan length

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Objective: To assess radiation dose for patients who received abdominal quantitative CT and to compare the midpoint dose [$D_L(0)$] at the centre of a 1-cm scan length with the volume CT dose index ($CTDI_{vol}$). Although the size-specific dose estimate (SSDE) proposed in The American Association of Physicists in Medicine Report No. 204 is not applicable for short-length scans, commercial dose-monitoring software, such as Radimetrics™ Enterprise Platform (Bayer HealthCare, Whippany, NJ), reports SSDE for all scans. SSDE was herein compared with $D_L(0)$.

Methods: Data were analyzed from 398 abdominal quantitative CT examinations in 165 males and 233 females. The $CTDI_{vol}$ was 4.66 mGy, and the scan length was 1 cm for all examinations. Radimetrics was used to extract patient diameter and SSDE. $D_L(0)$ was assessed using a previously reported method that takes into account both patient size and scan length.

Results: The mean patient diameter was 28.5 ± 6.3 cm (range, 16.5–46.6 cm); the mean SSDE was 6.22 ± 1.36 mGy (range, 3.12–9.42 mGy); and the mean $D_L(0)$ was 2.97 ± 0.95 mGy (range, 1.18–5.77 mGy). As patient diameter increased, the $D_L(0)$ to $CTDI_{vol}$ ratio decreased, ranging from 1.24 to 0.25; the $D_L(0)$ to SSDE ratio also decreased, ranging from 0.61 to 0.38.

Conclusion: The dose to the patients from abdominal quantitative CT may be largely different from $CTDI_{vol}$ and SSDE. This study demonstrates the necessity of taking into account not only patient size but also scan length for evaluating the dose from short-length scans.

Advances in knowledge: In CT examinations with 1-cm scan length, dose evaluation needs to take into account both patient size and scan length. An omission of either factor can result in an erroneous result.

INTRODUCTION

With the rapid advances in medical imaging, CT is increasingly used for diagnostic evaluation, for image-guided interventional procedures and in screening for lung cancer and colon cancer. As the total number of CT examinations has been increasing worldwide,¹ radiation-induced risk for patients undergoing x-ray CT scans has received high attention. Medical institutions respond by adopting CT dose reduction strategies and optimizing the balance between radiation dose and image quality.^{2–6} For that objective, it is crucial to have accurate and relevant metrics of patient dose from CT examinations.

For each scan series, a CT scanner does not provide exact patient dose. Instead, the system usually reports the volume CT dose index ($CTDI_{vol}$), derived from the $CTDI_{100}$ measurements in a standard head or body CT dose index ($CTDI$) phantom of 16 or 32 cm in diameter, respectively.⁷ The $CTDI_{vol}$ can be used for quantifying radiation output of CT systems, but it is not a measure of patient dose, because the CT dosimetry phantoms are physically very

different from human patients in terms of size and X-ray attenuation. To account for patient size and attenuation in CT dose evaluation, the American Association of Physicists in Medicine (AAPM) Report No. 204 proposed to correct $CTDI_{vol}$ with size-dependent conversion factors for calculating the size-specific dose estimate (SSDE) in paediatric and adult body CT.⁸ The conversion factors were evaluated by four research groups, whose data showed that the $CTDI_{vol}$ to SSDE ratio is approximately independent of the CT scanner model. SSDE can provide an estimate for the average dose over the central section of the scanned range of 15–30 cm, with an accuracy of 10–20%, but SSDE is not applicable for scan lengths <15 cm.⁸ An alternative method is needed for evaluating the dose from short-length scans which are becoming more common in the practice of limiting scan range to the anatomy of clinical interest and minimizing radiation-induced risk to patients.

Recently, Li et al⁹ used a GEANT4-based CT simulation program to simulate single-rotation axial scans of acrylic head and body CTDI phantoms and 50 water cylinders

(diameters 6–55 cm). From the simulations, they obtained CTDI_{100} at the centres and the peripheries (1 cm below the phantom surfaces) of the CTDI phantoms, and the results were used to calculate the weighted CTDI,⁷

$$\text{CTDI}_w(\text{acrylic}) = \frac{1}{3}\text{CTDI}_{100,\text{centre}} + \frac{2}{3}\text{CTDI}_{100,\text{periphery}} \quad (1)$$

which is related to the CTDI_{vol} from CT scans by⁷

$$\text{CTDI}_{\text{vol}} = \text{CTDI}_w(\text{acrylic})/\text{pitch} \quad (2)$$

They also obtained the planar (cross-sectional) average dose in each 1-mm slice along the longitudinal axes of the water phantoms, and the results were used to calculate the midpoint dose $D_L(0)$ ¹⁰ at the centres of the CT scan ranges for the water phantoms. They found that, for scan lengths <15 cm, the $D_L(0)$ decreases as the scan length decreases, and this effect is accentuated with larger water phantom diameters. Comprehensive data of CTDI_{vol} to $D_L(0)$ (water) conversion factors are available elsewhere⁹ and can be used for assessing the midpoint dose in water cylinders during CT scan of any scan length.

In this study, we applied the above method to evaluate the doses to patients who received abdominal quantitative CT scans and compared the results with the CTDI_{vol} values reported by the CT scanners. A commercial dose monitoring and tracking software, Radimetrics™ Enterprise Platform (Bayer HealthCare, Whippany, NJ), reports the SSDE for all CT scans, including short scan lengths for which SSDE is not applicable. To investigate the accuracy of the reported SSDE for short-length scans, we compared it with the midpoint dose assessed for the patient examinations.

METHODS AND MATERIALS

Patient data collection

The institutional review board of Partners HealthCare approved this retrospective study with a waiver of written informed consent. The study complied with the requirements of the Health Insurance Portability and Accountability Act. The authors have no conflict of interest to disclose. This study included 398 consecutive patients (165 males and 233 females) who underwent abdominal quantitative CT examinations between July 2013 and September 2016 on two LightSpeed® Pro 16 scanners (GE Healthcare, Waukesha, WI). The abdominal quantitative CT protocol prescribed two axial scans at the level of the fourth lumbar vertebra (with 80 kV, 140 mAs and 16×0.625 -mm beam collimation) and at the middle of the left femur. The dose from the latter scan was not considered in this work. The scan length was 1 cm for all acquisitions. For each abdominal quantitative CT series, Radimetrics was used to extract patient sex, age, diameter, body weight, CTDI_{vol} and SSDE, where the patient diameter was calculated from the midscan length (median image of the craniocaudal scan range); SSDE was calculated based on the diameter, by the method of AAPM Report No. 204.⁹ The mean patient age was 56 ± 11 years (range, 25–76 years) for males and 32 ± 11 years (range, 18–76 years) for females, respectively. There was a substantial statistical difference in age between males and females ($p < 0.001$ with

Welch's unequal variances *t*-test). The mean patient weight was 95 ± 23 kg (range, 54–163 kg) for males and 57 ± 18 kg (range, 34–122 kg) for females, respectively.

Midpoint dose calculations

In the CTDI paradigm, the dose integral of longitudinal dose profile from single rotation axial scan is used to predict the midpoint dose for CT scan series,¹¹

$$D_L(0) = \text{CTDI}_L/\text{pitch} \quad (3)$$

where *L* is the scan length or dose integration length. The well-known CTDI_{100} metrics (including CTDI_w and CTDI_{vol}) are related to a scan length of 10 cm, *i.e.* $D_{L=10\text{cm}}(0) = \text{CTDI}_{100}/\text{pitch}$. Both $D_L(0)$ and CTDI_L asymptotically increase with *L* and approach the limiting levels (the equilibrium dose and the ideal CTDI)¹¹

$$D_{\text{eq}} = \text{CTDI}_{\infty}/\text{pitch} \quad (4)$$

at large lengths. The dependency of $D_L(0)$ on scan length may be empirically characterized by the approach to equilibrium function:¹⁰

$$H(L) = \frac{D_L(0)}{D_{\text{eq}}} \quad (5)$$

Based on Equations (2), (4) and (5), the dose at the centre of the scanned range in a patient undergoing a CT scan may be computed by⁹

Figure 1. The volume CT dose index (referenced to body CT dose index phantom) to $D_L(0)$ (water) conversion factors for 6- to 55-cm diameter water phantoms undergoing single-rotation axial scans at a tube voltage of 80 kV and a primary beam width of 12 mm. The least squares fit was calculated using Equation (7), and the coefficient of determination (R^2) was >0.99.

Figure 2. Graphs of volume CT dose index ($CTDI_{vol}$), size-specific dose estimate (SSDE) and midpoint dose [$D_L(0)$] vs patient diameter for (a) males and (b) females. The $CTDI_{vol}$ was 4.66 mGy (referenced to body CT phantom) for all patients.

$$D_L(0) = CTDI_{vol} \times \frac{CTDI_{\infty}}{CTDI_w} \times H(L) \quad (6)$$

where both $CTDI_w$ and $CTDI_{vol}$ are referenced to a CTDI phantom, and each $D_L(0)$, $CTDI_{\infty}$ and $H(L)$ is dependent on the patient size.

As described earlier, Li et al.⁹ previously evaluated the $CTDI_{\infty}$ (water) to $CTDI_w$ (CTDI phantom) ratio and $H(L)$ in water phantoms with diameters from 6 to 55 cm; comprehensive results are available for five tube voltages of 70, 80, 100, 120 and 140 kV. Specifically, $CTDI_{\infty}$ (water)/ $CTDI_w$ (body CT phantom) can be calculated using Equation (A2) and the data in table 1 of that reference; with any scan length, $H(L)$ can be computed using Equations (A3) and (A5)–(A7) and the data in table 2 of that reference.

These calculations were simplified in this work for abdominal quantitative CT with single-rotation axial scan of 10-mm nominal beam width. The measured primary beam width on CT scanners was 12 mm, close to the CT manufacturer's specification of 11.7 mm, whereas the X-ray beam penumbra is usually taken into account in $CTDI_{100}$ and $CTDI_{vol}$ assessments. In this work, $D_L(0)$

(water) was calculated with the primary beam width. For convenience, the $CTDI_{vol}$ (referenced to a body CT phantom) to $D_L(0)$ (water) conversion factors for 80 kV and 12-mm primary beam width are shown in Figure 1, and the data of conversion factor vs water phantom diameter were fit with ROOT (available from: <https://root.cern.ch>) and an empirical function:⁹

$$\frac{D_L(0)(\text{water})}{CTDI_{vol}(\text{body CT phantom})} = 3.349 \times \left[\frac{x}{12.41} + \exp\left(-\frac{x}{15.45}\right) \right]^{-1.935} \quad (7)$$

where x was the water phantom diameter (cm). The squared coefficient of determination (R^2) was >0.99 . For each patient, the midpoint dose calculation was based on patient diameter.

Statistical analysis

To facilitate computerized applications, the set of $D_L(0)/CTDI_{vol}$ data for water phantom diameters in 6–55 cm was processed with least squares fit, and R^2 was computed. Welch's unequal variances t -test was used to test the hypothesis that two groups had equal means, and statistical significance was set to $p < 0.05$. Correlation was calculated using the Pearson correlation

Figure 3. Shows the graphs of dose ratios of midpoint dose [$D_L(0)$]/volume CT dose index ($CTDI_{vol}$) and $D_L(0)$ /size-specific dose estimate (SSDE) vs patient diameter for (a) males and (b) females.

coefficient. The patient data sets in this work were summarized using descriptive statistical analysis, and the mean, standard deviation and range were computed for patient age, body weight, patient diameter, SSDE and $D_L(0)$.

RESULTS

For the patient examinations included in this study, the mean diameter was 33.5 ± 4.6 cm (range, 20.6–46.6 cm) for males and 25.0 ± 4.9 cm (range, 16.5–42.5 cm) for females. There was a significant correlation between patient diameter and body weight for both males ($r = 0.89$) and females ($r = 0.90$), which was consistent with two previous studies by Khawaja et al¹² and by Boos et al.¹³ Nevertheless, the correlation between the patient diameter and age was insignificant ($r = 0.47$) for females or even negative ($r = -0.35$) for males.

Figure 2 shows the graphs of $CTDI_{vol}$, SSDE and $D_L(0)$ vs patient diameter. The $CTDI_{vol}$ was 4.66 mGy (referenced to a body CTDI phantom) for all examinations. The mean SSDE was 5.12 ± 0.83 mGy (range, 3.12–8.11 mGy) for males and 7.00 ± 1.09 mGy (range, 3.62–9.42 mGy) for females. The mean $D_L(0)$ was 2.19 ± 0.49 mGy (range, 1.18–4.41 mGy) for males and 3.52 ± 0.81 mGy (range, 1.39–5.77 mGy) for females. Figure 3 shows the graphs of $D_L(0)/CTDI_{vol}$ and $D_L(0)/SSDE$ vs patient diameter. The mean $D_L(0)/CTDI_{vol}$ was 0.47 ± 0.11 (range, 0.25–0.95) for males and 0.76 ± 0.17 (range, 0.30–1.24) for females. The mean $D_L(0)/SSDE$ was 0.42 ± 0.03 (range, 0.38–0.54) for males and 0.50 ± 0.04 (range, 0.38–0.61) for females. The trend of SSDE decreasing with larger patient diameters was due to the $CTDI_{vol}$ to SSDE conversion factor decreasing with larger diameters, as illustrated in AAPM Report No. 204,⁸ whereas the trend of $D_L(0)$ decreasing with larger patient diameters was due to $D_L(0)/CTDI_{vol}$ decreasing with larger diameters, as illustrated in Figure 1.

The patient demographic information and radiation dose results in this study are summarized in Table 1.

DISCUSSION

Two AAPM Reports (No. 111 and No. 204) have shown that the radiation dose from CT examinations depends on patient size and scan length. With a single scan length, such as 1 cm in abdominal quantitative CT, the dose can change significantly with subject size, as depicted in Figure 1. For patient diameters

of 16.5–46.6 cm in this study, $D_L(0)$ is greater than $CTDI_{vol}$ (referenced to a body CTDI phantom) for diameters <20 cm but is less than $CTDI_{vol}$ for larger diameters. The $D_L(0)$ to $CTDI_{vol}$ ratio has a large range (0.25–1.24) because $CTDI_{vol}$ is determined for a standard CTDI phantom, independent of subject size. Although this factor is taken into account in SSDE, this estimate is much higher than the dose from 1-cm scan length by 63–165% for the above diameter range. Our study demonstrates that dose evaluation for short-length scans needs to take into account both patient size and scan length. An omission of either factor can result in an erroneous result.

Abdominal quantitative CT is a clinically proven method for measuring body composition and bone mineral density in the spine, for testing osteoporosis and for monitoring treatment.¹⁴ For the patient examinations included in this work, Table 1 shows statistical differences in patient diameter and $D_L(0)$ between males and females ($p < 0.001$ with Welch's unequal variances *t*-test). As a setting of 80 kV, 140 mAs and 1-cm scan length was used for all patients, the females received higher absorbed dose than the males because they were, on average, smaller than the males. With a dose-length product of 4.66 mGy cm, the effective dose to both the males and females was 93 μ Sv, based on a dose-length product to effective dose conversion factor of 0.020 mSv per mGy cm by Shrimpton et al¹⁵ for abdomen and pelvis examination using the tissue-weighting factors in the International Commission on Radiological Protection Publication 103 (2007). The above effective dose is much lower than that of common CT examinations in the UK in 2011.

This communication is focused on abdominal quantitative CT, but the presented results can also give insight into other applications, such as bolus-tracking studies and test bolus studies that are common in the clinic for monitoring contrast media. At our hospital, these studies are performed using single-axial scans of 10-mm nominal beam width. Although each acquisition is performed using a low-dose technique, e.g. 120 kV and 50 mAs, the same body region is scanned multiple times, and the sum of the $CTDI_{vol}$ values from each rotation can be large or even >100 mGy. The clinic usually cannot determine the dose to the patient, but Figure 1 shows the $CTDI_{vol}$ to $D_L(0)$ ratios for a large range of body sizes, and Equation (7) can be conveniently used for assessing the dose in

Table 1. Patient demographics and radiation dose metrics from abdominal quantitative CT in this study

Metric	Males	Females
Number of examinations	165	233
Age (years)	56 ± 11 (25–76)	32 ± 11 (18–76)
Weight (kg)	95 ± 23 (54–163)	57 ± 18 (34–122)
Diameter (cm)	33.5 ± 4.6 (20.6–46.6)	25.0 ± 4.9 (16.5–42.5)
$CTDI_{vol}$ (mGy)	4.66	4.66
SSDE (mGy)	5.12 ± 0.83 (3.12–8.11)	7.00 ± 1.09 (3.62–9.42)
$D_L(0)$	2.19 ± 0.49 (1.18–4.41)	3.52 ± 0.81 (1.39–5.77)

$CTDI_{vol}$, volume CT dose index; $D_L(0)$, midpoint dose; SSDE, size-specific dose estimate. Ranges are shown in parentheses.

the studies at 80 kV. It is worthwhile to note that $D_L(0)$ (water)/CTDI_{vol} (body CT phantom) changes slightly with tube voltage, and the maximum difference between 80 and 120 kVs is 12% for water phantom diameters from 6 to 55 cm.⁹ To assist dose evaluation for contrast media-monitoring studies at 120 kV, which may be more common in the clinic, the ratio data of 120 kV and 12-mm primary beam width were fit with an empirical function:⁹

$$\frac{D_L(0) \text{ (water)}}{\text{CTDI}_{\text{vol}} \text{ (body CT phantom)}} = 2.868 \times \left[\frac{x}{13.37} + \exp\left(-\frac{x}{17.27}\right) \right]^{-1.845} \quad (8)$$

where x was the water phantom diameter (cm); R^2 was >0.99 . The CTDI_{vol} to $D_L(0)$ (water) conversion factors at other tube voltages and scan lengths can be similarly evaluated.⁹

CONCLUSION

The radiation dose from abdominal quantitative CT may be largely different from the CTDI_{vol} reported by the CT scanner, as well as the SSDE assessed with the method of AAPM Report No. 204. For short-length scans, dose evaluation needs to take into account not only the patient size but also the scan length. This can be achieved using a method from a recent publication cited in this communication.

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