Hybrid computational phantoms of the 15-year male and female adolescent: Applications to CT organ dosimetry for patients of variable morphometry

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Currently, two classes of the computational phantoms have been developed for dosimetry calculation: (1) stylized (or mathematical) and (2) voxel (or tomographic) phantoms describing human anatomy through mathematical surface equations and three-dimensional labeled voxel matrices, respectively. Mathematical surface equations in stylized phantoms provide flexibility in phantom design and alteration, but the resulting anatomical description is, in many cases, not very realistic. Voxel phantoms display far better anatomical realism, but they are limited in terms of their ability to alter organ shape, position, and depth, as well as body posture. A new class of computational phantoms—called hybrid phantoms—takes advantage of the best features of stylized and voxel phantoms—flexibility and anatomical realism, respectively. In the current study, hybrid computational phantoms representing reference 15-year male and female body anatomy and anthropometry are presented. For the male phantom, organ contours were extracted from the University of Florida (UF) 14-year series B male voxel phantom, while for the female phantom, original computed tomography (CT) data from two 14-year female patients were used. Polygon mesh models for the major organs and tissues were reconstructed for nonuniform rational B-spline (NURBS) surface modeling. The resulting NURBS/polygon mesh models representing body contour and internal anatomy were matched to anthropometric data and reference organ mass data provided by the Centers for Disease Control and Prevention (CDC) and the International Commission on Radiation Protection (ICRP), respectively. Finally, two hybrid 15-year male and female phantoms were completed where a total of eight anthropometric data categories were matched to standard values within 4% and organ masses matched to ICRP data within 1% with the exception of total skin. To highlight the flexibility of the hybrid phantoms, 10th and 90th weight percentile 15-year male and female phantoms were further developed from the 50th percentile phantoms through adjustments in the body contour to match the total body masses given in CDC pediatric growth curves. The resulting six NURBS phantoms, male and female phantoms representing their 10th, 50th, and 90th weight percentiles, were used to investigate the influence of body fat distributions on internal organ doses following CT imaging. The phantoms were exposed to multislice chest and abdomen helical CT scans, and in-field organ absorbed doses were calculated. The results demonstrated that the use of traditional stylized phantoms yielded organ dose estimates that deviate from those given by the UF reference hybrid phantoms by up to a factor of 2. The study also showed that use of reference, or 50th percentile, phantoms to assess organ doses in underweight 15-year-old children would not lead to significant organ dose errors (typically less than 10%). However, more significant errors were noted (up to ~30%) when reference phantoms are used to represent overweight children in CT imaging dosimetry. These errors are expected to only further increase as one considers CT organ doses in overweight and obese individuals of the adult patient population, thus emphasizing the advantages of patient-sculptable phantom technology. © 2008 American Association of Physicists in Medicine. [DOI: [10.1118/1.2912178](https://doi.org/10.1118/1.2912178)]

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I. INTRODUCTION

Computational phantoms of human anatomy have been used extensively to assess the absorbed dose to individual organs received in patients undergoing imaging examinations and interventional medical procedures. The first generation of these phantoms are stylized (or mathematical) anatomic models within which three-dimensional (3D) surface equations are used to describe internal organ structure and external body regions.¹⁻³ While these equation-based phantoms provide the flexibility needed for organ repositioning and posture modification,⁴ they do not provide for extremely realistic descriptions of the finer complexities of organ shape and position. The second generation of computational phantoms is voxel (or tomographic) models as introduced by several authors and summarized in recent reviews by Caon⁵ and by Zaidi and Xu.⁶ Voxel phantoms are developed from cross-sectional medical images such as magnetic resonance and computed tomography (CT) scans obtained prospectively from healthy volunteers, or retrospectively from either medical patients or cadavers. Realistic anatomy of the scanned subject is faithfully implemented in the resulting voxel phantoms through the time-consuming and generally manual image-segmentation processes, with subsequent coupling to Monte Carlo radiation transport codes. While they surpass stylized phantoms in anatomic realism, voxel phantoms are less flexible in terms of permitting changes in either body posture and contour, or internal organ shape, position, and depth.

A hybrid approach to phantom construction incorporates the best features of both stylized and voxel phantoms. Hybrid phantoms make use of nonuniform rational B-spline (NURBS) surfaces⁷ to describe the boundaries of both internal organs and exterior body surfaces. NURBS is a mathematical modeling technique commonly used for generating curves and surfaces in computer animation. The technique offers a mathematical approach for representing not only standard analytic shapes, but free-form curves and surfaces, many of which are very appropriate for describing complex tissue structures. Moreover, NURBS provides the flexibility to design a large variety of shapes by manipulating individual or groups of surface control points. This feature makes it possible to more easily modify organ volumes and body contours than is possible with either stylized or voxel phantoms. Recently, our research group at the University of Florida (UF) introduced a pair of hybrid phantoms representative of a reference male and female newborn patient as given in Publication 89 of the International Commission on Radiation Protection (ICRP).^{8,9} Similar techniques have been used to develop three pregnant female models¹⁰ and a human torso phantom for simulating nuclear medicine functional images.¹¹

In this study, our development of pediatric hybrid phantoms is extended to the ICRP 89 reference 15-year male and female adolescent. These two reference phantoms were subsequently used to create additional virtual patient models representative of 15-year males and females at their 10th and 90th weight percentiles. All six phantoms were then used to

investigate variations in organ dose delivered under multi-slice CT imaging. While reference phantoms continue to have important uses in prospective dosimetry for radiological protection, this study highlights their limitations in medical dosimetry and emphasizes the need for patient-sculptable phantoms that permit individualized assessments of organ dose needed in either medical epidemiological studies or in a patient organ-dose tracking system.

II. MATERIALS AND METHODS

II.A. Phantom development

II.A.1. Source anatomy

In this study, two independent and gender-specific image sources were employed in the construction of the 15-year male and female hybrid phantoms. For the male phantom, we utilized the UF 14-year male voxel phantom of Lee *et al.*¹² and its original CT images, while the female phantom was constructed from CT image sets from two different 14-year female patients.

As for the male phantom, the UF series B (whole body) 14-year male voxel phantom in 3D voxel matrix form was converted into a polygon mesh format as the base framework for NURBS surface modeling.¹² The UF 14-year male voxel phantom represents an extension of the UF series A (torso only) 14-year male phantom¹³ developed using head and chest-abdomen-pelvis (CAP) CT images of live patients of normal organ and body anatomy. This voxel phantom is composed of a voxel array $349 \times 193 \times 252$ in size with a voxel resolution of $0.118 \times 0.118 \times 0.672$ cm³. Contours of the presegmented organs and tissues in the voxel phantom were obtained using 3D-DOCTOR™ (Able Software Corp., Lexington, MA), a 3D modeling and image processing software for tomography data. Next, the contours were exported in Wavefront Object file format and imported to Rhinoceros™ (McNeel North America, Seattle, WA), a NURBS modeling, rendering, and analysis software.

As for a hybrid 15-year female phantom, the head and CAP CT images of two different 14-year female patients were employed to segment major organs and tissues. The CT records in the University of Florida Department of Radiology at Shands Children's Hospital were reviewed under IRB-approved and HIPAA-compliant protocols to find the best candidates for hybrid phantom construction. Selected image sets, based initially on only subject gender and age, were later reviewed by a pediatric radiologist for abnormal patient anatomy. Scans with organs that may have been affected by local or systemic disease were discarded, as well as those for which the CT examination or radiologist's report indicated trauma or major surgery. The CT images screened for normal anatomy were further reviewed to select those patients with sitting heights close to 50th percentile values as tabulated by the Centers for Disease Control and Prevention (CDC). The data selected for use in modeling the torso of the female hybrid phantom were from a 13.7-year female patient and were given as 108 transverse slices at a slice thickness of 6 mm. The head and cervical spine data were obtained from a

14.7-year female patient. The head data consisted of 47 slices at 4.5-mm slice thickness and the c-spine data consisted of 338 slices at 0.5-mm slice thickness. 3D-DOCTOR™ was used to segment major internal organs and skeleton from all CT image sets. This process is fairly similar to that for the construction of voxel phantoms where combinations of semiautomatic and manual segmentation are employed. The contour files representing internal organs and tissues were exported as Wavefront Object files for input to Rhinoceros™ for subsequent NURBS modeling.

The patients whose anatomy was incorporated into the hybrid 15-year-old male and female phantoms were scanned in a supine position with the arms raised for the CAP series and the arms at the patient's side for the head scans. Consequently, the arms were not available in the selected CT data for the phantom construction, and thus separate arm and leg images were segmented from high-resolution CT scans of a 18-year male cadaver. The arms (820 slices) and legs (1099 slices) were reconstructed each at 1.0-mm slice thickness. The arm and leg bones in the CT images were carefully segmented and attached to the torso of the 15-year-old male and female phantoms at the NURBS modeling stage.

II.A.2. NURBS surface modeling

The 15-year hybrid phantoms were constructed using similar modeling methods and an identical organ list to that defining the UF newborn hybrid phantoms,⁸ yet separate gender-specific image sources were employed for each phantom. All organs and tissues imported from 3D-DOCTOR™ in polygon mesh format were converted to NURBS surfaces with the exclusion of the skeleton, brain, and extrathoracic airways as the details and shapes of their original anatomy could not be modeled effectively via NURBS surfaces. For all remaining tissues, organ contours were obtained from the imported polygon mesh objects and then NURBS surfaces were generated from those contours, thus maintaining their original anatomic realism.

As for paired organs, right and left organs were forced to be of equivalent volumes and positions in the UF hybrid 15-year phantoms. These included selected bone sites (clavicles, scapulae, arm and leg bones, and ribs), salivary glands, testes (male), scrotum (male), ovaries (female), eye balls, eye lens, and tonsils. The positions and volumes of the right organs were matched to those of the left organs except for the kidneys and adrenals for which the left organs are generally superior in position to those on the patient's right. Organs and tissues whose anatomical shapes are theoretically close to stylistic and simple 3D surfaces were represented by simple NURBS objects such as spheres and ellipsoids. This stylistic approach was attempted for the sex-specific organs (breast, penis, scrotum, testes, and ovaries) and other selected tissues (urinary bladder, eye balls, lens, tongue, tonsil, and pituitary gland). Special modeling approaches were attempted for the respiratory and alimentary organ systems for which the original segmentation was anatomically poor in representing their original shapes and positions. These approaches included the use of NURBS pipe structures of ad-

justable orientation, dimension, and length as needed to match reference mass and length data, as well as original central lumen traces, for the esophagus, bronchi, intestine, and colon.⁸

The skeleton was modeled as a homogeneous mixture of cortical bone, trabecular bone, active and inactive bone marrow, and miscellaneous skeletal tissues. All bone sites were modeled via polygon mesh surfaces, with the exception of the ribs, which were modeled using NURBS surfaces. The latter approach was chosen as the inter-rib spacing was generally less than the original CT image slice thickness. Central contours and cross sections of ribs were carefully obtained from the original polygon mesh model, and pipe-shaped NURBS surfaces of the desired cross-sectional area were generated. NURBS surfaces for the ribs were running from the vertebral body of the thoracic spine to the beginning of the costal cartilage near the sternum. After the costal cartilage regions and ribs were separated, the total mass of the NURBS rib-cage model was calculated and matched to that of the original ribs through adjustments in the cross-sectional area of each individual rib bone. One additional site of skeletal cartilage was explicitly modeled in each phantom—that of the intervertebral disks of the spine, as segmented from the original CT data. Bone-associated cartilage (which for the 15-year-old would be predominately found at joints, tendons, and ligaments) was not modeled explicitly but was considered in the tissue category residual soft tissues as described below.

II.A.3. Standardization of hybrid phantoms

Once all organs and tissues were modeled by NURBS or polygon mesh surfaces, the male and female phantoms were matched to anthropometric data obtained from several literature sources and reference organ masses given in ICRP Publication 89.⁹ First, a set of body contours which permitted independent changes to the head, torso, and limb dimensions to match either reference and/or patient-specific values were developed since the original body contour from CT data was limited to fixed body dimensions. Currently, a total of eight anthropometric data is available for the 15-year male and female: height (standing and sitting), arm length (acromion-radiale, radiale-styilion, and hand), circumference (head, neck, waist, and buttock), and biacromial breadth. Of these, ICRP Publication 89 provides only standing height.⁹ Sitting height and buttock circumference were obtained from the Third National Health and Nutrition Examination Survey (NHANES III) which is a program of studies designed by the CDC to assess the health and nutritional status of adults and children in the United States.²⁴ The third NHANES survey was performed from 1988 to 1994. The fourth NHANES survey ran from 1999 to 2002 and additionally provides waist circumference for the 15-year-old male and female. Total arm length which is the sum of acromion-radiale length, radiale-styilion length, and hand length, as well as head and neck circumferences, were obtained from the anthropometric database Anthrokids given by the U.S. Consumer Product Safety Commission in 1977.²⁵ Although this

TABLE I. Reference anthropometric parameters for the 15-year male and female patient as obtained from various literature sources and the values realized in the final UF hybrid 15-year male and female phantoms.

Anthropometric parameters		Reference values		UF hybrid phantoms			
		Male	Female	Male	RE (%)	Female	RE (%)
Height	Standing ^a	167.0	161.0	167.0	0.0	161.0	0.0
	Sitting ^b	88.8	85.5	86.5	-2.6	83.0	-2.9
Length	Total arm	75.0	70.7	75.1	0.1	71.8	1.6
	Acromion-radiale ^c	31.5	30.0				
	Radiale-styilion ^c	25.3	23.4				
	Hand ^c	18.2	17.3				
Circumference	Head ^c	55.4	54.3	55.5	0.2	56.1	3.3
	Neck ^c	32.8	30.8	32.2	-1.8	31.0	0.6
	Waist ^d	80.1	78.8	83.0	3.6	79.2	0.5
	Buttock ^b	92.5	93.4	90.5	-2.2	93.0	-0.4
Breadth	Biacromial ^b	38.8	36.3	37.2	-4.0	35.4	-2.6

^aICRP Publication 89.^bNHANES III (1988–1994).^cANTHROKIDS (1977).^dNHANES IV (1999–2002).

data set was collected from children in the 1970s, it is still heavily relied upon by clothing and other industries and remains the only world-wide comprehensive source of pediatric anthropometry data. All of the anthropometric parameters in the UF hybrid 15-year-old male and female phantoms were matched to 50th percentile values within a relative error of 4% as shown in Table I.

Once body dimensions were matched to standard anthropometric data, the masses of individual organs and tissues in the 15-year hybrid phantoms were adjusted to match those given in ICRP Publication 89 within a tolerance of 1%. Reference densities provided in ICRU Report 46 were used to calculate targeted organ volumes given their corresponding reference masses.¹⁴ An effective content density was assigned to all walled organs to force a match to the reference content mass in ICRP Publication 89, a procedure not attempted in the previous UF hybrid newborn phantoms. This approach was applied to the contents of the small intestine, right and left colon, and recto-sigmoid colon. The mass of stomach contents was matched to its reference value by adjusting the level of content from the base of stomach with the residual space assigned as air. Lengths of the esophagus, small intestine, right colon, left colon, and recto-sigmoid colon were matched to their ICRP 89 reference lengths to within 5%. These reference lengths are 27 cm for the male and 26 cm for the female esophagus, 270 cm for the male and 260 cm for the female small intestine, 30 cm for the male and female right colon, 35 cm for male and female left colon, and 35 cm for male and female rectosigmoid colon. Each of parotid, submaxillary, and sublingual glands comprising the salivary glands was matched to their individual reference values given in ICRP Publication 89. Regions not explicitly segmented in the phantom were termed residual soft tissues (RST) and include separable fat, skeletal muscle,

connective tissue, fixed lymphatic tissues, large blood vessels, and bone-associated cartilage exclusive of that found in the ears, nose, larynx, trachea, pharynx, costal cartilage, and intervertebral disks (all explicitly modeled in the final phantoms). The elemental composition and mass density of RST was determined as volume-weighted averages of these tissue constituents.

While the larger groups of skeletal muscle could have been segmented from adipose tissue in the original CT source images, this step was intentionally avoided in our study so as to allow for maximum flexibility in subsequent patient-specific phantom sculpting. As described below, virtual patients of smaller or larger bodyweights can be readily created through the contraction or expansion of the surface control points of the NURBS phantom with a reassignment of residual soft tissue to different fat—muscle ratios as needed to match patient body composition. If, on the other hand, the hybrid reference phantom had included NURBS or polygon mesh models for each individual skeletal muscle, patient sculpting of the phantom would become exceedingly more complex, as individual adjustments to the size and shape of each muscle in the body would be needed as well. The downside of this approach is the lack of a specific anatomic model for muscle in the reference patient as needed for assessment of the absorbed dose to one of the 13 remainder tissues of the effective dose.¹⁵ Nevertheless, we assert that this feature can be added to voxelized hybrid phantoms at a later stage for radiological protection applications, while inclusion of skeletal muscle within the tissue regions RST provides for a more flexible hybrid phantom for patient-specific body sculpting.

The reference skin thicknesses for 15-year male and female phantoms were derived from three other reference parameters, namely the ICRP 89 skin mass (2000 g for the

male and 1700 g for the female), body surface area (1.62 m^2 for the male and 1.55 m^2 for the female) and the skin density (1.1 g cm^{-3} for both the male and female). The resulting reference skin thicknesses were 0.1122 and 0.0997 cm for 15-year male and female phantoms, respectively. The skin volumes of the UF hybrid 15-year phantoms were able to be obtained only in their voxelized format which was created from the corresponding NURBS phantom via a voxelization process described previously by Lee *et al.*⁸ The phantom's skin layer (dermis and epidermis) was generated by assigning a skin tag to the outermost voxel layer during this voxelization process. As the skin was the thinnest tissue layer to be represented in the final hybrid voxel phantoms, the voxel resolutions of the entire phantoms were set at 0.1122 and 0.0997 cm for 15-year male and female, respectively. The resulting total body masses were 55.93 and 53.11 kg for male and female, respectively, which are 0.3% lower and 0.1% higher than the corresponding ICRP 89 reference values (56 kg for male and 53 kg for female), respectively. It is noted that the ICRP 89 reference total body masses are equivalent to the median (50th percentile) weights for U.S. male and female 15-year olds as reported by the U.S. National Center for Health Statistics given in their May 30, 2000 growth charts (see Ref. 26). We further note that values of reference total body mass and height given in ICRP Publication 89 were derived primarily from data on central estimates or median values, as opposed to mean values that are subject to outlier bias. This feature thus conveniently facilitates reference phantom sculpting to match individuals of non-50th percentile morphometry values.

II.A.4. Phantoms of non-50th weight percentiles

Following the completion of the male and female reference (or 50th percentile) phantoms, four additional phantoms were created representing 15-year male and female patients at their 10th and 90th weight percentiles. These phantoms were developed through adjustment of control points at the NURBS surfaces of the torso, arms, and legs. Targeted total bodyweights were taken from the CDC growth curves^{16,17} at values of 45.5 kg (male at 10th percentile), 72.5 kg (male at 90th percentile), 42.5 kg (female at 10th percentile), and 68.5 kg (female at 90th percentile), respectively. These values confirm the observation of a skewed (log-normal) distribution in body mass, with absolute differences between 50th and 90th percentile values exceeding corresponding mass difference between the 50th and 10th percentile values. In the adjustment of phantom body shape, the following issues were carefully considered.

First, we assumed that increases or decreases in phantom total bodyweight from their 50th percentile values were attributed to corresponding changes in either separable fat or skeletal muscle, and not to changes in either body stature (all phantoms were kept at the same total height) or internal organ masses. As a result, we acknowledge that only a portion of this non-50th percentile patient population is represented by these additional phantoms which are given for demonstration purposes only. Both adipose tissue and skeletal muscle

are accounted for in the phantom region RST—residual soft tissue—and thus simple adjustments to the outer body contour and reassignment of the RST tissue density were sufficient for imposing changes in phantom total body mass. For simplicity, however, we further assumed that weight changes from the 50th percentile phantoms are attributed only to changes in separable adipose tissue. We also did not alter internal organ masses from their 50th percentile reference values, as the study by Whalen *et al.*¹⁸ demonstrates that organ volumes are strongly correlated with patient trunk height (assumed fixed in this study).

Second, we note that adipose tissue accumulates in two main regions of the body. The first is subcutaneous fat (SF), which is located in a layer below the skin and just superficial to the thoracoabdominal cavity. The second is intra-abdominal fat (IAF), which is comprised of visceral and retroperitoneal fat. While the amounts of IAF and SF have been correlated in adult patients using different anthropometric measurements such as waist circumference, chest circumference, and skin-fold thickness,¹⁹ no significant correlation has been found in children for IAF. In adults, there is a statistically significant increase in the ratio of visceral fat to subcutaneous fat with increasing age.²⁰ However, one study showed that the amount of visceral fat as a percent of body surface was shown to be only 5.4% for adolescent males and rose to 18% for males over 65 years. Subcutaneous fat thus comprises the majority of all adipose tissue in children, regardless of their level of obesity.²¹ In this study, increases and decreases in adipose tissues were thus restricted to regions of subcutaneous fat. In addition to the torso region, the fat distribution around upper arms and legs was also modified to match the 15-year male and female weights at their 10th and 90th percentile values.

Third, different spatial distributions of SF were modeled between the 15-year-old male and female phantoms. In males, adipose tissue typically accumulates in the central segments of the torso resulting in a bulging abdomen giving an “apple-shaped” body profile.²¹ In females, adipose tissue accumulates predominantly over the thighs in a “pear-shaped” gluteal distribution. The control points surrounding the torso were carefully adjusted to address these gender-specific distributions of subcutaneous fat. Matching total bodyweight to the 10th and 90th weight percentiles was performed through an iterative process between the NURBS modeling and the voxelized phantom as the measurement of total body mass is not directly permitted in NURBS model. All total bodyweights in the 10th, 50th, and 90th weight percentile phantoms representing 15-year-old male and female patients were matched to their CDC tabulated values to within an error of 0.3%.

II.A.5. Voxelization of the NURBS and polygon mesh model

The voxelization process is crucial for the resulting NURBS phantoms to be imported to radiation transport codes as currently there are no Monte Carlo codes available

that can directly handle NURBS or polygon mesh geometry for radiation transport. A procedure presented previously was adopted in this study⁸ using an upgraded in-house MATLAB code, Voxelizer 4, where speed-up algorithms and additional user-friendly features were implemented. All objects in the phantom were saved in one ASCII Raw Triangles file and voxelized simultaneously. The meshing tolerance was set at 10 deg based on our previous sensitivity study in order to minimize the possibility of volumetric errors exceeding 1% across all organs of the voxelized phantoms. As mentioned above, voxel resolutions were set at 0.1122 and 0.0997 cm for 15-year-old male and female phantoms, respectively, as based on reference skin thicknesses. The total array size is ~198 million voxels for the male phantom and ~251 million voxels for the female phantom. After voxelization, the skin tag was assigned to the single outermost voxel layer of each phantom. To address issues of computational efficiency and memory array-size limitations within the current MCNP code system, a series of lower resolution phantoms was created with voxel dimensions set at $0.2 \times 0.2 \times 0.2$ cm³ for coupling to the Monte Carlo radiation transport code, MCNPX version 2.5.²² These lower-resolution phantoms are thus defined by more manageable array sizes of ~35 million and ~32 million voxels for male and female phantoms, respectively. The voxelization code took ~3 h to voxelize the 50th weight percentile male phantom using a personal computer equipped with a 3.5 GHz Intel Core and 4Gbyte RAM operated under the LINUX operating system.

II.B. Applications to computed tomography dosimetry

To investigate the effect of differing subcutaneous fat distributions on organ doses within 15-year patients under CT examination, a total of 6 hybrid phantoms were voxelized at 0.2 mm resolution from their original NURBS formats yielding 10th, 50th, and 90th percentile 15-year male and female phantoms. In this study, the position and shape of the arms in the 15-year-old hybrid phantoms were carefully transformed to represent a more realistic arm-raised position. Both clavicles and scapulae were rotated and shifted with corresponding changes in the humeri.

A SOMATOM Sensation 16 helical multislice CT scanner (Siemens Medical Solutions, Erlangen, Germany) was simulated within MCNPX. An in-house source subroutine was written and recompiled in the MCNPX to allow the simulation of axial and variable detector pitch helical scans. The source subroutine generates the starting spatial coordinates and directional vectors for each simulated x-ray photon. The CT x-ray source was modeled as a fan beam originating from the focal spot with a beam angle of 52° and a focal spot-to-axis distance of 57 cm. The helical path of the source was explicitly modeled based on the selection of detector pitch and scan length. The spatial coordinates of each photon were sampled randomly and uniformly over the helical path (mA modulation techniques were not considered) and the direction of the photon was then randomly sampled within the fan beam. In the Department of Radiology at University of

Florida, 15-year patients are scanned at a tube potential of 120 kVp independent of patient body weight or shape. Chest and abdomen scans were simulated at 120 kVp and with a collimator width of 1.2 cm. Absorbed doses for major in-field organs were calculated for a total of six different male and female phantoms using MCNPX.

Tally outputs from MCNPX for an organ dose are given in the units of absorbed dose per launched photon (mGy/photon). In order to calculate the absolute organ absorbed dose, normalization factors (NF) were developed to relate simulated dose values with experimental measurements. In this study, the NFs obtained from Monte Carlo simulation and ion chamber measurement given in our previous study were employed.²³ NF is in units of photons per mA s and is calculated as a function of tube potential kVp at a collimator width of 1.2 cm,

$$NF_{kVp} = \frac{(K_{air-M})_{kVp}}{(K_{air-S})_{kVp}}, \quad (1)$$

where K_{air-M} is the air kerma measured free-in-air with the 10 cm ion chamber at the center of rotation for a given kVp normalized to the mA s used in the measurement, which was 100 mA s. K_{air-M} is therefore given in units of mGy per mA s. K_{air-S} is air kerma calculated by the Monte Carlo simulation of the ion chamber for the same measurement setup and is given in units of mGy per photon. Using the factor NF, the absolute tissue absorbed dose is thus calculated as

FIG. 1. Frontal views following 3D rendering of (a) UFH-NURBS 15-year-old male phantom and (b) UFH-NURBS 15-year-old female phantom. Body contours are made transparent for better viewing internal organs and the skeleton.

FIG. 2. Transaxial views (cross sections) of the UFH-voxel 15-year-old (a) male and (b) female phantoms.

$$(D_T^A)_{\text{kVp}} = (D_T^S)_{\text{kVp}} \times \text{NF}_{\text{kVp}} \times \left(\frac{\text{mAs}}{\text{rotation}} \right) \times (N_{\text{rotation}}), \quad (2)$$

where D_T^S is the Monte Carlo simulation estimate of the absorbed dose (mGy/photon) in the tissue T , NF_{kVp} is the normalization factor for a given kVp, with total mAs given as the product of the mAs per rotation and the total number of rotations in the scan N_{rotation} . In this study, the organ absorbed dose was calculated in units of mGy per 100 mAs.

III. RESULTS AND DISCUSSION

III.A. UF hybrid 15-year-old male and female phantoms

The UF hybrid 15-year-old male and female phantoms representing the reference anatomy defined in ICRP Publication 89 were developed from the realistic anatomy sources: the UF 14-year-old male voxel phantom and CT image data of approximately 15-year-old female subjects. The 50th weight-percentile hybrid phantoms of the 15-year reference male and 15-year reference female are named UFH15M₅₀ and UFH15F₅₀, respectively. Frontal views of the UFH15M₅₀ and UFH15F₅₀ phantoms are shown in Fig. 1

with semitransparent skin and residual tissue for better viewing of internal organ structure. Cross-sectional presentations of the two phantoms in voxel format are given in Figs. 2–4 showing transaxial, coronal, and sagittal views with organ labels, respectively. In general, the high level of anatomic detail shown in Fig. 2 is also displayed in transaxial views of traditional voxel phantoms. When viewed in their coronal (Fig. 3) and sagittal (Fig. 4) anatomic planes, however, the advantages of the hybrid phantom over the traditional voxel phantom are clearly seen. The continuity of organ anatomy found in the transaxial plane is also seen in the other two planes, whereas slice-to-slice discontinuities are sometimes evident in traditional voxel phantoms.

A total of eight anthropometric parameters were matched to the 50th percentile values obtained from the four different resources within the error of less than 4%. The 50th percentile anthropometric parameters obtained from literatures and measured in UF hybrid 15-year-old phantoms are tabulated and compared in Table I. Biacromial breadth in the UF hybrid 15-year-old male phantom showed the largest discrepancy—up to 4% from the 50th percentile value in the male phantom.

Organ masses of the UF hybrid-NURBS male and female phantoms are compared to those given in the ICRP Publica-

FIG. 3. Coronal views (cross sections) of the UFH-voxel 15-year-old (a) male and (b) female phantoms.

tion 89 in Tables II and III, respectively. Percent differences between hybrid phantoms and ICRP 89 values are evaluated in columns 5 and 6 of these tables. All body organs and tissues are shown to be matched to within 1% of their reference values. For UF hybrid-NURBS male phantom, the largest discrepancies are noted for bones of the skeleton (0.9% overestimate) and stomach wall (−0.2% underestimate). For UF hybrid-NURBS female phantom, the largest discrepancies are noted for small intestine wall (0.8% overestimate) and left colon wall (−0.4% underestimate).

Columns 7 and 8 similarly present organ masses and their percent difference from ICRP 89 values for the higher-resolution UF hybrid-voxel in these same tables. Only two tissues are shown to have percent differences exceeding $\pm 1\%$. Skin masses are noted to be 14.9% higher for the male hybrid-voxel phantom and 13.2% higher for the female hybrid-voxel phantom, while residual soft tissues are underestimated by −1.7% in the male hybrid-voxel phantom, but by only −0.9% in the corresponding female phantom.

Finally, columns 9 and 10 of Tables II and III compare masses and percent differences from reference values for the lower-resolution male and female voxel phantoms created for CT organ dosimetry. As anticipated, higher mass errors are seen for many of the smaller tissue structures. Skin masses are again overestimated, but in this case by 102.5% and 124.7%, respectively, in the male and female lower-resolution voxel phantoms. Residual soft tissues are correspondingly underestimated by −5.7% and by −5.3% for the

lower-resolution voxel male and voxel female phantoms. Other smaller organs have errors ranging from slightly over 1% (urinary bladder wall in the female) to 3.6% (trachea in the male phantom). Aside from errors in skin mass (a problem common to many voxel phantoms), these smaller mass differences are not considered to result in any appreciable differences in tissue dose under CT imaging.

Finally, phantoms of the 10th and 90th weight percentiles were generated from the template 50th percentile phantoms by adjusting control points surrounding the torso contour to match the total bodyweights reported by CDC. Frontal and lateral 3D views of the three male and three female phantoms are given in Figs. 5 and 6, respectively, with semitransparent skin and residual soft tissues. Figure 7 shows the repositioning of the arms for subsequent use in simulating patient CT examinations. Total body masses of the 10th and 90th weight percentile male phantoms were 45.4 and 72.3 kg, respectively, and those of female phantoms were 42.5 and 68.5 kg, respectively. These total body masses were matched to the CDC standard values to within $\pm 0.3\%$.

III.B. CT dosimetry calculation

Absorbed doses to the organs within the field-of-view were calculated for chest and abdomen CT examinations using the three male and three female 15-year phantoms at a

FIG. 4. Sagittal views (cross sections) of the UFH-voxel 15-year-old (a) male and (b) female phantoms.

tube potential of 120 kVp and a collimator width of 1.2 mm. Normalized values of organ absorbed dose (mGy/100 mA s) are given in Table IV for the male phantoms and in Table V for the female phantoms for both chest and abdominal CT examinations. In each table, organ doses are given for the reference stylized phantom (e.g., ORNL 15-year hermaphrodite), and three different versions of the UF hybrid phantom: one at the 50th weight percentile (reference phantom), and two other 15-year phantoms at their 10th and 90th weight percentiles. For these latter phantoms, the difference in total body mass was assumed to be due only to variations in subcutaneous fat thicknesses as shown in Figs. 5 and 6, and all hybrid phantoms were set at a single reference value of trunk and total body height.

In Table IV, columns 2 and 3 show the absolute organ doses per 100 mA s for the ORNL and UFH15M₅₀ phantoms, respectively, with their ratio given in column 4. These absorbed dose ratios range from 0.59 (kidneys) to 2.05 (thyroid) for the chest examination, and from 0.71 (esophagus) to 1.40 (lungs) for the abdominal examination. Only 2 of 9 organs are within 10% of each other for the chest examination, and only 3 of 8 are within 10% for the abdominal examination. In each case, however, organ masses are within 1% of their ICRP 89 reference values, and thus these differences are directly reflective of differences in anatomical

shape, position, and depth of each organ within each phantom. Comparable differences are noted in comparing the two reference (50th percentile) female phantoms in column 4 of Table V. Here we note that organ dose ratios range from 0.30 (kidney) to 2.09 (thyroid) for the chest CT examinations, and from 0.84 (esophagus) to 1.44 (colon and rectum) for the abdominal CT examinations. Significant dosimetry errors are thus noted in the use of older stylized phantoms to properly model CT examinations of 15-year children who are near their 50th weight percentiles.

The flexibility of the hybrid computational phantoms is further demonstrated in column 6 of Tables IV and V for the male and female phantoms, respectively. For the 10th percentile phantoms, organ doses are shown to be within $\pm 10\%$ of those given by the corresponding 50th percentile reference hybrid phantom for 9 of 9 organs in the male chest examination, 3 of 8 for the male abdominal examination, 6 of 9 for the female chest examination, and 8 of 8 for the female abdominal examination. The composite range of dose ratios was a low of only 0.98 (kidneys—female chest CT) to a high of 1.18 (small intestine—male abdominal CT).

Larger errors in organ dose estimates, however, can be seen when using 50th percentile reference phantoms to represent overweight children in CT body examinations. These larger errors are expected given the skewed shape of the

TABLE II. Summary of organ masses within three different computational phantoms of 15-year-old male: (1) UF hybrid-NURBS, (2) UF hybrid-voxel, and (3) UF hybrid-voxel (CT). These masses are then compared to ICRP Publication 89 reference masses by organ, organ system, and for total body tissues (exclusive of walled-organ content) and total body mass (inclusive of walled-organ content).

Organ system	Density (g/cm ³)	Comment (ICRU 46)	Target volume (cm ³)	UFH-NURBS		UFH-voxel		UFH-voxel (CT)		ICRP 89 Mass (g)
				Mass (g)	% diff	Mass (g)	% diff	Mass (g)	% diff	
Respiratory system										
ET1 (anterior nasal layer)	1.03	ICRU-46 ave soft tissue		0.35		0.44		0.36		ND
ET2 (posterior nasal layer)	1.03	ICRU-46 ave soft tissue		14.05		14.64		14.02		ND
ET2 (oral cavity layer)	1.03	ICRU-46 ave soft tissue		5.14		4.85		4.86		ND
ET2 (larynx)	1.07	50:50 soft tissue/cartilage	20.66	22.03	0.1	21.85	0.7	22.32	1.5	22
ET2 (pharynx)	1.03	ICRU-46 ave soft tissue		5.79		2.86		2.81		ND
Trachea	1.07	50:50 soft tissue/cartilage	7.04	7.49	−0.1	7.49	−0.1	7.77	3.6	7.5
Bronchi—extrapulmonary	1.07	50:50 soft tissue/cartilage		7.99		7.84		7.80		ND
Lungs (inclusive of blood)	0.24	Calculated		900.00	0.0	898.23	−0.2	898.11	−0.2	900
Left lung	0.24	Calculated		407.97		407.00		406.94		
Right lung	0.24	Calculated		492.03		491.23		491.17		
Alimentary system										
Tongue	1.05	Muscle	53.33	55.94	−0.1	55.58	−0.7	55.54	−0.8	56
Salivary glands	1.03	ICRU-46 ave soft tissue	66.02	68.02	0.0	67.91	−0.1	67.17	−1.2	68
Parotid	1.03	ICRU-46 ave soft tissue	38.83	40.01	0.0	39.98	0.0	39.21	−2.0	40
Submaxillary	1.03	ICRU-46 ave soft tissue	19.42	20.01	0.1	19.95	−0.3	20.07	0.4	20
Sublingual	1.03	ICRU-46 ave soft tissue	7.77	7.99	−0.1	7.98	−0.3	7.89	−1.4	8
Tonsils	1.03	ICRU-46 ave soft tissue	2.91	3.01	0.3	2.98	−0.7	2.98	−0.6	3
Esophagus—wall	1.03	Gastrointestine (adult)	29.13	29.96	−0.1	29.83	−0.6	29.47	−1.8	30
Stomach—wall	1.03	Gastrointestine (adult)	116.50	119.71	−0.2	119.51	−0.4	119.11	−0.7	120
Stomach—contents	1.03	ICRU-46 ave soft tissue	194.17	200.47	0.2	199.66	−0.2	199.66	−0.2	200
Small intestine—wall	1.03	Gastrointestine (adult)	504.85	522.46	0.5	516.81	−0.6	516.40	−0.7	520
Small intestine—contents	0.41	Calculated	689.61	280.00	0.0	277.84	−0.8	277.98	−0.7	280
Colon										
Right—wall	1.03	Gastrointestine (adult)	118.45	122.20	0.2	121.64	−0.3	121.72	−0.2	122
Right—contents	0.83	Calculated	145.41	120.00	0.0	119.64	−0.3	119.53	−0.4	120
Left—wall	1.03	Gastrointestine (adult)	118.45	122.09	0.1	121.69	−0.3	121.74	−0.2	122
Left—contents	0.34	calculated	177.39	60.00	0.0	59.87	−0.2	59.96	−0.1	60
Rectosigmoid—wall	1.03	Gastrointestine (adult)	54.37	56.18	0.3	55.73	−0.5	55.27	−1.3	56
Rectosigmoid—contents	0.49	Calculated	121.62	60.00	0.0	59.83	−0.3	60.00	0.0	60
Liver	1.05	Liver (fetus/child/adult)	1238.10	1300.27	0.0	1297.75	−0.2	1297.81	−0.2	1300
Gall bladder—wall	1.03	ICRU-46 ave soft tissue	7.48	7.69	−0.1	7.65	−0.7	7.44	−3.4	8
Gall bladder—contents	1.03	ICRU-46 ave soft tissue	43.69	45.00	0.0	44.96	−0.1	45.08	0.2	45
Pancreas	1.03	ICRU-46 ave soft tissue	106.80	110.00	0.0	109.82	−0.2	109.72	−0.3	110
Circulatory system										
Heart—wall	1.04	Heart (fetus/child/adult)	221.15	230.13	0.1	228.88	−0.5	229.17	−0.4	230
Heart—content	1.06	Blood (newborn/adult)	405.66	429.88	0.0	428.83	−0.3	428.58	−0.3	430
Urogenital system										
Kidneys (cortex and medulla)	1.04	Kidney (fetus/child/adult)	240.38	249.94	0.0	249.45	−0.2	249.33	−0.3	250
Cortex	1.04	Kidney (fetus/child/adult)	177.12	184.12	0.0	183.69	−0.3	183.60	−0.3	184
Medulla	1.04	Kidney (fetus/child/adult)	63.26	65.83	0.1	65.76	0.0	65.73	−0.1	66
Pelvis	1.04	Kidney (fetus/child/adult)	12.65	13.18	0.1	13.15	−0.1	13.20	0.3	13
Urinary bladder—wall	1.04	Bladder (adult-empty)	38.46	39.99	0.0	39.85	−0.4	39.94	−0.2	40
Urinary bladder—contents ^a	1.01	Urine of ave density	152.48	153.95	0.0	153.39	−0.4	153.13	−0.6	154
Penis	1.05	Muscle (newborn/adult)		28.33		28.70		23.54		ND
Scrotum	1.03	ICRU-46 ave soft tissue		22.72		17.78		14.21		ND
Testes (2)	1.04	Testes (adult)	15.38	16.01	0.0	15.90	−0.6	15.87	−0.8	16
Prostate gland	1.03	ICRU-46 ave soft tissue	4.17	4.30	0.0	4.29	−0.2	4.21	−2.1	4.3
Skeletal System										
Coastal cartilage ^b	1.10	Cartilage (adult)		87.54		79.09		78.80		
Intervertebral disks ^b	1.10	Cartilage (adult)		79.49		62.90		62.45		
Bone tissues	1.36	Volume-averaged	4959.23	6824.65	0.9	6790.90	0.4	6778.78	0.2	6765
Mineral bone (CB, TB)	1.80	Cortical bone (ICRP89 Para 436)	2250.00							4050
Active marrow ^c	1.03	Red marrow (adult)	1048.54							1080

TABLE II. (Continued.)

Organ system	Density (g/cm ³)	Comment (ICRU 46)	Target volume (cm ³)	UFH-NURBS		UFH-voxel		UFH-voxel (CT)		ICRP 89 Mass (g)
				Mass (g)	% diff	Mass (g)	% diff	Mass (g)	% diff	
Inactive marrow	0.98	Yellow marrow (adult)	1510.20							1480
Miscellaneous ^d	1.03	ICRU-46 ave soft tissue	150.49							155
Integumentary system										
Skin	1.10	All ages (ICRP89 Para 529)	1818.18	ND		2298.42	14.9	4050.71	102.5	2000
Additional tissues										
Adrenal glands (2)	1.03	ICRU-46 ave soft tissue	9.71	10.00	0.0	10.02	0.2	10.02	0.2	10
Brain	1.04	Brain (newborn/infant/adult)	1365.38	1422.53	0.2	1421.52	0.1	1421.83	0.1	1420
Breasts (2)	0.94	Adipose #2 (NB/child/adult)	15.96	15.02	0.1	14.96	−0.3	14.90	−0.6	15
Ears	1.10	Cartilage (adult)		9.20		5.91		3.68		ND
External nose	1.05	66:33 soft tissue/cartilage		6.07		3.76		2.74		ND
Eyes (2)	1.03	ICRU-46 ave soft tissue	12.62	13.01	0.1	12.91	−0.7	12.97	−0.2	13
Lens (2)	1.07	Eye lens (adult)		0.49		0.52		0.48		ND
Pituitary gland	1.03	ICRU-46 ave soft tissue	0.49	0.50	0.0	0.50	−0.5	0.50	0.5	0.5
Spinal cord	1.04	Brain (newborn/adult)		70.31		47.87		48.30		ND
Spleen	1.06	Spleen (40 week fetus/adult)	122.64	130.00	0.0	129.42	−0.4	129.47	−0.4	130
Teeth	3.00	ICRP 89-Para 465	15.00	44.99	0.0	44.84	−0.4	45.84	1.9	45
Thymus	1.03	NB/adult ICRP 89 Para 606	34.15	34.99	0.0	34.98	−0.1	35.03	0.1	35
Thyroid	1.05	Thyroid (adult)	11.43	12.02	0.2	12.00	0.0	12.00	0.0	12
Residual soft tissues (RST)	1.03	Volume-averaged	39 188.78			39 556.82	−1.7	37 944.82	−5.7	40 224
Bone—associated cartilage	1.10	Cartilage (adult)	858.28							944
Separable fat	0.96	Adipose # 2 (NB/child/adult)	9895.83							9500
Skeletal muscle	1.05	Muscle (newborn/adult)	22 857.14							24 000
Separable connective tissues	1.03	ICRU-46 ave soft tissue	1844.66							1900
Fixed lymphatic tissues ^e	1.03	ICRU-46 ave soft tissue	387.29							399
Blood (large vessels) ^f	1.06	Blood (newborn/adult)	1173.74							1244
Miscellaneous RST ^g	1.03	ICRU-46 ave soft tissue	2171.84							2237
Totals by organ system										
Respiratory system ^h				962.84		958.20		958.07		930
Alimentary system—tissues of organ walls				2517.53		2506.88	−0.3	2504.39	−0.4	2515
Alimentary system—GI tract and gall bladder content				765.47		761.80	−0.4	762.21	−0.4	765
Circulatory system—heart wall and content				660.01		657.70	−0.3	657.75	−0.3	660
Urogenital system—kidneys and urinary bladder wall				289.93		289.30	−0.2	289.26	−0.3	290
Urogenital system—renal pelvis and urinary bladder content				207.11		166.54	−0.4	166.33	−0.5	167
Urogenital system—internal sex organs (prostate)				4.30		4.29	−0.2	4.21	−2.1	4
Urogenital system—external sex organs (penis, scrotum, and testes) ^h				67.06		62.38		53.62		ND
Skeletal system—costal cartilage and intervertebral disks ^h				167.02		141.99		141.25		ND
Skeletal system—bone tissues				6824.65		6790.90	0.4	6778.78	0.2	6765
Integumentary system				ND		2298.42	14.9	4050.71	102.5	2000
Additional tissues—excluding residual soft tissue ^h				1769.13		1739.19		1737.77		1681
Additional tissues—residual soft tissue				ND		39 556.82	4.2	37 944.82	−5.7	40 224
Total body tissues						55 006	−0.3	55 121	−0.1	55 068
Total body mass						55 934	−0.3	56 049	−0.1	56 000

^aNo reference value is given in ICRP 89 and thus an approximate value is used as defined in the ORNL stylized newborn phantom.

^bSkeletal cartilage excludes the following nonbone associated regions of cartilage: external nose and ears, larynx, trachea, and extrapulmonary bronchi.

^cAssumed to include the 7% of total blood volume as per Sec. 7.7.2 of ICRP 89.

^dAs per Sec. 9.2.15 of ICRP 89, miscellaneous skeletal tissues include periosteum and blood vessels, but exclude periarticular tissue and blood.

^eEstimated from the reference adult values given in Sec. 7.8.2 of ICRP Publication 89 and scaled by total body mass.

^fTaken as 25.92% of total blood pool as per Sec. 7.7.2 of ICRP 89 (other tissues, aorta, large arteries, large veins).

^gMiscellaneous residual soft tissues are added to force the total body mass to its ICRP 89 reference value.

^hPercent differences are not reported as not all tissues in this organ system are defined in ICRP Publication 89.

body mass distribution in the CDC growth curves, with larger absolute changes in body mass in going from the 50th to 90th weight percentile. In the final column of Tables IV and V, we give the ratio of the normalized organ absorbed

dose in chest and abdominal CT examinations for the 90th percentile male (Table IV) and female (Table V) to those given by the corresponding 50th percentile reference hybrid phantoms. For the male chest CT, organ doses are overesti-

TABLE III. Summary of organ masses within three different computational phantoms of 15-year-old female: (1) UF hybrid-NURBS, (2) UF hybrid-voxel, and (3) UF hybrid-voxel (CT). These masses are then compared to ICRP Publication 89 reference masses by organ, organ system, and for total body tissues (exclusive of walled-organ content) and total body mass (inclusive of walled-organ content).

Organ system	Density (g/cm ³)	Comment (ICRU 46)	Target volume (cm ³)	UFH-NURBS		UFH-voxel		UFH-voxel (CT)		ICRP 89 Mass (g)
				Mass (g)	% diff	Mass (g)	% diff	Mass (g)	% diff	
Respiratory system										
ET1 (anterior nasal layer)	1.02	ICRU-46 ave soft tissue				0.30		0.29		ND
ET2 (posterior nasal layer)	1.02	ICRU-46 ave soft tissue				6.73		6.72		ND
ET2 (oral cavity layer)	1.02	ICRU-46 ave soft tissue				7.61		7.38		ND
ET2 (larynx)	1.07	50:50 soft tissue/cartilage	14.08	14.99	−0.1	14.96	−0.3	14.70	−2.0	15
ET2 (pharynx)	1.02	ICRU-46 ave soft tissue				2.73		2.77		ND
Trachea	1.07	50:50 soft tissue/cartilage	5.63	6.00	0.1	5.96	−0.7	5.96	−0.6	6
Bronchi—extrapulmonary	1.07	50:50 soft tissue/cartilage				6.60		6.65		ND
Lungs (inclusive of blood)	0.24	Calculated		750.00	0.0	747.22	−0.4	747.22	−0.4	750
Left lung	0.24	Calculated		355.14		353.27		353.27		
Right lung	0.24	Calculated		394.86		393.95		393.95		
Alimentary system										
Tongue	1.05	Muscle	50.48	53.02	0.0	52.79	−0.4	52.86	−0.3	53
Salivary glands	1.02	ICRU-46 ave soft tissue	63.73	65.03	0.0	64.73	−0.4	64.28	−1.1	65
Parotid	1.02	ICRU-46 ave soft tissue	37.25	38.01	0.0	37.84	−0.4	37.53	−1.2	38
Submaxillary	1.02	ICRU-46 ave soft tissue	18.63	19.02	0.1	18.94	−0.3	18.99	−0.1	19
Sublingual	1.02	ICRU-46 ave soft tissue	7.84	8.00	0.0	7.95	−0.7	7.76	−3.0	8
Tonsils	1.02	ICRU-46 ave soft tissue	2.94	3.00	0.0	3.00	0.0	2.95	−1.5	3
Esophagus—wall	1.03	Gastrointestine (adult)	29.13	30.15	0.5	29.98	−0.1	29.78	−0.7	30
Stomach—wall	1.03	Gastrointestine (adult)	116.50	120.07	0.1	119.72	−0.2	119.45	−0.5	120
Stomach—contents	1.02	ICRU-46 ave soft tissue	196.08	200.05	0.0	199.51	−0.2	199.02	−0.5	200
Small intestine—wall	1.03	Gastrointestine (adult)	504.85	524.40	0.8	515.11	−0.9	514.78	−1.0	520
Small intestine—contents	0.50	Calculated	554.96	280.00	0.0	279.05	−0.3	279.04	−0.3	280
Colon										
Right—wall	1.03	Gastrointestine (adult)	118.45	121.73	−0.2	121.66	−0.3	121.84	−0.1	122
Right—contents	1.06	Calculated	113.65	120.00	0.0	119.62	−0.3	119.48	−0.4	120
Left—wall	1.03	Gastrointestine (adult)	118.45	121.45	−0.4	122.64	0.5	122.55	0.4	122
Left—contents	0.36	Calculated	165.85	60.00	0.0	59.81	−0.3	59.80	−0.3	60
Rectosigmoid—wall	1.03	Gastrointestine (adult)	54.37	56.29	0.5	55.65	−0.6	55.33	−1.2	56
Rectosigmoid—contents	0.53	Calculated	112.44	60.00	0.0	59.89	−0.2	59.89	−0.2	60
Liver	1.05	Liver (fetus/child/adult)	1238.10	1301.26	0.1	1299.09	−0.1	1298.71	−0.1	1300
Gall bladder—wall	1.02	ICRU-46 ave soft tissue	7.16	7.34	0.6	7.28	−0.3	7.18	−1.6	7.3
Gall bladder—contents	1.02	ICRU-46 ave soft tissue	41.18	42.02	0.0	41.89	−0.3	41.95	−0.1	42
Pancreas	1.02	ICRU-46 ave soft tissue	98.04	100.06	0.1	99.86	−0.1	99.97	0.0	100
Circulatory system										
Heart—wall	1.04	Heart (fetus/child/adult)	211.54	219.93	0.0	219.72	−0.1	219.92	0.0	220
Heart—content	1.06	Blood (newborn/adult)	301.89	320.09	0.0	319.56	−0.1	319.58	−0.1	320
Urogenital system										
Kidneys (cortex + medulla)	1.04	Kidney (fetus/child/adult)	230.76	239.78	−0.1	239.32	−0.3	239.16	−0.3	240
Cortex	1.04	Kidney (fetus/child/adult)	170.04	176.66	−0.1	176.30	−0.3	176.13	−0.4	177
Medulla	1.04	Kidney (fetus/child/adult)	60.73	63.12	−0.1	63.02	−0.2	63.03	−0.2	63
Pelvis	1.04	Kidney (fetus/child/adult)	12.15	12.63	0.0	12.61	−0.2	12.60	−0.2	13
Urinary bladder—wall	1.04	Bladder (adult-empty)	33.65	35.01	0.0	34.85	−0.4	34.65	−0.1	35
Urinary bladder—contents ^a	1.01	Urine of ave density	133.42	134.76	0.0	134.24	−0.4	134.32	−0.3	135
Ovaries (2)	1.05	Ovaries (adult)	5.71	5.99	−0.1	5.96	−0.6	5.90	−1.7	6
Uterus	1.05	Muscle (newborn/adult)	28.57	30.02	0.1	29.95	−0.2	30.17	0.6	30
Skeletal system										
Coastal cartilage ^b	1.10	Cartilage (adult)		97.1		86.81		86.28		
Intervertebral disks ^b	1.10	Cartilage (adult)		65.0		59.27		61.35		
Bone tissues	1.36	Volume-average	4576.75	6275.88	0.8	6230.14	0.1	6208.27	−0.3	6225
Mineral bone (CB, TB)	1.80	Cortical bone (ICRP89 Para 436)	2055.56							3700
Active marrow ^c	1.03	Red marrow (adult)	970.87							1000
Inactive marrow	0.98	Yellow marrow (adult)	1408.16							1380
Miscellaneous ^d	1.02	ICRU-46 ave soft tissue	142.16							145

TABLE III. (Continued.)

Organ system	Density (g/cm ³)	Comment (ICRU 46)	Target volume (cm ³)	UFH-NURBS		UFH-voxel		UFH-voxel (CT)		ICRP 89 Mass (g)
				Mass (g)	% diff	Mass (g)	% diff	Mass (g)	% diff	
Integumentary system										
Skin	1.10	All ages (ICRP89 Para 529)	1545.45	ND		1923.97	13.2	3819.32	124.7	1700
Additional tissues										
Adrenal glands (2)	1.02	ICRU-46 ave soft tissue	8.82	9.01	0.1	8.92	−0.9	8.80	−2.3	9
Brain	1.04	Brain (newborn/infant/adult)	1250.00	1300.05	0.0	1296.87	−0.2	1297.11	−0.2	1300
Breasts (2)	0.94	Adipose #2 (NB/child/adult)	265.96	249.79	−0.1	249.29	−0.3	247.89	−0.8	250
Ears	1.10	Cartilage (adult)		9.20		6.22		4.22		ND
External nose	1.05	66:33 soft tissue/cartilage		4.63		3.20		2.06		ND
Eyes (2)	1.02	ICRU-46 ave soft tissue	12.75	13.01	0.0	12.92	−0.6	13.06	0.5	13
Lens (2)	1.07	Eye lens (adult)		1.03		1.02		1.03		ND
Pituitary gland	1.02	ICRU-46 ave soft tissue	0.49	0.50	0.2	0.50	−0.5	0.51	2.8	0.5
Spinal cord	1.04	Brain (newborn/adult)		67.75		56.63		57.32		ND
Spleen	1.06	Spleen (40 week fetus/adult)	122.64	130.04	0.0	129.66	−0.3	129.66	−0.3	130
Teeth	3.00	ICRP 89-Para 465	11.67	35.22	0.6	35.31	0.9	35.52	1.5	35
Thymus	1.03	NB/adult ICRP 89 Para 606	29.27	30.02	0.1	29.96	−0.1	29.92	−0.3	30
Thyroid	1.05	Thyroid (adult)	11.43	12.02	0.2	11.99	−0.1	12.00	0.0	12
Residual soft tissues (RST)	1.01	Effective ave density	37 962.92			37 970.67	−0.9	36 290.50	−5.3	38 307
Bone-associated cartilage	1.10	Cartilage (adult)	817.05							899
Separable fat	0.96	Adipose #2 (NB/child/adult)	16 666.67							16 000
Skeletal muscle	1.05	Muscle (newborn/adult)	16 190.48							17 000
Separable connective tissues	1.02	ICRU-46 ave soft tissue	1764.71							1800
Fixed lymphatic tissues ^c	1.02	ICRU-46 ave soft tissue	370.13							378
Blood (large vessels) ^f	1.06	Blood (newborn/adult)	855.85							907
Miscellaneous RST ^g	1.02	ICRU-46 ave soft tissue	1298.04							1324
Totals by organ system										
Respiratory system ^h				770.99		792.11		761.69		771
Alimentary system—tissues of organ walls				2503.78		2491.58	−0.3	2489.67	−0.3	2498
Alimentary system—GI tract and gall bladder content				720.05		717.88	−0.3	717.23	−0.4	720
Circulatory system—heart wall and content				540.02		539.28	−0.1	539.50	−0.1	540
Urogenital system—kidneys and urinary bladder wall				274.79		274.16	−0.3	273.81	−0.4	275
Urogenital system—renal pelvis and urinary bladder content				147.39		146.85	−0.4	146.93	−0.3	147
Urogenital system—internal sex organs (ovaries and uterus)				36.01		35.91	−0.2	36.07	0.2	36
Skeletal system—costal cartidge and intervertebral disk ^h				162.15		146.08		147.63		ND
Skeletal system—bone tissues				6275.88		6230.14	0.1	6208.27	−0.3	6225
Integumentary system				ND		1923.97	13.2	3819.32	124.7	1700
Additional tissues—excluding residual soft tissue				1862.3		1842.5	3.5	1839.1	3.3	1780
Additional tissues—residual soft tissue				ND		37 970.67	−0.9	36 290.50	−5.3	38 307
Total body tissues										
						52 246	0.1	52 436	0.5	52 132
Total body mass						53 111	0.1	53 300	0.5	53 000

^aNo reference value is given in ICRP 89 and thus an approximate value is used as defined in the ORNL stylized newborn phantom.

^bSkeletal cartilage excludes the following nonbone associated regions of cartilage: external nose and ears, larynx, trachea, and extrapulmonary bronchi.

^cAssumed to include the 7% of total blood volume as per Sec. 7.7.2 of ICRP 89.

^dAs per Sec. 9.2.15 of ICRP 89, miscellaneous skeletal tissues include periosteum and blood vessels, but exclude periarticular tissue and blood.

^eEstimated from the reference adult values given in Sec. 7.8.2 of ICRP Publication 89 and scaled by total body mass.

^fTaken as 25.92% of total blood pool as per Sec. 7.7.2 of ICRP 89 (other tissues, aortal, large arteries, large veins).

^gMiscellaneous residual soft tissues are added to force the total body mass to its ICRP 89 reference value.

^hPercent differences are not reported as not all tissues in this organ system are defined in ICRP Publication 89.

mated by use of the reference phantom by as little of 5% (dose ratio of 0.95 for the male breast) to as much as 28% (dose ratio of 0.72 for the liver). Dose ratios range from 0.68 (liver) to 0.86 (heart) for the male abdominal CT examinations.

Closer agreement is seen between organ doses assessed in the 90th and 50th percentile female phantoms for the chest CT examination (see dose ratios in column 8 of Table V).

Here, only the lungs and esophagus show differences as much as 7%, and all organs are thus within a tolerance of $\pm 10\%$. This is not surprising, however, as the additional 15.5 kg of total bodyweight apportioned to the heavier female phantom was primarily placed in the abdominal region and upper thighs, and not within the upper regions of the torso. In column 8 of the lower half of Table V, we thus show dose ratios of normalized organ doses between the 90th

FIG. 5. Frontal views of 3D rendering of the 10th (left), 50th (middle), and 90th (right) weight percentile UFH-NURBS 15-year (a) male and (b) female phantoms.

and 50th percentile female phantoms for the abdominal CT examination. Only 3 of 8 organ doses are within a tolerance of $\pm 10\%$, and organ doses are seen to be overestimated in the reference phantom by as high as 29% to 25% (small intestine, colon, and kidneys).

IV. CONCLUSIONS

In this study, we present two new computational reference phantoms—those of the 15-year male and female—created in a hybrid format using combinations of polygon mesh and NURBS surface models of internal organs and exterior body

region contours. Both phantoms were assembled using segmented CT images of live patients and were matched to reference anatomic data from ICRP Publication 89 and various anthropometric sources to within tolerances of 1% and 4%, respectively. In a Monte Carlo simulation of multislice CT imaging, organ doses assessed using traditional stylized hermaphrodite phantoms of the ORNL series were shown to deviate from those given by the UF reference hybrid phantoms by up to a factor of 2. In addition to providing improved anatomic realism, hybrid phantom permit changes in body composition through relatively simple repositioning of

FIG. 6. Lateral views of 3D rendering of the 10th (left), 50th (middle), and 90th (right) weight percentile UFH-NURBS 15-year (a) male and (b) female phantoms.

FIG. 7. (a) Top, (b) front, and (c) lateral views of 3D rendering of the arm-raised posture of the UFH-NURBS 15-year-old female phantom for chest and abdominal CT simulations. Arms, clavicles, and scapulae were modified from their original positions as shown in Figs. 3 and 4.

control points on the phantom’s body surfaces. In this study, we demonstrate their flexibility in modeling 10th and 90th weight percentile 15-year-old male and female children. The study showed that use of reference, or 50th percentile, phantoms to assess organ doses in underweight 15-year-old chil-

dren would not lead to significant organ dose errors (typically less than 10%). However, more significant errors were noted (up to ~30%) when reference phantoms are used to represent overweight children in CT imaging dosimetry. These errors are expected to only further increase as one

TABLE IV. Normalized values of organ absorbed does (mGy/100 mA s) calculated from the reference ORNL 15-year phantom, and the 10th, 50th, and 90th weight percentile UF hybrid 15-year-old male phantoms for chest and abdominal CT exams. The ratios of organ doses between the ORNL and 50th percentile phantoms, 10th and 50th phantoms, 90th and 50th phantoms are given.

Male phantoms		D_{ORNL} (mGy/100 mA s)	D_{UFH50} (mGy/100 mA s)	$D_{\text{UFH50}}/D_{\text{ORNL}}$	D_{UFH10} (mGy/100 mA s)	$D_{\text{UFH10}}/D_{\text{UFH50}}$	D_{UFH90} (mGy/100 mA s)	$D_{\text{UFH90}}/D_{\text{UFH50}}$
Chest CT	Esophagus	8.05E+00	8.63E+00	1.07	9.44E+00	1.09	6.65E+00	0.77
	Breast	8.08E+00	1.11E+01	1.38	1.15E+01	1.04	1.05E+01	0.95
	Heart	1.00E+01	1.12E+01	1.12	1.21E+01	1.08	8.50E+00	0.76
	Kidney	3.88E+00	2.28E+00	0.59	2.36E+00	1.03	1.83E+00	0.80
	Liver	6.77E+00	5.67E+00	0.84	6.05E+00	1.07	4.07E+00	0.72
	Lungs	1.03E+01	1.06E+01	1.03	1.14E+01	1.08	8.41E+00	0.79
	Stomach wall	5.90E+00	4.03E+00	0.68	4.31E+00	1.07	3.07E+00	0.76
	Thymus	1.12E+01	9.81E+00	0.88	1.04E+01	1.06	7.91E+00	0.81
	Thyroid	4.18E+00	8.55E+00	2.05	8.73E+00	1.02	7.43E+00	0.87
			Min	0.59		1.02		0.72
Abdomen CT			Max	2.05		1.09		0.95
	Colon and rectum	3.80E+00	4.34E+00	1.14	4.82E+00	1.11	3.09E+00	0.71
	Esophagus	2.41E+00	1.71E+00	0.71	1.82E+00	1.06	1.32E+00	0.77
	Heart	1.51E+00	1.49E+00	0.98	1.50E+00	1.01	1.27E+00	0.86
	Kidney	9.37E+00	7.89E+00	0.84	9.08E+00	1.15	5.73E+00	0.73
	Liver	8.14E+00	8.23E+00	1.01	9.10E+00	1.11	5.56E+00	0.68
	Lungs	1.46E+00	2.04E+00	1.40	2.09E+00	1.03	1.70E+00	0.83
	Stomach wall	8.82E+00	7.99E+00	0.91	8.99E+00	1.13	5.50E+00	0.69
	Small intestine	4.53E+00	3.54E+00	0.78	4.18E+00	1.18	2.54E+00	0.72
			Min	0.71		1.01		0.68
			Max	1.40		1.18		0.86

TABLE V. Normalized values of organ absorbed dose (mGy/100 mA s) calculated from the reference ORNL 15-year phantom, and the 10th, 50th, and 90th weight percentile UF hybrid 15-year-old female phantoms for chest and abdominal CT exams. The ratios of organ doses between the ORNL and 50th percentile phantoms, 10th and 50th phantoms, and 90th and 50th phantoms are given.

Female phantoms		D_{ORNL} (mGy/100 mA s)	D_{UFH50} (mGy/100 mA s)	$D_{\text{UFH50}}/$ D_{ORNL}	D_{UFH10} (mGy/100 mA s)	$D_{\text{UFH10}}/$ D_{UFH50}	D_{UFH90} (mGy/100 mA s)	$D_{\text{UFH90}}/$ D_{UFH50}
Chest CT	Esophagus	8.05E+00	8.46E+00	1.05	9.33E+00	1.10	7.90E+00	0.93
	Breast	8.08E+00	9.43E+00	1.17	1.09E+01	1.15	9.37E+00	0.99
	Heart	1.00E+01	1.03E+01	1.03	1.18E+01	1.14	9.82E+00	0.95
	Kidney	3.88E+00	1.18E+00	0.30	1.16E+00	0.98	1.18E+00	1.00
	Liver	6.77E+00	6.59E+00	0.97	7.14E+00	1.08	6.27E+00	0.95
	Lungs	1.03E+01	1.05E+01	1.01	1.17E+01	1.11	9.77E+00	0.93
	Stomach wall	5.90E+00	5.54E+00	0.94	5.93E+00	1.07	5.25E+00	0.95
	Thymus	1.12E+01	9.31E+00	0.83	9.92E+00	1.07	8.82E+00	0.95
	Thyroid	4.18E+00	8.72E+00	2.09	8.88E+00	1.02	8.42E+00	0.96
			Min	0.30		0.98		0.93
			Max	2.09		1.15		1.00
Abdomen CT	Colon and rectum	3.80E+00	5.46E+00	1.44	5.73E+00	1.05	4.12E+00	0.75
	Esophagus	2.41E+00	2.02E+00	0.84	2.18E+00	1.08	1.91E+00	0.95
	Heart	1.51E+00	1.68E+00	1.11	1.68E+00	1.00	1.65E+00	0.99
	Kidney	9.37E+00	9.78E+00	1.04	1.05E+01	1.08	7.00E+00	0.72
	Liver	8.14E+00	8.94E+00	1.10	9.71E+00	1.09	7.92E+00	0.89
	Lungs	1.46E+00	2.01E+00	1.37	2.04E+00	1.02	1.95E+00	0.97
	Stomach wall	8.82E+00	9.20E+00	1.04	1.00E+01	1.09	8.06E+00	0.88
	Small intestine	4.53E+00	5.85E+00	1.29	6.35E+00	1.09	4.14E+00	0.71
			Min	0.84		1.00		0.71
			Max	1.44		1.09		0.99

considers overweight and obese individuals in the adult patient population where there is an increased variability in adiposity.

Hybrid phantoms can play two important roles in updating medical dosimetry for risk assessment. First, they permit one to expand the concept of a reference phantom as only being an individual at the 50th percentile of weight and height. As shown in this study, one can envision an expanded family of reference phantoms that vary, not just by age, but by height and weight percentile. Standardized medical exposures in radiography, computed tomography, and interventional fluoroscopy can thus be modeled and a more rich, and patient-specific database of organ dose coefficients could be generated.

Second, they can be used as the basis for patient-sculpted phantoms in medical dose reconstruction studies. The process would start with the selection of a 50th weight-percentile reference phantom which has a trunk height that closely matches to that measured in the patient. Whalen *et al.*¹⁸ has demonstrated that this approach, which supersedes traditional age-based phantom matching, can reduce uncertainties in internal organ volumes by as much as a factor of 2. Next, finer adjustments can be made to the phantom's trunk width and breath to further match the patient's ventral cavity volume, which was also shown by Whalen *et al.*¹⁸ to even further reduce organ volume uncertainties. Finally, outer body contours could be adjusted to uniquely match those measured across the patient. One could even reassign

the percentages of adipose tissue and skeletal muscle in the residual soft tissue regions of the patient-sculpted phantom to better approximate the individual's unique body composition. The hybrid phantom technology and its ability to provide patient-sculpted phantoms should significantly improve assessments of organ doses in medical epidemiological studies for not only diagnostic exposures, but potentially for secondary exposures in out-of-field organs following radiotherapy.

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