Patient-Specific Organ and Effective Dose Estimates in Adult Oncologic CT

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OBJECTIVE. Patient-specific organ and effective dose provide essential information for CT protocol optimization. However, such information is not readily available in the scan records. The purpose of this study was to develop a method to obtain accurate examination- and patient-specific organ and effective dose estimates by use of available scan data and patient body size information for a large cohort of patients.

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MATERIALS AND METHODS. The data were randomly collected for 1200 patients who underwent CT in a 2-year period. Physical characteristics of the patients and CT technique were processed as inputs for the dose estimator. Organ and effective doses were estimated by use of the information and computational human phantoms matched to patients on the basis of sex and effective diameter. Size-based ratios were applied to correct for patient-phantom body size differences.

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RESULTS. Patients received a mean of 60.1 mGy to the lens of eye per brain scan, 9.5 mGy to the thyroid per chest scan, 17.9 mGy to the liver per abdomen and pelvis scan, and 19.1 mGy to the liver per body scan. A factor of 2 difference in dose estimates was observed between patients of various habitus.

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CONCLUSION. Examination- and patient-specific organ and effective doses were estimated for 1200 adult oncology patients undergoing CT. The dose conversion factors calculated facilitate rapid organ and effective dose estimation in clinics. Compared with nonspecific dose estimation methods, patient dose estimations with data specific to the patient and examination can differ by a factor of 2.

Keywords: adult patient specific, correction, CT, effective dose, organ dose, size-specific dose estimate

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CT assists in the localization and diagnosis of primary and metastatic malignances and in the planning of radiologic treatment [1]. CT has become one of the most popular noninvasive diagnostic measures that many physicians all over the world rely on, but it also results in a radiation dose to patients that must be both justified and optimized [2–4]. CT studies are estimated to account for one-half of medical diagnostic radiation exposure of the population in the United States [5].

The principle of justification in medical imaging posits that the benefit of the examination be weighed against the biologic risk incurred in radiation exposure. In this sense, assessment of image quality and estimation of radiation dose are important considerations in the medical decision-making process. According to the concept of optimization, the radiation dose shall be no greater than that needed to achieve the imaging objective. Guidelines for justification and optimization of imaging dose in the radiologic community are established in the United States, but some are subject to outdated data and must be updated [3, 6–8].

In light of the dynamic nature of CT technology, in which advances in detectors and data processing are continuously implemented, radiation dose data of patients who have undergone CT scans with the latest protocols and technologies are needed to provide solid ground for dose optimization, protocol assessment, and protocol development. Ensuring that dose estimates reflect actual CT conventions allows clinicians to better inform not only the patient but also themselves during the clinical decision-making process.

Diagnostic reference levels (DRLs) are the recommended dose levels specified by scan type. They are established by national, regional, or local radiologic protection institutions and are used to identify CT practices with unusually high doses and assist with the dosimetric optimization of CT protocols [3,

9–11]. The dose quantities used in establishing CT DRLs typically include volume CT dose index ($CTDI_{vol}$), dose-length product (DLP), and more recently size-specific dose estimate (SSDE) [3, 10–12]. DRLs are typically set as the 75th percentiles of the distributions of the dose quantities based on national, regional, or local dose surveys [3, 10, 11]. Countries all over the world have established DRLs for CT dose optimization [10, 11, 13–17]. The establishment and application of DRLs has been found to facilitate protocol optimization and reduce unnecessary radiation dose in CT examinations while maintaining image quality [17, 18].

Optimization of existing protocols and assessment of new protocols entails tradeoffs between the benefit of timely diagnosis and the risk of radiation-induced effects, such as secondary cancer [19–22]. Organ dose and effective dose are required to estimate the risk of radiation-induced stochastic effects [22], but they are not readily available in scan records or images. Complex modern CT protocols further complicate estimation of organ doses to patients. For oncology patients, multiple diagnostic CT studies may be prescribed before, during, and after treatments [23, 24]. Moreover, loosely defined CT scan range, which varies according to preference and local convention, can have considerable impact on radiation dose.

The scan range of a protocol often varies among institutions and among physicians and technologists. An extended range can include more radiosensitive organs at the ends of scanning [25]. The dose to small radiosensitive organs, such as the thyroid, male gonads, and salivary glands, can increase as many as five times in a matter of a few centimeters of scan range extension [25]. Modern scanning techniques also affect radiation dose and are not necessarily accounted for in all dose estimation methods, as is the case with tube current modulation (TCM). TCM changes the x-ray quantity based on the attenuation of the body section, and it can change the dose to superficial organs by approximately 60% compared with the dose from scans without this technique [26–28]. American Association of Physicists in Medicine (AAPM) report 96 [29] provides conversion factors (*k* factors) for effective dose estimation but not for organ dose estimation, and the effect of TCM on dose is not considered. Thus, sophisticated organ dose estimation tools, which can account for small variations in scan range and use of modern scanner features, should be used to perform organ dose estimation for the complex and various modern CT scan protocols.

Effective dose has been recommended for comparing doses in different populations, doses in different protocols, and doses at different institutions [29, 30]. Effective dose can be accurately calculated from the weighted sum of tissue equivalent doses of both sexes [30] or roughly estimated from a CT tube output parameter, such as DLP [29]. Accurate organ doses (and subsequently tissue equivalent doses) are the foundation of accurate effective dose estimates. On the other hand, quick effective dose estimates can be obtained by converting from a CT output indicator such as DLP by use of a dose conversion coefficient for a fast and efficient approximation in the clinical setting [31–34]. The convenience of such coefficients is compromised by the influence of patient body size variations and patient-specific scan parameter variations. Researchers have found that *k* factors decrease as body mass index (BMI) increases in adult populations [35]. BMI-based and size-based *k* factors have been generated to provide more reasonably accurate dose estimates in clinics for cohorts of patients of various sizes [35, 36].

The objectives of this study were to develop a method to obtain accurate examination- and patient-specific organ and effective dose estimates by use of available scan data and patient body size information and Monte Carlo approaches for over a thousand adult oncology patients who underwent CT at our institution (Memorial Sloan Kettering Cancer Center). More accurate organ and effective doses can assist in clinical protocol optimization, clinical decision making, and future epidemiologic studies. Patient-specific results were compared with other methods and national DRLs, and conversion factors were generated to characterize the patient population and facilitate fast dose estimation in our clinic.

Materials and Methods

Patient Population

This HIPAA-compliant retrospective study received institutional review board approval with a waiver of the requirement for patient informed consent for the use of CT scans of adult oncology patients obtained during a contiguous 2-year period. All DICOM images were anonymized before use. A total of 1200 adult CT studies were selected for diagnostic protocols covering four body regions: head (brain), chest, abdomen-pelvis, and chest-abdomen-pelvis. Specifically, for each body region and each sex, 150 cases were randomly selected.

The patient body anteroposterior size and lateral size were reported by the vendor-provided dose management application (DoseWatch, GE Healthcare). Effective diameter was then calculated by the methods described in AAPM report 204 [6]. The body sizes reported with the application were verified by manual measurement of the

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TABLE 1: Effective Diameter (EDs) of Patients and Corresponding Human Phantoms

No. of Examinations	Mean Weight (kg)		Minimum–Maximum ED (cm)		Phantom ED (cm)			SSDE Ratio (Patient to Phantom)[a]		
	Men	Women	Men	Women	Weight Category	Men	Women	Chest	Abdomen	Pelvis
Head										
300	—	—	—	—	—	—	—	—	—	—
Chest										
115	66 (47–85)	59 (37–87)	23.7–27.8	21.4–28.5	Normal	27.0	28.1	1.14 ± 0.15		
40	78 (67–91)	72 (59–86)	28.0–29.2	28.6–29.7	Overweight	28.5	29.0			
30	81 (66–94)	74 (58–94)	29.3–30.1	29.7–30.4	Obese 1	30.0	30.3			
39	89 (63–106)	87 (60–194)	30.3–31.3	30.7–31.9	Obese 2	30.6	31.1			
76	103 (78–153)	95 (57–154)	31.3–43.0	32.0–43.7	Obese 3	32.0	32.8			

(Table 1 continues on next page)

TABLE 1: Effective Diameter (EDs) of Patients and Corresponding Human Phantoms (continued)

No. of Examinations	Mean Weight (kg)		Minimum–Maximum ED (cm)		Phantom ED (cm)			SSDE Ratio (Patient to Phantom)[a]		
	Men	Women	Men	Women	Weight Category	Men	Women	Chest	Abdomen	Pelvis
Contrast-enhanced abdomen-pelvis										
134	66 (45–90)	59 (39–77)	22.4–27.5	20.8–26.3	Normal	26.8	24.1		1.03 ± 0.07	1.10 ± 0.10
110	82 (66–115)	77 (57–96)	27.6–30.9	26.3–30.2	Overweight	28.2	28.5			
39	95 (73–124)	98 (73–143)	31.2–35.6	30.3–33.2	Obese 1	33.8	31.9			
17	118 (103–135)	108 (79–123)	36.0–37.4	33.4–37.2	Obese 2	37.5	34.8			
0	—	—	—	—	Obese 3	40.8	40.5			
Contrast-enhanced chest-abdomen-pelvis										
136	69 (55–88)	62 (42–92)	23.3–27.9	19.5–28.0	Normal	27.6	27.3	1.03 ± 0.10	1.03 ± 0.07	1.14 ± 0.13
80	80 (62–97)	80 (70–96)	28.2–30.7	28.2–30.0	Overweight	28.5	29.0			
54	91 (76–115)	88 (73–100)	30.7–33.9	30.2–31.0	Obese 1	32.9	31.1			
15	112 (98–120)	100 (96–104)	34.1–36.0	31.9–32.9	Obese 2	35.2	32.4			
15	115 (96–136)	98 (81–115)	36.9–39.8	33.3–39.0	Obese 3	38.2	34.1			

Note—Dash (—) indicates not applicable. Effective diameter (ED) is used to find the representative phantom with closest size to a patient. For head scans ED was not used, and all patients are represented by normal-weight phantoms. Values in parentheses are minimum–maximum. SSDE = size-specific dose estimate.
[a]Values are mean ± SD.

anteroposterior and lateral sizes on the CT images of 20 randomly assigned patients. A dose estimator (VirtualDose CT, Virtual Phantoms) was used to compare the effective diameters of the patients with those of anthropomorphic computational phantoms by subtracting one diameter from the other and calculating the absolute differences. By matching each patient with a phantom of the least size difference, the software then categorized the patients into five subgroups (normal-weight to obese class 3) characterized by phantoms that had been made to fit in the World Health Organization BMI category classification shown in Table 1 [37, 38].

CT Protocols

All studies were performed with Discovery CT750 HD scanners (GE Healthcare) (Table 2). The tube voltage for all scans was 120 kVp. The tube current varied from case to case depending on the use of TCM, the size and density of the scanned region, and the noise index prescribed for the diagnostic task. The exposure time per gantry rotation ranged from 0.5 second to 1 second. The pitch was 0.984 for body scans and 1.0 for head scans. The nominal total collimation was 20 mm for head scans and 40 mm for body scans. A body bow-tie filter was used for body scans and a medium bow-tie filter for head scans. A 2-cm overscan (one-half of a rotation) was assumed and added to both ends of helical body scans in dose estimation.

Routine CT protocols for four regions were investigated: head, chest, abdomen-pelvis, and chest-abdomen-pelvis. The scan ranges were defined by anatomic landmarks as shown in Table 2. The most commonly used protocols were selected. For head scans, the selected protocols were head with contrast administration, head without contrast administration, and head with or without contrast administration. For chest scans they were chest with contrast administration and chest without contrast administration. For abdomen-pelvis scans, the protocol was abdomen-pelvis with contrast administration. For chest-abdomen-pelvis scans, it was chest-abdomen-pelvis with contrast administration.

Scan technique and basic dosimetric information ($CTDI_{vol}$, DLP, and SSDE) of CT examinations of adults were gathered by means of the dose management application. Then the desired scans (routine clinical scan of the four investigated body regions, excluding impromptu extra scans and nonclinical scans, with scan parameters and patient size information) were filtered out of tens of thousands of scans with in-house database queries (Microsoft Access database application). A list of male

TABLE 2: CT Technique Summary

Examination	Tube Potential (kVp)	Tube Current (mA)	Revolution Time (s)	Bow Tie Filter	Pitch	Collimation (mm)	Scan Range
Head	120	300	1	Medium	1.000	20	Hard palate–base of occipital bone to vertex
Chest	120	TCM 120–380	0.5	Body	0.984	40	Supraclavicular fossa through adrenal glands (level of L2 vertebra)
Contrast-enhanced abdomen-pelvis	120	TCM 220–380	0.7	Body	0.984	40	Diaphragm to pubic symphysis
Contrast-enhanced chest-abdomen-pelvis	120	TCM 220–380	0.7	Body	0.984	40	Supraclavicular fossa to pubic symphysis

Note—TCM = tube current modulation.

TABLE 3: Dose Measurements (75th Percentile) for Each Type of CT Examination

Examination	No.	$CTDI_{vol}$ (mGy)		SSDE (mGy)		DLP (mGy · cm)	
		Current Study	DIR	Current Study	DIR	Current Study	DIR
Head	300	60 (56–60)	57	—	—	1078 (958–2156)	1011
Chest	300	12 (5–15)	15	14 (7–18)	16	475 (150–658)	545
Contrast-enhanced abdomen-pelvis	300	17 (12–26)	19	20 (16–25)	19	1007 (555–1439)	995
Contrast-enhanced chest-abdomen-pelvis	300	16 (10–21)	19	19 (14–22)	19	1263 (684–1708)	1193

Note—Dash (—) indicates not applicable. Values in parentheses are minimum–maximum. Dose Index Registry (DIR) data were summarized by Kanal et al. [12] from 1.3 million records. $CTDI_{vol}$ = volume CT dose index, SSDE = size-specific dose estimate, DLP = dose-length product.

patients and a list of female patients were generated for each of the four regions. The third step was randomized allocation of 150 men and 150 women for each body region from the corresponding list by use of Matlab software (version 2016b, MathWorks). Finally, because most of the CT examinations were performed with TCM, archived and anonymized DICOM images of these CT scans were gathered through the Hermes Gold (Hermes Medical Solutions) system as the source of slice-by-slice scan parameters for dose estimation.

Dose Percentiles for Diagnostic Reference Level

$CTDI_{vol}$, DLP, and SSDE were gathered from the records of the dose management application. The SSDEs for head scans were ignored because head sizes were incorrectly estimated by the vendor software in approximately 10% of cases, the adult head does not vary as much as the body does, and adult routine head scan technique is fixed. The 75th percentiles of the three quantities were summarized for each protocol covered in this study. They were compared with the national DRLs derived from over 1 million CT records of the Dose Index Registry [12].

Estimation of Organ and Effective Doses With Body Region–Specific Corrections

Protocol parameters, including slice-by-slice tube current, were extracted from the DICOM headers of images with a previously developed tool (DICOMDataImportExportTool, written in C# programming language) and then were sent to the application programming interface of the Monte Carlo–based organ dose and effective dose estimator and stored in a database ready for retrieval in the following steps [38]. The dose estimator was modified to automatically match a human phantom to each patient by comparing effective diameter of the patient's scanned body region (calculated from dose management application data) with that of the phantoms, which were previously measured in the 3D-Doctor program (Able Software) according to AAPM publication 204 methods [6]. The phantom with the least diameter difference from the patient was selected. Normal-weight phantoms were used for all head scans. After phantom selection, the parameters of the CT scan protocol were retrieved from the database and automatically used to estimate the organ doses and effective doses. The effect on dose of the remaining size difference between the phantom and the patient was addressed by applying a table of SSDE ratios for phantom-patient size correction presented according to the following description.

To account for size variations among patients and between body regions, ratios of body region–specific patient SSDE to phantom SSDE were calculated and used during dose estimation. Specifically, as shown in equation 1, for chest scans the ratios of chest SSDE were applied: For abdomen-pelvis scans, the ratios of abdomen SSDE were applied to the abdominal region, and the ratios of pelvis SSDE were applied to the pelvic region. For chest-abdomen-pelvis scans, the ratios of chest SSDE, the ratios of abdomen SSDE, and the ratios of pelvis SSDE were applied to chest, abdomen, and pelvis regions. These ratios are summarized in Table 1. As a result, the dose to any organ from a body scan was the sum of the dose from the chest scan (if any), abdomen scan (if any), and pelvis scan (if any) after application of SSDE ratios.

$$Organ\ dose = \sum_{i=1}^{N} D_i \times \frac{SSDE_{i,\,patient}}{SSDE_{i,\,phantom}}, \qquad (1)$$

where organ dose is the dose in milligrays to any organ defined in the phantom, and N is the total number of scanned regions: one region (chest) for chest scans, two regions (abdomen and pelvis) for abdomen-pelvis scans, and three regions (chest, abdomen and pelvis) for chest-abdomen-pelvis scans. The ratio was calculated for each region individually. D_i is the dose in milligrays to the organ from the primary or scatter photons of scanned region i. $SSDE_{i,\,patient}$ is the SSDE of the patient for the scanned region i. $SSDE_{i,\,phantom}$ is the SSDE of the phantom of scanned region i, generated by multiplying the $CTDI_{vol}$ for the region and the AAPM factor in equation 2 for the size of the body region [6, 39]:

$$f_{size}^{32X}, \qquad (2)$$

With the method described earlier, organ doses were estimated and compared with doses estimated with size-specific methods in the literature [40, 41]. Effective doses were calculated with the dose estimator, which operates with ICRP publication 103 [30] methods. For comparison purposes, effective doses were also calculated by converting DLPs by use of DLP–to–effective-dose k factors from AAPM report 96 [29].

Size-Based Dose Conversion Factors

In this study, adult patients were categorized into five groups by BMI category: normal weight, overweight, obese class 1, obese class 2, and obese class 3. The k factors (DLP-normalized effective dose) for each category were calculated for all of the body regions. The k_{org} factors for converting DLP to organ doses for men and women of various sizes were also calculated to enable rapid clinical dose estimations.

Results

Patient Demographics

CT scan data from a total of 1200 adult patients (600 men, 600 women) were used for dose calculations in this study. The percentages of patients in the normal weight category were 38% (chest), 45% (abdomen-pelvis), and 45% (chest-abdomen-pelvis). The percentages of patients in the overweight category were 13% (chest), 36% (abdomen-pelvis), and 27% (chest-abdomen-pelvis). The percentages of patients in obese class 1–3 were 49% (chest), 19% (abdomen-pelvis), and 28% (chest-abdomen-pelvis).

Dose Percentiles for Diagnostic Reference Level

Table 3 shows the 75th percentiles, minimum, and maximum of our study $CTDI_{vol}$, SSDE, and DLP. The table also shows the U.S. national 75th percentiles of the same parameters (national DRLs) from the literature [12]. The 75th percentiles of the current study were very close to the national DRLs [12]. Most of the 75th percentiles were lower than those of the national values, and the

others were no more than 7% higher than the corresponding national values.

Patient-Specific Organ Doses and Effective Doses

Table 4 summarizes the estimated organ doses and effective doses. After considering the ICRP publication 103 [30] tissue-weighting factors and the size of the radiation dose the organs received from the scans, we considered the top 5 of 29 organ doses for head scans and the top 10 of 29 organ doses for body scans sorted in descending order. Between patients, the ratios of maximum to minimum of the top organ doses were 2.5 for head scans, 3.4 for chest scans, 2.2 for abdomen-pelvis scans, and 2.1 for chest-abdomen-pelvis scan on average.

The mean effective doses from the dose estimator and those obtained with the *k* factors in AAPM report 96 [29] are also shown in Table 4. Between patients the ratios of maximal effective dose to minimal effective dose were 2.1 (head), 3.1 (chest), 1.6 (abdomen-pelvis), and 1.7 (chest-abdomen-pelvis).

Table 5 shows the derived *k* factors based on the effective doses and DLP values in the current study. The *k* factors decreased as BMI category increased for body scans. Table 5 also shows the DLP–to–organ dose factors (k_{org} factors) for 10 organs (five organs for head scans) that received the higher doses in both male and female patients of various body sizes. Although these factors are not as accurate as using the dose estimator and TCM information in estimating patient organ doses, they provide an alternative method for quick estimation of organ dose from DLP in clinics.

Discussion

Understanding CT doses in a given clinic and comparing them with national DRLs reveals opportunities for optimization with potential dose reduction while maintaining image quality. Conformance of clinical CT doses to national and regional DRLs has been found to effectively reduce CT radiation dose without compromising diagnostic outcome [17, 18]. In this study we summarized the 75th percentiles of $CTDI_{vol}$, DLP, and SSDE for the protocols investigated. Across the four body regions, $CTDI_{vol}$ was the highest for head CT because large numbers of photons are needed to penetrate the thick skull. DLP was also higher for head scans because of the high $CTDI_{vol}$, the extended scan length above the patient's head (up to 4 cm above the top of head), and acquisition of multiple phase scans with a contrast agent. For head CT with or without contrast administration, one scan before and one scan after contrast administration were always obtained, so the DLP was twice that of other head scans. Overall our percentiles were consistent with and comparable to national Dose Index Registry percentiles, showing successful management of CT radiation dose at our institution compared with national optimization patterns.

The dose estimator used in this study included realistic computational human phantoms of five BMI categories (normal weight to obese class 3) to represent patients. The effective diameter of the scanned region of each patient was used to find the closest-size human phantom. Even with the closest-size

TABLE 4: Organ and Effective Doses

Organ	Dose (mSv)		
	Men	Woman	All
Head			
Lens	60.1 ± 13.0 (54.6–114.8)	59.7 ± 6.7 (55.2–118.6)	59.9 ± 10.3 (54.6–118.6)
Brain	51.9 ± 11.3 (46.2–99.3)	46.6 ± 5.2 (43.1–92.7)	49.3 ± 9.2 (43.1–99.3)
Salivary glands	41.9 ± 9.1 (38.0–79.9)	49.6 ± 5.6 (45.9–98.5)	45.8 ± 8.4 (38.0–98.5)
Extrathoracic region	37.2 ± 8.1 (33.7–70.8)	44.6 ± 5.0 (41.2–88.6)	40.9 ± 7.7 (33.7–88.6)
Red bone marrow	5.7 ± 1.2 (5.2–10.8)	6.6 ± 0.7 (6.1–13.1)	6.1 ± 1.1 (5.2–13.1)
Effective dose	2.8 ± 0.6 (2.5–5.3)	2.7 ± 0.3 (2.5–5.3)	2.7 ± 0.5 (2.5–5.3)
Effective dose AAPM 96	2.3 ± 0.5 (2.0–4.5)	2.1 ± 0.2 (2.0–4.0)	2.2 ± 0.4 (2.0–4.5)
Chest			
Breasts	7.8 ± 2.3 (5.0–12.6)	6.8 ± 1.9 (4.2–11.4)	7.3 ± 2.2 (4.2–12.6)
Colon	5.5 ± 1.5 (3.2–9.6)	4.9 ± 1.3 (2.4–11.2)	5.2 ± 1.4 (2.4–11.2)
Esophagus	6.3 ± 1.3 (3.6–9.3)	6.6 ± 1.8 (4.1–11.4)	6.4 ± 1.6 (3.6–11.4)
Gonads	0.3 ± 0.1 (0.2–0.5)	0.5 ± 0.1 (0.3–1.1)	0.4 ± 0.2 (0.2–1.1)
Liver	10.1 ± 2.1 (6.3–16.1)	8.7 ± 2.1 (4.9–17.1)	9.4 ± 2.2 (4.9–17.1)
Lungs	9.4 ± 1.9 (6.3–13.8)	8.8 ± 2.3 (5.5–15.5)	9.1 ± 2.1 (5.5–15.5)
Red bone marrow	3.7 ± 0.6 (2.4–5.1)	3.4 ± 0.8 (2.1–5.9)	3.6 ± 0.8 (2.1–5.9)
Stomach	8.0 ± 1.6 (5.4–12.8)	7.1 ± 1.6 (3.8–14.4)	7.5 ± 1.7 (3.8–14.4)
Thyroid	9.5 ± 2.1 (5.7–16.1)	10.7 ± 3.2 (6.2–20.4)	10.1 ± 2.8 (5.7–20.4)
Urinary bladder	0.6 ± 0.1 (0.3–0.9)	0.5 ± 0.1 (0.3–1)	0.5 ± 0.1 (0.3–1)
Effective dose	6.3 ± 1.0 (4.2–8.4)	5.4 ± 1.2 (3.2–9.8)	5.9 ± 1.2 (3.2–9.8)
Effective dose AAPM 96	5.9 ± 1.6 (2.8–9.2)	4.6 ± 1.9 (2.1–9.2)	5.2 ± 1.9 (2.1–9.2)
Abdomen-pelvis			
Breasts	6.8 ± 3.5 (2.7–15.8)	4.2 ± 1.8 (2.5–8.1)	5.5 ± 3.1 (2.5–15.8)
Colon	15.5 ± 1.7 (12.5–19.5)	16.4 ± 1.6 (12.8–20.7)	16.0 ± 1.7 (12.5–20.7)
Esophagus	1.0 ± 0.1 (0.8–1.3)	1.3 ± 0.2 (1.1–1.9)	1.1 ± 0.2 (0.8–1.9)
Gonads	3.4 ± 0.7 (2.3–5.9)	13.0 ± 1.9 (8.8–17.3)	8.2 ± 5.0 (2.3–17.3)
Liver	17.9 ± 2.4 (14.1–23.4)	17.0 ± 1.9 (13.2–23.4)	17.5 ± 2.2 (13.2–23.4)
Lungs	6.2 ± 0.8 (4.9–7.9)	5.9 ± 0.7 (4.8–8.3)	6.0 ± 0.7 (4.8–8.3)
Red bone marrow	5.5 ± 0.5 (4.5–6.8)	5.9 ± 0.5 (4.9–7.6)	5.7 ± 0.6 (4.5–7.6)
Stomach	13.5 ± 1.6 (10.4–17.9)	12.8 ± 1.4 (9.7–17.1)	13.1 ± 1.5 (9.7–17.9)
Thyroid	0.7 ± 0.1 (0.5–1.1)	0.8 ± 0.1 (0.6–1.1)	0.7 ± 0.1 (0.5–1.1)
Urinary bladder	11.1 ± 1.0 (9.1–14.8)	13.6 ± 1.9 (9.4–18.2)	12.3 ± 1.9 (9.1–18.2)
Effective dose	8.9 ± 0.9 (7.1–10.9)	8.6 ± 0.8 (7.2–11.7)	8.7 ± 0.9 (7.1–11.7)
Effective dose AAPM 96	13.1 ± 3.0 (8.6–21.6)	12.0 ± 3.0 (8.3–19.8)	12.6 ± 3.1 (8.3–21.6)

(Table 4 continues on next page)

TABLE 4: Organ and Effective Doses (continued)

Organ	Dose (mSv)		
	Men	Woman	All
Chest-abdomen-pelvis			
Breasts	15.8 ± 3.0 (8.2–20.0)	12.7 ± 2.4 (8.6–19.1)	14.3 ± 3.1 (8.2–20.0)
Colon	15.5 ± 1.5 (11.1–19.6)	17.2 ± 2.0 (11.3–22.7)	16.3 ± 2.0 (11.1–22.7)
Esophagus	7.6 ± 1.7 (5.1–11.4)	8.8 ± 1.9 (6.7–14)	8.2 ± 1.9 (5.1–14)
Gonads	3.7 ± 0.8 (2.5–5.9)	13.6 ± 1.9 (8–17.8)	8.6 ± 5.2 (2.5–17.8)
Liver	19.1 ± 2.4 (14.3–24.5)	18.8 ± 2.2 (14.5–24.8)	19.0 ± 2.3 (14.3–24.8)
Lungs	15.1 ± 2.6 (10.3–21.7)	14.9 ± 2.4 (12.1–22.3)	15.0 ± 2.5 (10.3–22.3)
Red bone marrow	8.4 ± 1 (6.5–10.5)	8.8 ± 0.9 (7.4–11.2)	8.6 ± 1 (6.5–11.2)
Stomach	15.8 ± 2.0 (11.0–20.9)	15.7 ± 1.7 (10.7–20.6)	15.8 ± 1.9 (10.7–20.9)
Thyroid	10.7 ± 2.4 (6.6–21.3)	13 ± 3.3 (9.1–22)	11.8 ± 3.1 (6.6–22)
Urinary bladder	10.9 ± 1.0 (8.3–14.1)	14.2 ± 1.8 (8.7–18.6)	12.5 ± 2.2 (8.3–18.6)
Effective dose	13.0 ± 1.4 (9.9–15.9)	12.6 ± 1.3 (10.6–16.8)	12.8 ± 1.3 (9.9–16.8)
Effective dose AAPM 96	17.1 ± 3.8 (11.3–25.6)	14.7 ± 3.7 (10.3–24.4)	15.9 ± 3.9 (10.3–25.6)

Note—Effective dose derived by use of dose-length product in current study and *k* factors in American Association of Physicists in Medicine report 96 (AAPM 96). Values are mean ± SD with minimum–maximum in parentheses.

phantoms selected, patient body sizes are usually different from their representative phantoms. Moreover, in each patient, the sizes of the chest, abdomen, and pelvis can be different from those of the phantom, and the scanner output for each of these regions will be different. In this study, we addressed such size variation by calculating and applying the ratio of patient SSDE to phantom SSDE for each scanned body region (except head) of each patient. SSDE for the head was ignored because approximately 10% of the adult head size reported by the dose estimator was erroneously comparable to adult body size. Moreover, adult head breadth and length in the United States vary by approximately 12% (5th or 95th percentiles compared with 50th percentiles) [42], so head size does not vary as much as the body size. Finally, most clinical routine adult brain scans are performed with fixed tube current at our institution, so scanner-reported $CTDI_{vol}$ and SSDE (if correctly calculated) are very similar among adult patients. Subsequent investigation showed apparatuses (e.g., pillow, contrast infusion catheters) surrounding the patient's head were mistakenly included in automated head size measured by the dose estimator, but this potential error was not observed in the manual verification of body size measurements.

The SSDE ratios summarized in Table 1 show that on average patient SSDE was slightly higher (3–14%) than phantom SSDE, suggesting the patient size was slightly smaller than the corresponding phantom. This was because underweight patients were represented by normal-weight phantoms. On the other hand, patients of extremely large body sizes were represented by obese class 3 phantoms, and doses were also corrected by their SSDE ratios. Thus, the use of SSDE ratios addressed the remaining effect that size differences between phantoms and patients have on doses. Moreover, the use of the ratios cancelled out most of the error caused by the difference between effective diameter and water-equivalent effective diameter for chest scans, whereas for abdominal scans these two kinds of diameters agreed within 2% [39].

AAPM report 96 [29] provides *k* factors for converting DLP to effective dose for average-size adults. Studies [35, 43] have shown that the *k* factors decrease as patient body sizes increase and that the *k* factors for obese patients can be one-half of those of average-size patients. Our estimated *k* factors showed a similar trend that agreed with and consolidated findings in the literature [35, 36, 40, 41, 44]. Our DLP-normalized organ doses (k_{org} factors) decreased with patient size, and the trend was consistent with findings in the literature [36, 40]. The *t* tests between male and female organ doses for all investigated body regions showed significant ($p < 0.05$) differences for most of the organs, so k_{org} factors for men and women were calculated separately (Table 5). This table of k_{org} factors for 10 organs that received higher doses provides an alternative tool for estimating organ dose with reasonable accuracy in clinical settings where time would be limited and TCM information would not be readily available. When more accurate doses are needed, the modified dose estimator, DICOM images, and dose management application records can be used according to the methods in this study to calculate organ and effective doses.

For our study protocols and patient population, the highest dose to an organ per scan was to the lens of the eye (60.1 mGy), which was due to the high tube current–time setting (300 mAs and pitch of 1 without TCM) used in head scans. For head CT examinations consisting of one acquisition before contrast infusion and another acquisition after, patient radiation dose is doubled, indicating the lens can receive up to 120 mGy in one examination. Head CT should be carefully prescribed and optimized to control the dose. Studies [45–47] have shown a threshold of 500 mGy for the tissue reaction of lens opacities from fractionated or protracted exposures irrespective of the rate of dose delivery. In chest scans, the thyroid received a fairly high dose of 9.5 mGy per scan owing to the supraclavicular scan range that covered this superficial organ. In all three kinds of investigated body scans, visceral organs such as the liver received higher doses than other visceral organs because they were close to the body surface and not as well shielded as other organs were by visceral fat that was modeled in the dose estimator [38, 48]. The mean ratio between maximum and minimum of organ doses of different patients undergoing similar scanning was more than 2.0 for all investigated scans. This showed the use of a single dose value is insufficient and associated with large error when patients of various habitus undergo CT with various techniques. Thus, patient-specific dose estimation methods should be used to provide a more accurate dose for individual patients.

Figure S1 shows our chest dose estimates compared with the dose estimates generated by the size-based dose estimation method used by Sahbaee et al. [41]. (Figs. S1 and S2 can be viewed in the *AJR* electronic supplement to this article, available at www.ajronline.org.) To obtain dose in milligrays using the previous method, we applied patient chest effective diameter to those investigators' equations and then multiplied $CTDI_{vol}$ by the resultant $CTDI_{vol}$-normalized organ dose. The largest difference of 38% was the dose to the thymus. For most of the organs investigat-

TABLE 5: Organ *k* Factors (DLP-Normalized Organ Doses) and *k* Factors (DLP-Normalized Effective Dose)

	k_{org} (mGy/mGy · cm) or *k* (mSv/mGy · cm)									
	Normal Weight		Overweight		Obese 1		Obese 2		Obese 3	
Region and Organ	Men	Women	Men	Women	Men	Women	Men	Women	Men	Women
Head										
Lens	0.056	0.060	—	—	—	—	—	—	—	—
Brain	0.048	0.047	—	—	—	—	—	—	—	—
Salivary glands	0.039	0.050	—	—	—	—	—	—	—	—
Extrathoracic region	0.034	0.045	—	—	—	—	—	—	—	—
Red bone marrow	0.005	0.007	—	—	—	—	—	—	—	—
Effective dose	0.0026		—		—		—		—	
Chest										
Thyroid	0.033	0.041	0.021	0.035	0.021	0.035	0.020	0.029	0.020	0.025
Spleen	0.033	0.036	0.033	0.033	0.032	0.031	0.026	0.031	0.021	0.024
Adrenals	0.031	0.034	0.031	0.031	0.031	0.028	0.025	0.027	0.022	0.022
Liver	0.033	0.035	0.031	0.030	0.028	0.026	0.021	0.024	0.017	0.019
Thymus	0.028	0.034	0.024	0.028	0.022	0.027	0.021	0.025	0.020	0.021
Kidneys	0.032	0.033	0.031	0.029	0.028	0.025	0.022	0.024	0.017	0.017
Lungs	0.028	0.034	0.023	0.028	0.023	0.026	0.021	0.025	0.020	0.022
Heart	0.025	0.032	0.021	0.025	0.020	0.023	0.019	0.022	0.018	0.019
Stomach	0.028	0.031	0.025	0.024	0.021	0.020	0.016	0.018	0.013	0.014
Breasts	0.021	0.026	0.018	0.021	0.019	0.019	0.019	0.020	0.018	0.018
Effective dose	0.021		0.017		0.016		0.014		0.012	
Abdomen and pelvis										
Spleen	0.023	0.026	0.023	0.022	0.020	0.019	0.015	0.018	—	—
Liver	0.023	0.025	0.022	0.020	0.017	0.016	0.013	0.014	—	—
Adrenals	0.021	0.023	0.022	0.020	0.019	0.017	0.014	0.015	—	—
Kidneys	0.023	0.023	0.022	0.020	0.018	0.016	0.013	0.014	—	—
Colon	0.021	0.025	0.018	0.019	0.015	0.014	0.011	0.012	—	—
Small intestine	0.021	0.026	0.017	0.018	0.013	0.013	0.009	0.010	—	—
Pancreas	0.019	0.020	0.017	0.015	0.012	0.012	0.008	0.009	—	—
Stomach	0.018	0.020	0.017	0.015	0.012	0.011	0.009	0.009	—	—
Uterus, prostate	0.018	0.020	0.014	0.014	0.011	0.011	0.010	0.009	—	—
Urinary bladder	0.016	0.022	0.013	0.014	0.010	0.011	0.008	0.009	—	—
Effective dose	0.012		0.010		0.009		0.007		—	
Chest, abdomen, and pelvis										
Spleen	0.019	0.022	0.020	0.020	0.018	0.019	0.013	0.018	0.012	0.014
Adrenals	0.018	0.021	0.020	0.018	0.019	0.017	0.013	0.016	0.012	0.012
Liver	0.020	0.022	0.019	0.018	0.016	0.016	0.011	0.014	0.010	0.011
Kidneys	0.019	0.020	0.019	0.017	0.016	0.015	0.011	0.014	0.010	0.010
Colon	0.017	0.021	0.015	0.015	0.013	0.013	0.010	0.011	0.008	0.008
Stomach	0.017	0.019	0.016	0.015	0.013	0.013	0.009	0.011	0.008	0.008
Small intestine	0.017	0.022	0.014	0.014	0.011	0.012	0.009	0.010	0.007	0.007
Lungs	0.015	0.017	0.014	0.014	0.013	0.014	0.011	0.013	0.011	0.012
Breasts	0.014	0.014	0.015	0.013	0.014	0.012	0.012	0.012	0.011	0.011
Pancreas	0.016	0.017	0.015	0.013	0.011	0.011	0.007	0.009	0.006	0.006
Effective dose	0.014		0.012		0.011		0.009		0.008	

Note—Dash (—) indicates not applicable. DLP = dose-length product.

ed, the dose estimates by Sahbaee et al. were higher than ours. This was because the effect of TCM was not considered in their method. In addition, their pitch was 1.375 whereas ours was 0.984. Given the same weighted CTDI, our pitch could lead to a 40% higher $CTDI_{vol}$ and consequently 40% higher dose estimates by use of their method. With their method, spleen and liver dose estimates were lower than ours owing to differences in scan range: our chest scans included the adrenals and at the same time covered the spleen and most of the liver. Their chest protocol was ended at the base of the lungs. On average our estimates were 11% lower than theirs.

Figure S2 shows our abdomen-pelvis dose estimates compared with the dose estimates generated by the size-based dose estimation method used by Tian et al. [40]. Those investigators used both patient effective diameter and $CTDI_{vol}$ to generate dose estimates. The largest difference of 47% was the dose to the gonads because our scans ended at the pubic symphysis but theirs went on through the ischium posterior. Even with 2 cm overscan, the male gonads were not fully covered in our scan range, leading to lower dose estimates in the male gonads and subsequently lower sex-averaged gonad dose. The large SD for gonad dose was also due to averaging the low testis dose with the high ovary dose. For most of the organs, the dose estimates by Tian et al. were higher than ours, again because no TCM was considered in their study and our $CTDI_{vol}$ was high owing to our low pitch of 0.984 compared with their 1.4. Other factors that contributed to the differences were our region-specific SSDE correction, inherent differences between human phantoms, and their use of a medium bow-tie filter as opposed to our use of a body bow-tie filter. On average our estimates were 18% lower than the ones with their method.

In our study, for dose estimation we tried to be as patient specific as possible by matching patients to five pairs of realistic human phantoms in the organ dose estimator on the basis of effective diameters and then applying region-specific SSDE corrections. The ideal situation would still be dose estimation with a computation phantom for each individual patient, which requires an exceedingly large amount of work for organ segmentation and registration and subsequent phantom construction. For TCM we considered only longitudinal modulation, because the other part of TCM (i.e., angular modulation) could change the dose to organs at or near the surface (such as lens or female breasts) by up to 38% in simulations or up to 19% in experiments [39–43]. In addition, we did not investigate the effect of contrast material on organ dose, which could increase dose to the liver by 18% and dose to the kidneys by 27% [49]. The variation of patient positioning for clinical scans was not considered, but 5-cm off-centering of the patient in the table height direction can lead to 13% breast dose change in chest CT studies [50]. Finally, to calculate effective diameter we used the anteroposterior and lateral dimensions reported by the dose management application, which was found to be up to 10% smaller than the dimensions manually measured on scout images. This discrepancy might lead to approximately 10% dose overestimation.

Conclusion

For 1200 adult patients who previously underwent CT examinations, patient-specific organ and effective doses were estimated. In addition, $CTDI_{vol}$, SSDE, and DLP were summarized and k factors specific to our patient population were generated. The 75th percentiles of $CTDI_{vol}$, SSDE, and DLP were found to be lower than or up to 7% higher than national DRLs. Dose to the lens was 60.1 mGy per unenhanced head scan and 120 mGy per scan with than without contrast administration. For body scans, doses to organs close to the body surface and not well shielded by abdominal or visceral fat (e.g., liver, thyroid) received high doses of approximately 10 mGy per chest scan, 18 mGy per abdomen-pelvis scan, and 19 mGy per chest-abdomen-pelvis scan. Compared with methods without TCM, the organ doses estimated in the current study were associated with 18% lower dose on average. Generated k factors were found to decrease with increase in body size, as previously reported in the literature [35, 36].

Because the dose estimation method in this study accounts for the effects of TCM and uses body region–specific SSDE corrections for patient body size variations among patients and between body regions, it should be an appealing option for reasonably quick and accurate organ and effective dose estimations. The k factors and k_{org} factors for patients of various sizes generated in this study enable rapid clinical dose estimations. By accounting for varying scan techniques and differences in patient habitus, this patient-specific dose estimation method results in estimates showing that some patients can receive twice the organ dose of other patients in scans of the same body region. In addition to the increased accuracy of patient dose resulting from incorporation of patient-specific factors, the process also characterizes dose for the clinic. Armed with more accurate dose information that is readily accessible, clinicians are better informed of risks, are more confident about communicating risk, and can incorporate risk into medical decisions.

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