A set of 4D pediatric XCAT reference phantoms for multimodality research

Hannah Norris,^{a)} Yakun Zhang, Jason Bond, and Gregory M. Sturgeon

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

Anum Minhas

Department of Radiology, Duke University Medical Center, Durham, North Carolina 27710

Daniel J. Tward, J. T. Ratnanather, and M. I. Miller

Center for Imaging Science, Johns Hopkins University, Baltimore, Maryland 21218

D. Frush

Department of Radiology, Duke University Medical Center, Durham, North Carolina 27710

E. Samei and W. P. Segars

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

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Purpose: The authors previously developed an adult population of 4D extended cardiac-torso (XCAT) phantoms for multimodality imaging research. In this work, the authors develop a reference set of 4D pediatric XCAT phantoms consisting of male and female anatomies at ages of newborn, 1, 5, 10, and 15 years. These models will serve as the foundation from which the authors will create a vast population of pediatric phantoms for optimizing pediatric CT imaging protocols.

Methods: Each phantom was based on a unique set of CT data from a normal patient obtained from the Duke University database. The datasets were selected to best match the reference values for height and weight for the different ages and genders according to ICRP Publication 89. The major organs and structures were segmented from the CT data and used to create an initial pediatric model defined using nonuniform rational B-spline surfaces. The CT data covered the entire torso and part of the head. To complete the body, the authors manually added on the top of the head and the arms and legs using scaled versions of the XCAT adult models or additional models created from cadaver data. A multichannel large deformation diffeomorphic metric mapping algorithm was then used to calculate the transform from a template XCAT phantom (male or female 50th percentile adult) to the target pediatric model. The transform was applied to the template XCAT to fill in any unsegmented structures within the target phantom and to implement the 4D cardiac and respiratory models in the new anatomy. The masses of the organs in each phantom were matched to the reference values given in ICRP Publication 89. The new reference models were checked for anatomical accuracy via visual inspection.

Results: The authors created a set of ten pediatric reference phantoms that have the same level of detail and functionality as the original XCAT phantom adults. Each consists of thousands of anatomical structures and includes parameterized models for the cardiac and respiratory motions. Based on patient data, the phantoms capture the anatomic variations of childhood, such as the development of bone in the skull, pelvis, and long bones, and the growth of the vertebrae and organs. The phantoms can be combined with existing simulation packages to generate realistic pediatric imaging data from different modalities.

Conclusions: The development of patient-derived pediatric computational phantoms is useful in providing variable anatomies for simulation. Future work will expand this ten-phantom base to a host of pediatric phantoms representative of the public at large. This can provide a means to evaluate and improve pediatric imaging devices and to optimize CT protocols in terms of image quality and radiation dose. © 2014 American Association of Physicists in Medicine. [<http://dx.doi.org/10.1118/1.4864238>]

Key words: medical imaging simulation, computer phantom, SPECT, PET, CT, MRI, ultrasound

1. INTRODUCTION

From the early 1980s to 2006, the per capita exposure to ionizing radiation from medical procedures in the United States in-

creased sevenfold. As of 2006, nearly one-half (49%) of medical exposure of patients was due to computed tomography (CT) exams.¹ Retrospective studies have shown that increased exposure to medical radiation increases the incidence of

cancer inductance,² especially for those exposed in childhood or adolescence,^{3–5} although the extent of the excess relative risk is still widely debated.

With this recent focus on the radiation dose from medical procedures, especially CT scans with their relatively high radiation exposure, and the associated long-term cancer risk, new imaging methods, and technologies have been developed to maximize image quality while minimizing radiation dose. Computational anthropomorphic phantoms provide an accurate and effective way to test and optimize these new methods.

In computer-based simulations, the exact anatomies of computational phantoms are known, so they present a gold-standard for image quality metrics. Multiple scans with different imaging parameters can be performed on the same computational phantom, allowing a direct comparison; this is not feasible with human subjects due to the high cumulative radiation dose. Radiation doses for each organ and effective doses can be calculated for a range of imaging studies using Monte Carlo simulations.^{6–13} This allows a prospective estimate of dose to a single patient; the more closely the patient's anatomy matches that of the computational phantom, the more accurate the estimation.¹⁴

In order to more closely mimic a clinical study or trial and to better estimate patient-specific dose, a large population of phantoms is needed to reflect the range of anatomical variations representative of the public at large. Computer phantoms can be modified to create vast populations of anatomically variable subjects making them advantageous over physical phantoms. It would be prohibitively expensive to fabricate a population of physical phantoms representing a realistic range of patient sizes.

The development of computerized phantoms has advanced, leading to more realistic anatomies with 4D functionality. Computerized phantoms originated as mathematical models¹⁵ with crude estimates of organ shape and location, with organ dimensions and masses meeting the MIRD schema. Voxelized phantoms,^{16–18} which are based on segmented patient data, provide a realistic anatomy; however, their voxelized nature limits anatomical variations and motion. Hybrid phantoms^{19–24} combine the advantages of voxelized and mathematical phantoms: they are based on segmented patient data to create a realistic anthropomorphic anatomy, and use nonuniform rational B-spline (NURBS) surfaces and polygon meshes to define each anatomical object, so that organ variations and movement are easily performed with rigid and nonrigid transformations. However, due to the time-consuming process of development, the number of existing hybrid phantoms is limited, most modeling adults with few pediatric anatomies. Libraries of new hybrid models have been created by altering existing models by scaling surfaces and organ volumes;^{13,25–29} however, this method does not capture the variations in organ shape and location seen across a population.

We previously developed the 4D extended cardiac-torso (XCAT) phantom³⁰ for multimodality imaging research to evaluate and compare imaging devices and techniques. The XCAT is a hybrid phantom that includes models for a 50th

percentile (height and weight) male and female adult based on segmented imaging data and using NURBS surfaces to define the organs and structures. The male and female anatomies of the XCAT are extremely realistic, defining individual surfaces for each organ, muscle, bone, ligament, tendon, and blood vessel. The XCAT also includes 4D models for the cardiac and respiratory motions that are parameterized to simulate different normal and abnormal variations.

To extend the XCAT beyond the standard adult models, we developed a framework to efficiently morph the XCAT to create 58 new 4D adult phantoms of varying body-mass-indices (BMI) (Ref. 31) based on patient CT data. This method is similar to other studies mentioned above that transform template phantoms to create new ones. In our case, though, the morphing process is governed by the segmentation of the patient data, and as a result, the new phantoms capture more of the interior variability from patient to patient.

In this work, we take the next step to extend the XCAT phantom to model pediatric anatomies. The pediatric phantoms created in this work differ from those previously developed^{21–23} in two main areas. First, they are more highly detailed, containing every structure originally defined in the XCAT. As mentioned above, this includes individual surfaces for each organ, muscle, bone, ligament, tendon, and blood vessel resulting in over 3000 defined structures. This level of detail is important so that the phantoms are applicable to the research of high-resolution imaging applications such as CT and MRI. Without such detail, the imaging data simulated from the phantoms would not be close to what one would see from actual patients, limiting their use. We plan to apply our pediatric XCAT phantoms to optimize CT applications in terms of image quality versus dose. To simulate realistic images for this purpose requires a great deal of anatomical detail that previous pediatric models lack. Second, the new pediatric XCAT phantoms include parameterized 4D cardiac and respiratory motions with which they can simulate any number of normal and abnormal cases to investigate 4D imaging techniques. The existing pediatric phantoms are limited to 3D and do not include motion.

We utilize our morphing methods to develop a reference set of 4D pediatric XCAT phantoms, for the following age ranges: newborn, 1, 5, 10, and 15 years of age. In morphing from an adult anatomy to pediatric ones, a great deal of work (additional segmentation and manual correction) is necessary to correct for anatomic variations of childhood, such as the development of bone in the skull, pelvis, and long bones, and the growth of the vertebrae and organs. By first establishing these reference phantoms, we will, in future work, be able to use them as templates to create a large population of pediatric models using our techniques. With more age appropriate templates, the morphing process will be more efficient.

2. METHODS

2.A. Patient data and creation of initial target models

Under IRB approval and in compliance with the Health Insurance Portability and Accountability Act (HIPAA), high

TABLE I. Height and mass values for ICRP 89 reference and for the selected patient CT data for each age group.

Age	Male			Female		
	ICRP	CT	% Difference	ICRP	CT	% Difference
Height (cm)						
Newborn	51	52	1.9	51	52	1.9
1 year	76	77	1.3	76	77	1.3
5 years	109	110	0.9	109	110	0.9
10 years	138	139	0.7	138	139	0.7
15 years	167	167	0.0	161	162	0.6
Mass (kg)						
Newborn	3.5	3.8	8.2	3.5	3.8	8.6
1 year	10	10.3	3.0	10	10.3	3.0
5 years	19	19.9	4.6	19	19.9	4.6
10 years	32	33	3.1	32	33	3.1
15 years	56	58	3.5	53	54	1.9

resolution CT datasets from PET-CT scans in the Duke University imaging database were acquired for male and female patients aged newborn, 1, 5, 10, and 15 years. PET-CT scans were chosen instead of typical CT-only scans because of the scan length in PET-CT: the scans covered the entire length of the torso and part of the head. The datasets were selected such that the patients were at or near the 50th percentile in bodyweight for age according to the CDC weight-for-age percentiles,³² as shown in Table I. The patient cases were selected to exhibit normal anatomy, such that if a disease was present, it did not manifest itself in any gross changes to internal organs in terms of size or location. Six datasets were selected in all. Male patient data were used to build hermaphroditic phantoms for the newborn, 1, 5, and 10 year olds. According to the ICRP values, the anatomies for males and females are very similar up to age 10.³³ Different male and female datasets were selected for the 15 year olds as the anatomies for the genders vary at this point. Only the CT portion of the data was used to build our models; we did not use the patient PET data. The CT image resolutions ranged between 0.352 and 0.98 mm² in plane with slice thicknesses ranging from 3.27 to 5 mm.

To build the reference pediatric phantoms, we followed a similar procedure to that used to create our adult population.³¹ We first create an initial patient model by segmenting the CT data using *ImageSegment*, a graphical application developed in our laboratory. Segmentation was performed for the following structures: the body outline, skull, eyes, sternum, ribs, backbone, pelvis, scapulas, clavicles, left and right humerus, left and right femur, heart, lungs, liver, gallbladder, stomach, spleen, thyroid, kidneys, pancreas, intestines, prostate, testes, and bladder. For the bones, the marrow was not segmented. The marrow is modeled later as an inner surface to the bones given thickness values specified by the user.³⁰

The segmented structures were converted into 3D polygon models using the marching cubes algorithm from the Visualization Toolkit (www.vtk.org) included in the *ImageSegment* software. Using the Rhinoceros NURBS modeling software, www.rhino3d.com, cubic NURBS surfaces were fit to

the polygon models with the exception of the skull. The skull was left as a polygon model due to its more complex structure.

2.B. Extending the initial models to whole body

The PET-CT data did not fully include the arms, legs, and top of the head. In the creation of the adult population, we utilized the existing models from the standard XCAT phantoms to complete the target patient models. In this case, we could not automatically do that since the bones of the arms, legs, and skull change a great deal in pediatrics. We created new templates for the skull and long bones using high resolution newborn, 1- and 5-year-old cadaver scans obtained from the Massachusetts General Hospital (MGH). The different structures were segmented from the cadaver data. NURBS surfaces were fit to the arm and leg bones, and a polygon surface was fit to each skull using the techniques described above. For the 10 and 15 year olds, the original XCAT adult models, defined entirely with NURBS surfaces (skull is composed of multiple surfaces pieced together), were used as the templates for the skull, arms, and legs. In viewing cadaver data from these ages, the segmented bones appeared very similar to scaled down adult models.

To complete the head for each model, the skull and outer skin surface from the age appropriate template was manually scaled to match the existing skull and skin surfaces segmented from the patient data, as shown in Fig. 1 for the skull surface of a teenager. This was performed within the Rhinoceros modeling program. The template and target skulls were lined up using the eye orbits, nasal passages, and brain compartments. Once aligned, the template skull and skin surface were scaled to smoothly transition into the patient model.

The templates for the arms and legs were then matched to the corresponding anatomy for each patient. We used the PeopleSize program, <http://www.openeng.com/psz/index.html>, to determine arm and leg measurements (arm length, upper and lower arm skin circumferences, upper and lower leg skin circumferences) for the target pediatric model. The leg length was determined based on the recorded height of the patient. The height from the top of the head to the bottom of the pelvis was measured from the model. This distance was subtracted from the known patient height to determine the proper leg length. After scaling the limbs to match the body type of the patient, they were placed manually onto the rest of the anatomy within Rhinoceros using the segmented skeleton as a guide, completing the initial whole-body model for the

FIG. 1. A NURBS defined skullcap from a template skull (middle) is merged onto the polygon model of a segmented skull (left) to create a solid skull surface defined as a polygon model (right).

FIG. 2. Calculating the MC-LDDMM transform. A fully complete adult XCAT phantom is the template; the incomplete pediatric phantom is the target. The template is set to contain the same structures and intensities as the target so the images have a 1:1 correspondence. Given the template and target, the MC-LDDMM calculates the high level transform to map the whole-body template (XCAT) to the target (patient framework).

patient. The initial patient model was composed of NURBS and polygon surfaces.

2.C. Application of the multichannel large deformation diffeomorphic metric mapping (MC-LDDMM) method to complete the models

Once the initial pediatric models were constructed, we utilized a modified version of the MC-LDDMM (Ref. 34) algorithm to calculate a high-level nonrigid transform from a template XCAT phantom to each of the pediatric targets, shown in Fig. 2. A template (I_{template}) and target image (I_{target}) are required in order to calculate the MC-LDDMM transform. For this application, the template was either the male or female adult XCAT phantom. In the case of the newborn, 1, 5, and 10 year olds, we used both to create phantoms for both genders. For the 15 year olds, we used one or the other depending on the gender. The initial patient model based on the CT data, created above, served as the target. The template and target images for each patient case were created by voxelizing the template XCAT and the initial patient model into 3D images covering the whole body. The images were voxelized with isotropic resolutions ranging from 1.0 to 2.0 mm per pixel depending on the size of the target. Each structure (bones, body, organs) from the patient model was assigned a unique integer ID in the target image. The template image was set to contain the same structures and intensities as the target. To aid in the calculation of the transform, landmarks were defined using the template and target skeletons. Corresponding

landmarks were placed on the endpoints of bones such as the ribs and sternum and at the centers of the vertebrae. Given the selected landmarks and the template and target images, the MC-LDDMM algorithm calculated the transform to map the whole-body template (XCAT) to the target (patient framework).

The MC-LDDMM transform was then applied to the NURBS surfaces of the template XCAT phantom to transform it into the target, Fig. 3. The MC-LDDMM transform provides a vector (dx, dy, dz) for each voxel in the template image I_{template} . To apply the transform to the XCAT, the control points that define each NURBS surface in the phantom are first located within the template image by converting their 3D Cartesian coordinates to voxel locations. Given the voxel locations, each control point is then transformed or repositioned according to the vector defined at its voxel location. By applying the transform to the template XCAT phantom, surfaces for the missing organs and tissues are “filled in” within the target phantom. Table II lists the structures that were defined by segmenting the patient data versus the structures that were predicted using the MC-LDDMM transform.

The MC-LDDMM algorithm calculates a smooth, invertible transform from the template to the target.³⁴ With this, any small discontinuities in cranium thickness or brain structure that may occur from using a template skull to complete our patient target (Fig. 1) do not cause abnormalities in the final XCAT models. The skull model for each new pediatric phantom is obtained by transforming the NURBS-defined skull of the template XCAT. Therefore, the final pediatric skull, like

FIG. 3. Once the transform was determined, it was applied to the NURBS surfaces defining the template XCAT to create the patient-specific XCAT phantom containing all anatomical structures.

the rest of the new phantom, is defined entirely of NURBS surfaces.

2.D. Incorporation of cardiac and respiratory motions

In addition to completing the 3D anatomy of each pediatric model, the MC-LDDMM transform also helps to define 4D models for the cardiac and respiratory motions. The underlying cardiac and respiratory models already exist in the template XCAT adult phantoms. The MC-LDDMM transform is simply applied to these models to define them in the new pediatric anatomies.³¹ As in the original XCAT adult models, both cardiac and respiratory models are parameterized so a user can alter their patterns to simulate various normal or abnormal states.

2.E. Fine tuning of the models

Each new phantom was inspected visually to check for anatomical accuracy. This was performed in comparison to the University of Florida (UF) series of reference phantoms by Lee *et al.*²¹ based on segmented pediatric CT. For this comparison, we looked at the organs and bones. The UF series does not include detailed models for the muscles, ligaments, or vessels. The organ masses were also compared to those from the UF phantoms and ICRP Publication 89.³³ The organ volumes were collected from the Rhinoceros program, and masses were calculated using the densities provided in Lee *et al.*²¹ The organ masses were adjusted to be within 5% of the ICRP values. The adjustments were made by scaling undersized or oversized organs using the XCAT parameters setup within each new model (see Table II of Ref. 30). In going from adult templates to pediatric targets, extensive manual

fixing was required. The organs that required the most attention were the adrenals, thymus, and uterus. The reason for this was how their masses change with age. The adrenals decrease in mass going from newborn to 1 year old then increase gradually from 1 year onward. The uterus had a similar pattern, but had a rapid rise in mass from a 10 year old to an adult. The thymus increases greatly from newborn to 1 year old, increases slightly from 1 to 10 year old, then decreases in mass in adulthood. Organs with patterns that deviate from a straight linear increase are harder to predict using an adult template.

The total weight for each phantom was also calculated and compared to the desired weight from the ICRP reference values. The weights of the phantoms were finely adjusted to match the corresponding ICRP weight within 5%. This was done by scaling the skin surfaces of the arms and legs as was similarly done in the creation of our adult population.³¹ A good amount of the body's weight is carried in the arms and legs. These were added from templates and not patient specific, so they provided a good means for adjustment. Each new pediatric XCAT phantom was setup with parameters to perform this scaling, adjusting the muscles, tendons, ligaments, and vessels inside the arms and legs while keeping the bones constant. Measurements (skin and bone circumferences at different locations) from the scaled arms and legs for each phantom were compared to those from the UF series of reference phantoms to make sure they were anatomically correct. Using these methods, 4D pediatric reference phantoms were created for the different ages.

3. RESULTS

A complete reference set of ten 4D pediatric XCAT phantoms was completed, as shown in Fig. 4. The phantoms were

TABLE II. List of structures in the new pediatric XCAT phantoms that are obtained using template models, through segmentation, or by using the MC-LDDMM transform.

Obtained from templates (XCAT adults or segmented cadaver data)	Segmented in the CT data	Predicted with MC-LDDMM
Top of head (skin)	Body (skin)	Adrenals
Top of skull	Bottom of head	Arteries and veins in the body
Arms and legs (skin)	Bottom of skull	Muscle, ligaments, and tendons in the body
Humerus ^a	Eyes	Oral cavity
Radius	Breasts	Tonsils
Ulna	Thyroid	Tongue
Bones in hand and fingers	Pericardium ^b	Salivary glands
Femur ^a	Lungs	Brain and its interior structures
Tibia	Liver	Esophagus
Fibula	Gall bladder	Larynx
Patella	Stomach	Pharynx
Bones in foot and toes	Spleen	Thymus
	Pancreas	Heart and its interior structures ^b
	Kidneys	Ovaries
	Intestines	Fallopian tubes
	Bladder	Uterus
	Prostate	Vagina
	Sternum	Trachea and bronchi
	Ribs	Ejaculatory ducts
	Vertebrae	Epididymis
	Pelvis	Seminal vesicles
	Testes	Vas deferens
	Penis	Ureter
	Sacrum	Urethra
	Scapula	
	Clavicle	
	Humerus ^a	
	Femur ^a	

^aHumeri and femurs are partially segmented in the CT data and used to help place the template arm bones.

^bPericardial surface is segmented to guide the heart transform.

created using the XCAT framework previously established. The anatomies for the newborn, 1-, 5-, and 10-year old models were hermaphroditic, so the general anatomies are the same for the male and female versions. Figure 5 shows different layers of one of the completed phantoms, including the body surface, muscles, tendons, ligaments, skeleton, major organs, and vasculature. Each of the phantoms has a generic face and body that is a combination of the template XCAT model and the target patient data.

Table III shows the masses of the organs and structures in the new XCAT models. Marrow (active plus inactive) is currently modeled as an inner surface to the bones³⁰ given user-defined thickness values. Given the thickness value for a bone, the phantom program generates an inner surface for it to define as marrow. Similar parameters are defined for the wall thicknesses of the stomach, esophagus, and intestines. As a result, total values (wall plus contents) are shown for these structures. Fat is not explicitly modeled in the phantoms; it is currently defined as the background tissue that is not classified as any other tissue. The masses in Table III were calculated directly from the NURBS surfaces. These values will vary from ones calculated from voxelized versions of the phantoms. However, the XCAT phantom software contains parameters to adjust the masses, through scaling operations, to offset any difference caused by voxelization.

The phantoms realistically model the growth of the tissues and structures from newborn to the teen years. Figure 6 shows the skull, vertebrae, limbs, and pelvis, complete with developmental cartilage in the skull and pelvic bones at the different ages. The cartilage gives way to bone from newborn to 5 years. In addition to the realistic 3D anatomies, each phantom includes 4D models for the cardiac and respiratory motions. Figure 7 shows renderings of the newborn female at different time points in the cardiac and respiratory cycles.

Like the original XCAT phantoms, the new pediatric models can be used to simulate medical images from different modalities. Figure 8 shows simulated images from the 10 year

FIG. 4. The pediatric reference set. Shown here are female newborn, male 1 year, female 5 years, male 10 years, female 15 years, and male 15 years.

FIG. 5. The different layers of the completed 5-year-old female phantom. From left to right: skin surface; muscle, tendons, and ligaments; skeleton; organs; and vasculature.

TABLE III. Tissue mass values in each age group for ICRP 89 values, phantom model values, and percent difference.

Organ/tissue	Newborn	NB phantom	% Difference	1 year	1 yo phantom	% Difference
Adrenals (2)	6.00	5.75	−4.09	4.00	4.00	0.01
Tongue	3.50	3.62	3.44	10.00	10.12	1.23
Salivary glands	6.00	6.00	0.03	24.00	24.00	−0.01
Esophagus wall ^a	2.00	2.00	0.00	5.00	5.00	0.00
Stomach	47.00	45.64	−2.90	87.00	87.03	0.04
Small intestine	86.00	83.00	−3.48	178.00	176.42	−0.89
Large intestine	65.00	63.30	−2.62	130.00	131.13	0.87
Liver	130.00	128.78	−0.94	330.00	333.29	1.00
Gallbladder	3.30	3.32	0.57	9.40	9.40	0.03
Pancreas	6.00	5.88	−2.01	20.00	20.36	1.81
Brain	380.00	398.61	4.90	950.00	906.40	−4.59
Breasts	...	...	...	...	...	...
Eyes (2)	6.00	6.00	−0.04	7.00	7.21	2.93
Muscle	800.00	821.89	2.74	1900.00	1985.84	4.52
Pituitary gland	0.10	0.10	−0.09	0.15	0.15	−1.75
Larynx	1.30	1.32	1.32	4.00	4.19	4.75
Trachea ^a	0.50	0.50	0.00	1.50	1.50	0.00
Total skeleton	370.00	388.00	4.86	1170.00	1186.00	1.37
Marrow ^a	50.00	50.00	0.00	170.00	170.00	0.00
Spleen	9.50	9.41	−0.97	29.00	29.03	0.10
Thymus	13.00	13.00	0.00	30.00	29.86	−0.46
Thyroid	1.30	1.32	1.69	1.80	1.84	2.08
Tonsils (2 palatine)	0.10	0.10	0.94	0.50	0.50	−0.09
Kidneys (2)	25.00	24.53	−1.87	70.00	69.64	−0.52
Urinary bladder ^a	4.00	4.00	0.00	9.00	9.00	0.00
Testes (2)	0.85	0.85	0.33	1.50	1.51	0.46
Epididymes (2)	0.25	0.25	−0.91	0.35	0.36	3.59
Prostate	0.80	0.81	1.07	1.00	0.99	−0.95
Ovaries (2)	0.30	0.30	0.10	0.80	0.80	−0.52
Fallopian tubes (2)	0.25	0.24	−2.56	0.25	0.26	2.78
Uterus	4.00	4.00	−0.01	1.50	1.47	−2.01
Total body	3.50	3.63	3.71	10.00	10.22	2.24
Organ/tissue	5 year	5 yo phantom	% Difference	10 year	10 yo phantom	% Difference
Adrenals (2)	5.00	4.8987	−2.03	7.00	7.003	0.0424
Tongue	19.00	18.87	−0.67	32.00	30.46	−4.81
Salivary glands	34.00	32.62	−4.06	44.00	43.15	−1.94
Esophagus wall ^a	10.00	10.00	0.00	18.00	18.00	0.00
Stomach	133.00	133.96	0.72	202.00	201.31	−0.34
Small intestine	337.00	345.63	2.56	533.00	530.74	−0.42
Large intestine	220.00	228.66	3.94	350.00	349.35	−0.19

TABLE III. (Continued.)

Organ/tissue	5 year	5 yo phantom	% Difference	10 year	10 yo phantom	% Difference
Liver	570.00	573.61	0.63	830.00	840.04	1.21
Gallbladder	17.60	16.87	− 4.12	30.40	30.65	0.83
Pancreas	35.00	35.02	0.06	60.00	59.24	− 1.27
Brain	1310.00	1288.58	− 1.64	1310.00	1323.06	1.00
Breasts	...			...		
Eyes (2)	11.00	11.28	2.51	12.00	12.32	2.68
Muscle	5600.00	5666.61	1.19	11 000.00	10 450.38	− 5.00
Pituitary gland	0.25	0.26	2.95	0.35	0.35	− 0.83
Larynx	7.00	6.99	− 0.12	12.00	12.04	0.32
Trachea ^a	2.50	2.50	0.00	4.50	4.50	0.00
Total skeleton	2430.00	2542.00	4.61	4500.00	4601.00	2.24
Marrow ^a	500.00	500.00	0.00	1360.00	1360.00	0.00
Spleen	50.00	51.36	2.73	80.00	82.58	3.22
Thymus	30.00	29.79	− 0.71	37.50	37.21	− 0.78
Thyroid	3.40	3.40	0.00	7.90	8.20	3.84
Tonsils (2 palatine)	2.00	2.00	− 0.04	3.00	3.00	− 0.06
Kidneys (2)	110.00	111.28	1.16	180.00	181.87	1.04
Urinary bladder ^a	16.00	16.00	0.00	25.00	25.00	0.00
Testes (2)	1.70	1.70	− 0.28	2.00	2.02	0.88
Epididymes (2)	0.45	0.45	0.53	0.60	0.62	3.13
Prostate	1.20	1.20	0.00	1.60	1.60	− 0.22
Ovaries (2)	2.00	2.00	− 0.25	3.50	3.55	1.45
Fallopian tubes (2)	0.35	0.36	2.28	0.50	0.52	4.38
Uterus	3.00	3.00	0.10	4.00	3.99	− 0.20
Total body	19.00	19.90	4.74	32.00	33.00	− 3.13
Organ/tissue	15 year M	15 yo M phantom	% Difference	15 year F	15 yo F phantom	% Difference
Adrenals (2)	10.00	9.64	− 3.61	9.00	9.06	0.65
Tongue	56.00	54.31	− 3.01	53.00	51.66	− 2.52
Salivary glands	68.00	67.08	− 1.35	65.00	64.26	− 1.14
Esophagus wall ^a	30.00	30.00	0.00	30.00	30.00	0.00
Stomach	320.00	318.76	− 0.39	320.00	320.85	0.26
Small intestine	800.00	800.64	0.08	800.00	765.98	− 4.25
Large intestine	540.00	555.99	2.96	540.00	556.30	3.02
Liver	1300.00	1324.67	1.90	1300.00	1235.04	− 5.00
Gallbladder	52.70	50.60	− 3.98	49.30	49.30	0.01
Pancreas	110.00	110.19	0.18	100.00	96.56	− 3.44
Brain	1420.00	1390.42	− 2.08	1300.00	1251.11	− 3.76
Breasts	...			250.00	250.91	0.36
Eyes (2)	13.00	13.35	2.68	13.00	12.97	− 0.26
Muscle	24 000.00	23 625.15	− 1.56	17 000.00	16 737.63	− 1.54
Pituitary gland	0.50	0.50	− 0.09	0.50	0.50	− 0.09
Larynx	22.00	22.11	0.51	15.00	15.20	1.32
Trachea ^a	7.50	7.50	0.00	6.00	6.00	0.00
Total skeleton	7950.00	7553.00	− 4.99	7180.00	7474.00	4.09
Marrow ^a	2560.00	2560.00	0.00	2380.00	2380.00	0.00
Spleen	130.00	128.69	− 1.01	130.00	128.04	− 1.51
Thymus	35.00	33.52	− 4.23	30.00	30.15	0.50
Thyroid	12.00	12.52	4.31	12.00	12.45	3.77
Tonsils (2 palatine)	3.00	2.99	− 0.23	3.00	3.00	− 0.09
Kidneys (2)	250.00	252.50	1.00	240.00	229.06	− 4.56
Urinary bladder ^a	40.00	40.00	0.00	35.00	35.00	0.00
Testes (2)	16.00	16.02	0.10	0.00	0.00	0.00
Epididymes (2)	1.60	1.61	0.56	0.00	0.00	0.00
Prostate	4.30	4.27	− 0.64	0.00	0.00	0.00
Ovaries (2)	0.00	0.00	0.00	6.00	6.12	2.06
Fallopian tubes (2)	0.00	0.00	0.00	1.10	1.13	2.63
Uterus	0.00	0.00	0.00	30.00	29.93	− 0.23
Total body	56.00	57.80	3.21	53.00	54.00	− 1.89

^aTissues whose thicknesses and inner surfaces are user defined.

FIG. 6. The development of cartilage (dark green) into bone in the skull, pelvis, hands, and feet, and the development of the vertebrae are shown for the newborn, 1-, and 5-year old phantoms. The arrows point to the regions of cartilage which decrease from the newborn model to the 5 year old.

old male pediatric XCAT phantom versus real patient data for [18F]-fluorodeoxyglucose (FDG) PET, technetium-99 m sestamibi SPECT, and x-ray CT. The PET and SPECT data were simulated using analytical methods in our laboratory while the CT data were simulated using the XCAT CT projector.³⁵ It is important to note that the simulated and experimental data are from different anatomies. The pairs of images demonstrate how simulated images can closely resemble the general appearance of actual patient images. Figure 9 shows a phantom for each age group and its respective simulated CT results, simulated with contrast. All simulated images show high levels of realism: the chambers of the heart and the major blood vessels are well visualized; the soft-tissue contrast is realistic; and the cartilage in the skull can be visualized in the newborn and 1-year-old scans.

4. DISCUSSION

We created a set of ten pediatric reference phantoms that have the same level of detail and functionality as the original XCAT phantom adults. Based on patient data, the phantoms capture the anatomic variations of childhood, such as the de-

FIG. 7. 3D renderings of the female infant at different time frames of the cardiac and respiratory cycles. In the respiratory images, the dotted line indicates the height of the liver at end-expiration.

velopment of bone in the skull, pelvis, and long bones, and the growth of the vertebrae and organs. With thousands of defined structures, the phantoms created in this work are more highly detailed than previous pediatric models. This level of detail gives them the ability to simulate medical images close to that from actual patients. Unlike other models, the phantoms we developed are also 4D, including parameterized models for

FIG. 8. Imaging simulations performed using the 10 year old male XCAT phantom. PET (top), SPECT (middle), and CT (bottom) images are shown compared to data from a separate patient. Image planes of the reconstructed images are shown on the phantom model.

FIG. 9. Coronal slices of simulated CT scans with their respective phantoms. Left to right, top to bottom: newborn female, 1-year-old male, 5-year-old female, 10-year-old male, and 15-year-old female.

the cardiac and respiratory motions, giving them the ability to investigate 4D imaging devices and techniques.

A drawback to these models is that not every structure in them is defined by segmenting the patient data. We segmented the structures we could easily see in the data, including the major organs and all the bones, then used the MC-LDDMM algorithm to fill in the rest of the anatomy by transforming an adult template. The MC-LDDMM algorithm has been found in our work to provide a predicted anatomy that is a good match to what we segment.³¹ To further verify our anatomies, we compared them to the UF pediatric series of Lee *et al.*²¹ The predicted structures in our models were similar in size, shape, and location to those in the UF series.

Another drawback to the models is that the cardiac and respiratory motions are similarly predicted using adult templates. Both models are parameterized; however, so it is possible for a user to alter the cardiac and breathing patterns to better match those indicative of pediatrics. In future work, we will investigate creating more pediatric-specific models for the motions.

5. CONCLUSION

The development of patient-derived pediatric computational phantoms is useful in providing variable anatomies for simulation. With the ability to simulate realistic imaging data, the pediatric XCAT phantoms developed in this work have applications in a broad range of multimodality imaging research topics to evaluate and improve pediatric imaging devices and techniques. They may be used in tandem with imaging simu-

lation software to investigate the effects of anatomy and motion on medical imaging and to research new image acquisition strategies, processing, and reconstruction methods. For CT, in particular, they can be used to research new patient-tailored imaging protocols, without the risk of radiation dose from repeat exposures as would be of concern with a human cohort. They can also provide tools to assess radiation dose in pediatric CT. Specifically, they can be used to determine dose-specific and patient-specific effective doses for a CT scan with any given parameters.

In future work, these reference models will serve as the templates in the MC-LDDMM algorithm to generate a large population of pediatric phantoms, of varying ages and weight percentiles. The reference phantom of the same sex and closest age will be selected, which will reduce the time spent on manual corrections and will make the process more efficient. Once the large cohort is complete, it can be utilized to conduct large-scale research studies, such as the optimization of CT imaging protocols in terms of image quality and dose for a given age and body habitus.

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and organ masses of our phantoms to their set of reference phantoms.²¹ This project was sponsored by NIH Grant No. RO1-EB001838.

- ^{a)} Author to whom correspondence should be addressed. Electronic mail: Hannah.norris@duke.edu; Telephone: (919) 684-1440.
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