Multisection computed tomography: Results from a Chinese survey on radiation dose metrics

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Abstract

Background: As multisection spiral computed tomography (MSCT) have been extensively used, it is important to consider the amounts of doses the patients are exposed during a computed tomography (CT) examination. The aim of the current study was to summarize MSCT doses in Chinese patients to establish the diagnostic reference levels (DRLs).

Methods: Radiation dose metrics were retrospectively collected from 164,073 CT examinations via the Radimetrics Enterprise Platform. Radiation dose metrics (volume CT dose index [CTDIvol], dose-length product [DLP], effective dose [ED], and organ dose) and size-specific dose estimate (SSDE) were calculated for adults and children based on anatomic area and scanner type.

Results: The median CTDIvol and DLP values were highest in the head at 51.7 mGy (interquartile range [IQR], 33.2-51.7 mGy) and 906.5 mGy·cm (IQR, 582.4–1068.2 mGy·cm) and lowest in the chest at 7.9 mGy (IQR, 7.9-10.3 mGy) and 284.8 mGy·cm (IQR, 249.0-412.6 mGy·cm), respectively. The median SSDE values of chest and pelvis were 12.1 mGy (IQR, 10.8-14.1 mGy) and 36.3 mGy (IQR, 34.0-38.9 mGy), respectively. EDs for children were similar to adults except for an increased 1.5-, 0.77-, and 1.7-fold in the chest, neck, and pelvis, respectively ($p < 0.001$). Furthermore, radiation doses tended to increase with increasing slice number and decrease when exposure reduction techniques were used.

Conclusion: Our findings provide a basis for the evaluation of CT radiation doses and evidence for establishment of DRLs in China.

Keywords: Diagnostic reference levels; Dose-length product; Effective dose; Radiation dose metrics; Volume CT dose index

1. INTRODUCTION

The development of multisection (multislice) spiral computed tomography (MSCT) has led to a noticeable quantum leap in clinical performance of computed tomography (CT), enabling faster and accurate diagnosis of diseases. Nevertheless, the associated high radiation dose of CT is a major concern regarding an increased risk of carcinogenesis in the receivers,[1] especially in multiphasic CT where the same organ is scanned multiple times (~four times) in different phases of contrast enhancement, thereby increasing the risk of carcinogenicity.[2] Radiation doses from CT examinations are highly variable based on the scanner type and number, operation condition, examination, and protocol. The most efficient CT types are often associated with a high risk of carcinogenesis due to high radiation efficiency.[3] Although it is mandatory to ensure safety against ionizing radiation during the procedure, general dose limits cannot be utilized for CT examinations as the potential risks and benefits must be weighed on an individual basis.[4] European regulation[5] and US National Council on Radiation Protection and Measurement[6] implemented the use of specific diagnostic reference levels (DRLs), which represent the dose levels at which an investigation of appropriate dose should be initiated, rather than the absolute upper limit for a dose,[7] which was proposed by the International Commission on Radiation Protection (ICRP) in 1996.[8] Following this, several surveys were globally conducted to set DRLs to limit radiation exposure arising from CT procedures.[4–17] The dose parameters recommended in the European guidelines are weighted CT dose index for a single slice and dose-length product (DLP) for an entire examination.[18] Various commercial software systems can manage radiation doses, and one of them is Radimetrics, a software tool that monitors, tracks, and manages patient radiation exposures from CT.[19] Monte Carlo techniques are used to derive the effective dose (ED) by calculating the organ doses that are further multiplied by weighting factors published in the ICRP 103.[20]

Because MSCTs have been recently introduced into many developing and developed countries and have been extensively used in many studies almost replacing the conventional X-ray technique, it is important to give utmost consideration to patient doses.[21] Given the scarcity of surveys, DRLs have not been established in China. Therefore, we aimed to summarize MSCT doses from examinations performed at our hospital to help institutions evaluate CT doses and contribute to the creation of DRLs for radiation in China.

2. METHODS

2.1. Study design and population

In this retrospective survey, radiation doses of 169,802 MSCT examinations performed by eight CT scanners between July

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2015 and January 2016 were analyzed to estimate the radiation dose metrics for adult and pediatric patients, which may assist the clinicians to set DRLs for Chinese patients.

A total of 164,073 examinations from patients who underwent MSCT were included, after excluding CT examinations (5729 examinations) that lacked complete information on age, anatomical sites and clinical indications, clear indication, and clear definition of the scanned area; positron emission tomography/CT examinations; and MSCT examinations performed for research or interventional procedures. Examinations were grouped according to whether they were performed on teenagers and adults (aged >14 years) or children (aged ≤14 years).

The study was approved by the ethical committee of our hospital, and the requirement to obtain informed consent was waived because of the retrospective design of the study.

2.2. CT scanners

Eight CT (The General Electric Company, Waukesha, WI 53188, USA) facilities in the hospital from three manufacturers were included in this study: three from Siemens (Siemens Medical Solutions, Malvern, PA, USA), two from GE Healthcare, and three from Philips (Philips Medical Systems Nederland BV, a Philips Healthcare company, Best, The Netherlands) (Appendix 1). We divided these CT facilities into three groups based on the number of slices and whether dose-saving techniques were used or not: CT group A (CT 1, 2, 3, 7) were 64 sliced and above, CT group B (CT 4, 5) were 16 sliced, and group C (CT 6, 8) were 64 sliced using radiation exposure reduction algorithms including Adaptive Statistical Iterative Reconstruction (ASIR, for CT6) and iDose (for CT8), which improve the image quality and allow the use of lower tube currents (data not shown). A total of 95 experienced radiologists were involved in scanning and reading of CT images.

2.3. Data collection and CT protocol

Radiation dose data from MSCT examinations were collected and downloaded from Radimetrics Enterprise Platform (Bayer HealthCare, Whippany, NJ, USA) for analysis. Radimetrics collects dose metrics from the Digital Imaging and Communications in Medicine and Picture Archiving and Communications System (PACS) and derives the size-specific dose estimate (SSDE) by calculating patient diameter from the mid-scan length. Radimetrics uses the library of Cristy phantoms[18] to calculate the ED by matching patients to a particular computational phantom based on the patient's age, weight, or diameter.

For different scanning protocols with various examination parameters, a set of Monte Carlo simulations are prerun for every phantom in the library to calculate organ doses, which are then used to derive the ED, according to the published ICRP 103 tissue-weighting factors.[20] The radiation dose metrics such as volume CT dose index (CTDIvol), DLP, ED, and organ dose were calculated along with SSDE.

Although the individual radiation dose was recorded and we advocate suggestions as an important indicator of health monitoring, however, this analysis could not be performed due to: (1) data not available in previous reports, (2) complex situation due to the daily work of the individual or patient having multiple position or multiple scanning, and (3) DRL being a part of the standard for standard scan.[20]

2.4. Definitions and measures of radiation dose metrics

CTDIvol is measured in terms of air kerma (milligray) and is provided by all commercial scanners. It depends on the choice of X-ray techniques (eg, kilovolt and milliampere-second). The reported values are based on the protocol selection using a 32-cm body phantom or a 16-cm head phantom.

DLP is the dose for the length irradiated and is expressed in milligray-centimeters, increasing with an increase in total scan length or with those variables that can affect the CTDIvol. Generally, CTDI (air kerma) is multiplied by scan length.

SSDE dose is used for body CT to account for differences in patient size, especially when comparing dose levels from different organizations that may have significant differences in patient demographics (affecting size or weight).

ED is calculated based on the organs exposed by the applied radiation multiplied by tissue-weighting factors. In Radimetrics, the organ doses are first calculated using Monte Carlo probabilistic simulations that account for scattered radiation using a library that includes standardized male and female anthropomorphic mathematical phantoms, then the ED is estimated according to the published ICRP103 tissue-weighting factors.[20]

Patient sex, age, date and time of the examination, scan region (head, chest, abdomen, spine, neck, pelvis, and other anatomic areas), study description, protocol name, scanner manufacturer, and model were extracted from Radimetrics and PACS.

2.5. Statistical analysis

The study findings are presented as median, upper and lower quartile (interquartile range, IQR). Radiation dose metrics, CTDIvol, DLP, SSDE, ED, and organ doses between multiple groups were analyzed and compared between two groups using Kruskal-Wallis test and Wilcoxon rank-sum test using SAS version 9.4 (SAS Institute, Cary, NC, USA). A p value of <0.05 was considered to be statistically significant.

3. RESULTS

3.1. Patients demographics

A total of 164,073 patients were examined for radiation dose metrics (adults: n = 153,149; adult men: n = 86,791). The median age of all patients was 52.18 (37.85-62.73) years.

3.2. CT image distribution and radiation doses in all patients

Overall, the most common areas imaged were the chest (38.60%), head (31.04%), abdomen (23.43%), spine (4.24%), neck (0.78%), and pelvis (0.50%). Apart from these, only 1.42% of the examinations were of other anatomic areas (Figure 1A). The median radiation doses and IQRs are detailed in Table 1. The median CTDIvol values were highest in the head at 51.7 mGy (IQR, 33.2-51.7 mGy) and lowest in the chest at 7.9 mGy (IQR, 7.9-10.3 mGy). Similarly, the median DLPs were 906.5 mGy·cm (IQR, 582.4-1068.2 mGy·cm) in the head and 284.8 mGy·cm (IQR, 249.0-412.6 mGy·cm) in the chest. The median SSDE values were lowest in the chest at 12.1 mGy (IQR, 10.8-14.1 mGy) and highest in the pelvis at 36.3 mGy (IQR, 34.0-38.9 mGy). The median EDs were highest in the abdomen at 16.7 mSv (IQR, 12.7-22.4 mSv) and lowest in the head at 2.3 mSv (IQR, 1.5-2.7 mSv).

3.3. CT image distribution and radiation doses in adults and children

There were slight differences between adults and children in the most commonly imaged areas (Figure 2). In adults, the most common areas were the chest (37.1%), head (26.8%), abdomen (23.0%), spine (4.2%), neck (0.7%), and pelvis (0.5%), and 1.2% of the examinations were of other anatomic areas (Figure 2). In children, the most common areas were the head (4.2%), chest (1.5%), abdomen (0.5%), spine (0.06%), neck (0.05%), and pelvis (0.01%), and 0.07% of the examinations were of other anatomic areas (Figure 1B).

There were significant differences in radiation dose metrics between adults and children in all the areas, except CTDIvol and DLP of the pelvis and EDs of the abdomen, spine, and neck (Table 2). The EDs were significantly high in children compared with adults with 1.5- and 1.7-fold in the head and pelvis, respectively ($p < 0.001$ for all).

3.4. CT image distribution and radiation doses in different groups

Different CT group were dispersed based on patients' triage to examine different anatomical areas (Figure 1C). A total of

103,149 CT examinations were collected from group A and 14,798 examinations were collected from group C. For group B, these two facilities were mostly used for routine head (18,149, 11.1%) and chest (27,871, 17.0%) examinations, and only 9 (<0.1%) and 91 (0.1%) patients had their abdomen or spine scanned. There were 1574 (1.0%), 6 (<0.1%), and 289 (0.2%) examinees in groups A, B, and C for other anatomic areas, respectively.

The median radiation doses and IQRs in each group are reported in Table 3. Among the three teams, CTDIvol and DLP of the chest ([9.8 versus 7.9 versus 8.8 mGy] and [387.8 versus 262.1 versus 334.5 mGy·cm], respectively) and the spine ([19.9 versus 21.3 versus 16.6 mGy) and (564.6 versus 1023.6 versus 417.6 mGy·cm], respectively) were significantly different ($p < 0.0001$ for all). Abdominal and pelvic CTDIvol (18.2 versus 13.8 mGy) and (26.7 versus 15.4 mGy) and DLP (894.4 versus 709.2 mGy·cm) and (502.1 versus 338.3 mGy·cm) differed significantly only between groups A and C ($p < 0.0001$, for both regions). CTDIvol of the head in group B were significantly lower only compared with team A (33.2 versus 51.7 mGy; $p < 0.0001$).

Overall, it was apparent that radiation dose tended to increase as slice number increased from group B to A, and doses tended to reduce with the use of exposure reduction techniques in group C.

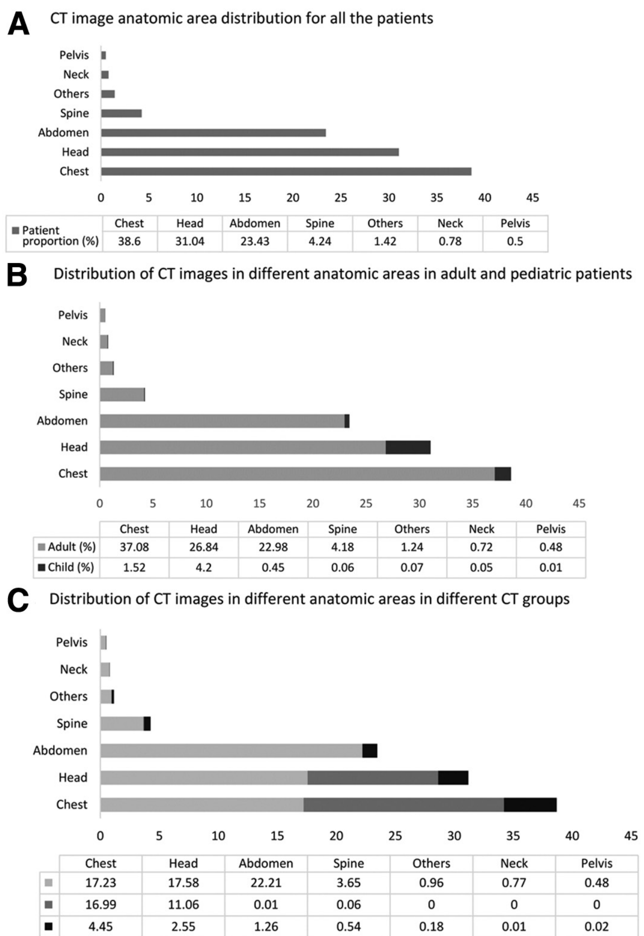

Fig. 1 Distribution of CT images in different anatomic areas in different CT groups and patient groups. A. CT image showing anatomic area distribution for all the patients. B, Distribution of CT images in different anatomic areas in adult and pediatric patients. C, Distribution of CT images in different anatomic areas in different CT groups.

3.5. Radiation doses in different organs

The median organ doses were listed in Figure 2. During the ED calculation, the Monte Carlo simulations were used by Radimetrics for different scanning protocols with various examination parameters. Using the Monte Carlo simulations, the median highest dose received by the head was 24.8 mGy in the eye lenses and 18 mGy in the brain. The lowest doses were received by the pelvis and the ovaries at 4.3 mGy, testicles at 4.2 mGy, bladder at 3.2 mGy, and uterus at 2.8 mGy.

4. DISCUSSION

The disproportionate increase in radiation-induced cancer risk compared with the benefits of CT has been a challenge for its use, especially in children worldwide.[22,23] A number of CT dose surveys have been published worldwide based on this. However, Asian surveys have focused on only protocols or phantoms.[15–18] To the best of our knowledge, this is the first large-sample patient survey that could be the basis for developing radiation dose standards in China. As there are no specific national reference levels in China, we compared the DRLs with DRLs from European guidelines.[9] Our results showed similar or lower results on CTDIvol and a higher DLP, the latter probably occurring due to the longer scan length, as DLP is dependent on scan length, whereas CTDI is almost independent.[24] Also, we tried to compare the dose metric parameters of this study with that of the study by Zhou et al.[25] who surveyed adult patients from the Jiangsu province of China for CT radiation doses for more ethnic generalizability of results. Compared with the Zhou et al. findings, our study had high CTDIvol values for head (51.7 mGy versus 44.54 mGy) and low for chest (7.9 mGy versus 17.31 mGy) anatomical segments. Similarly, the DLP of head (906.5 mGy·cm versus 493.16 mGy·cm) was high and low for chest (284.8 mGy·cm versus 408.96 mGy·cm) in our study compared with the findings of Zhou et al. Compared with CTDIvol and DLP, ED is widely used, as it is the only measure of dose that can be easily compared with radiation dose measurements from other imaging tests and environmental exposures.[26–29] When the EDs were compared with Zhou et al. findings, and the US[30] and UK[31] DRLs, the EDs observed in this study were slightly lower than that of doses from the UK and US population and were higher than the EDs of those from the study of Zhou et al. This discrepancy may be due to the smaller population surveyed in the study by Zhou et al. (n = 245) from a

Table 1

Radiation dose metrics of all patients

Anatomical region	Median CTDIvol, mGy[2a] (IQR)	Median DLP, mGy·cm[a] (IQR)	Median SSDE, mGy[a] (IQR)	Median effective dose, mSv[a] (IQR)
Head	51.7 (33.2-51.7)	906.5 (582.4-1068.2)	…	02.3 (1.5-2.7)
Chest	07.9 (7.9-10.3)	284.2 (249.0-412.6)	12.1 (10.8-14.1)	07.1 (6.0-8.6)
Abdomen	18.2 (14.6-18.5)	886.9 (647.8-1259.9)	24.5 (20.4-28.0)	16.7 (12.7-22.4)
Spine	19.9 (18.1-19.9)	552.6 (498.9-634.4)	…	13.2 (10.5-15.4)
Neck	12.6 (10.9-14.6)	356.0 (277.2-534.0)	…	03.6 (2.8-5.9)
Pelvis	26.7 (26.7-26.8)	498.2 (387.1-670.8)	36.3 (34.0-38.9)	08.1 (5.8-10.6)

[a] $p<0.0001$ among different anatomic areas compared with chest.

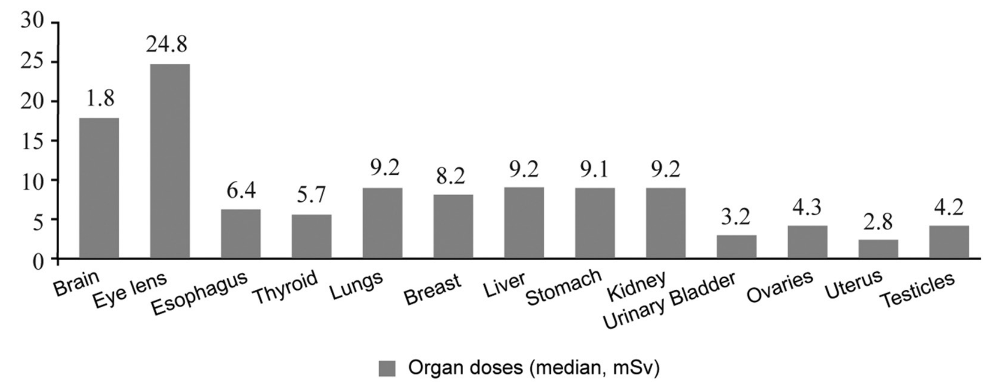

Fig. 2 Median radiation doses in different organs. The figure shows median radiation doses in each organ.

Table 2

Radiation dose metrics in children and adult patients

Anatomical region	Age Group	Median CTDIvol, mGy^{2}[a] (IQR)	*p*	Median DLP, mGy·cm[a] (IQR)	*p*	Median SSDE, mGy[a] (IQR)	*p*	Median effective dose, mSv[a] (IQR)	*p*
Head	Children	51.5 (33.2-51.7)	<0.001	989.0 (582.4-1047.3)	0.0091	…	…	03.4 (2.2-4.5)	<0.001
	Adults	51.7 (33.2-51.7)	…	906.5 (582.4-1071.9)	…	…	…	02.3 (1.4-2.6)	…
Chest	Children	04.3 (3.1-7.9)	<0.0001	110.1 (65.2-206.3)	<0.0001	08.3 (6.5-14.2)	<0.0001	05.5 (4.0-8.9)	<0.0001
	Adults	07.9 (7.9-10.4)	…	286.8 (252.7-420.0)	…	12.1 (10.9-14.1)	…	07.1 (6.1-8.6)	…
Abdomen	Children	18.2 (6.9-18.2)	<0.0001	526.1 (283.0-757.4)	<0.0001	28.6 (13.4-36.0)	0.0006	18.6 (10.3-27.1)	0.4877
	Adults	18.2 (14.7-18.6)	…	893.3 (658.0-1272.0)	…	24.5 (20.5-27.9)	…	16.7 (12.6-22.1)	…
Spine	Children	19.9 (6.6-19.9)	<0.0001	362.5 (173.7-534.5)	<0.0001	…	…	15.1 (5.6-19.4)	0.3759
	Adults	19.9 (18.3-19.9)	…	989.0 (502.9-636.0)	…	…	…	13.2 (10.6-15.4)	…
Neck	Children	09.5 (7.9-11.2)	<0.0001	906.5 (126.8-284.9)	<0.0001	…	…	03.7 (2.6-5.8)	0.3203
	Adults	12.9 (11.1-15.0)	…	110.1 (287.1-550.0)	…	…	…	03.6 (2.8-6.0)	…
Pelvis	Children	26.7 (26.4-26.8)	0.1555	286.8 (385.3-584.8)	0.2616	46.1 (41.3-51.0)	<0.0001	13.8 (10.4-16.9)	<0.0001
	Adults	26.7 (26.7-26.8)	…	526.1 (387.6-674.9)	…	36.2 (33.8-38.8)	…	07.9 (5.8-10.4)	…

[a]$p < 0.0001$ among different anatomic areas compared with chest.

Table 3

Radiation dose metrics of patients in different CT scanner group

		CTDIvol, mGy^{2}		DLP, mGy·cm	
Scanner teams	Anatomical region	Median	IQR	Median	IQR
Team A	Head	51.7[a]	51.5-51.7	1046.4[a]	995.0-1103.7
	Chest	9.8[a]	7.4-13.5	387.8[a]	284.0-556.1
	Abdomen	18.2[a]	15.1-18.5	894.4[a]	663.6-1281.0
	Spine	19.9[a]	19.6-19.9	564.6[a]	528.1-643.0
	Neck	12.6	10.9-14.5	355	277.3-532.3
	Pelvis	26.7[b]	26.7-26.8	502.1[b]	391.0-674.9
Team B	Head	33.2	33.2-33.2	582.4	516.0-582.4
	Chest	7.9	7.9-7.9	262.1	240.1-280.9
	Abdomen	21.4	21.4-21.4	878.2	439.7-985.2
	Spine	21.3	21.3-21.3	1023.6	690.7-1407.1
	Neck	…	…	…	…
	Pelvis	…	…	…	…
Team C	Head	51.9	51.5-51.9	726.7	726.7-830.5
	Chest	8.8	6.3-12.4	334.5	243.2-468.2
	Abdomen	13.8	10.8-18.2	709.2	487.6-1032.4
	Spine	16.6	10.4-19.1	417.6	311.2-506.5
	Neck	14.7	8.5-15.4	468.4	271.2-761.1
	Pelvis	15.4	10.9-21.8	338.3	280.6-570.6

[a]$p < 0.0001$ among three groups in the same anatomic area.
[b]$p < 0.0001$ between groups A and C in the same anatomic area.

single province in China. Moreover, individual body or organ surface area may have played a crucial role on the outcome. A study by Li et al. reported that the organ dose and ED decreased with increased organ (chest) diameter.[32] Given that the Zhou et al. study involved only adult patients who tend to have larger organ diameter than pediatric patients. It is sensible that the high EDs and CTDIs obtained in this study may be due to the enrollment of both adult and pediatric patients who receive increased radiation doses. Moreover, the findings of this survey show that EDs for children were similar to those for adults in the abdomen, neck, and spine, but increased approximately 1.5-fold in the head and 1.7-fold in the pelvis. This is in line with the study by Thomas and Wang, who reported higher ED estimates for younger age groups than older age groups for head, abdomen, and pelvis MSCT scans.[33] Further, the relationship between ED and stochastic risk is assumed to be linear[34] and the risk of carcinogenesis is estimated to increase proportionally with organ dose.[35,36] Furthermore, we should also notice that the number of abdominal scans was small, especially in children (732 cases [0.45%]), as many children would have opted for other imaging techniques such as magnetic resonance (MR) and ultrasound. In addition, MR reports were also preferred for complicated cases in adult patients who underwent CT for cancer staging before surgery. In contrast, we report similar or lower doses to previous values reported for the head, chest, neck, and pelvis.[10–12] Due to their lower body weight and sizes, children often receive higher ED than adults when adult-size imaging techniques and protocols are used.[37] Usage of age- and child-specific protocols,[38] optimizing scan parameters based on patient anatomy, and reducing the number of multiphase scans can go a long way in reducing ED in children.[39] Radiation doses showed an obvious tendency to increase with slice number and decrease with the use of exposure reduction techniques such as ASIR and iDose. Particularly, there was an increasing trend toward radiation dose with increasing number of slices, especially in the head and chest, which is in contrast with a study in which dose reduction was achieved for all types of CT examinations with the 256-slice scanner.[40] However, the results were similar to the doses associated with 4-, 8-, 16-, and 64-slice CT scanners.[41] Hence, small slice CT scanners and large sliced scanners with exposure reduction techniques such as ASIR and iDose may be used efficiently to scan anatomical areas with low radiation doses.

It should be noted that although CTDIvol and DLP were higher in the head compared with the chest in our study, the latter was higher in terms of ED. CTDIvol measures the radiation output of a CT scanner, which is useful to compare devices. However, CTDIvol depends on tube current, which changes as per the type of scan being performed. Since the penetrating power required to visualize the brain is higher compared with the chest due to its anatomy, the tube current used is higher, causing the CTDIvol of head scans to rise. On the other hand, ED is a measure of the dose received by the patient, with tissue-weighting factors coming into play. This factor is smaller for the head compared with the chest (0.0021 versus 0.014 mSv·mGy·cm),[42] causing the ED received during head scans to be much lower as compared with chest scans. Hence, the patients who had chest scans received more radiation than patients who had head scans. Furthermore, since the incidence of cancer has been reported to be larger after chest scans,[43] it is possible that such patients in our study could also be at risk.

There are several limitations to our study. It was a retrospective, single-center study, similar to many other dose surveys, resulting in an inherent bias in patient selection. The number of examinations included in the evaluation was small compared with the total examinations in our hospital. The time of observation was only 6 months, given the recent introduction of Radimetrics in China. Because of the large number of patients (about 1000 examinations per day) undergoing CT, we had to distribute them into different CT groups: physical examinations and clinical examinations using 16 slices, and coronary CT angiography or cardiac imaging. There was a scarcity of patients in the group using 16-slice scanners for physical examinations and clinical patients, leading to a smaller number of patients in the abdomen and spine CT group and none in the neck and pelvis group. Furthermore, although pediatric-specific CT protocols were used in this study, they were not well optimized as also seen in previous studies.[12,44] However, adult CT protocols were not used in pediatric patients. Lastly, the CT equipment used in our analysis were from different manufacturers and had different use situations; for example, CT4 was used for lung scanning because of the larger number of patients, whereas CT5 was used mostly for head and few lungs scans. This led to difficulties in analyzing the scans from the two scanners. In the future studies, we also plan to add more equipment for analysis in case of increase in the patient sample size. Nevertheless, this first survey in China to estimate the radiation doses may be of significant importance for future studies and also clinicians to set DRLs for patients.

In conclusion, the findings of this study reveal the radiation doses in China for a large number of observations using automated data collection. These data provide a basis for evaluation of CT radiation doses in China and allow institutions to understand doses by anatomical area to develop DRLs and allow for cross-country comparisons.

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APPENDIX. SUPPLEMENTARY DATA

Supplementary data related to this article can be found at http://links.lww.com/JCMA/A13.

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