Published in final edited form as:

Radiat Environ Biophys. 2010 May ; 49(2): 155–168. doi:10.1007/s00411-009-0260-x.

HYBRID COMPUTATIONAL PHANTOMS FOR MEDICAL DOSE RECONSTRUCTION

Wesley Bolch^{1,2}, Choonsik Lee³, Michael Wayson¹, and Perry Johnson¹

¹Department of Nuclear & Radiological Engineering, University of Florida, Gainesville, FL

²Department of Biomedical Engineering, University of Florida, Gainesville, FL

³Division of Cancer Epidemiology and Genetics, National Cancer Institute, National Institute of Health, Bethesda, MD 20852

Abstract

As outlined in NCRP Report No. 160, the average value of the effective dose to exposed individual in the United States has increased by a factor of 1.7 over the time period 1982 to 2006, with the contribution of medical exposures correspondingly increasing by a factor of 5.7. at present, medical contributors to the effective dose include computed tomography (50% of total medical exposure), nuclear medicine (25%), interventional fluoroscopy (15%), and conventional radiography and diagnostic fluoroscopy (10%). This increased awareness of medical exposures has led to a graduate shift in the focus of radiation epidemiological studies from traditional occupational and environmental exposures to those focusing on cohorts of medical patients exposed to both diagnostic and therapeutic sources. The assignment of organ doses to patients in either a retrospective or prospective study has increasingly relied on the use of computational anatomical phantoms. In this paper, we review the various methods and approaches used to construction patient phantom models to include anthropometric databases, cadaver imaging, prospective volunteer imaging studies, and retrospective image reviews. Phantom format types – stylized, voxel, and hybrid – as well as phantom morphometric categories – reference, patient-dependent, and patient-specific – are next defined and discussed. Specific emphasis is given to hybrid phantoms – those defined through the use of combinations of polygon mesh and NURBS surfaces. The concept of a patient-dependent phantom is reviewed in which phantoms of non-50th percentile heights and weights are designed from population-based morphometric databases and provided as a larger library of phantoms for patient matching and lookup of refined values of organ dose coefficients and/or radionuclide S values. We close with two brief examples of the use of hybrid phantoms in medical dose reconstruction – diagnostic nuclear medicine for pediatric subjects and interventional fluoroscopy for adult patients.

Keywords

Stylized phantom; voxel phantom; hybrid phantom; reference phantom; patient-specific phantom; patient-dependent phantom; medical dose reconstruction; organ dosimetry

Introduction

In its Report No. 160, the National Council on Radiation Protection and Measurement (NCRP) indicates that from 1982 to 2006, the average per capita effective dose contributed from all radiation sources in the United States increased from 3.6 to 6.2 mSv (NCRP, 2009). The major driving force for this increase was medical exposures, resulting in a change of from 15% of total exposure in 1982 to 48% of total exposure in 2006. At present, medical contributors to the average effective dose include computed tomography (50% of total medical exposure), nuclear medicine (25%), interventional fluoroscopy (15%), and conventional radiography and fluoroscopy (10%).

This growing awareness of increased medical exposures has had two major effects. The first is a gradual shift in the focus of radiation epidemiological studies from traditional occupational and environmental exposure studies, to those focusing on cohorts of medical patients exposed to both diagnostic and therapeutic sources. The enhanced radiosensitivity of children make pediatric studies of prime importance (BEIR, 2005). Examples include those under the Childhood Cancer Survivor Study,¹ and the study of children who have undergone computed tomography imaging.² The second is an increased awareness of the need to reduce radiation exposures to current patients through optimization of image quality and patient dose in diagnostic imaging, or through maximizing tumor dose while minimizing non-target tissue dose in radiation therapy within both the near- and far-field regions of the patient. Furthermore, professional societies are increasing advocating the recording of patient dose in imaging studies via indicator dose quantities (Amis *et al.*, 2007). The ideal situation, however, would be the ability to record individual organ doses for each patient and each imaging exam or therapy procedure, and record that dose in electronic form. This information would be invaluable for both prospective monitoring of cumulative exposures to seriously ill patients requiring multiple diagnostic and therapeutic procedures, as well as retrospective epidemiological studies undertaken in the future.

Need for Computational Phantoms in Medical Dosimetry

Estimating organ doses to medical patients, either prospectively or retrospectively, require the use of computational anatomical models of human anatomy, although some information can be derived through physical phantoms and embedded dosimeters (Hintenlang *et al.*, 2009). A *computational anatomic phantom* is a computerized representation of human anatomy for use in radiation transport simulations of a medical imaging examination or a radiation therapy procedure. The need for such a phantom varies among the various medical applications for which organ dose estimates are sought. In nuclear medicine, detailed 3D patient anatomy is available through the CT portion of SPECT/CT or PET/CT imaging systems. However, the vast majority of nuclear medicine studies are conducted using single or dual headed planar imaging systems, and thus organ doses are generally estimated through pre-computed and phantom-based S values under the MIRD system (Bolch *et al.*, 2009). In radiography and fluoroscopy, no 3D image of patient anatomy is generated, and essentially all organ dosimetry is accomplished through the use of computational phantoms and pre-computed organ dose conversion coefficients. In computed tomography, 3D anatomic data is acquired by design and can in principle be used to define the patient's own computational phantom. A major problem of this approach is that image segmentation is required to properly define tissue boundaries for reporting average organ dose or dose-volume histograms. While advances in automated image segmentation algorithms are ongoing (Han, 2008; Heimann, 2009), the vast majority of computational phantoms

¹<http://www.cancer.gov/cancertopics/coping/ccss>

²<http://dceg.cancer.gov/reb/research/ionizing/medical/4>

generated from patient CT images are performed through manual contouring (Zaidi and Xu, 2007). A secondary issue in CT dosimetry is that most CT images have limited anatomic coverage, and thus no anatomic information exists regarding organs and tissues that are partially imaged or are just beyond the edges of the scan field. A similar situation exists in external beam radiotherapy, where CT images of the cancer patient are used for treatment planning. While these images are more than sufficient to characterize the dose distributions within the tumor, and to establish dose gradients to near-field tissues, no anatomic information is available for characterizing radiation dose from treatment head and in-patient scatter in far-field tissue regions. The issues of photon scatter dose in intensity modulated radiation therapy (IMRT) and neutron scatter dose in proton therapy are prime examples of the need for additional anatomic information of the patient beyond that acquired during treatment planning (Hall, 2006; Athar and Paganetti, 2009; Fontenot *et al.*, 2009).

Methods and Approaches to Phantom Construction

Anatomic Sources

Four broad sources of anatomic information exist for the construction of a computational anatomic phantom for dose reconstruction. As shown in Table 1, these four sources include (1) anthropometric and autopsy databases, (2) human cadavers, (3) prospective volunteer imaging studies, and (4) retrospective image reviews. The first source includes population-based surveys of body morphometry including weights, heights, and perhaps secondary and tertiary parameters such as sitting heights, body region circumferences, and extremity lengths. Phantoms, under a variety of formats (see below), can then be constructed to match different percentiles of these morphometric parameters to create virtual patients from that same population (Clairand *et al.*, 2000). Internal anatomy is then constructed based upon an assumed tissue density and reported values of organ masses via autopsy examination (de la Grandmaison *et al.*, 2001). Organ shape, depth, and position, however, remain undefined and thus unconstrained.

The second imaging source is human cadavers. Due to distortions in T1 and T2 relaxation times, cadaver imaging is generally restricted to CT scanning, although cryosectioning and digital photography have been used to provide unique and high-resolution anatomic data in a few unique cases (Spitzer and Whitlock, 1998). Cadavers obtained from body donation programs are typically of older individuals, and thus anatomic information for the construction of younger adults and children is limited.

The third option is prospective volunteers for which a CT or MR image is acquired strictly for the purpose of phantom construction. In this case, Institutional Review Board (IRB) approval is required and informed consent must be obtained. Tradeoffs between CT and MR imaging of volunteer subjects include issues related to the risks associated with ionizing radiation exposure, scan times and associated motion artifacts, and skeletal versus soft tissue image contrast. Whole-body imaging is possible, as well as specific positioning of the body within the resultant image. For example, many CT images show the feet pointed downward (natural position during scanning) while an upright, flat-footed phantom might be the intended outcome of the image segmentation process.

The fourth option of Table 1 is a retrospective review of existing medical image archives. Again, IRB approval will be required, but typically these will either be exempt or expedited protocols, resulting in the potential for larger numbers of subject images to be collected and reviewed for phantom construction. However, many of these images will be from partial body scans, and thus supplemental techniques will be needed to fashion a whole-body phantom from multiple image sets (Lee *et al.*, 2006).

Phantom Format Types

At present, there exist three different formats for computational anatomic phantoms: stylized (or mathematical), voxel (or tomographic), and hybrid formats based upon NURBS and/or polygon mesh surfaces. Examples of each are shown graphically in Figure 1. Stylized phantoms have been the workhorse of radiation dosimetry for over 40 years (Eckerman *et al.*, 2009), and even today, form the basis for many reference sets of dose and risk coefficients (Eckerman *et al.*, 1988; Eckerman and Ryman, 1993; Eckerman *et al.*, 1999). They are composed of 3D geometric surface equations defining both internal organs and outer body surfaces (Poston *et al.*, 2002). While they are flexible in terms of allowing changes in organ size, body shape, and extremity positioning, they are generally deficient with respect to anatomic realism. Voxel phantoms, in contrast, are composed of a three-dimensional array of voxels, each with a unique organ identity, elemental composition, and density. Voxel phantoms are assembled through segmentation (pixel tagging) of individual image slices from the CT or MR image set, and thus they provide a high level of anatomic realism. Their main limitation is that they are very difficult to alter to represent the body morphometry of subjects other than the person providing the source image.

Hybrid phantoms – the third model format – are so named because they preserve both the anatomic realism of voxel phantoms and the mathematical flexibility of stylized phantoms as shown in Figure 2. The steps used to construct hybrid phantoms are outlined graphically in Figure 3. First, image sources – typically from CT or MR – are segmented just as would be done in the creation of a traditional voxel phantom. This step is performed at the *Advanced Laboratory for Radiation Dosimetry Studies (ALRADS)* at the University of Florida using the software *3D-DOCTOR™* (Able Software Corp., Lexington, MA). A resulting 3D rendering of the subject anatomy is exported as a polygon mesh (PM) model, in which individual organs and the outer body contour are represented by a large array of triangular surfaces. For some complex structures, such as the vertebrae, this format is preferred and retained in the final hybrid phantom. For many other organs and all outer body surfaces, these polygon mesh models are subsequently converted to non-uniform rational B-spline (or NURBS) surfaces, where 3D control points can be individually or regionally altered to permit organ reshaping and repositioning, as well as allowing for uniform enlargement or reduction. The software code *RHINOERCOS™* (McNeel North America, Seattle, WA) may be used for this step. The resultant phantom is termed a hybrid-NURBS/PM phantom. However, most present-day radiation transport codes require a voxelized structure for particle tracking, and so a user-defined MATLAB routine (*Voxelizer™*) was written to fill the NURBS/PM structures with cubic voxels of any user-defined size. This resultant anatomic model is termed a hybrid-voxel phantom, where the adjective denotes that the resultant voxel structure was derived from NURBS/PM surfaces, and not directly from a segmented medical image. This is an important distinction in that while in the hybrid-NURBS/PM format, significant changes can be made to the phantom to conform to different phantom categories as defined below.

Advantages of Hybrid Phantoms over Voxel Phantoms

The method by which a traditional voxel phantom is constructed is demonstrated in Figure 4 for five transaxial views of one of the UF pediatric voxel phantoms (Lee *et al.*, 2006). Within each XY voxel array, excellent anatomic detail is seen, as the in-plane resolution of modern CT scanners is generally 0.5 mm or better. However, the Z dimension of the phantom voxels (corresponding to the image slice thickness) can be a few to several mm for typical clinical imaging protocols. As a result, stair-stepped artifacts may arise as seen in the first panel of Figure 5 for the left lung of the UF newborn voxel phantom. Through the conversion of the segmented image to polygon mesh (Fig. 5B) and then to NURBS surface structure (Fig. 5C), a model of the lung surface can be created that is smooth and contiguous

in all dimensions. Final hybrid-voxel models of the newborn lung shown in Figs. 5C and 5E retain smooth surface as viewed in not only the transaxial plane, but the coronal and sagittal planes as well.

Another distinct advantage of hybrid phantoms is their ability to reshape surfaces in complex tissue regions. Some of the more challenging tissues to model in a voxel phantom are the facial bones of the skull. Figure 6A shows rendered images (using *Rhinoceros*) of the skulls of the KTMAN2 and the MAX voxel phantoms. In the KTMAN2 phantom, holes in the frontal bone and maxilla are evident which are difficult to identify and to “repair” within sequential 2D transaxial slices of the voxel phantom. The situation is significantly worse for the MAX phantom where the original model of Zubal *et al.* was altered to match total skeletal volumes given in ICRP Publication 89 (ICRP, 2002). Similar holes were seen in the early development of the UF pediatric series of hybrid phantoms as shown in Figure 6B (left panel). However, as shown in Figure 6C, individual regions of polygon mesh models of the facial bones can be adjusted inward or outward in *3D-DOCTOR*TM so that these anomalies can be corrected and a smooth representation of the bony structures realized in the final hybrid phantom (Fig. 6B – right panel).

Phantom Morphometric Categories

Another consideration is the morphometric category of the resultant phantom. As shown in Table 2, three categories are possible. The first is a *reference* phantom defined typically as an individual at 50th height/weight percentile in a given human population. The characteristics of a reference phantom for radiation protection purposes are defined by the International Commission on Radiological Protection in its Publication 89 (ICRP, 2002). This document outlines reference values for organ masses (from which targeted organ volumes may be derived given a reference tissue density) and subject height, weight, and body surface area. More specific characteristics such as extremity lengths, sitting heights, body circumferences are not given in ICRP Publication 89, and thus additional databases must be consulted to find 50th percentile values during reference phantom design. Examples of reference stylized phantoms are those of the Oak Ridge National Laboratory (ORNL) series (Cristy and Eckerman, 1987; Han *et al.*, 2006). The ICRP Reference Phantoms (ICRP, in press), and the MAX and FAX phantoms (Kramer *et al.*, 2006) are examples of reference phantoms in a voxelized format. Two examples of reference hybrid phantoms are those of the University of Florida (UF) series (pediatric and adults) (Lee *et al.*, 2007; Lee *et al.*, 2008; Hurtado *et al.*, in press), and those from Rensselaer Polytechnic Institute (pregnant female series) (Xu *et al.*, 2007). Graphical images of the UF reference hybrid phantom series are shown in Figure 7.

At the other extreme of Table 2 are patient-specific phantoms – those that uniquely match the body morphometry and organ anatomy of an individual medical patient. Examples of patient-specific (or individual-specific) voxel phantoms include the VIP-Man and KTMAN2 phantoms – both constructed through direct image segmentation without alteration of subject anatomy. Advances in image segmentation and image processing software will eventually permit the creation of patient-specific hybrid phantoms, and thus this remains a future development.

Patient-Dependent Phantoms

While reference phantoms are valuable for defining idealized exposures conditions and for developing dose coefficients for radiological protection, they are of much more limited use in assigning organ doses from medical imaging and therapy procedures, especially when the individual patient has a body morphometry far from the 50th height / weight percentile. Under these conditions, and when a patient-specific phantom cannot be created, an

intermediate solution is to match patient to phantom using a large library of phantoms covering a broad range of body shapes and sizes. As shown in Table 2, such a library already exists at a few institutions such as Helmholtz Zentrum München (formerly GSF) (Zankl, 2009). In addition, an expanded library of patient-dependent stylized phantoms can be created using the software code BodyBuilder™ (Van Riper, 1999; Van Riper *et al.*, 1996).

At the University of Florida, efforts are underway to create a hybrid phantom library that matches variations in body size and shape among the U.S. population of adults and children. The process is displayed schematically in Figure 8. For adults, standing height data from the U.S. National Health and Nutrition Examination Survey (NHANES)³ are collected and fit to a Gaussian distribution to determine 10th, 25th, 50th, 75th, and 90th height percentiles for adult males and for adult females to within a tolerance of ± 1 cm. For each percentile, the data were subsequently culled further, and with a combination of Gaussian and polynomial fits, the 10th, 25th, 50th, 75th, and 90th body mass percentiles for each standing height percentile were then determined to within a tolerance of ± 0.5 kg. Secondary anthropometric parameters for each standing height / body mass combination were selected based upon the average individual found within each sub-grouping. These parameters were then used to rescale both the UF adult male and UF adult female reference hybrid phantoms to generate a library of adult hybrid phantoms – 25 males and 25 females. Similar techniques are being applied to the creation of a large library of paediatric patient-dependent hybrid phantoms. Figure 9 and Figure 10 graphically show correlations of individual standing and sitting heights as a function of body mass from the NHANES database for paediatric and adult subjects, respectively.

Applications to Medical Dose Reconstruction

Two brief examples are given below for the use of hybrid phantoms in medical dose reconstruction. The first highlights differences in radionuclide S values for Tc-99m assessed in a stylized and a hybrid phantom both representing the ICRP reference 15-year female patient. The second highlights differences in organ dose coefficients in adult males of various body sizes undergoing interventional fluoroscopy imaging.

Nuclear Medicine Dosimetry

The UF hybrid phantom representing the ICRP 89 reference 15-year female was voxelized at 2 mm isotropic resolution using the in-house MATLAB code *Voxelizer 4*. The resulting hybrid-voxel phantom was next imported to the radiation transport code MCNPX 2.5 (Pelowitz, 2005). Photon and electron emission spectra from ^{99m}Tc were then abstracted from a recent updated monograph published by the MIRD committee (Eckerman and Endo, 2008). Two Monte-Carlo simulations were thus run – one for photon emissions (x and γ rays) and one for electron emissions (β , IC, and Auger electrons) – each with 10^7 particle histories. Photon and electron components of the S value were then combined to yield total spectral S values (absorbed dose per nuclear transformation in the source tissue). Source organs correspond to those in biokinetic models of ^{99m}Tc-labeled DMSA, while target tissues were those assigned values of w_T in the ICRP 103 definition of the effective dose (ICRP, 2007).

S values generated for the UF reference 15-year female hybrid phantom were then compared to those from the OLINDA software which utilizes the stylized 15-year hermaphrodite phantom of the ORNL pediatric series (Stabin *et al.*, 2005). Table 3 gives ratios of radionuclide S values for ^{99m}Tc obtained from the OLINDA code and its ORNL 15-year

³<http://www.cdc.gov/nchs/nhanes.htm>

phantom to those generated for the UF 15-year reference hybrid phantom. Significant differences are noted between the two sources of S values, and these may be attributed to several factors including differences in organ mass and inter-organ separation distance. More minor differences may be attributed to disparities in the emission spectra used in OLINDA versus that given in the 2008 MIRD monograph.

The ORNL phantom is a hermaphrodite representing both the ICRP reference 15-year male and 15-year female. This phantom was originally designed in 1980 (Cristy, 1980), and thus predates the 2002 update to the reference pediatric series in ICRP Publication 89 (ICRP, 2002). As shown in Table 4, organ masses in the ORNL 15-year phantom are generally larger than defined in ICRP 89. Significant discrepancies are noted for the breast (361 vs 250 g), skin (2150 vs 1700 g), and ovaries (10.5 vs 6.0 g). Conversely, the lungs in the ORNL stylized phantom are smaller than current reference values (651 vs 750 g). These mass differences account in part for observed S value ratios exceeding 1.0 for liver self-dose (ratio of 1.3), and below 1.0 for lung self-dose (ratio of 0.8). Other discrepancies in S values between the two phantoms may be attributed to disparities in inter-organ separation distances. For example, and as shown graphically in Figures 11A and 11B, the stomach is positioned much further away from liver in the ORNL phantom than seen in the UF hybrid phantom. Accordingly, values of $S(\text{stomach wall} \leftarrow \text{liver})$ are much lower in the ORNL stylized phantom than realized in the UF hybrid phantom (S value ratio of 0.6 in Table 3). Similarly, the ovaries are positioned closer to the urinary bladder in the UF hybrid phantom than in the ORNL stylized phantom (S value ratio of 0.3 in Table 3). A review of organ masses in the newborn, 1-year, 5-year, and 10-year ORNL phantoms indicate much closer agreement with current ICRP 89 reference values than was seen for the 15-year phantoms. Still, anatomical differences in organ shape, depth, and inter-organ positioning will still result in further discrepancies in radionuclide S values generated by these two very different anatomic models.

Interventional Fluoroscopy Dosimetry

In a recent study by Johnson et al. (Johnson *et al.*, 2009), the influence of body size on organ dosimetry in interventional fluoroscopy was explored using three patient-dependent hybrid phantoms of the adult male – one each at the 10th, 50th, and 90th weight percentile and all at 50th height percentile. The 50th height / 50th weight percentile phantom corresponded to the ICRP reference adult male in this present study, and not the average US adult male who is 5 kg heavier. Four typical fluoroscopic fields were generated – AP, PA, LAO, and RAO – and organ dose conversion coefficients (organ absorbed dose per dose-area product) were generated at 60, 90, and 120 kVp tube potential. Table 5 displays the percent difference in the DCC between the 10th and 50th percentile phantoms for that energy, field, and organ, and corresponding percent differences between the 50th and 90th percentile phantoms. As seen in Table 5, relative errors can be as large as 113% for certain projections and in all cases the organ dose to an underweight patient will be underestimated by use of a 50th weight percentile reference phantoms, while the organ dose to an overweight patient will be similarly overestimated if patient size is neglected in the fluoroscopy dose assessment.

Conclusions

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 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 reference phantom which has a trunk height that closely matches to that measured in the patient. Whalen et al. (2008) 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. (2008) 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 re-assign 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.

References

- Amis ES Jr, Butler PF, Applegate KE, Birnbaum SB, Brateman LF, Hevezi JM, Mettler FA, Morin RL, Pentecost MJ, Smith GG, Strauss KJ, Zeman RK. American College of Radiology white paper on radiation dose in medicine. *J Am Coll Radiol* 2007;4:272–284. [PubMed: 17467608]
- Athar BS, Paganetti H. Neutron equivalent doses and associated lifetime cancer incidence risks for head & neck and spinal proton therapy. *Phys Med Biol* 2009;54:4907–4926. [PubMed: 19641238]
- BEIR. Health risks from exposure to low levels of ionizing radiation: BEIR VII - Phase 2. Washington, DC: National Research Council; 2005.
- Bolch WE, Eckerman KF, Sgouros G, Thomas SR. MIRD Pamphlet No. 21 – A generalized schema for radiopharmaceutical dosimetry: Standardization of nomenclature. *J Nucl Med* 2009;50:477–484. [PubMed: 19258258]
- Clairand I, Bouchet LG, Ricard M, Durigon M, Di Paola M, Aubert B. Improvement of internal dose calculations using mathematical models of different adult heights. *Phys Med Biol* 2000;45:2771–2785. [PubMed: 11049171]
- Cristy, M. Mathematical phantoms representing children of various ages for use in estimates of internal dose. Oak Ridge, Tennessee: Oak Ridge National Laboratory; 1980.
- Cristy, M.; Eckerman, KF. Specific absorbed fractions of energy at various ages from internal photon sources. Oak Ridge, TN: Oak Ridge National Laboratory; 1987.
- de la Grandmaison GL, Clairand I, Durigon M. Organ weight in 684 adult autopsies: new tables for a Caucasoid population. *Forensic Sci Int* 2001;119:149–154. [PubMed: 11376980]
- Eckerman, KF.; Endo, A. MIRD: Radionuclide Data and Decay Schemes. Reston, VA: The Society of Nuclear Medicine; 2008.
- Eckerman, KF.; Leggett, RW.; Nelson, CB.; Puskin, JS.; Richardson, ACB. Federal Guidance Report No. 13: Cancer risk coefficients for environmental exposure to radionuclides. Washington, DC: US EPA; 1999.
- Eckerman, KF.; Poston, JW.; Bolch, WE.; Xu, XG. Handbook of anatomical models for radiation dosimetry. Xu, XG.; Eckerman, KF., editors. London, UK: Taylor & Francis; 2009.
- Eckerman, KF.; Ryman, JC. Federal Guidance Report No. 12: External exposure to radionuclides in air, water, and soil. Washington, DC: US EPA; 1993.
- Eckerman, KF.; Wolbarst, AB.; Richardson, ACB. Federal Guidance Report No. 11: Limiting values of radionuclide intake and air concentration and dose conversion factors for inhalation, submersion, and ingestion. Washington, DC: US EPA; 1988.
- Fontenot JD, Lee AK, Newhauser WD. Risk of secondary malignant neoplasms from proton therapy and intensity-modulated x-ray therapy for early-stage prostate cancer. *Int J Radiat Oncol Biol Phys* 2009;74:616–622. [PubMed: 19427561]

- Hall EJ. Intensity-modulated radiation therapy, protons, and the risk of second cancers. *Int J Radiat Oncol Biol Phys* 2006;65:1–7. [PubMed: 16618572]
- Han E, Bolch W, Eckerman K. Revisions to the ORNL series of adult and pediatric computational phantoms for use with the MIRD schema. *Health Phys* 2006;90:337–356. [PubMed: 16538139]
- Han, X. Medical image segmentation using level set method and digital topology: concepts and new developments. Saarbrücken, Germany: VDM Verlag; 2008.
- Heimann, T. Statistical shape models for 3D medical image segmentation. Saarbrücken, Germany: VDM Verlag; 2009.
- Hintenlang, DE.; Moloney, W.; Winslow, J. Handbook of Anatomical Models for Radiation Dosimetry. Xu, XG.; Eckerman, KF., editors. London, UK: Taylor & Francis Group; 2009.
- Hurtado JL, Lee C, Lodwick D, Geode T, Williams JL, Bolch WE. Hybrid computational phantoms representing the reference adult male and adult female: Construction and applications to retrospective dosimetry. *Health Phys*. in press.
- ICRP. ICRP Publication 89: Basic anatomical and physiological data for use in radiological protection - reference values. *Ann ICRP* 2002;32:1–277.
- ICRP. ICRP Publication 103: Recommendations of the International Commission on Radiological Protection. *Ann ICRP* 2007;37:1–332.
- ICRP. Adult reference computational phantoms. *Ann ICRP*. in press.
- Johnson P, Lee C, Johnson K, Siragusa D, Bolch W. Influences of patient size on dose conversion coefficients: A hybrid phantom study for adult cardiac catheterization. *Phys Med Biol* 2009;54:3613–3629. [PubMed: 19458408]
- Kramer R, Khoury HJ, Vieira JW, Lima VJ. MAX06 and FAX06: update of two adult human phantoms for radiation protection dosimetry. *Phys Med Biol* 2006;51:3331–3346. [PubMed: 16825733]
- Lee C, Lee C, Williams JL, Bolch WE. Whole-body voxel phantoms of paediatric patients - UF Series B. *Phys Med Biol* 2006;51:4649–4661. [PubMed: 16953048]
- Lee C, Lodwick D, Hasenauer D, Williams JL, Lee C, Bolch WE. Hybrid computational phantoms of the male and female newborn patient: NURBS-based whole-body models. *Phys Med Biol* 2007;52:3309–3333. [PubMed: 17664546]
- Lee C, Lodwick D, Williams JL, Bolch WE. Hybrid computational phantoms of the 15-year male and female adolescent: applications to CT organ dosimetry for patients of variable morphometry. *Med Phys* 2008;35:2366–2382. [PubMed: 18649470]
- NCRP. NCRP Report No. 160: Ionizing Radiation Exposure of the Population of the United States. Bethesda, MD: National Council on Radiation Protection and Measurement; 2009.
- Pelowitz, DB. MCNPX User's Manual Version 2.5.0. Los Alamos, NM: Los Alamos National Laboratory; 2005.
- Poston, J.; Bolch, W.; Bouchet, L. Monte Carlo calculations in nuclear medicine: therapeutic applications. Zaidi, H.; Sgouros, G., editors. Bristol, UK: Institute of Physics Publishing; 2002. p. 108-132.
- Spitzer VM, Whitlock DG. The Visible Human Dataset: the anatomical platform for human simulation. *Anat Rec* 1998;253:49–57. [PubMed: 9605360]
- Stabin MG, Sparks RB, Crowe E. OLINDA/EXM: the second-generation personal computer software for internal dose assessment in nuclear medicine. *J Nucl Med* 2005;46:1023–1027. [PubMed: 15937315]
- Van Riper, KA. BodyBuilder. White Rock, NM: White Rock Science; 1999.
- Van Riper, KA.; Spikes, DL.; McDowell, RG. Advances and Applications in Radiation Protection and Shielding. American Nuclear Society; 1996. Variable human anthropomorphic models; p. 643
- Whalen S, Lee C, Williams JL, Bolch WE. Anthropometric approaches and their uncertainties to assigning computational phantoms to individual patients in pediatric dosimetry studies. *Phys Med Biol* 2008;53:453–471. [PubMed: 18184999]
- Xu XG, Taranenko V, Zhang J, Shi C. A boundary-representation method for designing whole-body radiation dosimetry models: pregnant females at the ends of three gestational periods--RPI-P3, -P6 and -P9. *Phys Med Biol* 2007;52:7023–7044. [PubMed: 18029991]

- Zaidi H, Xu XG. Computational anthropomorphic models of the human anatomy: the path to realistic Monte Carlo modeling in radiological sciences. *Annu Rev Biomed Eng* 2007;9:471–500. [PubMed: 17298237]
- Zankl, M. Handbook of anatomical models for radiation dosimetry. Xu, XG.; Eckerman, KF., editors. London, UK: Taylor & Francis; 2009.

Figure 1.
Graphical examples of a stylized, voxel, and hybrid adult male phantom.

Figure 2.
Schematic displaying the joint attributes of hybrid phantoms.

Figure 3.
Steps needed to create both a hybrid-NURBS/PM and hybrid-voxel phantom.

Figure 4.
Representative transaxial slices through one of the UF pediatric voxel phantoms.

Figure 5.
Conversion of the left lung of the UF voxel newborn phantom to a hybrid-voxel format.

Figure 6.
 (A) Skull models in the KTMAN2 and MAX voxel phantoms as viewed in *Rhinoceros*TM.
 (B) Repair of the cranial model of the UF 1-year reference hybrid phantom. (C)
 Demonstration of the use of *3D-Doctor*TM to “repair” holes in the originally segmented
 model of the 1-year cranium.

Figure 7.
Perspective view of the UF Family of reference hybrid phantoms.

Hybrid Phantoms

Patient-Dependent Series

Purpose -

Design criterion for a new class of reference phantoms based on a US population.

Figure 8.

Flowchart relevant to the creation of a library of patient-dependent hybrid phantoms for patient matching in a medical dose reconstruction project.

Figure 9.

Scatter plots from the NHANES database for 5-year, 10-year, and 15-year children showing the relationship between both standing heights (upper grouping) and sitting heights (lower groupings) as a function of subject body mass.

Figure 10.

Corresponding data on adult female and adult male standing and sitting heights as a function of body mass from the NHANES database.

Figure 11.

Anterior (A and B) and posterior (C and D) views of the UF 15-year female hybrid phantom (left) and the corresponding ORNL stylized phantom (right). Liver (green), stomach (red), ovaries (white), and bladder (yellow).

Table 1

Comments regarding sources and methods for anatomic data used to construct computational anatomic phantoms.

Anatomic Source	General Issues with Anatomic Source	Issues with MR Imaging	Issues with CT Imaging
<i>Anthrometric and Autopsy Database</i>	<ul style="list-style-type: none"> • Information available only for organ masses and body height/weight for different percentiles of the population. No information on organ shape, depth, or position. 	<i>No Imaging Data by Definition</i>	<i>No Imaging Data by Definition</i>
<i>Cadavers</i>	<ul style="list-style-type: none"> • Typically limited to older individuals; difficult to obtain pediatric cadavers for phantom construction. Possible to also have photographic images of sectioned slices of the body 	<ul style="list-style-type: none"> • Not feasible due to distorting in T1 and T2 within frozen or recently frozen tissues 	<ul style="list-style-type: none"> • Feasible - allows high resolution imaging and whole-body coverage
<i>Prospective Volunteers</i>	<ul style="list-style-type: none"> • More challenging to obtain IRB approval relative to retrospective image review • Possible limitation of the number of subjects enrolled in study, thus limiting the size of the phantom library • Possibility of positioning the body in a defined and desirable fashion • Whole-body coverage is possible 	<ul style="list-style-type: none"> • Ethically feasible due to lack of ionizing radiation exposure • Long scan times and subsequent problems with respiratory, cardiac, and intestinal movement • Poor definition of the skeletal tissues relative to CT imaging • Good definition of finer soft tissue structures relative to CT imaging 	<ul style="list-style-type: none"> • Ethically challenging due to use of ionizing radiation • Very short scan times, thus minimizing problems with organ and tissue movement • Good definition of the skeletal tissues relative to MR imaging • Poor definition of finer soft tissue structures relative to MR imaging. Can be helped with CT contrast
<i>Retrospective Image Review</i>	<ul style="list-style-type: none"> • Less challenging to obtain IRB approval compared to a prospective study as the images have already been acquired • Possibility of enrolling a larger number of subjects than a prospective study 	<ul style="list-style-type: none"> • Whole-body coverage potentially difficult, but not impossible to find in image archive. Head imaging usually far exceeds torso imaging. • Poor definition of the skeletal tissues relative to CT imaging • Good definition of finer soft tissue structures relative to CT imaging 	<ul style="list-style-type: none"> • Whole-body coverage rarely available due to radiation dose considerations and lack of clinical need. • Good definition of the skeletal tissues relative to MR imaging • Poor definition of finer soft tissue structures relative to MR imaging. Can be helped with CT contrast.

Table 2

Examples of different phantom types and categories used for dose reconstruction studies.

Type / Category	Reference	Patient-Dependent	Patient-Specific
Stylized	ORNL Series	Body Builder™	Not Applicable
Voxel	ICRP Publication 110, Rex/Regina, MAX/FAX	GSF Family	VIP-Man, KTMAN2
Hybrid	UF Adult & Pediatric Series, RPI Pregnant Female Series	UF (<i>in development</i>)	Future Applications

Table 3
S value ratios (ORNL 15-year phantom / UF Hybrid 15-year female) for Tc-99m.

Target Organs	Source Organs						
	Heart	Kidneys	Liver	Lungs	Skeleton	Spleen	UB Cont
<i>Active Marrow</i>	2.4	0.8	1.4	0.9	1.4	1.4	0.8
<i>Brain</i>	1.8	0.3	0.8	1.2	6.2	1.2	0.6
<i>Breasts</i>	2.5	0.9	1.0	1.6	22.7	1.5	3.6
<i>Liver</i>	2.3	0.9	1.3	1.3	10.0	1.0	2.7
<i>Lungs</i>	1.1	0.4	0.6	0.8	1.3	0.7	1.1
<i>Ovaries</i>	52.0	1.8	5.9	3.6	2.6	6.5	0.3
<i>Skin</i>	3.8	0.8	1.6	1.7	11.7	1.0	2.0
<i>Stomach Wall</i>	2.2	0.7	0.6	1.0	6.2	1.1	2.7
<i>Thyroid</i>	1.0	0.3	0.6	0.6	4.4	0.8	1.2
<i>Urinary Bladder Wall</i>	9.1	1.3	2.7	2.6	3.1	2.6	2.6

Table 4

Ratio of organ masses for the 15-year ORNL stylized and UF hybrid 15-year female.

Organ	Mass (g)		Ratio
	ORNL	ICRP 89	
Active marrow	1050	1000	1.05
Brain	1410	1300	1.08
Breast	361	250	1.44
Heart (total)	588	540	1.09
Kidneys	248	240	1.03
Liver	1400	1300	1.08
Lung	651	750	0.87
Ovaries	10.5	6.0	1.75
Skeleton (total)	7650	7180	1.07
Skin	2150	1700	1.26
Spleen	123	130	0.95
Stomach wall	118	120	0.98
Thyroid	12.4	12	1.03
UB wall	35.9	35	1.03

Table 5

Relative error when patient size is neglected in interventional fluoroscopy dose coefficients. All values were calculated as the percent difference between the 10th and the 50th percentile DCCs and the 90th and 50th percentile DCCs, respectively.

	60 kVp			90 kVp			120 kVp		
	UFHADM mass percentile			UFHADM mass percentile			UFHADM mass percentile		
	10%	90%		10%	90%		10%	90%	
AP									
Heart	-14.8%	112.9%		-13.0%	81.5%		-12.1%	70.2%	
Liver	-24.0%	59.7%		-20.9%	39.5%		-19.5%	32.8%	
Stomach	-20.6%	68.4%		-16.4%	46.9%		-14.7%	39.7%	
Lung	-39.7%	95.5%		-35.2%	65.6%		-33.3%	55.5%	
Esophagus	-31.1%	102.7%		-25.1%	76.8%		-23.1%	66.8%	
Effective dose	-43.0%	43.2%		-37.4%	36.5%		-35.0%	33.1%	
PA									
Heart	-34.1%	4.8%		-29.3%	3.5%		-27.2%	2.9%	
Liver	-48.1%	2.7%		-39.5%	1.0%		-36.0%	0.1%	
Stomach	-31.5%	5.8%		-26.2%	3.1%		-24.0%	2.3%	
Lung	-34.1%	3.4%		-31.4%	1.8%		-30.0%	1.2%	
Esophagus	-33.4%	3.9%		-25.7%	3.1%		-22.7%	2.7%	
Effective dose	-34.5%	6.8%		-30.7%	5.4%		-29.0%	4.9%	
LAO									
Heart	-30.8%	4.8%		-27.4%	3.2%		-25.8%	2.3%	
Liver	-22.9%	8.3%		-19.3%	5.4%		-17.7%	4.3%	
Stomach	-45.5%	4.5%		-39.3%	1.9%		-36.6%	0.5%	
Lung	-19.8%	5.4%		-18.4%	3.8%		-17.7%	3.0%	
Esophagus	-26.1%	4.7%		-21.9%	3.6%		-20.0%	2.9%	
Effective dose	-23.2%	6.6%		-22.0%	5.0%		-21.4%	4.2%	
RAO									
Heart	-23.8%	6.5%		-20.6%	4.5%		-19.1%	3.7%	
Liver	-39.3%	6.0%		-35.6%	2.5%		-34.2%	1.1%	
Stomach	-18.4%	8.6%		-14.8%	5.4%		-13.3%	4.2%	

	60 kVp			90 kVp			120 kVp		
	UFHADM mass percentile			UFHADM mass percentile			UFHADM mass percentile		
	10%	90%		10%	90%		10%	90%	
Lung	-17.3%	5.5%		-16.5%	3.6%		-16.1%	2.8%	
Esophagus	-30.6%	5.0%		-27.4%	2.8%		-26.2%	1.9%	
Effective dose	-21.5%	7.9%		-20.6%	6.0%		-19.8%	5.2%	