Organ doses, effective doses, and risk indices in adult CT: Comparison of four types of reference phantoms across different examination protocols

Yakun Zhang

Medical Physics Graduate Program, Duke University, Durham, North Carolina 27705 and Carl E. Ravin Advanced Imaging Laboratories, Duke University, Durham, North Carolina 27705

Xiang Li

Carl E. Ravin Advanced Imaging Laboratories, Duke University, Durham, North Carolina 27705 and Department of Radiology, Duke University, Durham, North Carolina 27705

W. Paul Segars

Medical Physics Graduate Program, Duke University, Durham, North Carolina 27705; Carl E. Ravin Advanced Imaging Laboratories, Duke University, Durham, North Carolina 27705; and Department of Radiology, Duke University, Durham, North Carolina 27705

Ehsan Samei^{a)}

Medical Physics Graduate Program, Duke University, Durham, North Carolina 27705; Carl E. Ravin Advanced Imaging Laboratories, Duke University, Durham, North Carolina 27705; Department of Radiology, Duke University, Durham, North Carolina 27705; and Departments of Physics, Biomedical Engineering, and Electrical and Computer Engineering, Duke University, Durham, North Carolina 27705

(Received 16 December 2011; revised 26 March 2012; accepted for publication 28 April 2012; published 24 May 2012)

Purpose: Radiation exposure from computed tomography (CT) to the public has increased the concern among radiation protection professionals. Being able to accurately assess the radiation dose patients receive during CT procedures is a crucial step in the management of CT dose. Currently, various computational anthropomorphic phantoms are used to assess radiation dose by different research groups. It is desirable to better understand how the dose results are affected by different choices of phantoms. In this study, the authors assessed the uncertainties in CT dose and risk estimation associated with different types of computational phantoms for a selected group of representative CT protocols.

Methods: Routinely used CT examinations were categorized into ten body and three neurological examination categories. Organ doses, effective doses, risk indices, and conversion coefficients to effective dose and risk index (k and q factors, respectively) were estimated for these examinations for a clinical CT system (LightSpeed VCT, GE Healthcare). Four methods were used, each employing a different type of reference phantoms. The first and second methods employed a Monte Carlo program previously developed and validated in our laboratory. In the first method, the reference male and female extended cardiac-torso (XCAT) phantoms were used, which were initially created from the Visible Human data and later adjusted to match organ masses defined in ICRP publication 89. In the second method, the reference male and female phantoms described in ICRP publication 110 were used, which were initially developed from tomographic data of two patients and later modified to match ICRP 89 organ masses. The third method employed a commercial dosimetry spreadsheet (ImPACT group, London, England) with its own hermaphrodite stylized phantom. In the fourth method, another widely used dosimetry spreadsheet (CT-Expo, Medizinische Hochschule, Hannover, Germany) was employed together with its associated male and female stylized phantoms.

Results: For fully irradiated organs, average coefficients of variation (COV) ranged from 0.07 to 0.22 across the four male phantoms and from 0.06 to 0.18 across the four female phantoms; for partially irradiated organs, average COV ranged from 0.13 to 0.30 across the four male phantoms and from 0.15 to 0.30 across the four female phantoms. Doses to the testes, breasts, and esophagus showed large variations between phantoms. COV for gender-averaged effective dose and k factor ranged from 0.03 to 0.23 and from 0.06 to 0.30, respectively. COV for male risk index and q factor ranged from 0.06 to 0.30 and from 0.05 to 0.36, respectively; COV for female risk index and q factor ranged from 0.06 to 0.49 and from 0.07 to 0.54, respectively.

Conclusions: Despite closely matched organ mass, total body weight, and height, large differences in organ dose exist due to variation in organ location, spatial distribution, and dose approximation method. Dose differences for fully irradiated radiosensitive organs were much smaller than those for partially irradiated organs. Weighted dosimetry quantities including effective dose, male risk indices, k factors, and male q factors agreed well across phantoms. The female risk indices and q factors varied considerably across phantoms. © 2012 American Association of Physicists in Medicine. [<http://dx.doi.org/10.1118/1.4718710>]

Key words: CT, Computed Tomography, dose, CT dose, organ dose, effective dose, risk index, k factor, q factor, reference phantom, comparison of phantoms

I. INTRODUCTION

Over the past few decades, technological advances in x-ray computed tomography (CT) have made CT an essential diagnostic imaging tool. While this technology is bringing convenience and high quality tomography to the medical imaging world, it also introduces radiation exposure to the public.¹ From the data published in 2006, the use of CT has increased at a rate of 8%–15% per year for the last 7–10 years.² In 2006, nearly half of the total medical radiation exposure was from CT.² This has increased concern about CT imaging among radiation protection professionals as well as the general public.^{3–5} Therefore, it is important to be able to accurately estimate the radiation dose that patients receive during CT procedures so that any potential risk can be estimated and minimized.

Computational anthropomorphic phantoms combined with Monte Carlo simulation of radiation transport have proven to be an accurate and reliable method to estimate organ doses during CT examinations.^{6–19} Such phantoms have evolved from the original stylized phantoms,²⁰ to voxelized phantoms,^{21,22} and to more advanced hybrid phantoms.^{11,23,24} Stylized phantoms define the organs and structures in the human body through mathematical equations and simple geometric primitives. While highly flexible, stylized phantoms are limited in their ability to model the complexities of the human anatomy accurately.^{25,26} To overcome the unrealistic nature of the stylized phantoms, voxelized phantoms have been developed over the last 20 years. These phantoms are based directly on segmented patient data from high resolution MRI or CT whole body scans and have a high degree of realism. However, voxelized phantoms do not have the flexibility of stylized phantoms and cannot be easily used to model anatomical variations. To overcome this limitation, more advanced phantoms, hybrids of stylized and voxelized phantoms seeking to combine the advantages of both, have been

developed by several research groups.^{23,24,27} Hybrid phantoms are also based on segmented tomographic data of real patients. However, the segmented data are further used to generate polygon mesh surfaces, which are then fitted to sophisticated mathematical descriptors such as nonuniform rational B-splines (NURBS). They represent anatomy realistically since they are based on tomographic data from real patients, while at the same time they offer the flexibility to model variations in anatomical geometry.

Some comparisons between hybrid and stylized phantoms used in CT dosimetry have been made by Liu *et al.*¹⁵ and Lee *et al.*^{10,11} However, earlier studies included only limited examination types, leaving out some other important and routinely used CT examinations, such as liver examinations. Furthermore, in the clinical environment, the effective dose is often estimated by a dose length product (DLP) to effective dose conversion coefficient, called the k factor. These earlier studies did not examine the choice of phantoms on the resulting dose conversion coefficients. In addition, comparisons between anatomically realistic reference phantoms developed by different research groups have not yet been explored.

The purpose of this study was to extend the earlier comparison efforts to four types of widely used reference phantoms, to a wide range of body and neurological examination types, and to dose and risk conversion coefficients.

II. METHODS

Figure 1 demonstrates the methodology used in this study. Four types of reference phantoms were employed: male and female hybrid phantoms in the extended cardiac-torso (XCAT) family,²⁴ male and female voxelized phantoms provided in ICRP publication 110,²¹ the hermaphrodite stylized phantom used in the ImPACT CT dose spreadsheet,²⁸ and male and female stylized phantoms used in the CT-Expo

FIG. 1. Flow chart of the methodology used in this study. RI: risk index; ED: effective dose.

dose spreadsheet. For the XCAT (Ref. 24) and ICRP 110 phantoms,²¹ a validated Monte Carlo program modeling a 64-slice CT scanner (LightSpeed VCT, GE Healthcare, Waukesha, WI) was employed to simulate organ doses, which were then used to calculate effective doses, risk indices (RIs), and conversion coefficients from DLP to effective dose and risk index (k and q factors). For the ImPACT and CT-Expo phantoms, organ doses were obtained directly from their associated dosimetry spreadsheets for the same CT scanner model, which were then used in the effective dose and risk index calculations.

II.A. Computational phantoms

The four types of reference phantoms used in this study are detailed below. Their organ masses are tabulated in Table I.

II.A.1. XCAT hybrid phantoms

The first set of phantoms was the reference male and female XCAT phantoms [Figs. 2(a) and 2(b)].²⁴ The XCAT reference phantoms were initially created from the Visible Human anatomical data distributed by the National Library of Medicine (NLM).²⁹ Segmentation of anatomical structures was applied semi-automatically by using a tablet PC with the help of a custom graphical application IMAGESEGMENT (RAI Laboratories, Duke University, Durham, NC). The resulting segmented structure was converted to a 3D polygon model and later fitted to cubic NURBS surfaces for a more compact mathematical description of the objects. Brains were modeled separately using MRI data of a normal male subject. After segmentation and conversion to a polygon model of the brain, subdivision surfaces replaced

TABLE I. Organ masses for the four types of reference phantoms employed in this study. Reference organ masses published in ICRP 89 are also listed for comparison. Note that the CT-Expo male and female phantoms were matched to ICRP publication 23.

Organ/structure	Mass (g)								
	XCAT reference male	XCAT reference female	ICRP 110 reference male	ICRP 110 reference female	ImPACT herma-phrodite	CT-Expo male	CT-Expo female	ICRP 89 male	ICRP 89 female
Breast	24	474	25	491	302	—	532	25	500
Soft tissue ^a	58 548	49 796	48 294	45 166	48 893	49 111	40 924	47 930	40 600
Heart	850	646	819	605	830	595	494	840	620
Kidneys	307	274	304	270	310	284	236	310	275
Lungs ^b	1105	986	1141	915	999	1000	830	1200	950
Liver	1736	1335	1765	1373	1810	1806	1471	1800	1400
Gall bladder ^c	68	56	14	10	10	10	8.1	10	8
Spleen	151	131	149	129	180	174	144	150	130
Stomach ^c	391	355	149	139	350	150	125.3	150	140
Bladder ^d	50	41	50	40	147	45	45	50	40
Large intestine ^c	671	599	366	357	722	367	304	370	360
Pancreas	138	116	137	118	100	96	79.6	140	120
Prostate	16	—	17	—	—	—	—	17	—
Adrenals	14	13	14	13	14	15.5	12.9	14	13
Thyroid	21	16	20	17	20	20	16.4	20	17
Thymus	25	20	25	20	20	20	20	25	20
Larynx–pharynx	30	19	28	14	—	—	—	28	19
Trachea–bronchi	117	104	76	17	—	—	—	—	—
Testes	34	—	35	—	37	37	—	35	—
Eyes	14	15	15	15	—	—	—	15	15
Small intestine ^c	1009	875	644	594	640	1046	894	1000	600
Esophagus	39	36	40	35	90	—	—	40	35
Brain	1452	1306	1422	1275	1400	1349	1120	1450	1300
Skin	7033	6362	3668	2599	2862	3130	2803	3300	2300
Ovaries	—	11	—	11	—	—	11	—	11
Uterus	—	75	—	80	—	—	80	—	80
Skeleton ^e	10 904	10 307	10 629	7246	9516	10 175	8360	10 450	7760
Total body weight	84 746	74 031	73 000	60 000	70 910	70 450	59 193	73 000	60 000
Height (cm)	176	163	176	163	—	170	160	176	163

^aSoft tissue included skeletal muscle, adipose tissue, cartilage, blood, lymphatic tissues, and connective tissues. For ICRP 110 phantoms, teeth, tongue, tonsils, and ureters were all set to soft tissue for comparison with the XCAT phantoms.

^bLungs were compressed in the ICRP 110 phantoms, but dilated in the XCAT reference phantoms. The densities of the lungs were set such that the total mass of the lungs matched the reference lung mass.

^cThese GI track organs included both wall and contents for XCAT reference phantoms but only wall for ICRP 110 reference phantoms. The ICRP 89 reference values were organ walls.

^dBladder included only wall.

^eSkeleton included cortical bone, trabecular bone, yellow marrow, red marrow, and various connective tissues.

FIG. 2. Lateral and frontal views of the four types of phantoms used in this study. (a) and (b) XCAT reference male and female hybrid phantoms after voxelization. (c) and (d) ICRP 110 reference male and female voxelized phantoms. The organs were relabeled to be consistent with the XCAT phantoms. (e) ImPACT stylized/mathematical hermaphrodite phantom. (f) and (g) CT-Expo male and female stylized/mathematical phantoms.

NURBS surfaces in order to more accurately represent the arbitrary topological structure in the brain.²⁴

The NURBS based phantoms developed from the Visible Human data were subsequently modified to match ICRP reference values. The body measurements and organ volumes were first matched to a 50th percentile (height and weight) male and female with desired data obtained using the survey data of U.S. adults from the “PEOPLESIZE Program” (available URL: <http://www.openenerg.com/psz/index.html>). The organ masses were then matched to ICRP publication 89 values. Thus, the resulting phantoms were named reference male and female phantoms in the XCAT phantoms family. In the voxelized versions of the XCAT phantoms, skin was modeled as a single voxel layer on the surface, which caused the skin mass to be higher than the ICRP 89 reference mass.

II.A.2. ICRP 110 voxelized phantoms

The second set of phantoms was the reference male and female phantoms [Figs. 2(c) and 2(d)] provided in ICRP publication 110.²¹ The phantoms were constructed from tomographic data of individuals whose body heights closely matched to the reference values defined in ICRP publication 89. Initially, radiosensitive organs were directly segmented from the tomographic data using commercial image processing software by applying CT number thresholding. The resulting male and female voxelized phantoms, referred to as Golem and Laura, were then modified to match the following reference body parameters: height, organ mass, and total body mass. Specifically, the voxels were scaled along the body long axis to match the reference height and then adjusted again to match the skeletal mass according to ICRP publication 70, ICRP publication 89, and ICRU report 46.^{30–32} Subsequently, individual organ volume was modified to match the reference mass. Finally, additional tissues and different body regions were modified to match the total reference mass.²¹ The resulting voxel sizes for the reference male phantom were 8 mm

along the body long axis and 2.137 mm in the transverse plane. The respective values for the female phantom were 4.84 and 1.775 mm. Similar to the XCAT phantoms, the skin was also modeled as a single voxel layer on the surface, causing the skin mass to be higher than the ICRP 89 reference mass.

II.A.3. ImPACT stylized phantom

The third type of phantom [Fig. 2(e)] was a stylized/mathematical phantom—the ImPACT hermaphrodite phantom—which is available commercially from the ImPACT website (ImPACT CT Patient Dosimetry Calculator, version 1.0.3; ImPACT, London, England).²⁸ This phantom is composed of 208 contiguous 5 mm thick slabs extending from upper legs to head. It was first designed for a UK national survey of doses to patients from conventional x-ray examinations.³³ Definition of individual organs and cross-section data can be found in NRPB-R186.³⁴

II.A.4. CT-Expo stylized phantoms

The fourth set of phantoms was stylized/mathematical phantoms [Figs. 2(f) and 2(g)] based on the design characteristics of the MIRD-5 phantom.³⁵ The two sex-specific adult phantoms ADAM and EVA were originally created in the German National Research Center for Environment and Health (GSF) based on reference male and female organ masses given by ICRP publication 23. The ratios of reference female to male organ masses were analyzed, yielding an average value of 0.89 and the whole body mass ratio of 0.83. As the MIRD-5 phantom had similar dimensions of the male reference adult, the female phantom was derived to a first approximation by shrinking all relevant volumes of the MIRD-5 phantom with the total whole body mass ratio of 0.83. Then, female organ masses were modified to match the reference ratios. Finally, sex-specific organs including testes, ovaries, uterus, and breasts were added to the phantoms. The resulting phantoms consisted of an elliptical cylinder for the

TABLE II. CT examination categories investigated in this study.

Examination categories	Simulated image coverage	
	Start (1 cm above)	End (1 cm below)
Body	Chest–abdomen–pelvis	Lung apex
	Chest	Lung apex
	Abdomen–pelvis	Superior liver
	Abdomen	Superior liver
	Pelvis	Superior iliac crest
	Adrenals	Superior adrenals
	Liver	Superior liver
	Kidneys	Superior kidney
	Liver-to-kidneys	Superior liver
	Kidneys-to-bladder	Superior kidney
Neurological	Head	Vertex of skull
	Neck	C1
	Head-and-neck	Vertex of skull

trunk and arms, two truncated circular cones for the legs, and a circular cylinder with an elliptical cylinder capped by half an ellipsoid for the neck and head.³⁵ Organ masses, total body mass, and height was tabulated in Table I.

II.B. CT examination categories

Body and neurological CT protocols routinely used at our institution were reviewed. Thirteen examination categories were selected for this study, consisting of ten body categories and three neurological categories (Table II). Each examination category represented a class of protocols that cover the same anatomical region and share the same scan parameters, including tube voltage, pitch, beam collimation, and the type of scan field-of-view (Table III). These scan parameters were explicitly modeled in the Monte Carlo simulations. Before simulating a given protocol, relevant organ locations were computed along the longitudinal body axis to locate the starting and ending anatomical landmarks (Table II). For helical scans, over-ranging (necessary for data interpolation in helical reconstruction) was added to the total scan length. For the helical scan parameters in Table III, the total over-ranging distance (a sum of the over-ranging distances at the beginning and the end of the scan) was estimated to be 6.4 cm.³⁶ This value was used for all but the CT-Expo phantoms; an over-ranging distance of 5.55 cm was automatically considered by the CT-Expo dosimetry spreadsheet.

II.C. Organ doses simulations

II.C.1. XCAT and ICRP 110 phantoms

For XCAT and ICRP 110 phantoms, a Monte Carlo program previously developed in our laboratory was used to

simulate organ doses (Fig. 1).¹³ This program was based on a benchmarked Monte Carlo subroutine package (PENELOPE, version 2006, Universitat de Barcelona, Spain) specialized for photon, electron, and positron transport.^{37,38} This program explicitly simulates the geometry of the GE Light-Speed VCT system (GE Healthcare, Waukesha, WI), including the complex 3D bowtie filters as well as the trajectories of x-ray tube motion during axial and helical scans. The accuracy of the simulated dose was previously validated in a cylindrical phantom and two anthropomorphic phantoms in both axial and helical scanning modes. Simulations agreed with measurements to within 1%–11% on average and 5%–17% maximum.¹³ Arms of XCAT reference phantoms were positioned up for body examinations and down for neurological examinations; arms of ICRP 110 phantoms were set to vacuum for body examinations and remained unchanged for neurological examinations. Organ labels and densities for ICRP 110 phantoms were adapted in order to run the phantoms through the Monte Carlo simulation.

Energy deposited in organs and tissues was tallied for the dose computation.¹⁴ To estimate dose to the red bone marrow, volume-averaged photon fluence spectrum was tallied individually at each skeletal site and used to calculate dose to the red bone marrow via fluence-to-dose conversion coefficients.²⁰ A single active marrow dose was then calculated as its skeletal average using the age-dependent fractional distribution of active marrow tabulated in ICRP 89.³¹ Dose to the bone surface was approximated by the mass-weighted average of dose to the homogeneous bones.³⁹ Doses to organs that were not explicitly modeled were approximated by doses to neighboring organs.¹⁴ A total of 8×10^7 histories were simulated to achieve relative errors of less than 1% for organs inside the scan coverage.

II.C.2. ImPACT phantom

For the ImPACT phantom, the ImPACT CT dosimetry spreadsheet provides organ doses based on 23 Monte Carlo data sets from National Radiological Protection Board (NRPB)'s SR250 report.⁴⁰ The Monte Carlo techniques were initially developed at the NRPB in support of a UK national survey of doses to patients from conventional x-ray examinations.^{33,34} Modifications, including rotating fan beam spectral x-ray source and bow-tie shaped filter, were accommodated to the Monte Carlo program to simulate commercial CT scanners. Doses generated by this program were compared to doses from GSF Monte Carlo code using a female GSF phantom. Good agreements among doses were found between these two programs for the same input conditions.⁴⁰

The data set for one model of CT scanner included doses received when each of 208 contiguous 5 mm thick slabs of

TABLE III. Scan parameters for body and neurological examination categories.

	Scan mode	Tube voltage	Pitch	Beam collimation	Scan field-of-view
Body examination categories	Helical	120 kVp	1.375	40 mm	Large body
Neurological examination categories	Axial	120 kVp	1	20 mm	Head

the hermaphrodite phantom is individually irradiated. The dose was expressed as absorbed dose in the organ relative to the dose on the axis of rotation of the scanner in the absence of the phantom, i.e., free-in-air axial dose. In order to use the normalized organ dose data to estimate patient dose for a specific CT examination on a specific scanner, several steps were employed by the spreadsheet. These steps involved obtaining scan volume, total normalized organ doses ($\sum_V D_f$), packing factor (p), and CTDI_n . Doses to organs were calculated by the multiplication of $\sum_V D_f$, p , and CTDI_n . Over-ranging was also added to the total scan region when defining the start and end position of the scan.

II.C.3. CT-Expo phantoms

For the CT-Expo male and female phantoms, similar to the ImPACT dosimetry spreadsheet, the CT-Expo dosimetry spreadsheet provides organ doses. The spreadsheet is based on computational methods for evaluating the data collected in two German surveys on CT exposure practice in 1999 and 2002. The methods used Monte Carlo simulation to transport radiation in the phantoms. Doses were calculated as conversion factors (f) of individual mean organ doses per axial free-in-air kerma for single slices at positions varying contiguously from 10 cm below the bottom of the trunk up to the top of the head with slice thickness of 1 cm. Mean organ doses can then be obtained by summing up the values of $f(\text{organ}, z)$ over the scanned region as $D(\text{organ}) = K_{\text{air}} \times \sum_{z_l}^{z_u} f(\text{organ}, z)$, where z_l and z_u indicate the lower and upper boundaries of the scanned region and K_{air} is the axial free-in-air kerma.

II.D. Effective dose and cancer risk index calculations

Effective dose was calculated from the obtained organ doses using the tissue weighting factors defined in ICRP publication 103.⁴¹ Effective dose for the ImPACT and the CT-Expo phantoms were conveniently provided by the dosimetry spreadsheets. For XCAT and ICRP 110 reference phantoms, which were run through the validated Monte Carlo simulation code, effective dose was calculated as follows. Organ doses obtained from the Monte Carlo method were first averaged over male and female for each type of phantoms. Dose to the testes or ovaries was averaged to obtain the dose to gonads. Following the recommendations of ICRP 103, dose to the remainder tissues was first calculated separately for each gender, including gender-specific reproductive organ (male: prostate; female: uterus/cervix). The results were then averaged across genders to obtain gender-averaged dose to the remainder tissues. These gender-averaged organ doses were then weighted by the tissue weighting factors and summed to obtain effective dose, as

$$\text{ED} = \sum_T w_T \frac{H_T^{\text{Male}} + H_T^{\text{Female}}}{2}, \quad (1)$$

where w_T is the tissue weighting factor defined by ICRP publication 103 and H_T is the dose for organ T . DLP was calculated as the product of volume-weighted CT dose index (CTDI_{vol}) and total scan length, where the CTDI_{vol} was obtained from the technical manual of the GE LightSpeed

VCT scanner simulated in this study. After calculation of DLP for each anthropomorphic phantom, DLPs for XCAT phantoms and ICRP 110 phantoms were averaged over their male and female phantoms. Gender-averaged k factor was determined by dividing the obtained effective dose over the gender-averaged DLP.

In order to estimate cancer risk, RI was obtained as

$$\text{RI} = \sum_T r_{T(\text{gender,age})} H_T, \quad (2)$$

where r_T is the gender-, age-, and tissue-specific risk coefficient with the unit of cases/100 000 exposed to 0.1 Gy and H_T is the equivalent dose to organ T . The values of r_T were tabulated in BEIR VII report for lifetime attributable risk of cancer incidence.⁴² In this study, all phantoms were assumed to be 20 yr old for a conservative risk estimation. For males, values of r_T are available for leukemia and for cancers of stomach, colon, liver, lung, prostate, bladder, and thyroid. For females, values of r_T are available for leukemia and for cancers of stomach, colon, liver, lung, breast, uterus, ovary, bladder, and thyroid. Cancers of other radiosensitive organs share a collective risk coefficient r_{other} , also provided in BEIR VII report.⁴² r_{other} was applied to a weighted average of the dose to other radiosensitive organs as described by Li *et al.*¹⁴ For the XCAT, the ICRP 110, and the CT-Expo phantoms, risk index was calculated for each gender separately. For the ImPACT hermaphrodite phantom, since only one set of organ doses was provided for each examination category, that set of data was used to calculate risk index with different r_T values for male and female. Risk index values were then normalized over their corresponding DLPs to obtain q factors (Fig. 1).

III. RESULTS

III.A. Comparison of organ doses

Figure 3 shows the organ doses estimated using the four types of phantoms for the 13 examination categories. Some organs received noticeably different doses between phantoms for the same examination. For example, in the chest–abdomen–pelvis and abdomen–pelvis examinations, doses to the testes for the XCAT and the ICRP 110 male phantoms were less than half of the doses to the testes for the ImPACT and the CT-Expo male phantoms. In the pelvis examination, doses to the testes for the ICRP 110 phantoms differed by fourfold from the XCAT phantom and even more from the ImPACT and the CT-Expo phantoms. In the abdomen–pelvis, abdomen, liver, and liver-to-kidneys examinations, dose to breasts for the ImPACT phantom was much smaller compared to doses for the other three female phantoms. Esophageal doses for the two voxelized phantoms (XCAT and ICRP 110) were smaller than the two stylized phantoms (ImPACT and CT-Expo) in the chest–abdomen–pelvis and chest examinations, but were larger in the abdomen–pelvis, abdomen, liver, and liver-to-kidneys examinations.

The quantitative differences between phantoms are summarized in Tables IV and V for fully irradiated organs (organs directly irradiated and completely within the scan

FIG. 3. Comparison between different types of phantoms in terms of organ doses and effective doses (ED) in 13 examination categories: (a) chest–abdomen–pelvis; (b) chest; (c) abdomen–pelvis; (d) abdomen; (e) pelvis; (f) adrenals; (g) liver; (h) kidneys; (i) liver-to-kidneys; (j) kidneys-to-bladder; (k) head; (l) neck; (m) head-and-neck. Note that doses for ImPACT are the same for male and female except for testes and ovaries. Doses are normalized to 100 mAs. The quantitative differences were tabulated in Tables IV and V. The coefficient of variation for ED is displayed above the bars for each examination.

coverage for all four types of phantoms) and partially irradiated organs (organs directly irradiated in four types of phantoms and partially inside the scan coverage for at least one type of phantoms). Two comparison methods were used: comparisons across all four types of phantoms using coefficient of variation (COV) and the difference between the

ICRP 110 phantoms used as the reference standard and the other three types of phantoms. It is obvious that the average COV for fully irradiated organs were smaller than the COV for partially irradiated organs.

FIG. 3. (Continued).

In general, the average differences between each type of phantoms and ICRP 110 phantoms were also smaller for fully irradiated organs than those for partially irradiated organs [Tables IV and V]. For male phantoms, the average differences between the XCAT and the ICRP 110 phantoms (ranging from 3% to 22% for fully irradiated and 6% to 21% for partially irradiated organs) were overall smaller than those between the ImpACT and the ICRP 110 phantoms

(ranging from 13% to 37% for fully irradiated and 12% to 72% for partially irradiated organs) or between the CT-Expo and the ICRP 110 phantoms (ranging from 8% to 38% for fully irradiated and 16% to 66% for partially irradiated). This trend was not demonstrated as prominently in the female phantoms. For fully irradiated female organs, the average differences between the CT-Expo and the ICRP 110 phantoms appeared to be the smallest (ranging from 3% to

FIG. 3. (Continued).

20%), and the average differences between the XCAT and the ICRP 110 phantoms for partially irradiated female organs were the smallest (ranging from 8% to 56%).

III.B. Comparison of effective doses and risk indices

The differences between effective doses of the four types of phantoms (Fig. 3) were not as dramatic as the differences

in organ doses. COV of effective doses across all four types of phantoms was calculated for each examination category and displayed in Fig. 3. The effective dose COV for all the examinations other than pelvis (0.21) and head (0.23) examinations, were less than 0.2, with the lowest value being 0.03 (abdomen–pelvis examination). Percent differences for effective doses using ICRP 110 phantoms as the reference standard showed that the XCAT and the ICRP 110 were

FIG. 3. (Continued).

very close; the percent differences between the two were under 10% for most examination categories except the head examination, which had a percent difference of 20%. In contrast, the maximum percent difference between the IMPACT and the ICRP 110 phantoms was 42% (pelvis examination) and between the CT-Expo and the ICRP 110 phantoms was 34% (pelvis examination).

Figure 4 illustrates the risk indices for the 13 examination categories with the COV of all four phantoms displayed above the bars. The COV for the male phantoms were all under 0.20 except in the pelvis (0.28) and head (0.30) examinations, indicating the risk indices agreed well across male phantoms. The COV for female phantoms were larger than for male phantoms with maximum value of 0.49 (neck

FIG. 3. (Continued).

examination). The risk indices also fluctuated more across examinations for females.

III.C. Comparison of k and q factors

Figure 5 and Table VI show DLP to effective dose conversion coefficient (k factor) for each examination category on all four types of phantoms. The k factors for each exami-

nation agreed well across phantoms, providing that the COV were all equal to or less than 0.20, with the exception of the head examination (0.30). Average difference with respect to the ICRP 110 phantoms showed that k factors from the XCAT phantoms were the closest to the ICRP 110 phantoms (average difference of 11% across 13 examination categories). The k factors from the ImPACT and CT-Expo phantoms had similar average differences relative to ICRP 110

FIG. 3. (Continued).

phantoms (20% for ImPACT and 21% for CT-Expo). As expected, the k factors for body examinations were significantly higher than those of neurological examinations. For body examinations, k factors for ICRP 110 phantoms were the largest among all four types of phantoms except for the pelvis examination. The k factors from AAPM publication 96 are displayed in the same graph for reference. These values are smaller than any of the values calculated for body

examinations in this study, but no apparent trend was observed for neurological examinations.

Figure 6 and Table VI show the DLP to risk index conversion coefficient (q factor) for all four types of phantoms. The q factors from the four male phantoms agreed well, having COV all equal to or less than 0.20, with the exception of head examinations (0.36). For females, q factors showed more variance across different types of phantoms with the

FIG. 3. (Continued).

TABLE IV. COV and average differences of fully irradiated organs for all 13 examination categories. The average COV was obtained by first calculating COV for each organ across four phantoms, and then averaged over all fully irradiated organs. The average difference was calculated using: $ID_{XCAT}/ID_{ICRP110} - 1$, $ID_{ImPACT}/ID_{ICRP110} - 1$, and $ID_{CT-Expo}/ID_{ICRP110} - 1$, and then averaged over all fully irradiated organs. The CT-Expo male phantom does not have any breasts, so breasts were excluded in the calculation for male. The female only organs were bracketed in the organ list. Note that for the adrenals, kidneys, and neck examinations, there were no fully radiosensitive organs.

		Fully irradiated							
		Average COV across four phantoms		Average difference between XCAT and ICRP 110		Average difference between ImPACT and ICRP 110		Average difference between CT-Expo and ICRP 110	
Fully irradiated radiosensitive organs		Male	Female	Male	Female	Male	Female	Male	Female
Chest–abdomen–pelvis	Colon, lungs, stomach, bladder, liver (ovaries, breasts)	0.13	0.13	8	17	22	12	20	10
Chest	Lungs (breasts)	0.16	0.14	8	16	37	13	38	14
Abdomen–pelvis	Colon, stomach, bladder, liver (ovaries)	0.11	0.12	8	18	18	13	14	8
Abdomen	Stomach, liver	0.12	0.10	7	21	18	8	19	4
Pelvis	Bladder (ovaries)	0.22	0.18	22	21	33	19	13	14
Adrenals									
Liver	Stomach, liver	0.11	0.10	7	20	15	9	19	3
Kidneys									
Liver-to-kidneys	Stomach, liver	0.11	0.10	6	20	14	10	18	5
Kidneys-to-bladder	Colon, bladder (ovaries)	0.13	0.15	10	16	20	18	10	11
Head	Brain	0.07	0.06	5	3	18	13	8	9
Neck									
Head-and-neck	Brain, salivary glands	0.09	0.09	3	5	13	10	17	20

TABLE V. COV and average differences of partially irradiated organs for all 13 examination categories.

		Partially irradiated							
		Average COV across four phantoms		Average difference between XCAT and ICRP 110		Average difference between ImPACT and ICRP 110		Average difference between CT-Expo and ICRP 110	
	Partially irradiated radiosensitive organs	Male	Female	Male	Female	Male	Female	Male	Female
Chest–abdomen–pelvis	Marrow, esophagus, thyroid, skin, bones	0.25	0.24	12	13	37	30	43	40
Chest	Marrow, stomach, liver, esophagus, thyroid, skin, bones	0.30	0.29	7	13	44	39	46	44
Abdomen–pelvis	Marrow, lungs, skin, bones (breasts)	0.14	0.27	13	12	12	32	19	32
Abdomen	Marrow, colon, lungs, skin, bones	0.13	0.15	11	14	14	12	16	21
Pelvis	Marrow, colon, skin, bones	0.21	0.19	17	18	42	15	40	30
Adrenals	Marrow, lungs, stomach, liver, skin, bones	0.27	0.28	10	20	72	58	66	61
Liver	Marrow, colon, lungs, skin, bones	0.19	0.30	7	56	22	27	25	77
Kidneys	Marrow, colon, stomach, liver, skin, bones	0.22	0.22	10	34	32	15	32	27
Liver-to-kidneys	Marrow, colon, lungs, skin, bones	0.19	0.23	6	32	21	20	24	41
Kidneys-to-bladder	Marrow, stomach, liver, skin, bones	0.21	0.18	19	24	24	8	30	16
Head	Marrow, skin, bones	0.22	0.21	21	12	22	14	25	32
Neck	Marrow, thyroid, skin, bones	0.18	0.19	15	8	45	31	37	34
Head-and-neck	Marrow, thyroid, skin, bones	0.18	0.19	11	14	35	40	34	45

maximum COV of 0.54 from the head-and-neck examination. For both males and females, q factors calculated from the XCAT and the ICRP 110 phantoms agreed well, with an average difference of 10% for males and 13% for females across all examination categories. The q factors from CT-Expo phantoms had a higher percent difference from ICRP 110 phantoms, with an average difference of 17% for males and 22% for females. The q factors from the ImPACT phantom had the highest percent difference from ICRP 110, with an average difference of 20% for males and 31% for females.

The q factors showed drastic variation between male and female. For males, the q factors were small and consistent across body examinations (COV of 0.11 across all body examinations and male phantoms), while for females, the q factors showed a high degree of variability.

IV. DISCUSSION

In this study, we compared organ doses, effective doses, risk indices, k factors, and q factors across four types of phantoms. Several comparison studies between voxelized phantoms and stylized phantoms in CT have been conducted by two other research groups.^{10,11,15} These studies were focused on only one type of voxelized phantom and only examined a small number of protocols. In this study, two types of voxelized phantoms were studied, the voxelized version of the hybrid XCAT reference phantoms and the voxelized ICRP 110 reference phantoms. Monte Carlo simulated organ doses were compared for 13 routinely used body and neurological CT examination categories. DLP to effective dose conversion coefficient (k factor) was reported for each category to expand on the limited amount of published data available for various anatomical regions. Recognizing the limitations of the effective dose,^{43–45} we further estimated

cancer risk using the risk index concept^{14,36} and calculated DLP-to-risk index conversion coefficient (q factor).

Our study showed that sizable differences in organ dose exist among different types of reference phantoms despite their closely matched organ masses, total body weight, and height. One major cause of the organ dose differences is the difference in organ locations. For example, the locations of testes in the two stylized male phantoms (ImPACT and CT-Expo) are superior to the corresponding locations in the two voxelized male phantoms (XCAT and ICRP 110). In the chest–abdomen–pelvis and abdomen–pelvis examinations, where the scans both end at 1 cm below inferior ischium, testes in the four male phantoms were irradiated differently. The percentages of the testes length that were irradiated for the ImPACT, the CT-Expo, the XCAT, and the ICRP 110 male phantoms were 100%, 82%, 47%, and 0%, respectively. This resulted in the dose to the testes being highest for ImPACT, second highest for CT-Expo, third highest for XCAT, and minimal for ICRP 110. Another example is the colon. In the XCAT female phantom, the transverse colon was superior in the body in comparison to the location of the transverse colon in the ICRP 110 female phantom. Therefore, during the chest examination, part of the colon was irradiated in the XCAT phantom, while the colon in the ICRP 110 phantom was completely outside of the scan field. This resulted in an 18-fold difference in colon dose.

In addition to organ location, the spatial distribution (the spread) of an organ also plays an important role. The breasts of the ImPACT hermaphrodite phantom have a length of 4.1 cm, which is much shorter than the female breasts in the XCAT (15.2 cm), the ICRP 110 (13.6 cm), and the CT-Expo (11.6 cm) phantoms. While the breasts were out of the scan coverage for abdomen–pelvis, abdomen, liver, and liver-to-kidneys examinations on the ImPACT hermaphrodite phantom, they were fully irradiated on the ICRP 110 female

FIG. 4. Comparison of risk index (RI) over four types of phantoms for the 13 examination categories for male (a) and female (b) phantoms. The coefficient of variation for each examination is displayed above the bars.

phantom and partially irradiated on the XCAT and the CT-Expo female phantoms for these examinations. This caused the breast dose in the ImPACT phantom to be much lower than in the other three female phantoms.

Because no phantoms have all the radiosensitive organs, approximation methods had to be used, which also resulted in organ dose differences between phantoms. For example, in the ImPACT and the CT-Expo phantoms, dose to the

esophagus was approximated by dose to the thymus, which was much shorter than a real esophagus, causing the esophageal dose in the stylized phantoms to be very different from that in the voxelized phantoms. Thus, in the stylized phantoms, dose to esophagus was high for upper body examinations where thymus was fully irradiated, as in chest and chest-abdomen-pelvis exams, but really low for other examinations compared to the voxelized phantoms. Another

FIG. 5. Comparison of k factor among four types of phantoms for 13 examination categories. The k factor for XCAT, ICRP 110, and CT-Expo phantoms used gender-averaged effective dose and DLP. The tabulated k values for six protocol classes from the AAPM were also included for comparison in this graph. The coefficient of variation for each examination is displayed above the bars.

example of this effect is the salivary glands. For the ImPACT phantom, dose to the salivary glands was approximated by dose to the brain, while for the XCAT and the ICRP 110 phantoms, it was approximated by dose to the larynx–pharynx. In the head examination, the brain was fully irradiated, but the larynx–pharynx was partially irradiated. Therefore, dose to the salivary glands in the ImPACT phan-

tom was much higher than those in the XCAT or the ICRP 110 phantoms. The location of the larynx–pharynx in XCAT phantoms are greatly inferior to that of the ICRP 110 phantoms, resulting in even smaller dose in the XCAT phantoms. The opposite trend was found in the neck examination, where the brain was out of the scan coverage and the larynx–pharynx was mostly within the scan coverage.

TABLE VI. k and q factor over three types of phantoms for the 13 examination categories.

	k (mSv/mGy-cm)					q (cases/1,000,000 exposed/mGy-cm)									
						Male					Female				
	XCAT	ICRP110	ImPACT	CT-Expo	COV	XCAT	ICRP110	ImPACT ^a	CT-Expo	COV	XCAT	ICRP110	ImPACT ^a	CT-Expo	COV
Chest-abdomen-pelvis	0.018	0.019	0.018	0.017	0.06	1.6	1.7	1.8	1.7	0.05	3.2	3.8	2.9	3.3	0.11
Chest	0.025	0.026	0.020	0.019	0.17	1.8	1.8	1.6	1.5	0.09	5.1	6.2	4.7	5.4	0.12
Abdomen–pelvis	0.018	0.019	0.016	0.016	0.08	1.7	1.7	1.9	1.8	0.06	2.8	2.9	1.9	2.1	0.21
Abdomen	0.023	0.024	0.019	0.019	0.12	1.8	1.8	1.6	1.7	0.06	3.7	3.5	2.0	2.6	0.26
Pelvis	0.011	0.012	0.014	0.013	0.11	1.6	1.4	2.2	1.9	0.20	1.3	1.8	1.6	1.6	0.13
Adrenals	0.026	0.029	0.020	0.022	0.17	2.1	2.2	1.6	1.6	0.18	3.0	2.9	2.6	3.5	0.12
Liver	0.026	0.029	0.020	0.020	0.20	1.9	2.1	1.6	1.7	0.13	4.4	4.9	2.2	2.7	0.36
Kidneys	0.020	0.024	0.021	0.020	0.09	1.7	2.1	1.5	1.7	0.13	2.2	2.3	1.8	2.1	0.10
Liver-to-kidneys	0.024	0.027	0.020	0.020	0.15	1.8	2.0	1.6	1.7	0.11	3.9	3.8	2.2	2.7	0.26
Kidneys-to-bladder	0.015	0.018	0.016	0.016	0.05	1.7	1.7	1.9	1.7	0.04	1.9	2.2	1.9	1.9	0.07
Head	0.0014	0.0022	0.0030	0.0023	0.30	0.1	0.2	0.3	0.2	0.36	0.2	0.3	0.5	0.3	0.37
Neck	0.0051	0.0054	0.0058	0.0076	0.19	0.4	0.4	0.4	0.6	0.19	1.1	1.3	1.4	1.8	0.21
Head-and-neck	0.0034	0.0037	0.0045	0.0046	0.15	0.3	0.3	0.3	0.4	0.11	0.7	0.7	0.2	1.0	0.54

^aThe same set of organ doses data is used for each examination but with different risk coefficients for male and female.

FIG. 6. Comparison of q factor over four types of phantoms for the 13 examination categories for male (a) and female (b) phantoms. The coefficient of variation for each examination is displayed above the bars.

As mentioned in Sec. II.A, the organ masses in the XCAT reference, the ICRP 110 reference, and the ImPACT reference phantoms in this study were matched to the organ masses recommended in the ICRP publication 89; the organ masses in the CT-Expo reference phantoms were matched to the ICRP publication 23. Nevertheless, the masses of the organs (Table I) were very similar for all four types of phan-

toms, but some of the organ doses received were considerably different. This indicated that the anatomical locations and spatial distributions of organs in a phantom affected radiation dose much more than the masses of the organs.

When comparing phantoms using ICRP 110 phantoms as the reference standard, XCAT male was the closest match to ICRP 110 male for both fully and partially irradiated organs.

For female, XCAT was not the closest match to the ICRP 110 female for fully irradiated organs. Average diameters for the XCAT and the ICRP 110 phantoms were calculated for chest and abdomen using the following method. The body volume was first calculated by multiplying the voxel volume by the total number of voxels for chest and abdomen. The total volume was then divided by the z-axis length of each part to obtain the average axial plane area. This area was used to calculate the average diameters for chest and abdomen assuming the axial plane to be a circle. The average diameters for the XCAT female phantom are 29.32 cm for chest and 27.54 cm for abdomen, while for ICRP 110 these values are 27.1 and 25.75 cm, respectively. The average diameters for the XCAT female are 2.22 and 1.79 cm larger than the diameters for the ICRP 110 female. The larger diameter in the XCAT female was partially due to single voxel layer skin. Both phantoms used one single voxel layer skin, but the transverse plane voxel size for the XCAT female (3.45 mm) was slightly larger than the voxel size for the ICRP 110 female (1.775 mm). The average diameter difference caused major radiosensitive organs in the chest and abdomen regions (lungs, stomach, and liver) to receive less doses in the XCAT female phantom when these organs were fully irradiated. The effect of body diameters on radiation dose has been explored in the literature.^{16,36}

The variability in effective doses of the four types of phantoms (Fig. 3) was not as dramatic as the variability in organ doses because effective dose was weighted and summed over all radiosensitive organs. The organs that received small doses tended to show higher differences in dose between phantoms but were not as important in the summation. The same argument can be applied to risk indices for males. However, risk indices for females varied considerably across phantoms due to the large variance of lung and breast doses, which were the two highest risk organs for females.

In a clinical environment, estimating effective dose using Monte Carlo simulation is not practical. An easy and fast way to estimate effective dose is to use DLP to effective dose conversion coefficients, also known as k factors. The accuracy of k factors is therefore very important. In this study, we examined how k factors would vary when obtained from different types of phantoms and compared our results with the commonly used k factors published in AAPM 96.⁴⁶ The AAPM values were only available for a small number

of examinations, which did not include some routinely used CT examinations that were incorporated in this study. We showed that the k factors for the unreported scan regions were rather different from the body regions reported in AAPM 96. Take the ICRP 110 phantoms, for example, the k factor of the adrenal examination is 0.0294 mSv/mGy cm, about 1.5 times the value of chest–abdomen–pelvis examination. The result is that the effective dose calculated using the chest–abdomen–pelvis examination k factor represents a gross underestimation. Therefore, the k factor reported here is of great utility for clinical effective dose estimation. The k factor for each examination agreed well across phantoms, which can be explained using the same argument as effective dose. For the head examination, the COV for k factors was much higher than any other examination. This was due to the significant difference in doses to the salivary glands, mentioned earlier in this section.

Note that the k factors in this study were all calculated using the tissue weighting factors from the ICRP publication 103, while the commonly used k factors in AAPM 96 were calculated based on weighting factors from the ICRP publication 60. The k factors from AAPM 96 were smaller than the corresponding k factors calculated with the four types of reference phantoms for all examinations and the head-and-neck examination. In contrast, the k factor for the neck examination published in AAPM 96 report is larger than any of the k factors obtained in this study. Given the sizable differences, the published k factors should be updated to reflect the new tissue weighting factors.

The effect of new tissue weighting factors on conversion coefficients has also been reported by other researchers.^{47–49} Table VII shows the results from three other groups and compares this data with the data from the ImPACT and the CT-Expo phantoms. These two types of phantoms were chosen because the three groups all used stylized phantoms in their studies. Since the same phantom and software were used, the results from Huda *et al.*⁴⁹ and Christner *et al.*⁴⁷ were very similar to the data from the ImPACT phantom in this study. The only examination that showed a noticeable difference was the head exam. The inconsistency was caused by a variation in scan region. The data from Deak *et al.*⁴⁸ showed more variance than other groups' but closer match to the data from the CT-Expo phantoms in this study. This was expected because the CT-Expo phantoms were derived

TABLE VII. Comparison of k factors obtained using ImPACT and CT-Expo phantoms in this study and from other 3 research groups. All the k factors here were calculated using ICRP 103 tissue weighting factors.

Scan region	DLP to ED conversion coefficient— k (mSv/mGy cm)				
	ImPACT from this study	CT-Expo from this study	Huda <i>et al.</i> (Ref. 49)	Christner <i>et al.</i> (Ref. 47)	Deak <i>et al.</i> (Ref. 48)
Head	0.0030	0.0023	0.0024	0.0013	0.0019
Neck	0.0058	0.0076	0.0053		0.0051
Chest	0.0205	0.0185	0.0204	0.021	0.0145
Abdomen	0.0195	0.0191	0.0163		0.0153
Pelvis	0.0133	0.0134	0.0143		0.0129
Abdomen and pelvis	0.0161	0.0163		0.017	
Liver	0.0206	0.0198		0.018	

from the ORNL phantoms, which were used in the study of Deak *et al.* However, the two set of data still differed considerably because of the differences in scan length, anatomic variations, and Monte Carlo codes implemented in computer simulation.

Since the effective dose is based on tissue weighting factors that have been calculated from an extremely broad pool of data,⁴¹ it is not appropriate to use this concept on patients with specific age and gender. The effective dose provides dosimetry information on radiobiological risk associated detriment, but it is meant to be used in a general sense. In order to gain better understanding of dose received by different genders, the risk index was calculated for male and female separately in this study. The q factors for each examination agreed well across male phantoms. The q factors were also consistent across body examinations with the COV of 0.11 across all body examinations, indicating the possibility of using one q factor for all male body examinations.¹² The female q factors have a high degree of fluctuation across various phantoms and examinations for several reasons. The primary reason is the high risk of lung and breast cancer incidences. For female abdomen, liver and liver-to-kidneys examinations, the q factors of the ImPACT and the CT-EXPO phantoms were much smaller than q factors obtained from the other two phantoms. This can be explained by the relatively small dose to the breasts in the two stylized phantoms. Although gender-specific effective dose has been proposed, the real gender difference cannot be represented by the effective dose unless the gender-specific tissue weighting factors are used.

One limitation of this study was that only one CT scanner model was explored. The dose values for other scanners may be different from what we obtained here. However, when normalized to CTDI and DLP, doses from various scanner models show similar results.¹⁶ Furthermore, the major finding, i.e., organ dose differences across reference phantoms were mainly introduced by the locations, spatial distributions, and dose approximation methods, should still be applicable to other scanners. Additionally, the risk data used in the cancer risk estimation is based on studies of atomic bomb survivors and other limited research studies involving occupational exposures and thus suffers from large uncertainty. Finally, this study only addressed k and q factors across reference size adult phantoms. The effect of patient size requires a presentation of its own. Again, the main purpose of this study was to provide insight into the effects that different types of reference phantoms have on CT dosimetry and thus lead to a better understand of radiation dose received by patients undergoing CT examinations.

V. CONCLUSION

In this study, the XCAT reference male and female, the ICRP 110 reference male and female, the ImPACT reference hermaphrodite, and the CT-Expo reference male and female phantoms were compared for CT dosimetry. Dose differences for fully irradiated radiosensitive organs were much smaller than those for partially irradiated organs. The

observed differences were mainly introduced by variation in organ location (e.g., testes in the pelvis examination; colon in the female chest examinations), spatial distribution (e.g., female breasts in abdomen–pelvis, abdomen, liver, and liver-to-kidneys examinations), as well as the approximation method implemented (e.g., esophagus in chest and chest–abdomen–pelvis examinations; salivary glands in head-and-neck examinations). The weighted dosimetry quantities including effective doses, male risk indices, k factors, and male q factors agreed well across phantoms, because organs that received small doses tended to show higher variation in dose between phantoms, but were not as important in the summation. The female risk indices varied considerably across phantoms due to high risk of lung and breast cancer incidence.

ACKNOWLEDGMENTS

The authors are thankful to Dr. Georg Stamm for providing information on CT-Expo phantoms. This work was supported in part by the National Institutes of Health (Grant No. RO1 EB001838).

^{a)} Author to whom correspondence should be addressed. Electronic mail: samei@duke.edu

¹D. J. Brenner and E. J. Hall, “Computed tomography—An increasing source of radiation exposure,” *N. Engl. J. Med.* **357**, 2277–2284 (2007).

²National Council on Radiation Protection and Measurements. Scientific Committee 6-2 on Radiation Exposure of the U.S. Population, *Ionizing radiation exposure of the population of the United States: Recommendations of the National Council on Radiation Protection and Measurements* (National Council on Radiation Protection and Measurements, Bethesda, MD, 2009).

³ICRP, “Radiation protection in medicine. ICRP Publication 105,” *Ann. ICRP* **37**, 1–63 (2007).

⁴A. Berrington de Gonzalez, M. Mahesh, K. P. Kim, M. Bhargavan, R. Lewis, F. Mettler, and C. Land, “Projected cancer risks from computed tomographic scans performed in the United States in 2007,” *Arch. Intern. Med.* **169**, 2071–2077 (2009).

⁵E. S. Amis, Jr., P. F. Butler, K. E. Applegate, S. B. Birnbaum, L. F. Brateman, J. M. Hevezi, F. A. Mettler, R. L. Morin, M. J. Pentecost, G. G. Smith, K. J. Strauss, and R. K. Zeman, “American College of Radiology white paper on radiation dose in medicine,” *J. Am. Coll. Radiol.* **4**, 272–284 (2007).

⁶E. Angel, N. Yaghamai, C. M. Jude, J. J. Demarco, C. H. Cagnon, J. G. Goldin, A. N. Primak, D. M. Stevens, D. D. Cody, C. H. McCollough, and M. F. McNitt-Gray, “Monte Carlo simulations to assess the effects of tube current modulation on breast dose for multidetector CT,” *Phys. Med. Biol.* **54**, 497–512 (2009).

⁷M. Caon, G. Bibbo, and J. Pattison, “An EGS4-ready tomographic computational model of a 14-year-old female torso for calculating organ doses from CT examinations,” *Phys. Med. Biol.* **44**, 2213–2225 (1999).

⁸P. Deak, M. van Straten, P. C. Shrimpton, M. Zankl, and W. A. Kalender, “Validation of a Monte Carlo tool for patient-specific dose simulations in multi-slice computed tomography,” *Eur. Radiol.* **18**, 759–772 (2008).

⁹J. J. DeMarco, C. H. Cagnon, D. D. Cody, D. M. Stevens, C. H. McCollough, M. Zankl, E. Angel, and M. F. McNitt-Gray, “Estimating radiation doses from multidetector CT using Monte Carlo simulations: Effects of different size voxelized patient models on magnitudes of organ and effective dose,” *Phys. Med. Biol.* **52**, 2583–2597 (2007).

¹⁰C. Lee, K. P. Kim, D. Long, R. Fisher, C. Tien, S. L. Simon, A. Bouville, and W. E. Bolch, “Organ doses for reference adult male and female undergoing computed tomography estimated by Monte Carlo simulations,” *Med. Phys.* **38**, 1196–1206 (2011).

¹¹C. Lee, R. J. Staton, D. E. Hintenlang, M. M. Arreola, J. L. Williams, and W. E. Bolch, “Organ and effective doses in pediatric patients undergoing

- helical multislice computed tomography examination," *Med. Phys.* **34**, 1858–1873 (2007).
- ¹²X. Li, E. Samei, W. P. Segars, E. K. Paulson, and D. P. Frush, "The feasibility of universal DLP-to-risk conversion coefficients for body CT protocols," *Proc. SPIE* **7961**, 79612A (2011).
 - ¹³X. Li, E. Samei, W. P. Segars, G. M. Sturgeon, J. G. Colsher, G. Toncheva, T. T. Yoshizumi, and D. P. Frush, "Patient-specific radiation dose and cancer risk estimation in CT: Part I. development and validation of a Monte Carlo program," *Med. Phys.* **38**, 397–407 (2011).
 - ¹⁴X. Li, E. Samei, W. P. Segars, G. M. Sturgeon, J. G. Colsher, G. Toncheva, T. T. Yoshizumi, and D. P. Frush, "Patient-specific radiation dose and cancer risk estimation in CT. Part II. Application to patients," *Med. Phys.* **38**, 408–419 (2011).
 - ¹⁵H. Liu, J. Gu, P. F. Caracappa, and X. G. Xu, "Comparison of two types of adult phantoms in terms of organ doses from diagnostic CT procedures," *Phys. Med. Biol.* **55**, 1441–1451 (2010).
 - ¹⁶A. C. Turner, M. Zankl, J. J. DeMarco, C. H. Cagnon, D. Zhang, E. Angel, D. D. Cody, D. M. Stevens, C. H. McCollough, and M. F. McNitt-Gray, "The feasibility of a scanner-independent technique to estimate organ dose from MDCT scans: Using CTDIvol to account for differences between scanners," *Med. Phys.* **37**, 1816–1825 (2010).
 - ¹⁷I. A. Castellano, D. R. Dance, and P. M. Evans, "CT dosimetry: Getting the best from the adult Cristy phantom," *Radiat. Prot. Dosim.* **114**, 321–325 (2005).
 - ¹⁸J. Gu, B. Bednarz, P. F. Caracappa, and X. G. Xu, "The development, validation and application of a multi-detector CT (MDCT) scanner model for assessing organ doses to the pregnant patient and the fetus using Monte Carlo simulations," *Phys. Med. Biol.* **54**, 2699–2717 (2009).
 - ¹⁹A. Khursheed, M. C. Hillier, P. C. Shrimpton, and B. F. Wall, "Influence of patient age on normalized effective doses calculated for CT examinations," *Br. J. Radiol.* **75**, 819–830 (2002).
 - ²⁰M. Cristy and K. F. Eckerman, "Specific absorbed fractions of energy at various ages from internal photon sources," ORNL/TM-8381/Volumes I–VII (Oak Ridge National Laboratory, Oak Ridge, TN) (1987).
 - ²¹ICRP, "Adult Reference Computational Phantoms. ICRP Publication 110," *Ann. ICRP* **39** (2009).
 - ²²M. Caon, "Voxel-based computational models of real human anatomy: A review," *Radiat. Environ. Biophys.* **42**, 229–235 (2004).
 - ²³X. G. Xu, V. Taranenko, J. Zhang, and C. Shi, "A boundary-representation method for designing whole-body radiation dosimetry models: Pregnant females at the ends of three gestational periods—RPI-P3, -P6 and -P9," *Phys. Med. Biol.* **52**, 7023–7044 (2007).
 - ²⁴W. P. Segars, G. Sturgeon, S. Mendonca, J. Grimes, and B. M. Tsui, "4D XCAT phantom for multimodality imaging research," *Med. Phys.* **37**, 4902–4915 (2010).
 - ²⁵R. Kramer, H. J. Khoury, and J. W. Vieira, "Comparison between effective doses for voxel-based and stylized exposure models from photon and electron irradiation," *Phys. Med. Biol.* **50**, 5105–5126 (2005).
 - ²⁶C. Lee and W. E. Bolch, "Age-dependent organ and effective dose coefficients for external photons: A comparison of stylized and voxel-based paediatric phantoms," *Phys. Med. Biol.* **51**, 4663–4688 (2006).
 - ²⁷C. Lee, D. Lodwick, J. Hurtado, D. Pafundi, J. L. Williams, and W. E. Bolch, "The UF family of reference hybrid phantoms for computational radiation dosimetry," *Phys. Med. Biol.* **55**, 339–363 (2010).
 - ²⁸ImPACT's CT Dosimetry Tool: CT dosimetry version 1.0.3" (available URL: <http://www.impactscan.org/ctdosimetry.htm>). Last accessed February, 2011.
 - ²⁹"Visible Human Male and Female Datasets from National Library of Medicine" (available URL: http://www.nlm.nih.gov/research/visible_human.html).
 - ³⁰ICRP, "Basic anatomical and physiological data for use in radiological protection: The skeleton. ICRP Publication 70," *Ann. ICRP* **25** (1995).
 - ³¹ICRP, "Basic anatomical and physiological data for use in radiological protection: Reference values. ICRP Publication 89," *Ann. ICRP* **32** (2002).
 - ³²ICRU, "Photon, Electron, Proton and Neutron Interaction Data for Body Tissues. ICRU Report 46," ICRU Report 46 (1992).
 - ³³P. C. Shrimpton, B. F. Wall, D. G. Jones, E. S. Fisher, M. C. Hillier, G. M. Kendall, and R. M. Harrison, "Doses to patients from routine diagnostic x-ray examinations in England," *Br. J. Radiol.* **59**, 749–758 (1986).
 - ³⁴D. G. Jones and B. F. Wall, "Organ doses from medical x-ray examinations calculated using Monte Carlo techniques," Report No. NRPB-R186 (Chilton, London, HMSO) (1986).
 - ³⁵R. Kramer, M. Zankl, G. Williams, and G. Drexler, "The calculation of dose from external photon exposures using reference human phantoms and Monte Carlo methods: Part I," GSF-Bericht S-885 (1982).
 - ³⁶X. Li, E. Samei, W. P. Segars, G. M. Sturgeon, J. G. Colsher, and D. P. Frush, "Patient-specific radiation dose and cancer risk for pediatric chest CT," *Radiology* **259**, 862–874 (2011).
 - ³⁷J. Sempau, J. M. Fernandez-Varea, E. Acosta, and F. Salvat, "Experimental benchmarks of the Monte Carlo code PENELOPE," *Nucl. Instrum. Methods B* **207**, 107–123 (2003).
 - ³⁸J. Baro, J. Sempau, J. M. Fernandezvarea, and F. Salvat, "PENELOPE—An algorithm for Monte-Carlo simulation of the penetration and energy-loss of electrons and positrons in matter," *Nucl. Instrum. Methods B* **100**, 31–46 (1995).
 - ³⁹C. Lee, C. Lee, A. P. Shah, and W. E. Bolch, "An assessment of bone marrow and bone endosteum dosimetry methods for photon sources," *Phys. Med. Biol.* **51**, 5391–5407 (2006).
 - ⁴⁰P. C. Shrimpton and D. G. Jones, "Normalized organ doses for x-ray computed-tomography calculated using Monte-Carlo techniques and a mathematical anthropomorphic phantom," *Radiat. Prot. Dosim.* **49**, 241–243 (1993).
 - ⁴¹ICRP, "The 2007 Recommendations of the International Commission on Radiological Protection. ICRP publication 103," *Ann. ICRP* **37**, 1–332 (2007).
 - ⁴²National Research Council (U.S.). Committee to Assess Health Risks from Exposure to Low Level of Ionizing Radiation, *Health Risks from Exposure to Low Levels of Ionizing Radiation: BEIR VII Phase 2* (National Academies, Washington, DC, 2006).
 - ⁴³D. J. Brenner, "Effective dose: A flawed concept that could and should be replaced," *Br. J. Radiol.* **81**, 521–523 (2008).
 - ⁴⁴C. J. Martin, "Effective dose: How should it be applied to medical exposures?," *Br. J. Radiol.* **80**, 639–647 (2007).
 - ⁴⁵C. J. Martin, "The application of effective dose to medical exposures," *Radiat. Prot. Dosim.* **128**, 1–4 (2008).
 - ⁴⁶AAPM, "The Measurement, reporting, and management of radiation dose in CT," AAPM Report No. 96 (2008).
 - ⁴⁷J. A. Christner, J. M. Kofler, and C. H. McCollough, "Estimating effective dose for CT using dose-length product compared with using organ doses: Consequences of adopting International Commission on Radiological Protection publication 103 or dual-energy scanning," *AJR, Am. J. Roentgenol.* **194**, 881–889 (2010).
 - ⁴⁸P. 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**, 158–166 (2010).
 - ⁴⁹W. Huda, D. Magill, and W. He, "CT effective dose per dose length product using ICRP 103 weighting factors," *Med. Phys.* **38**, 1261–1265 (2011).