In-patient to isocenter KERMA ratios in CT

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Purpose: To estimate in-patient KERMA for specific organs in computed tomography (CT) scanning using ratios to isocenter free-in-air KERMA obtained using a Rando phantom.

Method: A CT scan of an anthropomorphic phantom results in an air KERMA K at a selected phantom location and air kerma K_{CT} at the CT scanner isocenter when the scan is repeated in the absence of the phantom. The authors define the KERMA ratio (R_K) as K/K_{CT} , which were experimentally determined in a Male Rando Phantom using lithium fluoride chips (TLD-100). R_K values were obtained for a total of 400 individual point locations, as well as for 25 individual organs of interest in CT dosimetry. CT examinations of Rando were performed on a GE LightSpeed Ultra scanner operated at 80 kV, 120 kV, and 140 kV, as well as a Siemens Sensation 16 operated at 120 kV.

Results: At 120 kV, median R_K values for the GE and Siemens scanners were 0.60 and 0.64, respectively. The 10th percentile R_K values ranged from 0.34 at 80 kV to 0.54 at 140 kV, and the 90th percentile R_K values ranged from 0.64 at 80 kV to 0.78 at 140 kV. The average R_K for the 25 Rando organs at 120 kV was 0.61 ± 0.08 . Average R_K values in the head, chest, and abdomen showed little variation. Relative to R_K values in the head, chest, and abdomen obtained at 120 kV, R_K values were about 12% lower in the pelvis and about 58% higher in the cervical spine region. Average R_K values were about 6% higher on the Siemens Sensation 16 scanner than the GE LightSpeed Ultra. Reducing the x-ray tube voltage from 120 kV to 80 kV resulted in an average reduction in R_K value of 34%, whereas increasing the x-ray tube voltage to 140 kV increased the average R_K value by 9%.

Conclusions: In-patient to isocenter relative KERMA values in Rando phantom can be used to estimate organ doses in similar sized adults undergoing CT examinations from easily measured air KERMA values at the isocenter (free in air). Conversion from in-patient air KERMA values to tissue dose would require the use of energy-appropriate conversion factors. © 2011 American Association of Physicists in Medicine. [DOI: 10.1118/1.3635222]

Key words: CT, radiation dose, organ dose, Rando, air kerma

I. INTRODUCTION

In computed tomography (CT), as in all radiological examinations, estimation of radiation risks requires the generation of organ doses where the energy deposited in an organ is divided by the corresponding organ mass.^{1,2} Organ doses are used to predict the probability of deterministic effects such as skin erythema, epilation, and cataract induction in the eye³ which may occur in CT under exceptional circumstance.⁴ Organ doses may also estimate stochastic radiation risks of carcinogenesis as well as the induction of genetic effects when the gonads are irradiated.^{5,6} Knowledge of patient radiation risks is a key prerequisite for identification of CT examinations where the patient benefit would be expected to exceed any corresponding estimated patient risk.⁷

Current CT radiation measurements routinely performed in Radiology departments relate to computed tomography dose index (CTDI), obtained in 16 cm and 32 cm diameter cylindrical phantoms.⁸ Use of dose measurements in CTDI phantoms generally do not accurately reflect actual patient

organ dose values. This is due to differences in size and composition from patients,⁹ as well as the fact that the dose metrics reported by CT scanners, $CTDI_{vol}$ and DLP, are calculated using a weighted average dose over the cross section of the phantom, which does not correspond to a specific organ system in the patient.

Work has been done to relate CTDI values with patient organ dose by Turner *et al.*¹⁰ Their method uses Monte Carlo simulations to estimate patient doses which are then normalized by scanner CTDI values. This use of CTDI is convenient as this parameter is generally reported by CT scanners. The work presented here is complementary to Turner's approach, as the x-ray KERMA levels are measured directly in anthropomorphic phantoms, and also utilize CTDI values measured in essentially scatter-free conditions. Using $CTDI_{air}$ may help avoid difficulties encountered when measuring phantom CTDI values in scanners utilizing wide x-ray beams.

CT doses for individual patients could be estimated using anthropomorphic phantoms that are manufactured to

simulate human physical characteristics,¹¹ but this requires the use of these (expensive) phantoms and is relatively labor intensive, prohibiting the widespread adoption of this method for routine use. Computational methods may also be used to obtain organ doses using CT dosimetry software packages.^{12–15} These methods, however, are currently based on a small number of Monte Carlo calculations performed on a limited range of CT scanners, some of which differ markedly from modern MDCT scanners.¹⁶ In this paper, we propose a method for obtaining organ doses in CT scanning by use of the KERMA ratio (R_K) which offers users the ability to predict patient organ doses using free in air measurements at a CT scanner isocenter, and where the x-ray intensities may be expressed as air KERMA (mGy) values.

II. METHOD

II.A. Rando phantom and relative intensities

A complete scan (covering the entire head/neck or torso) of an anthropomorphic phantom results in an air kerma K at a selected phantom location that is only dependent on the x-ray tube voltage/filter combination and the choice of milliamperes second. Complete scans are defined here as using contiguous axial scans, or a helical scan with a pitch of 1.0. The KERMA ratio for this point, R_K in the phantom is defined as

$$R_K = K/K_{CT}, \quad (1)$$

where K_{CT} is the corresponding air kerma at the CT scanner isocenter in the absence of the phantom.

We measured R_K values in the Male Rando Phantom (The Phantom Laboratory, Salem New York) that is constructed with a skeleton and tissue equivalent materials. Male Rando represents a 175 cm tall adult weighing 73.5 kg.¹⁷ The effective atomic number of soft tissues and lung is 7.3; soft tissue has a density of 0.985 g cm⁻³, whereas that of lung has a density of 0.32 g cm⁻³. These tissue equivalent materials are appropriate for patient dosimetry at the photon energies encountered in CT.¹⁸ The phantom consists of 36 sections numbered 0 (head) to 35 (lower pelvis), with sections 0 to 34 being 2.5 cm thick and containing drilled holes for the placement of small dosimeters such as thermoluminescent dosimeter chips.

We obtained mean doses to organs of interest in CT dosimetry using the organ sampling scheme for Rando recently proposed by Scalzetti *et al.*¹⁹ The method recommended by Scalzetti *et al.*, however, did not address the issue of the red

bone marrow which is one of the most radiosensitive organs in humans. Published data show that the bone marrow is distributed throughout the body with adults reported as having 15% within slices 0–9, 43% within slices 10–26, and the remaining 42% within slices 27–35.²⁰ To estimate the mean red bone marrow dose in Rando, the median R_K value in each of these three regions was multiplied by the corresponding fractional amount of red bone marrow.

II.B. TLD dosimetry

TLD-100 chips were used consisting of lithium fluoride doped with Mg and Ti. The physical dimensions of these LiF chips were 3.2 mm × 3.2 mm × 0.9 mm, and which have good tissue equivalence at x-ray photon energies encountered in CT.²¹ The useful range of these dosimeters is reported to be from 10 μGy to 10 Gy. TLD-100 chips fade less than 20% over 3 months. All TLDs were handled using vacuum tweezers to minimize the risk of contamination.

TLDs were annealed in batches of 100 which fitted into the oven, using a coated Al planchette. The anneal cycle that was used consisted of 1 h at 400 °C, followed by a 30 min cool down to ambient temperature, and then an additional 2 h at 100 °C. Before being read, exposed TLDs were heated for 10 min at 120 °C. The TLD read cycle lasted for a total of 30 s, with a maximum temperature of 260 °C.

All chips were individually calibrated by being exposed in batches of 100 to uniform air kerma of ~40 mGy. After correction for background using unexposed chips, the acquired signal of each TLD chip was divided by the average value of all 100 chips, which provided each chip with its individual sensitivity factor. Use of individual chip calibrations resulted in an estimated intra-batch uncertainty of 1.7%. Our experimental work only makes use of TLD signal ratios, and calibrations to convert measured signals (nC) into air kerma values are not required.

II.C. CT exposures

CT scans of Rando were performed using two commercial CT scanners, a GE LightSpeed Ultra (4 slice) and a Siemens Sensation 16. In all cases, the phantom was scanned from top to bottom using the CT laser lights for alignment, and with no digital projection radiograph. For the GE LightSpeed Ultra CT scanner, scans were performed in contiguous axial mode with acquisition geometry of 4 × 5 mm, an x-ray tube rotation speed of 1 s per 360° rotation, and an increment distance of 2 cm. On the Siemens Sensation 16 scanner, the phantom was exposed in helical mode using a pitch of 1.0

TABLE I. Nominal CTDI values for Rando scans obtained from the ImPACT CT patient dosimetry calculator (ImPACT).

Scanner	X-ray techniques (kV/mAs)	Nominal CTDI (mGy) measured in		
		Air	Head phantom	Body phantom
GE	80 kV/400 mAs	43	28	12
	120 kV/400 mAs	110	78	40
	140 kV/400 mAs	150	110	56
Siemens	120 kV/300 mAs	62	56	23

TABLE II. Distribution of R_K values as a function of x-ray tube voltage and body region.

Body region	Percentile	80 kV		120 kV		140 kV
		GE	GE	Siemens	GE	
Head (slices 1–5)	10th	0.37	0.54	0.58	0.63	
	25th	0.40	0.56	0.60	0.66	
	median	0.42	0.59	0.63	0.69	
	75th	0.46	0.61	0.66	0.74	
	90th	0.50	0.64	0.67	0.78	
Neck (slices 6–10)	10th	0.50	0.66	0.69	0.71	
	25th	0.54	0.70	0.74	0.76	
	median	0.67	0.76	0.80	0.84	
	75th	0.72	0.81	0.85	0.89	
	90th	0.76	0.86	0.89	0.96	
Chest (slices 10–24)	10th	0.37	0.53	0.56	0.56	
	25th	0.41	0.58	0.60	0.61	
	median	0.46	0.62	0.66	0.66	
	75th	0.50	0.67	0.70	0.70	
	90th	0.60	0.72	0.74	0.76	
Abdomen (slices 22–29)	10th	0.35	0.53	0.57	0.55	
	25th	0.39	0.56	0.58	0.59	
	Median	0.43	0.59	0.63	0.65	
	75th	0.50	0.64	0.68	0.70	
	90th	0.64	0.70	0.73	0.75	
Pelvis (slices 30–34)	10th	0.30	0.45	0.48	0.49	
	25th	0.32	0.48	0.50	0.51	
	median	0.38	0.53	0.54	0.57	
	75th	0.44	0.58	0.59	0.62	
	90th	0.55	0.65	0.66	0.70	

using an x-ray tube rotation speed of 1 s per 360° rotation. Table I summarizes the x-ray techniques (kV/mAs) used in these experiments, and also provides nominal CTDI data that pertain to the exposures described in this study.¹⁵ The CTDI values in Table II are reported by the ImPACT dose calculator. These data show that the range of exposures for K and K_{CT} ranged between 10 and 150 mGy, well above the detection threshold for these LiF dosimeters.

For each exposure, the Rando phantom contained 400 TLDs. In-air measurements were performed by arranging 15 TLDs on a cardboard holder over a distance of 10 cm on the CT scan table. The cardboard holder was placed on the table at a height of 1 cm, so that both “in air” and phantom exposures included the attenuating effect of the CT table. Each in air exposure was repeated five times at the CT isocenter, and K_{CT} values were calculated as the average of the 75 values measured. To acquire all data for the phantom and K_{CT} measurements required 475 TLDs (400 in-phantom and 75 in-air), so a total of five separately annealed batches (500 TLD’s, with 25 unused) were employed for each measurement condition.

III. RESULTS

III.A. R_K histograms

Figure 1 shows the R_K histograms for the whole Rando phantom that were obtained on the GE scanner (80 kV, 120

kV, and 140 kV), and the Siemens scanner (120 kV). Also shown in the figures are the percentile values of each global histogram distribution. At 120 kV, the median R_K values for the GE and Siemens scanners were 0.60 and 0.64, respectively. The 10th percentile R_K values ranged from 0.34 at 80 kV to 0.54 at 140 kV, and the 90th percentile R_K values ranged from 0.64 at 80 kV to 0.78 at 140 kV.

Table II shows an analysis of percentiles that were obtained for each of the four scan conditions, for CT scans of each individual body region (head, neck, chest, abdomen, and pelvis). At 120 kV, head, chest, and abdomen R_K values were very similar, but pelvis R_K values were about 12% lower. There was a 58% increase in R_K values in the cervical region relative to the average in the rest of the body.

Table III shows the spread of R_K values which we define as the ratio of the 90th percentile R_K value to the corresponding 10th percentile R_K value. The spread of R_K values in the head region is much less than in the rest of the body. The average spread of R_K values at 80 kV (~ 1.6) is higher than for scanning performed at 120 and 140 kV (~ 1.3).

Differences in R_K between the two CT scanners used in this work were relatively minor, with an average difference of only 6%. By contrast, the difference in normalized CTDI_{air} at 120 kV for body scanning is nearly 40%, which illustrates major differences in CT scanner design (e.g., added and beam shaping filtration). Scanner design therefore does not appear to have a major impact on R_K values. Similar findings have recently been reported for effective dose per unit dose length product conversion factors (E/DLP), which are also independent of design characteristics of commercial CT scanners.²²

III.B. R_K and Rando slice

Figure 2 shows the average slice R_K ($\pm$ standard deviation) plotted as a function of Rando slice number for data acquired on the GE scanner (80 kV, 120 kV, and 140 kV) and on the Siemens CT scanner (120 kV). These data show that R_K values in the head and chest and abdomen are generally very similar, and that there is a slight reduction of R_K values in the pelvis. The most striking observation is the marked increased in R_K values in the cervical region.

III.C. Organ R_K

Table IV shows the computed average values ($\pm$ standard deviation) of organ R_K for the GE scanner operated at 120 kV. Most organ R_K values at 120 kV fall in a relatively narrow range of 0.53 to 0.66. Exceptions at the low end were the prostate (R_K of 0.46), ovaries (R_K of 0.49) and uterus (R_K of 0.51). Exceptions at the high end were the thyroid (R_K of 0.88), salivary glands (R_K of 0.73), and the oral mucosa (R_K of 0.72). The experimentally determined coefficients of variations (COV) were generally below 10%, showing that the distribution of dose within organs undergoing whole body CT is relatively modest. The highest variation was observed to be the bladder with a COV of 17%. The overall average R_K for the 25 Rando organs listed in

FIG. 1. Histogram distributions of R_K values for the complete Rando phantom.

Table I was 0.61 ± 0.08 . Table V shows *relative* values of R_K values for the GE scanner operated at 80 kV and 140 kV, as well as the Siemens scanner operated at 120 kV which were obtained by dividing the experimentally determined R_K values by the corresponding R_K value on the GE scanner operated at 120 kV. On average, organ R_K values are about 6% higher on the Siemens scanner. Reducing the x-ray tube voltage from 120 kV to 80 kV resulted in an average reduction in R_K value of 34%, whereas increasing the x-ray tube voltage to 140 kV increased the average R_K value by 9%.

IV. DISCUSSION

CT is recognized as a relatively high dose modality.^{23,24} CT utilization is also increasing rapidly, driven in part by the valuable diagnostic information that this modality offers, and in part by the technical advances associated with the advent of multi-detector CT (MDCT).²⁵ In the US, it has been estimated that CT contributes nearly half of the total dose from diagnostic medical examinations while accounting for only 17% of all x-ray radiological examinations.²⁶ Understanding the amount of radiation that patients receive

TABLE III. Spread of R_K values in each body region of Rando which is defined as the ratio of the 90th percentile R_K value to the corresponding 10th percentile R_K value.

Body region	Spread of R_K values (90th percentile/10th percentile) at x-ray tube voltage			
	80 (GE)	120 (GE)	120 (S)	140 (GE)
Head	1.35	1.19	1.16	1.24
Neck	1.52	1.30	1.29	1.35
Chest	1.62	1.36	1.32	1.36
Abdomen	1.83	1.32	1.28	1.36
Pelvis	1.83	1.44	1.38	1.43

FIG. 2. Average R_K values as a function of slice number for the Rando phantom. Error bars are the standard deviation around the mean R_K values obtained in each slice.

undergoing CT examinations is important for protecting patients where any radiation exposure needs to be justified by a net benefit, and all indicated examinations should keep exposures as low as reasonably achievable (ALARA).⁷ The R_K concept introduced in this paper offers a practical method for estimating organ doses, which in turn can be used to estimate patient radiation risks.

One advantage of the R_K approach to CT dosimetry is the use of identical dosimeters to determine both K and K_{CT} . Specifically, there is no need for any correction factors to account for the energy response of the selected dosimeter. R_K data can be used to relate free in air x-ray beam air kerma at isocenter (i.e., K_{CT}), which are readily measured, to doses to selected regions within a patient. To use R_K to obtain organ doses, we need to take into account differences in x-ray absorption of air and patient tissues. For typical CT x-ray photon energies, a fixed air kerma is expected to result in absorbed doses to soft tissues that are increased by approximately 7%, and absorbed doses to bone will be up to a factor of four times higher.^{2,27}

R_K values are useful in calculating dose to the fetus when a pregnant patient receives a CT scan in which the pelvis is

exposed. As an example, consider a pregnant patient of size equal to the male Rando phantom (i.e., early pregnancy) involved in a motor vehicle accident, who receives a CT scan to the chest, abdomen, and pelvis on the GE 4 slice scanner investigated in this work. A typical technique would be 120 kVp, 360 mA, 0.5 s rotation time, and helical scanning with a pitch of 1.375. This gives an effective technique of 130 mAs. The isocenter output rate for the scanner is approximately 29 mGy/100 mAs giving a K_{CT} value of 37.7 mGy air KERMA for this technique. Using the R_K value for the uterus of 0.51, and an air KERMA to tissue dose conversion factor of 1.07 (Ref. 2) results in an estimated dose to the uterus (and fetus) of 20.6 mGy. This value is in good agreement with the 19.3 mGy uterus dose estimated by the ImPACT CT dose calculator¹⁵ for a GE Lightspeed Ultra scanner using 20 mm collimation and the given technique.

K_{CT} will be equal to the peak value in the CT beam intensity profile in the Z direction, $f(z)$.²⁷ K_{CT} may also be determined from measurements of $CTDI_{air}$, but the $CTDI_{air}$ values must be scaled by the reciprocal of the over-beaming factor $F = a/nT$. Here a represents the beam width in the z -axis direction (full-width at half-maximum) measured at the

TABLE IV. R_K values for all organs measured on the GE scanner at 120 kV.

Organ	Organ mass (kg)	Number of measurement locations	Mean $R_K \pm$ standard deviation	Coefficient of variation (%) ^a
Testes	—	2	0.64 ± 0.03	5.4
Ovaries	—	2	0.49 ± 0.01	1.4
Red bone marrow	—	N/A (see text)	0.59	N/A (see text)
Colon	0.370	13	0.57 ± 0.06	10.8
Lung	0.5	32	0.61 ± 0.07	11.1
Stomach	0.15	13	0.62 ± 0.05	7.5
Breast	0.025	4	0.63 ± 0.03	4.8
Bladder	0.05	7	0.57 ± 0.10	17.0
Esophagus	0.04	5	0.62 ± 0.02	3.1
Liver	1.8	19	0.61 ± 0.05	7.6
Thyroid	0.02	2	0.88 ± 0.01	1.5
Salivary glands	0.085	4	0.73 ± 0.06	8.4
Brain	1.45	16	0.60 ± 0.04	5.9
Kidney	0.31	20	0.56 ± 0.04	6.9
Adrenals	0.014	2	0.53 ± 0.02	2.8
Pancreas	0.14	3	0.58 ± 0.01	1.5
Small intestine	0.65	16	0.60 ± 0.04	7.2
Spleen	0.15	8	0.56 ± 0.02	4.2
Thymus	0.025	2	0.64 ± 0.01	1.8
Uterus	0.08	1	0.51	—
Heart	0.33	9	0.62 ± 0.03	4.1
Gall bladder	0.058	3	0.65 ± 0.09	13.1
Prostate	0.017	3	0.46 ± 0.02	3.3
Oral mucosa	—	3	0.72 ± 0.05	6.8
Eyes	—	2	0.66 ± 0.01	2.0

^a(Standard deviation)/(mean R_K) $\times$ 100%.

scanner isocenter, and nT represents the thickness of the volume imaged during one rotation of the scanner gantry²⁸ (i.e., the number of detector channels, n , multiplied by the nominal detector width per channel, T). We then calculate the isocenter KERMA as $K_{CT} = 1/F \text{ CTDI}_{air}$. K_{CT} can be obtained directly by point dosimeters (e.g., OSL dosimeters) or ionization chambers providing the chamber size is smaller than a . By contrast, measurement of CTDI_{air} requires a single axial scan with correction factors applied to take into account the nominal linear dimensions of the x-ray beam width and the length of the pencil shaped ionization chamber that is normally used to make this measurement.²⁹ Despite these differences, directly measuring K_{CT} vs derivation from CTDI_{air} values are expected to yield the same results because these measurements are made free-in-air where scatter is of very little practical importance.

Data on R_K values depicted in Fig. 2 illustrate that the most important determinant of organ dose in CT scanning is the physical size of the patient. Of particular interest is the fact that the specific organ shape, as well as the precise the organ location within the body, appear to be of minor importance. This conclusion is supported by the fact that R_K values for most organs (see Table IV) fall within a relatively narrow range, apart from the exceptions such as the thyroid gland. Ratios in the cervical spine region are much higher than average, and those in the pelvic region are lower than average. It is of interest that R_K values in the head are very similar to those in the chest and abdomen. The mass of the

head region can be modeled as a cylinder of water with a diameter of 18 cm,³⁰ which is less than that of the chest (~ 24 cm water equivalent³¹) and the abdomen (26 cm water equivalent³²). However, the skull also has a high atomic number and attenuates x-rays to much higher extent than soft tissues, so that R_K values in the head region are similar to those in the body region.⁹

The use of an x-ray tube voltage of 80 kV has a major impact on the experimental R_K values, with an average reduction of 34%. Organs that resulted in a relative R_K value more than one standard deviation *lower* than the mean (i.e., relative $R_K < 0.53$) were the lung (0.52), liver (0.50), salivary glands (0.49), breast (0.47), stomach (0.46), and thyroid (0.49). Organs that resulted in a relative R_K value more than one standard deviation *higher* than the mean (i.e., relative $R_K > \text{approximately } 0.79$) were the heart (0.77), gall bladder (0.78), eyes (0.81), ovaries (0.82), testes (0.86), and oral mucosa (0.87). Increasing the x-ray tube voltage from 120 to 140 kV increased the relative R_K values by 9%, with no marked differences between all 25 organs investigated. The highest relative R_K 's at 140 kV were the brain and ovaries (1.18), and the lowest relative R_K 's were the pancreas (1.03) and spleen (1.04).

The R_K values presented in this study are based on a whole body CT scan. In clinical practice, however, scans will be of limited extent, and most organ doses will therefore be lower than those predicted by the use of R_K values obtained in this work. The influence of scan length on organ

TABLE V. R_K values relative to those obtained on the GE scanner at 120 kV.

Organ	GE (80 kV)	Siemens (120 kV)	GE (140 kV)
Testes	0.86	1.04	1.06
Ovaries	0.82	1.11	1.18
Red bone marrow	0.70	1.06	1.09
Colon	0.70	1.09	1.12
Lung	0.52	1.07	1.07
Stomach	0.46	1.07	1.06
Breast	0.47	1.10	1.12
Bladder	0.67	1.02	1.07
Esophagus	0.58	1.06	1.07
Liver	0.50	1.06	1.07
Thyroid	0.41	1.06	1.12
Salivary glands	0.49	1.10	1.08
Brain	0.75	1.05	1.18
Kidney	0.68	1.07	1.08
Adrenals	0.62	1.08	1.08
Pancreas	0.64	1.04	1.03
Small intestine	0.67	1.07	1.09
Spleen	0.65	1.04	1.04
Thymus	0.75	0.97	1.05
Uterus	0.65	1.07	1.13
Heart	0.77	1.12	1.10
Gall bladder	0.78	1.04	1.09
Prostate	0.67	1.08	1.08
Oral mucosa	0.87	1.10	1.08
Eyes	0.81	1.02	1.16
Testes	0.68	1.07	1.08
Mean $\pm$ standard deviation	0.66 $\pm$ 0.13	1.06 $\pm$ 0.03	1.09 $\pm$ 0.04

doses have recently been investigated and empirical correction factors can be used to account for partial organ irradiation.^{27,33–35} In addition, software packages such as the ImPACT CT Patient Dosimetry Calculator¹⁵ and others readily permit the empirical investigation of partial body irradiations, and how this is likely to affect the dose to any particular organ.

R_K values obtained in this study can only be applied to a patient whose size is similar to the Male Rando. At constant techniques, patients who are smaller than Rando will generally receive higher doses, and patients who are larger will receive smaller doses. Data have been presented that can correct for patient body size in chest, cardiac, and abdominal imaging by modeling patients as mass equivalent cylinders of water, and making use of published scientific data on relative doses in cylinders of varying diameter.^{33,35,36} In the chest, for example, it has been shown that a 50 kg patient is expected to have doses that are 18% higher than those in a 70 kg adult, whereas a 100 kg patient will have doses that are 18% lower.³³ When using R_K values for estimating patient organ doses, it is essential that appropriate corrections are applied to take into account patient size. Turner *et al.* have shown as an extension to their earlier work, that patient size corrections are feasible for CTDI-based organ dose estimates in abdominal CT examinations.³⁷ For adult heads, however, no corrections are required because all adult heads are very similar, and have a mass equivalence of an 18 cm diameter cylinder of water.²⁹

There are currently major efforts underway by the medical imaging community to ensure that CT exams are not prescribed unless indicated, and that indicated examinations use dose levels appropriate for the diagnostic task.^{7,38} An essential ingredient of this endeavor is to understand the magnitude of patient doses, as well as the corresponding radiation risks. R_K values may be used to estimate risk of cancer induction in patients using age- and gender-appropriate risk conversion factors. For example, risk per unit dose for all cancer induction and fatal cancers are available in Part 2 of the BEIR VII report.³⁶ Alternative dose metrics, such as the effective dose, are useful for understanding the amount of radiation populations receive in CT examinations. Converting effective dose to risk is problematic because the organ weighting factors used for computing effective doses are age- and sex-averages and cannot be used for individual patients. The R_K values presented in this study are an additional tool for the medical imaging community to use to estimate patient organ doses, and thereby any corresponding radiation risks.

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¹ International Commission on Radiological Units and Measurements, "ICRU report 74: patient dosimetry for x rays used in medical imaging," *J. ICRU* **5**(2), 56 (2005).

² W. Huda, "Medical radiation dosimetry," *RSNA categorical course in diagnostic radiology physics: from invisible to visible—the science and practice of x-ray imaging and radiation dose optimization* (RSNA, Oak Brook, IL, 2006), pp. 29–39.

³ L. K. Wagner, P. J. Eifel, and R. A. Geise, "Potential biological effects following high X-ray dose interventional procedures," *J. Vasc. Interv. Radiol.* **5**(1), 71–84 (1994).

⁴ Y. Imanishi *et al.*, "Radiation-induced temporary hair loss as a radiation damage only occurring in patients who had the combination of MDCT and DSA," *Eur. Radiol.* **15**(1), 41–46 (2005).

⁵ The 2007 Recommendations of the International Commission on Radiological Protection, "ICRP publication 103," *Ann. ICRP* **37**(2-4), 1–332 (2007).

⁶ BEIR V, *Health Risks from Exposure to Low Levels of Ionizing Radiation (Phase 2)* (National Research Council, Washington, DC., 2006), p.406

⁷ "Radiation protection in medicine. ICRP publication 105," *Ann. ICRP* **37**(6), 1–63 (2007).

⁸ M. F. McNitt-Gray, "AAPM/RSNA physics tutorial for residents: topics in CT. Radiation dose in CT," *Radiographics*, **22**(6), 1541–1553 (2002).

⁹ W. Huda and K. M. Ogden, "Comparison of head and body organ doses in CT," *Phys. Med. Biol.* **53**(2), N9–N14 (2008).

¹⁰ A. C. Turner *et al.*, "The feasibility of a scanner-independent technique to estimate organ dose from MDCT scans: using CTDI vol to account for differences between scanners," *Med. Phys.* **37**, 1816–1825 (2010).

¹¹ V. Varchena, "Pediatric phantoms," *Pediatr. Radiol.* **32**(4), 280–284 (2002).

¹² G. Brix *et al.*, "Assessment of a theoretical formalism for dose estimation in CT: an anthropomorphic phantom study," *Eur. Radiol.* **14**(7), 1275–1584 (2004).

¹³ W. A. Kalender, B. Schmidt, M. Zankl, and M. Schmidt, "A PC program for estimating organ dose and effective dose values in computed tomography," *Eur. Radiol.* **9**(3), 555–562 (1999).

¹⁴ G. Stamm and H. D. Nagel, "[CT-expo—a novel program for dose evaluation in CT], *Rofo* **174**(12), 1570–156 (2002).

¹⁵ ImPACT, <http://www.impactscan.org/ctdosimetry.htm>.

- ¹⁶P. D. Deak, Y. Smal, and W. A. Kalender, "Multisection CT protocols: sex- and age-specific conversion factors used to determine effective dose from dose-length product," *Radiology* **257**(1), 158–166 (2010).
- ¹⁷S. W. Alderson, L. H. Lanzl, M. Rollins, and J. Spira, "An instrumented phantom system for analog computation of treatment plans," *Am. J. Roentgenol. Radium Ther. Nucl. Med.* **87**, 185–195 (1962).
- ¹⁸P. C. Shrimpton, B. F. Wall, and E. S. Fisher, "The tissue-equivalence of the Alderson Rando anthropomorphic phantom for x-rays of diagnostic qualities," *Phys. Med. Biol.* **26**(1), 133–139 (1981).
- ¹⁹E. M. Scalzetti, W. Huda, S. Bhatt, and K. M. Ogden, "A method to obtain mean organ doses in a RANDO phantom," *Health Phys.* **95**(2), 241–244 (2008).
- ²⁰W. Huda and G. A. Sandison, "Estimation of mean organ doses in diagnostic radiology from Rando phantom measurements," *Health Phys.* **47**(3), 463–467 (1984).
- ²¹A. M. Groves et al., "16-detector multislice CT: dosimetry estimation by TLD measurement compared with Monte Carlo simulation," *Br. J. Radiol.* **77**(920), 662–665 (2004).
- ²²W. Huda, K. M. Ogden, and M. R. Khorasani, "Converting dose-length product to effective dose at CT," *Radiology*, **248**(3), 995–1003 (2008).
- ²³"Managing patient dose in computed tomography. A report of the International Commission on Radiological Protection," *Ann. ICRP* **30**(4), 7–45 (2000).
- ²⁴J. Valentin, "Managing patient dose in multi-detector computed tomography(MDCT). ICRP Publication 102," *Ann. ICRP* **37**(1), 1–79, iii (2007).
- ²⁵C. H. McCollough, L. Guimaraes, and J. G. Fletcher, "In defense of body CT," *AJR Am. J. Roentgenol.* **193**(1), 28–39 (2009).
- ²⁶F. A. Mettler, Jr., et al., "Radiologic and nuclear medicine studies in the United States and worldwide: frequency, radiation dose, and comparison with other radiation sources—1950–2007," *Radiology* **253**(2), 520–531 (2009).
- ²⁷H. E. Johns and J. R. Cunningham, *The Physics of Radiology* (Charles C Thomas, Springfield, IL, 1983).
- ²⁸American Association of Physicists in Medicine AAPM Report No. 111, Comprehensive Methodology for the evaluation of radiation dose in x-ray computed tomography AAPM, February 2010, (http://www.aapm.org/pubs/reports/RPT_111.pdf).
- ²⁹H. D. Nagel, Radiation Exposure in Computed Tomography (CTB Publications, Hamburg, Germany, 2002).
- ³⁰W. Huda, K. A. Lieberman, J. Chang, and M. L. Roskopf, "Patient size and x-ray technique factors in head computed tomography examinations. I. Radiation doses," *Med. Phys.* **31**(3), 588–594 (2004).
- ³¹W. Huda, E. M. Scalzetti, and M. Roskopf, "Effective doses to patients undergoing thoracic computed tomography examinations," *Med. Phys.* **27**(5), 838–844 (2000).
- ³²D. E. Ware, W. Huda, P. J. Mergo, and A. L. Litwiller, "Radiation effective doses to patients undergoing abdominal CT examinations," *Radiology* **210**(3), 645–650 (1999).
- ³³W. Huda, A. Sterzik, S. Tipnis, and U. J. Schoepf, "Organ doses to adult patients for chest CT," *Med. Phys.* **37**(2), 842–847 (2010).
- ³⁴W. Huda, W. Randazzo, S. Tipnis, G. D. Frey, E. Mah, "Embryo dose estimates in body CT," *AJR Am. J. Roentgenol.* **194**(4) 874–880 (2010).
- ³⁵W. Huda, S. Tipnis, A. Sterzik, and U. J. Schoepf, "Computing effective dose in cardiac CT," *Phys. Med. Biol.* **55**(13), 3675–3684 (2010).
- ³⁶National Research Council Committee to Assess Health Risks from Exposure to Low Levels of Ionizing Radiation, *Health risks from exposure to low levels of ionizing radiation: BEIR VII, Phase 2* (National Academies Press, Washington, DC, 2006).
- ³⁷A. C. Turner et al., "The feasibility of patient size-corrected, scanner independent organ dose estimates for abdominal CT exams," *Med. Phys.* **38**(2) 820–829 (2011).
- ³⁸O. W. Linton and F. A. Mettler, Jr., "National conference on dose reduction in CT, with an emphasis on pediatric patients," *AJR Am. J. Roentgenol.* **181**(2), 321–329 (2003).