Herbert Wertheim College of Engineering
UNIVERSITY *of* FLORIDA

Pediatric Phantoms for Dosimetry Calculations

Joint FMU-ICRP Workshop on Radiological Protection in Medicine
Tuesday, October 3, 2017

Wesley Bolch, University of Florida

CT Dosimetry – Daniel Long, Elliott Stepusin, Edmond Olguin

Fluoroscopy Dosimetry – David Borrego, Emily Marshall, Trun Trang

Nuclear Medicine Dosimetry – Michael Wayson, Bryan Schwarz, Edmond Olguin

POWERING THE NEW ENGINEER TO TRANSFORM THE FUTURE

Presentation Objectives

1. ***Review the different pediatric phantom format types and morphometric categories available***
2. ***Review past and present concerns of medical imaging of children and cancer risks***
3. ***Emphasize difference between cancer risk projection and cancer risk assessment***
4. ***Specific aims of the R01 CA185687 RIC Project (Risks of Imaging and Cancer)***
5. ***Review of UF tasks in dose reconstruction within the RIC project***

   A. *Organ Doses from Computed Tomography Exams*
   B. *Organ Doses from Diagnostic Fluoroscopy*
   C. *Organ Doses from Diagnostic Nuclear Medicine*

Computational Anatomic Phantoms

Essential tool for organ dose assessment

- **Definition** - *Computerized representation of human anatomy for use in radiation transport simulation of the medical imaging or radiation therapy procedure*

- **Need for phantoms vary with the medical application**
  - *Nuclear Medicine*
    - *3D patient images generally not available, especially for children*
  - *Diagnostic radiology and interventional fluoroscopy*
    - *no 3D image*
  - *Computed tomography*
    - *3D patient images available, problem – organ segmentation*
    - *No anatomic information at edges of scan coverage*
  - *Radiotherapy*
    - *Needed for characterizing out-of-field organ doses*
    - *Examples – IMRT scatter, proton therapy neutron dose*

Computational Anatomic Phantoms

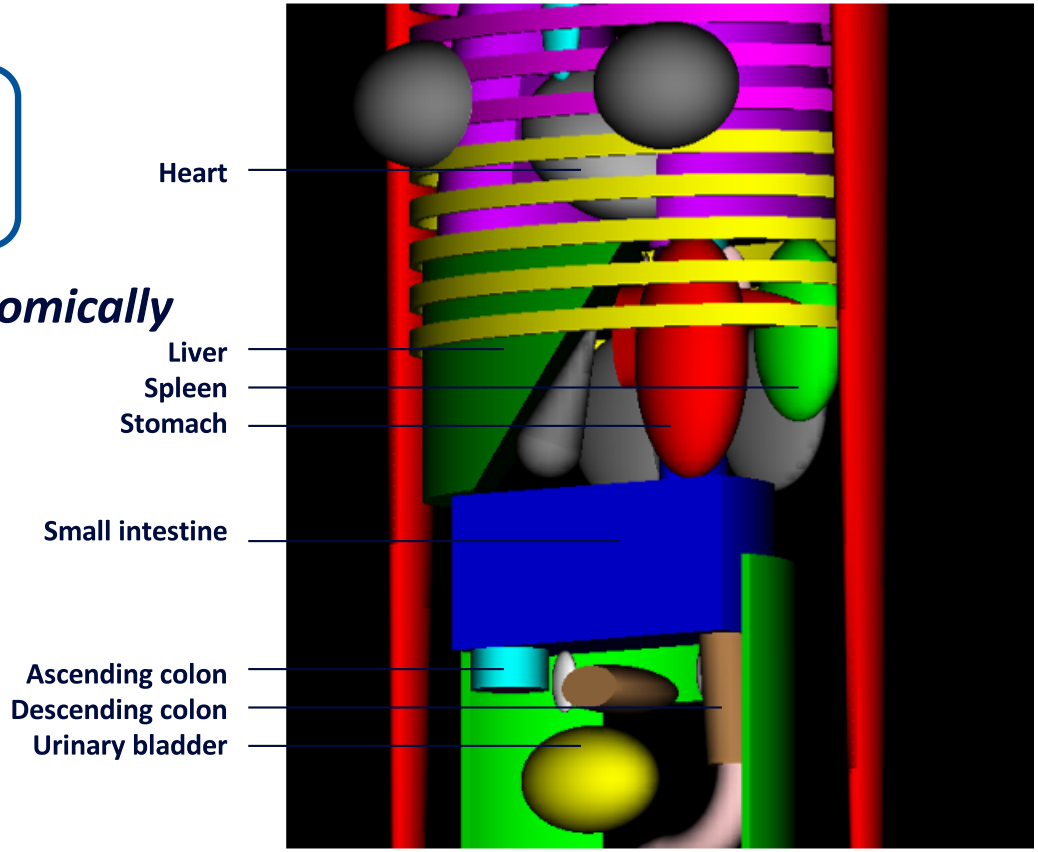
Phantom Types and Morphometric Categories

- *Phantom Format Types*
  - ⇨ *Stylized (or mathematical) phantoms*
  - ⇨ *Voxel (or tomographic) phantoms*
  - ⇨ *Hybrid (or NURBS/PM) phantoms*

Format Types - Stylized Phantoms

1960s Stylized Phantom

Flexible but anatomically unrealistic

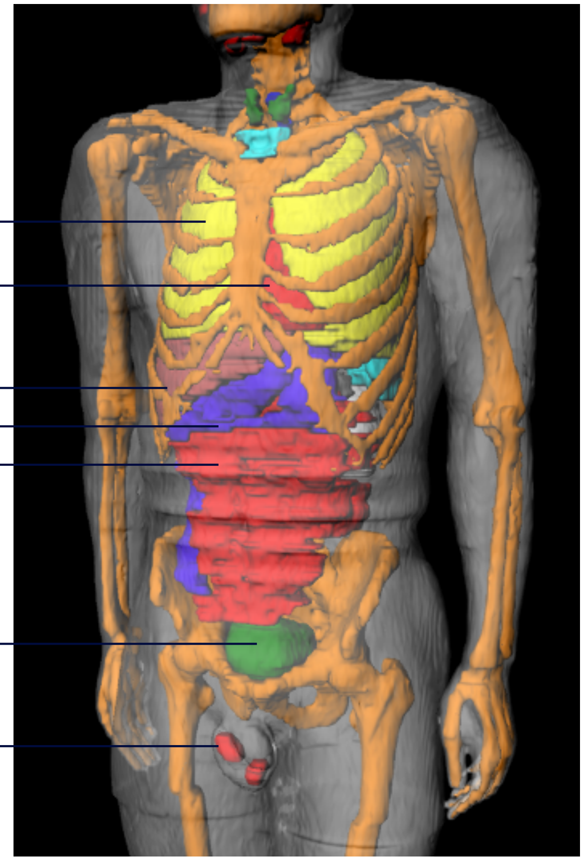


Anatomy of ORNL stylized adult phantom

Format Types - Voxel Phantoms

1980s Voxel Phantom

Anatomically Realistic but not very flexible

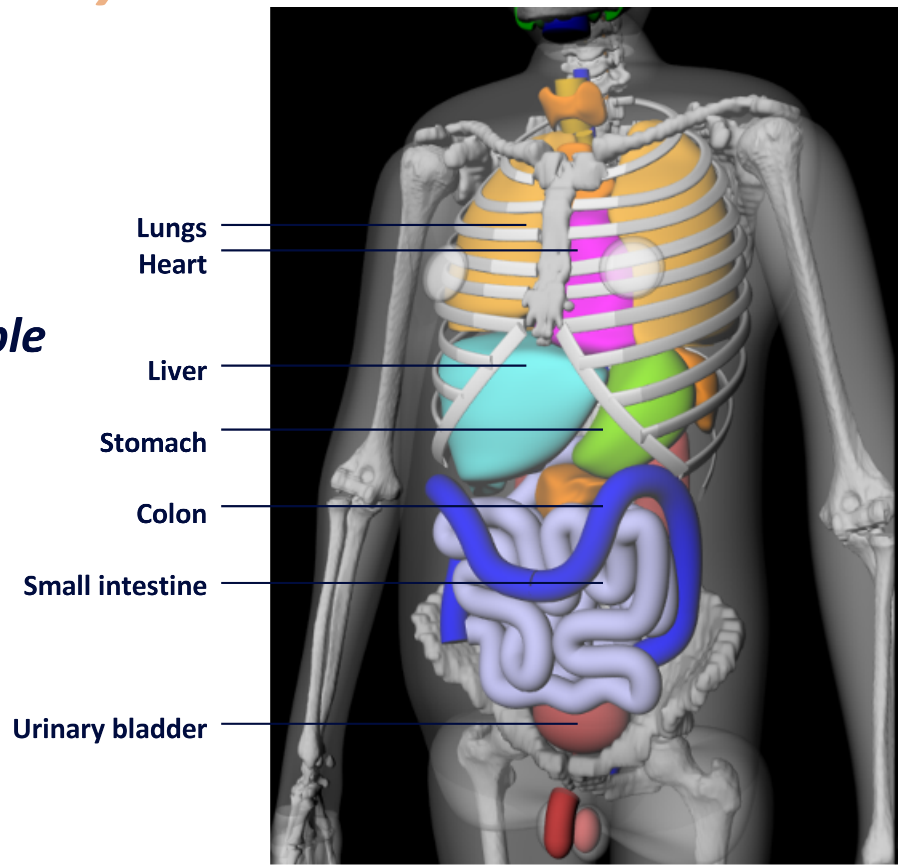


Anatomy of Korean male voxel phantom

Format Types – Hybrid Phantoms

2000s Hybrid Phantom

Realistic and flexible



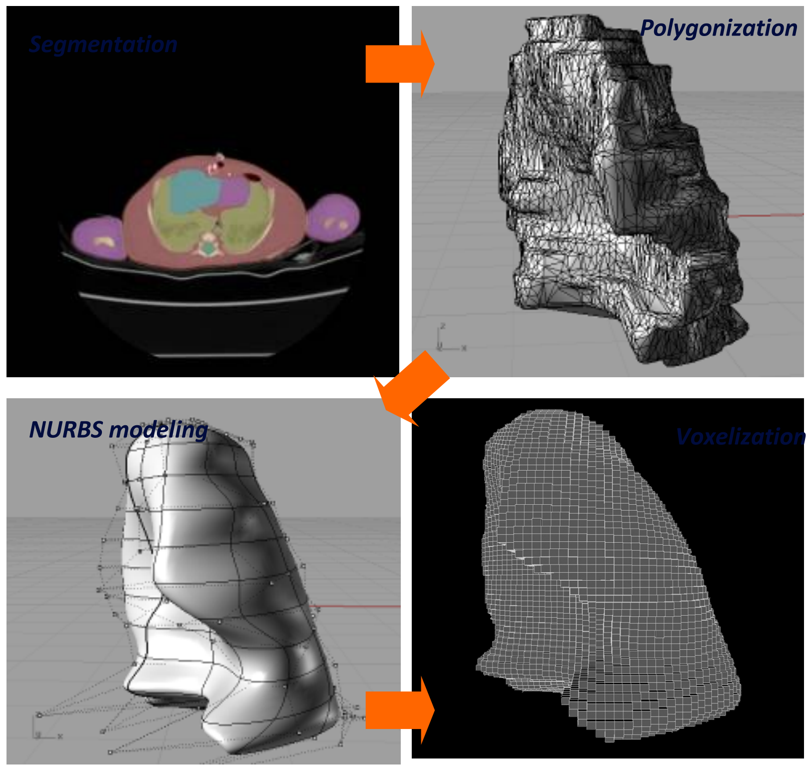
Anatomy of UF hybrid adult male phantom

Hybrid Phantom Construction

Example of the process used at the University of Florida

Segment patient CT images using 3D-DOCTOR™

Convert into polygon mesh using 3D-DOCTOR™



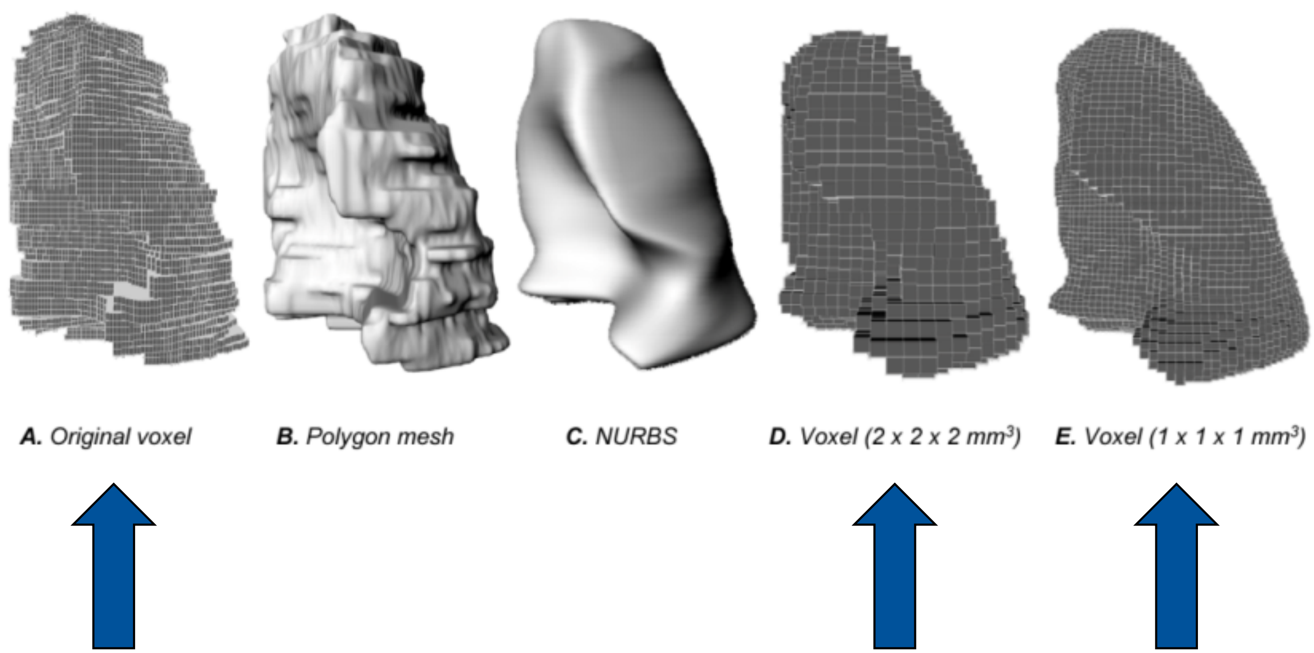
Make NURBS model from polygon mesh using Rhinoceros™

Convert NURBS model into voxel model using MATLAB code Voxelizer

Voxelizer Algorithm - See Phys Med Biol 52 (12) 3309-3333 (2007)

Hybrid Phantom Construction

Advantages of Hybrid over Voxel Phantoms – 3D shape of the body and organs



Lung of original UF voxel newborn phantom

Lung models of voxelized UF newborn hybrid phantom

Computational Anatomic Phantoms

Phantom Types and Categories

- **Phantom Format Types**
  - Stylized (or mathematical) phantoms
  - Voxel (or tomographic) phantoms
  - Hybrid (or NURBS/PM) phantoms

- **Phantom Morphometric Categories**
  - Reference (50^{th} percentile individual, patient matching by age only)
  - Patient-dependent (patient matched by nearest height / weight)
  - Patient-sculpted (patient matched to height, weight, and body contour)
  - Patient-specific (phantom uniquely matching patient morphometry)

Morphometric Categories – Reference Phantoms

***Reference Individual* - An idealised male or female with characteristics defined by the ICRP for the purpose of radiological protection, and with the anatomical and physiological characteristics defined in ICRP Publication 89 (ICRP 2002).**

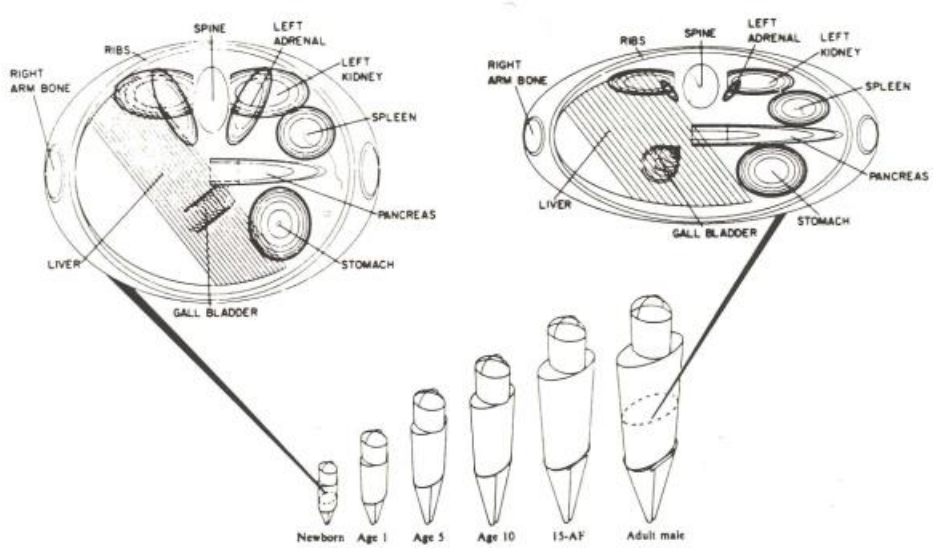
Table 2.9. Reference values for height, mass, and surface area of the total body

	Height (cm)		Mass (kg)	
Age	Male	Female	Male	Female
Newborn	51	51	3.5	3.5
1 year	76	76	10	10
5 years	109	109	19	19
10 years	138	138	32	32
15 years	167	161	56	53
Adult	176	163	73	60

***Note –** While organ size / mass <u>are specified</u> in an ICRP reference phantom, organ shape, depth, position within the body <u>are not defined</u> by reference values*

Reference Phantoms Used by the ICRP

Until very recently, all dose coefficients published by the ICRP were based on computational data generated using the ORNL stylized phantom series.



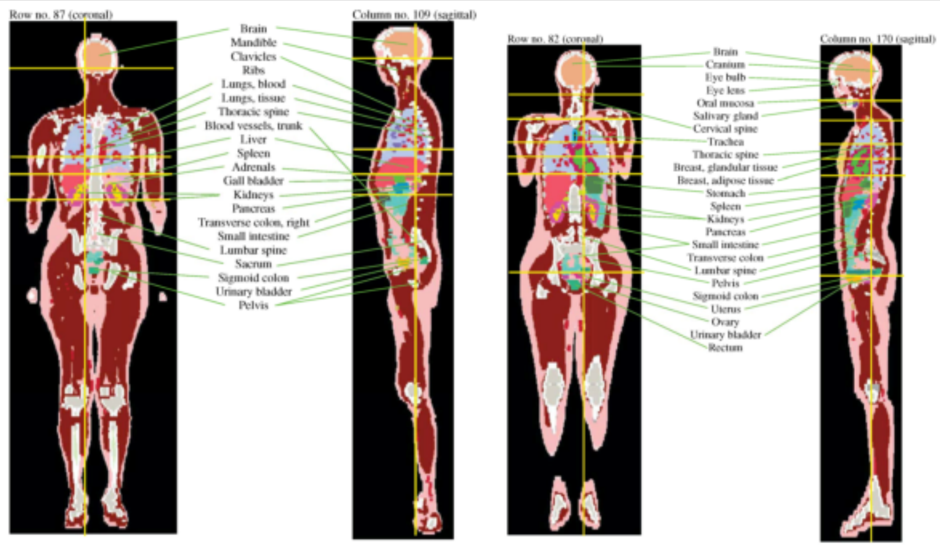
ORNL TM-8381
Cristy & Eckerman

Recent exceptions include the following ICRP/ICRU Reports …

- ***ICRP Publication 116 – External Dose Coefficients (2010)***
- ***ICRU Report 84 – Cosmic Radiation Exposure to Aircrew (2010)***
- ***ICRP Publication 123 – Assessment of Radiation Exposure of Astronauts in Space (2013)***

Reference Phantoms Adopted by the ICRP

ICRP Publication 110 – Adult Reference Computational Phantoms



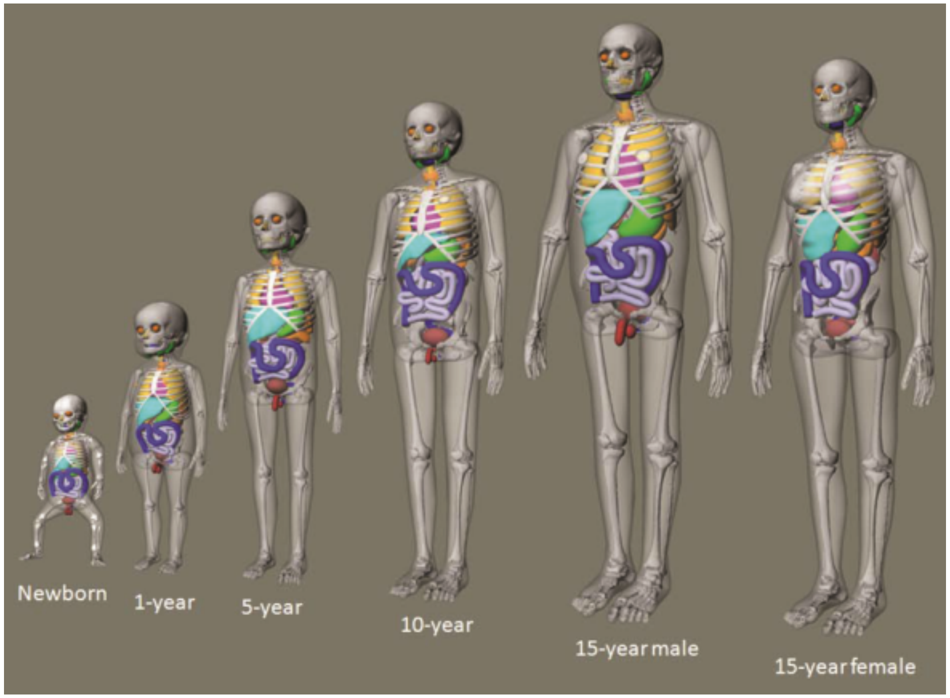
ICRP Reference Adult Male *ICRP Reference Adult Female*

Publications from ICRP using the Publication 110 Phantoms

- ***Publication 133 - Reference specific absorbed fractions (SAF) for internal dosimetry***
- ***Publication 130 Series - Dose coefficients for radionuclide internal dosimetry following inhalation / ingestion***

Reference Phantoms Adopted by the ICRP

ICRPs upcoming reference phantoms for pediatric individuals are based upon the UF/NCI series of hybrid phantoms



IOP PUBLISHING
Phys. Med. Biol. 55 (2010) 339–363

Morphometric Categories – Patient Dependent Phantoms

Definition -
Expanded library of reference phantoms covering a range of height / weight percentiles

ICRP - based UFHADM

NHANES Database
7320 individuals

Age
Weight
Standing height
Sitting height
BMI
Biacromial breadth
Biiliac breadth
Arm circumference
Waist circumference
Buttocks circumference
Thigh circumference

US based phantom library
10% 25% 50% 75% 90%

Reference weights @ 1 or more fixed anthropometric parameter(s)

NHANES - based UFHADM

2060 Proceedings of the IEEE | Vol. 97, No. 12, December 2009

Morphometric Categories – Patient Dependent Phantoms

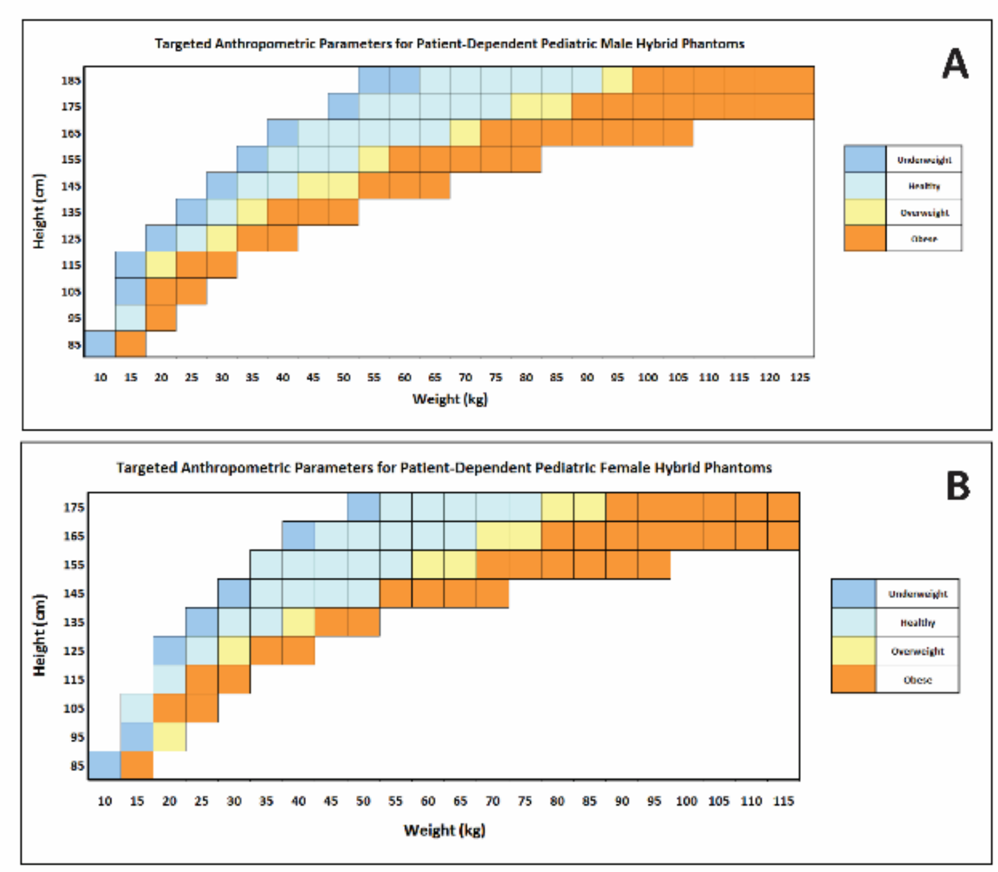
Patient-Dependent Hybrid Phantoms – UF Series

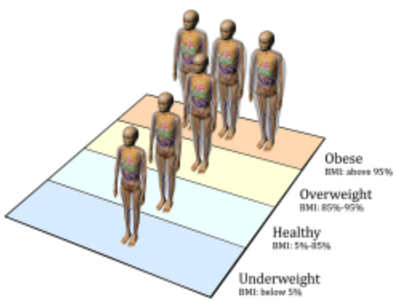
Phantom Height	Pediatric		Phantom Height	Adult	
(cm)	*Males*	*Females*	(cm)	*Males*	*Females*
185	UFHADM ⬆		190	UFHADM ⬆	
175	UFHADM ⬇	UFHADF ⬆	185	UFHADM ⬆	
165	UFH15M ⬇	UFHADF ⬆	180	UFHADM ⬆	
155	UFH15M ⬇	UFH15F ⬇	175	UFHADM ⬇	UFHADF ⬆
145	UFH10M ⬆	UFH10F ⬆	170	UFH15M ⬆	UFHADF ⬆
135	UFH10M ⬇	UFH10F ⬇	165	UFH15M ⬇	UFHADF ⬆
125	UFH10M ⬇	UFH10F ⬇	160	UFH15M ⬇	UFH15F ⬇
115	UFH05M ⬆	UFH05F ⬆	155		UFH15F ⬇
105	UFH05M ⬇	UFH05F ⬇	150		UFH15F ⬇
95	UFH05M ⬇	UFH05F ⬇			
85	UFH01M ⬆	UFH01F ⬆			

The naming convention for the UF phantom series begins with the identifier UFH (University of Florida Hybrid), followed by the reference phantom age in years (00, 01, 05, 10, 15 and AD for adult) and then the phantom gender (M for male and F for female).

Geyer et al. – Phys Med Biol (2014)

UF/NCI Phantom Library - Children

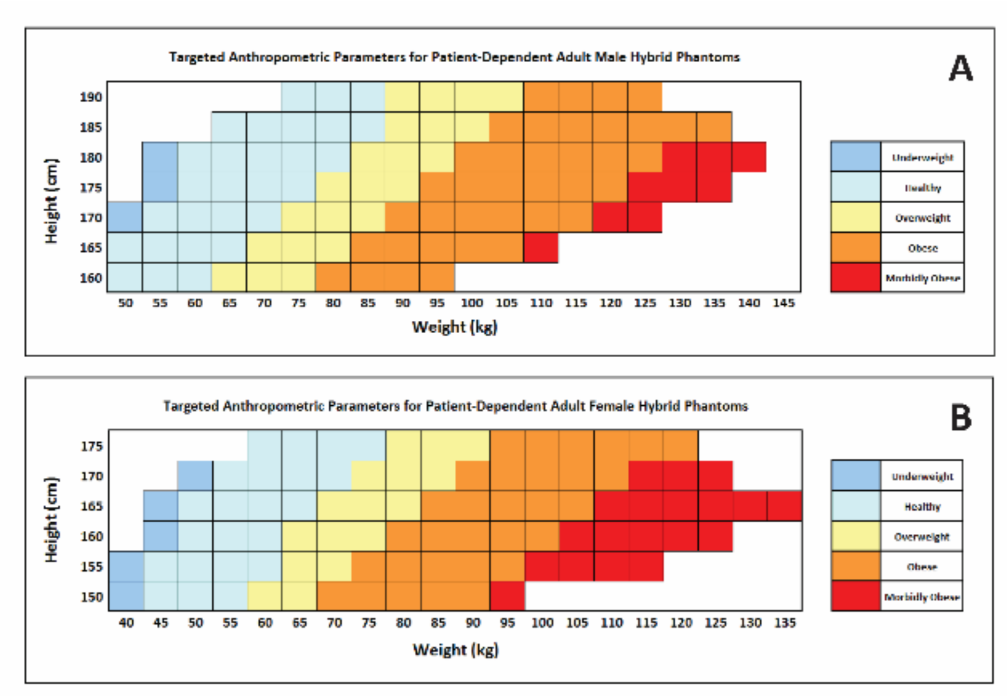


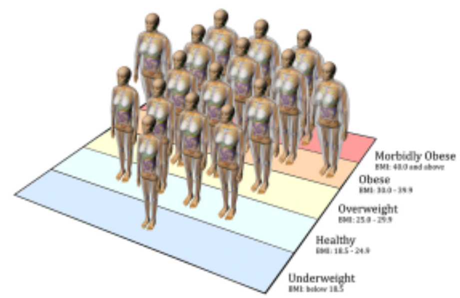


Phantom for each height/weight combination further matching average values of body circumference from CDC survey data

85 pediatric males
73 pediatric females

UF/NCI Phantom Library - Adults





Phantom for each height/weight combination further matching average values of body circumference from CDC survey data

100 adult males
93 adult females

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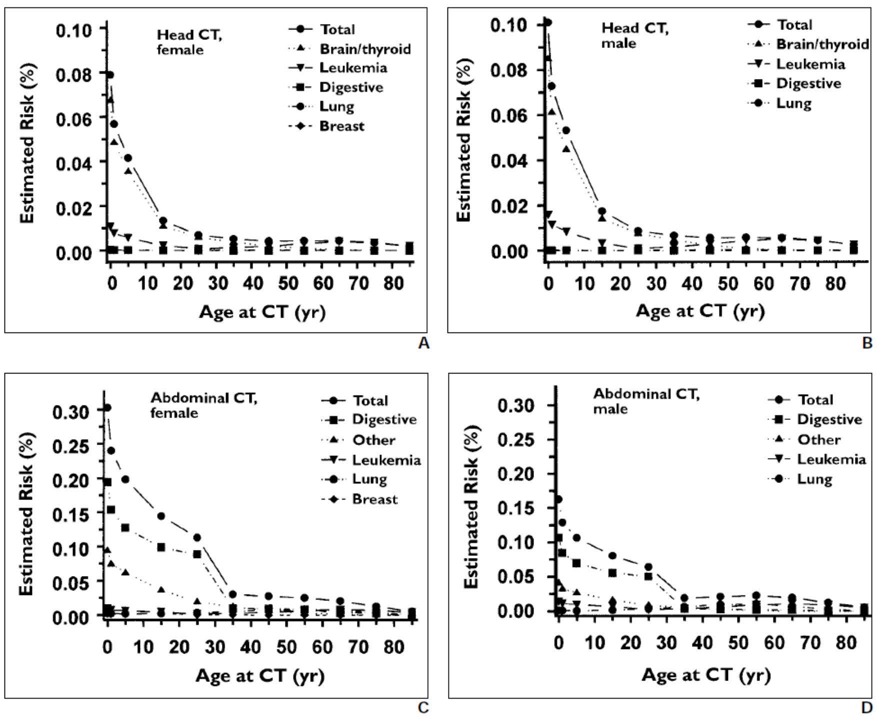
Do you remember what journal articles you were reading in February 2001?

You know, the month that this article appeared, and you received calls from parents!

Estimated Risks of Radiation-Induced Fatal Cancer from Pediatric CT

David J. Brenner[1]
Carl D. Elliston[1]
Eric J. Hall[1]
Walter E. Berdon[2]

AJR 2001;176:289–296



RESULTS. *The larger doses and increased lifetime radiation risks in children produce a sharp increase, relative to adults, in estimated risk from CT. Estimated lifetime cancer mortality risks attributable to the radiation exposure from a CT in a 1-year-old are 0.18% (abdominal) and 0.07% (head)—an order of magnitude higher than for adults—although those figures still represent a small increase in cancer mortality over the natural background rate. In the United States, of approximately 600,000 abdominal and head CT examinations annually performed in children under the age of 15 years, a rough estimate is that 500 of these individuals might ultimately die from cancer attributable to the CT radiation.*

Simplistic methods of organ dose

An Approach for the Estimation of Effective Radiation Dose at CT in Pediatric Patients[1]

Radiology 1997; 203:417–422

Responses to Brenner Article:

- ***Development of professional society alliances – Image Gently, Step Lightly, Go with the Guidelines***
- ***Development of size-specific and standardized imaging protocols***
- ***Development of new technologies***
    - ***Tube current modulation in CT***
    - ***Improved detector techniques***
    - ***Improved image reconstruction algorithms***

Distinction between…

***Risk projection –** organ dose estimates coupled with existing cancer risk models*

***Risk assessment –** direct measure of cancer risk through epidemiology studies*

Radiation exposure from CT scans in childhood and subsequent risk of leukaemia and brain tumours: a retrospective cohort study

Mark S Pearce, Jane A Salotti, Mark P Little, Kieran McHugh, Choonsik Lee, Kwang Pyo Kim, Nicola L Howe, Cecile M Ronckers, Preetha Rajaraman, Sir Alan W Craft, Louise Parker, Amy Berrington de González

www.thelancet.com Vol 380 August 4, 2012

Use of CT scans in children to deliver cumulative doses of about 50 mGy might almost triple the risk of leukaemia and doses of about 60 mGy might triple the risk of brain cancer. Because these cancers are relatively rare, the cumulative absolute risks are small: in the 10 years after the first scan for patients younger than 10 years, one excess case of leukaemia and one excess case of brain tumour per 10 000 head CT scans is estimated to occur. Nevertheless, although clinical benefi ts should outweigh the small absolute risks, radiation doses from CT scans ought to be kept as low as possible and alternative procedures, which do not involve ionising radiation, should be considered if appropriate.

Cancer risk in 680 000 people exposed to computed tomography scans in childhood or adolescence: data linkage study of 11 million Australians

John D Mathews *epidemiologist*[1], Anna V Forsythe *research officer*[1], Zoe Brady *medical physicist*[1,2], Martin W Butler *data analyst*[3], Stacy K Goergen *radiologist*[4], Graham B Byrnes *statistician*[5], Graham G Giles *epidemiologist*[6], Anthony B Wallace *medical physicist*[7], Philip R Anderson *epidemiologist*[8,9], Tenniel A Guiver *data analyst*[8], Paul McGale *statistician*[10], Timothy M Cain *radiologist*[11], James G Dowty *research fellow*[1], Adrian C Bickerstaffe *computer scientist*[1], Sarah C Darby *statistician*[10]

BMJ 2013;346:f2360

The increased incidence of cancer after CT scan exposure in this cohort was mostly due to irradiation. Because the cancer excess was still continuing at the end of follow-up, the eventual lifetime risk from CT scans cannot yet be determined. Radiation doses from contemporary CT scans are likely to be lower than those in 1985-2005, but some increase in cancer risk is still likely from current scans. Future CT scans should be limited to situations where there is a definite clinical indication, with every scan optimised to provide a diagnostic CT image at the lowest possible radiation dose.

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Risk of Pediatric and Adolescent Cancer Associated with Medical Imaging
R01 CA185687

The use of medical imaging that delivers ionizing radiation is high in the United States. The potential harmful effects of this imaging must be understood so they can be weighed against its diagnostic benefits, and this is especially critical for our vulnerable populations of children and pregnant women. The proposed study will comprehensively evaluate patterns of medical imaging, cumulative exposure to radiation, and subsequent risk of pediatric cancers in four integrated health care delivery systems comprising over 7 million enrolled patients enrolled from 1996-2017.

Project Management
University of California, San Francisco (UCSF)

Biostatistics and Epidemiology
University of California, Davis (UCD)

Organ Dose Assessment
University of Florida (UF)

Patient Enrollment Sites
Kaiser Permanente Northern California (KPNC)
Kaiser Permanente North West (KPNW)
Kaiser Permanente Hawaii (KPHI)
Kaiser Permanente Washington (KPWA)
Marshfield Clinic Research Institute (MCRI)
Pediatric Oncology Group of Ontario (POGO)
Geisinger Health Systems (GE)
Harvard Pilgrim Health Plan (HP)

Risk of Pediatric and Adolescent Cancer Associated with Medical Imaging
R01 CA185687

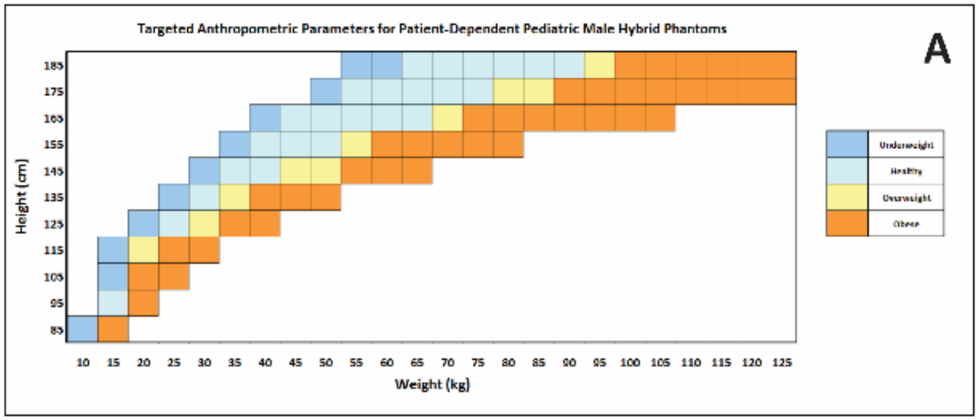
Aim 1: Imaging Utilization Patterns

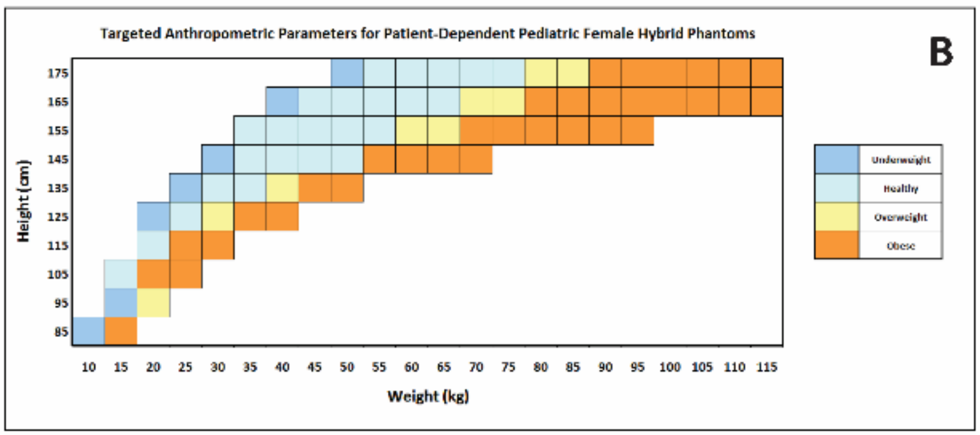
Aim 1A – Patterns of imaging utilization in pregnant women
Aim 1B – Patterns of imaging utilization in children
Aim 1C – Patterns of imaging utilization in adults and children

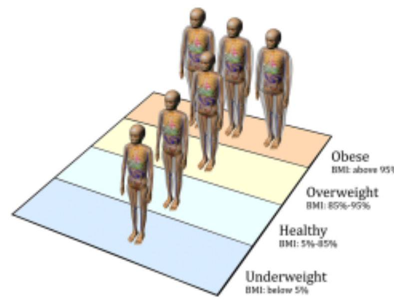
Aim 2: Organ Dose and Association with Cancer Outcomes

Aim 2A – Imaging in pregnant women and childhood cancer risk
Aim 2B – Imaging in children and childhood leukemia risk
Aim 2C – Imaging in pregnant women and children and childhood cancer risk

UF/NCI Phantom Library - Children







Phantom for each height/weight combination further matching average values of body circumference from CDC survey data

85 pediatric males
73 pediatric females

The UF family of reference hybrid phantoms for computational radiation dosimetry

Phys. Med. Biol. 55 (2010) 339–363

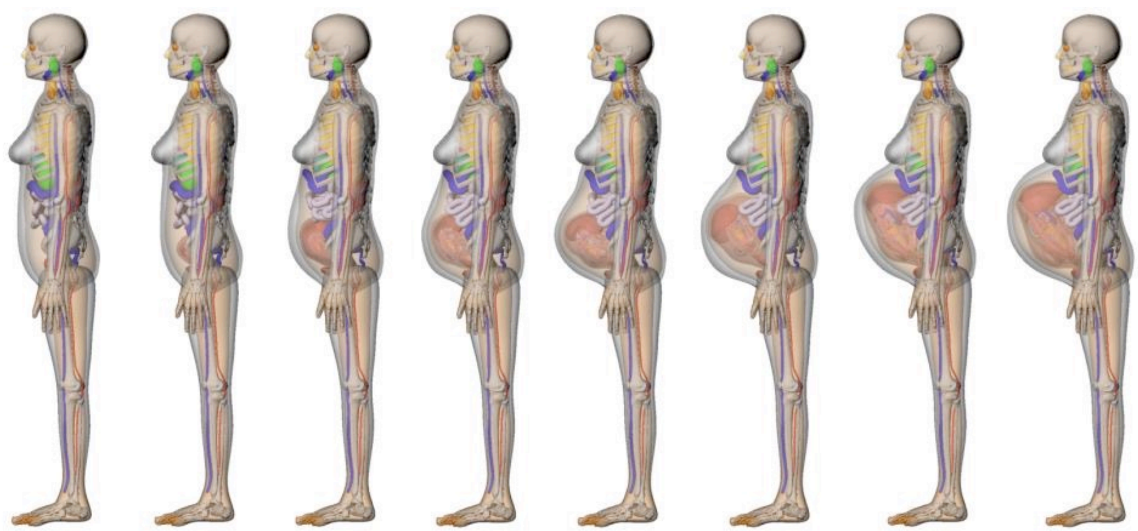
Choonsik Lee[1], Daniel Lodwick[2], Jorge Hurtado[2], Deanna Pafundi[2], Jonathan L Williams[3] and Wesley E Bolch[4,5]

The UF/NCI family of hybrid computational phantoms representing the current US population of male and female children, adolescents, and adults—application to CT dosimetry

Phys. Med. Biol. 59 (2014) 5225–5242

Amy M Geyer[1], Shannon O'Reilly[1], Choonsik Lee[2], Daniel J Long[1] and Wesley E Bolch[1]

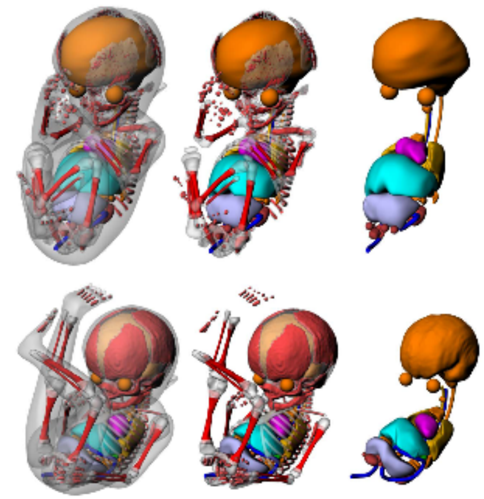
UF/NCI Phantom Library – Pregnant Females



8 wk *10 wk* *15 wk* *20 wk* *25 wk* *30 wk* *35 wk* *38 wk*

A

B



The UF Family of hybrid phantoms of the pregnant female for computational radiation dosimetry

Phys. Med. Biol. **59** (2014) 4325–4343

Matthew R Maynard[1], Nelia S Long[1], Nash S Moawad[2], Roger Y Shifrin[3], Amy M Geyer[1], Grant Fong[4] and Wesley E Bolch[1,5]

The UF family of hybrid phantoms of the developing human fetus for computational radiation dosimetry

Phys. Med. Biol. **56** (2011) 4839–4879

Matthew R Maynard[1], John W Geyer[1], John P Aris[2], Roger Y Shifrin[3] and Wesley Bolch[1,4,5]

1. Organ Dose Reconstruction in Computed Tomography

Data Collection – 2006 to 2017 ***Radimetrics***
Data Collection – 1996 to 2006 ***Data Abstraction***

Patient Data
Study ID
Age
Gender
Height
Weight
Effective diameter at center slice (cm)

Pregnant Females
Gestational age

CT Procedure Details
Year of scan
Scan # in current year
Series # in current scan
Body part imaged
Medical facility
CT scanner manufacturer
CT scanner model

CT Technique Factors
Scan length (cm)
Beam collimation (mm)
Beam energy (kVp)
Pitch
CTDIvol (mGy)
DLP (mGy-cm)
Fixed or modulated mA
Exam Averaged mAs

CT Source Term Validation with CTDI phantom

Energy (kVp)	Filter	Collimation (mm)	Measured* $CTDI_{100}$ Air Kerma (mGy) for 100 mAs/rotation			Simulated $CTDI_{100}$ Air Kerma (mGy) for 100 mAs/roation			Percent Difference†		
			Center	Periphery	$CTDI_W$‡	Center	Periphery	$CTDI_W$‡	Center	Periphery	$CTDI_W$‡
80	M	16	1.53	3.50	2.84	1.61	3.64	2.96	5.32	3.76	4.04
		32	1.35	3.09	2.51	1.41	3.20	2.61	4.73	3.58	3.79
	L	16	1.57	3.97	3.17	1.65	4.03	3.24	4.76	1.54	2.07
		32	1.39	3.50	2.80	1.45	3.56	2.86	4.14	1.66	2.07
100	M	16	3.40	6.85	5.70	3.46	6.97	5.80	1.75	1.78	1.77
		32	2.99	6.02	5.01	3.03	6.14	5.10	1.21	1.94	1.79
	L	16	3.54	7.83	6.40	3.55	7.79	6.38	0.45	-0.40	-0.24
		32	3.11	6.88	5.62	3.11	6.87	5.62	0.02	-0.09	-0.07
120	M	16	6.03	11.23	9.50	6.15	11.36	9.62	2.06	1.12	1.32
		32	5.24	9.79	8.28	5.37	9.94	8.42	2.41	1.53	1.71
	L	16	6.23	12.88	10.66	6.33	12.76	10.61	1.55	-0.91	-0.43
		32	5.44	11.25	9.31	5.51	11.14	9.27	1.38	-0.93	-0.48
135	M	16	8.49	15.28	13.02	8.63	15.26	13.05	1.69	-0.13	0.26
		32	7.32	13.20	11.24	7.52	13.32	11.39	2.74	0.93	1.32
	L	16	8.81	17.58	14.65	8.96	17.33	14.54	1.79	-1.42	-0.77
		32	7.57	15.17	12.64	7.74	14.99	12.57	2.14	-1.22	-0.55

*Average of three consecutive measurements in 100 mm ion chamber

†Calculated as 100*(Simulated Air Kerma - Measured Air Kerma)/Measured Air Kerma

‡Caclualted as $[(1/3)*CTDI_{100,center} + (2/3)*CTDI_{100,peripheral}]$

A method to generate equivalent energy spectra and filtration models based on measurement for multidetector CT Monte Carlo dosimetry simulations

Med. Phys. 36 (6), June 2009

Adam C. Turner and Di Zhang

Department of Biomedical Physics and Department of Radiology, David Geffen School of Medicine, University of California, Los Angeles, Los Angeles, California 90024

CT computational methodology – Fixed Tube Current

$$NF_{E,C}\left(\frac{photons}{mAs}\right) = \frac{Air\ Kerma_{measured}\ \left(\frac{mGy}{mAs}\right)}{Air\ Kerma_{simulated}\ \left(\frac{mGy}{photon}\right)}$$

$$Organ\ Dose\ \left(\frac{mGy}{mAs}\right) = \left[\sum_{i=z_{exam\ \ start}}^{z_{exam\ \ end}} Organ\ Dose_i\ \left(\frac{mGy}{photon}\right)\right] \times NF_{E,C}\left(\frac{photons}{mAs}\right)$$

Physical validation of a Monte Carlo-based, phantom-derived approach to computed tomography organ dosimetry under tube current modulation

Elliott J. Stepusin
J Crayton Pruitt Family Department of Biomedical Engineering, University of Florida, Gainesville, FL 32611-6131, USA

Daniel J. Long
???, Memorial Sloan Kettering Cancer Center, 1275 York Avenue, New York, NY 10065, USA

Kayla Ficarrotta,* David Hintenlang,† and Wesley E. Bolch[a)]
J Crayton Pruitt Family Department of Biomedical Engineering, University of Florida, Gainesville, FL 32611-6131, USA

Med. Phys. 0 (0), xxxx

CT computational methodology – Modulated Tube Current

$$Effective\ mAs = \frac{(Exam\ Average\ mA)\ \times\ Rotation\ Time\ (s)}{Exam\ Pitch}$$

$$WF(z) = \frac{AV_{average}\ (z)}{\sum_{i=Z_{exam\ \ start}}^{Z_{exam\ \ end}} AV_{average\ ,i}}$$

$$Organ\ Dose\ (mGy) = \left[\sum_{i=Z_{exam\ \ start}}^{Z_{exam\ \ end}} Organ\ Dose_i \left(\frac{mGy}{mAs}\right) \times WF_i\right] \times Effective\ mAs$$

Chest-Abdomen-Pelvis Scans of Two Custom-Built Physics Phantoms – UF15F, UFADM

Parameter	UF15F	UFADM
Tube Current Modulation	Yes	Yes
Collimation	0.5 mm x 64	0.5 mm x 64
Energy (kVp)	120, 135	100, 120, 135
Exam Start	Thoracic Inlet	Thoracic Inlet
Exam End	Lesser Trochanter	Lesser Trochanter
Filter	Large	Large
Gantry Tilt (°)	0	0
Average mA	140*, 120*	265*, 140*, 110*
mA (min, max)	(100, 500)	(100, 500)
Target Noise Index (SD)	12.5	12.5
Pitch	0.828	0.828
Rotation Time (s)	0.5	0.5

* Exam mA is Variable due to Tube Current Modulation, Reported Value is Average mA from CT Image Set

Placement of Landauer NanoDot^{TM} OSL dosimeters

Average point doses used to provide physical value of "average organ dose"

Organ	Position*	Dose (mGy)	Organ Dose (mGy)
Thyroid	Center-Middle	12.3	12.3
Lung	Right-Superior	9.9	11.1
	Left-Superior	9.8	
	Right-Middle	10.4	
	Left-Middle	10.5	
	Right-Inferior	13.0	
	Left-Inferior	12.8	
Thymus	Center-Middle	11.1	11.1
Stomach	Center-Anterior	13.1	11.8
	Center-Posterior	11.4	
	Center-Inferior	10.8	
Liver	Right-Superior	12.4	12.0
	Left-Superior	11.5	
	Center-Middle	12.0	
	Center-Inferior	12.0	
Gallbladder	Center-Middle	10.6	10.6
Esophagus	Center-Superior	9.5	10.0
	Center-Middle-Superior	10.3	
	Center-Middle	10.1	
	Center-Middle	9.8	
	Center-Middle-Inferior	10.1	
	Center-Inferior	10.0	
Spleen	Center-Middle	11.6	11.6
Kidney	Right-Superior	10.3	10.3
	Left-Superior	10.3	
	Right-Inferior	10.6	
	Left-Inferior	9.9	

Organ	Position*	Dose (mGy)	Organ Dose (mGy)
Pancreas	Center-Middle	10.1	10.1
Colon	Right-Superior	13.5	11.6
	Left-Superior	12.0	
	Right-Middle-Superior	15.2	
	Left-Middle-Superior	11.2	
	Center-Middle-Superior	14.0	
	Right-Middle	14.4	
	Left-Middle	11.7	
	Right-Middle-Inferior	13.9	
	Left-Middle-Inferior	10.4	
	Left-Inferior	9.7	
	Left-Inferior	9.9	
	Left-Inferior	7.2	
	Center-Inferior	7.9	
Small Intestine	Right-Superior	9.6	11.1
	Left-Superior	12.1	
	Right-Middle-Superior	10.7	
	Left-Middle-Superior	11.7	
	Right-Middle	10.1	
	Left-Middle	13.0	
	Right-Middle-Inferior	11.8	
	Left-Middle-Inferior	10.0	
	Right-Inferior	11.1	
	Left-Inferior	10.9	
Bladder	Center-Middle	8.1	8.1
Prostate	Center-Middle	7.3	7.3
Gonads	Right-Middle	11.3	10.8
	Left-Middle	10.2	

*Center refers to lateral direction and Middle referes to inferior-superior direction

%Difference in Organ Dose – UF15F

Organ	120 kVp Organ Doses (mGy)						
	Measured	Uniform	% Diff*	Weighted	% Diff*	Image	% Diff*
Thyroid	13.9	24.2	74.5	18.1	30.1	21.3	53.3
Lung	12.2	12.1	-1.2	13.6	11.4	12.4	1.5
Thymus	11.7	13.6	16.4	12.6	7.9	12.5	6.6
Stomach	14.6	14.4	-1.5	13.8	-5.6	13.7	-6.5
Liver	14.9	13.6	-8.4	13.7	-8.0	13.6	-8.6
Gallbladder	14.0	12.8	-8.3	12.3	-11.8	12.1	-13.4
Esophagus	12.1	12.5	3.2	12.6	3.8	12.4	1.8
Spleen	14.5	13.6	-6.2	13.2	-9.3	13.1	-10.2
Kidneys	12.7	13.9	9.4	12.6	-1.0	12.6	-1.3
Pancreas	12.6	13.6	7.4	12.5	-1.3	12.3	-2.7
Colon	13.6	14.6	7.5	13.7	0.9	13.8	1.6
Small Intestine	14.6	14.7	0.2	13.7	-6.2	13.8	-5.8
Bladder	11.5	11.5	-0.1	12.5	9.0	12.7	10.5
Gonads	11.3	10.1	-10.0	11.3	0.2	11.4	0.9
RMS Difference (%)			21.2		10.5		15.7

* Percent difference is calculated as follows: [(calculated dose - measured dose)/measured dose] x 100%

%Difference in Organ Dose – UFADM

Organ	120 kVp Organ Doses (mGy)						
	Measured	Uniform	% Diff*	Weighted	% Diff*	Image	% Diff*
Thyroid	12.3	18.8	52.7	13.1	6.2	11.9	-3.4
Lung	11.1	9.9	-10.9	11.6	5.1	11.7	5.5
Thymus	11.1	11.3	1.9	12.6	14.0	12.1	9.4
Stomach	11.8	11.6	-1.8	12.2	3.8	11.0	-6.5
Liver	12.0	10.8	-9.5	11.6	-2.9	10.5	-12.0
Gallbladder	10.6	10.4	-1.3	10.8	1.9	9.7	-8.2
Esophagus	10.0	9.5	-5.2	10.4	4.5	10.0	0.8
Spleen	11.6	11.2	-3.7	11.8	1.8	10.5	-9.0
Kidneys	10.3	11.1	8.6	11.3	9.9	10.0	-2.6
Pancreas	10.1	10.9	7.6	11.1	9.6	9.7	-4.0
Colon	11.6	12.1	4.2	12.1	4.2	11.4	-1.7
Small Intestine	11.1	11.8	6.3	12.0	7.7	12.0	7.7
Bladder	8.1	10.1	25.3	9.8	20.8	11.8	46.5
Prostate	7.3	9.6	30.5	8.3	13.2	9.0	22.4
Gonads	10.8	15.0	39.0	12.0	11.2	11.7	8.2
RMS Difference (%)			20.5		9.3		14.8

* Percent difference is calculated as follows: [(calculated dose - measured dose)/measured dose] x 100%

Summary of overall percent differences for all phantoms and energies using each of the three dose weighting schemes

	100 kVp			120 kVp			135 kVp		
	Uniform	Weighted	Image	Uniform	Weighted	Image	Uniform	Weighted	Image
% Min	-24.3	-37.1	-40.0	-10.0	-2.9	-12.0	-12.4	-11.5	-17.2
% Max	101.8	37.6	39.2	52.7	20.8	46.5	34.0	24.3	27.4
% |Median|	12.9	10.5	6.0	7.51	6.23	6.53	7.97	6.85	9
% RMS	30.8	17.5	17.9	20.9	9.9	15.2	14.4	10.5	13.2

	UF15F			UFADM			All		
	Uniform	Weighted	Image	Uniform	Weighted	Image	Uniform	Weighted	Image
% Min	-12.4	-16.8	-17.2	-24.3	-37.1	-40.0	-24.3	-37.1	-40.0
% Max	74.5	30.1	53.3	101.8	37.6	46.5	101.8	37.6	53.3
% |Median|	7.4	6.5	5.7	9.03	7.66	8.23	7.98	7.27	6.61
% RMS	18.4	10.5	13.8	22.8	13.0	15.8	21.2	12.1	15.1

Six Methods of Patient-to-Phantom Matching for CT Organ Dosimetry

1. ***Patient Age/Gender Only*** — ***UF/NCI Reference Phantom***
2. ***Height and Weight*** — ***UF/NCI Library Phantom***

3. ***Effective Diameter – Scan Averaged*** — ***UF/NCI Library Phantom***
4. ***Effective Diameter – Center Slice*** — ***UF/NCI Library Phantom***

$$Effective\ Diameter\ (cm) = \sqrt{Diameter_{Lateral}\,(cm) \times Diameter_{AP}\,(cm)}$$

AAPM Task Group 204

5. ***Water Equivalent Diameter – Scan Averaged*** — ***UF/NCI Library Phantom***
6. ***Water Equivalent Diameter – Center Slice*** — ***UF/NCI Library Phantom***

$$Water\ Equivalent\ Diameter\ (cm) = 2\sqrt{\left[\frac{1}{1000}\overline{CT(x,y)_{ROI}} + 1\right]\frac{A_{ROI}\,(cm^2)}{\pi}}$$

$$CT(x,y) = \left(\frac{\mu(x,y) - \mu_{water}}{\mu_{water}}\right) \times 1000 \qquad \tilde{\mu} = \rho \times \sum_{i}^{N_c}\left[\sum_{j}^{N_e}\left(w_i\left(\frac{\mu}{\rho}\right)_{i,j} p_j\right)\right]$$

AAPM Task Group 220

Assessment of different patient-to-phantom matching criteria applied in Monte Carlo–based computed tomography dosimetry

Elliott J. Stepusin
J Crayton Pruitt Family Department of Biomedical Engineering, University of Florida, Gainesville, FL 32611-6131, USA

Daniel J. Long
Memorial Sloan Kettering Cancer Center, 1275 York Avenue, New York, NY 10065, USA

Emily L. Marshall and Wesley E. Bolch
J Crayton Pruitt Family Department of Biomedical Engineering, University of Florida, Gainesville, FL 32611-6131, USA

Med. Phys. 0 (0), xxxx

Validation study for assignment of water-equivalent diameter (WED) to computational hybrid phantoms in the UF/NCI library

	Central Slice			Entire Exam Range Average		
Exam	$WED_{CT\ Image\text{-}Set}$ (cm)	$WED_{Phantom}$ (cm)	%Diff	$WED_{CT\ Image\text{-}Set}$ (cm)	$WED_{Phantom}$ (cm)	%Diff
Chest-Abdomen-Pelvis	24.4	24.6	-0.9	25.3	25.4	-0.7
Chest-Abdomen	28.8	28.4	1.4	24.9	24.8	0.4
Abdomen-Pelvis	23.3	24.0	-2.8	25.7	25.9	-0.8
Chest	29.2	27.3	7.0	25.4	25	1.4
Abdomen	24.1	25.0	-3.8	25.3	25	1
Pelvis	27.3	28.0	-2.5	26	26.7	-2.7

Patient-to-Phantom Matching Study – Use of 52 patient-specific voxel phantoms

Age-Gender	Patient ID	Height (cm)	Weight (kg)	BMI (kg m^{-2})	BMI Classification*	Age-Gender	Patient ID	Height (cm)	Weight (kg)	BMI (kg m^{-2})	Age (yr)	BMI Classification†
	AF1	152.4	66.2	28.5	Overweight		PF1‡	53.3	5	17.5	< 2	No Classification#
	AF2	154.9	47.6	19.8	Healthy Weight		PF2	88.9	11.8	14.9	< 2	No Classification#
	AF3	154.9	69.9	29.1	Overweight		PF3	88.9	13.6	17.2	2	Healthy Weight
	AF4	154.9	98	40.8	Obese		PF4	124.5	21.8	14.1	6	Healthy Weight
	AF5	160	51.3	20	Healthy Weight		PF5	134.6	26.8	14.8	7	Healthy Weight
	AF6	160	51.7	20.2	Healthy Weight	Pediatric Female	PF6	144.8	44.9	21.4	14	Healthy Weight
Adult Female	AF7	160	60.8	23.7	Healthy Weight		PF7	154.9	59.9	24.9	13	Overweight
	AF8	163.8	59	22	Healthy Weight		PF8	160	50.8	19.8	17	Healthy Weight
	AF9	162.6	80.3	30.4	Obese		PF9	160	52.6	20.5	13	Healthy Weight
	AF10	162.6	117.5	44.5	Obese		PF10	160	70.3	27.5	18	Overweight
	AF11	165.1	62.6	23	Healthy Weight		PF11	167.6	56.7	20.2	16	Healthy Weight
	AF12	172.7	82.1	27.5	Overweight		PF12	170.2	69.4	24	15	Overweight
	AF13	175.3	135.6	44.2	Obese		PF13	175.3	68	22.2	16	Healthy Weight
	AM1	157.5	43.5	17.6	Underweight		PM1	104.1	13.2	12.1	3	Underweight
	AM2	165.1	74.4	27.3	Overweight		PM2‖	104.1	15	13.8	4	Underweight
	AM3	167.6	78.5	27.9	Overweight		PM3	114.3	24	18.4	6	Overweight
	AM4	172.7	74.4	24.9	Healthy Weight		PM4	144.8	35.8	17.1	8	Healthy Weight
	AM5	172.7	98	32.8	Obese		PM5	152.4	46.7	20.1	12	Healthy Weight
	AM6	175.3	66.2	21.6	Healthy Weight	Pediatric Male	PM6	154.9	38.6	16.1	11	Healthy Weight
Adult Male	AM7	175.3	80.7	26.3	Overweight		PM7	154.9	45.4	18.9	14	Healthy Weight
	AM8	177.8	73.5	23.2	Healthy Weight		PM8	162.6	63.5	24	18	Healthy Weight
	AM9	177.8	99.8	31.6	Obese		PM9	172.7	64.9	21.7	14	Healthy Weight
	AM10	180.3	81.6	25.1	Overweight		PM10	177.8	63.5	20.1	17	Healthy Weight
	AM11	182.9	85.7	25.6	Overweight		PM11	180.3	89.8	27.6	17	Overweight
	AM12	182.9	112.5	33.6	Obese		PM12	182.9	68.9	20.6	15	Healthy Weight
	AM13	182.9	119.7	35.8	Obese		PM13	185.4	94.8	27.6	16	Obese

*Adult BMI classifications (CDC): Underweight (<18.5), Healthy Weight (18.5 ≤ … ≤ 24.9), Overweight (25.0 ≤ … ≤ 29.9), and Obese (≥ 30.0)

†Pediatric BMI classifications (CDC): Underweight (< 5^{th}-Percentile), Healthy Weight (5^{th}-Percentile ≤ … < 85^{th}-Percentile), Overweight (85^{th}-Percentile ≤ … < 95^{th}-Percentile), and Obese (≥ 95^{th}-Percentile)

‡Matched to reference newborn phantom

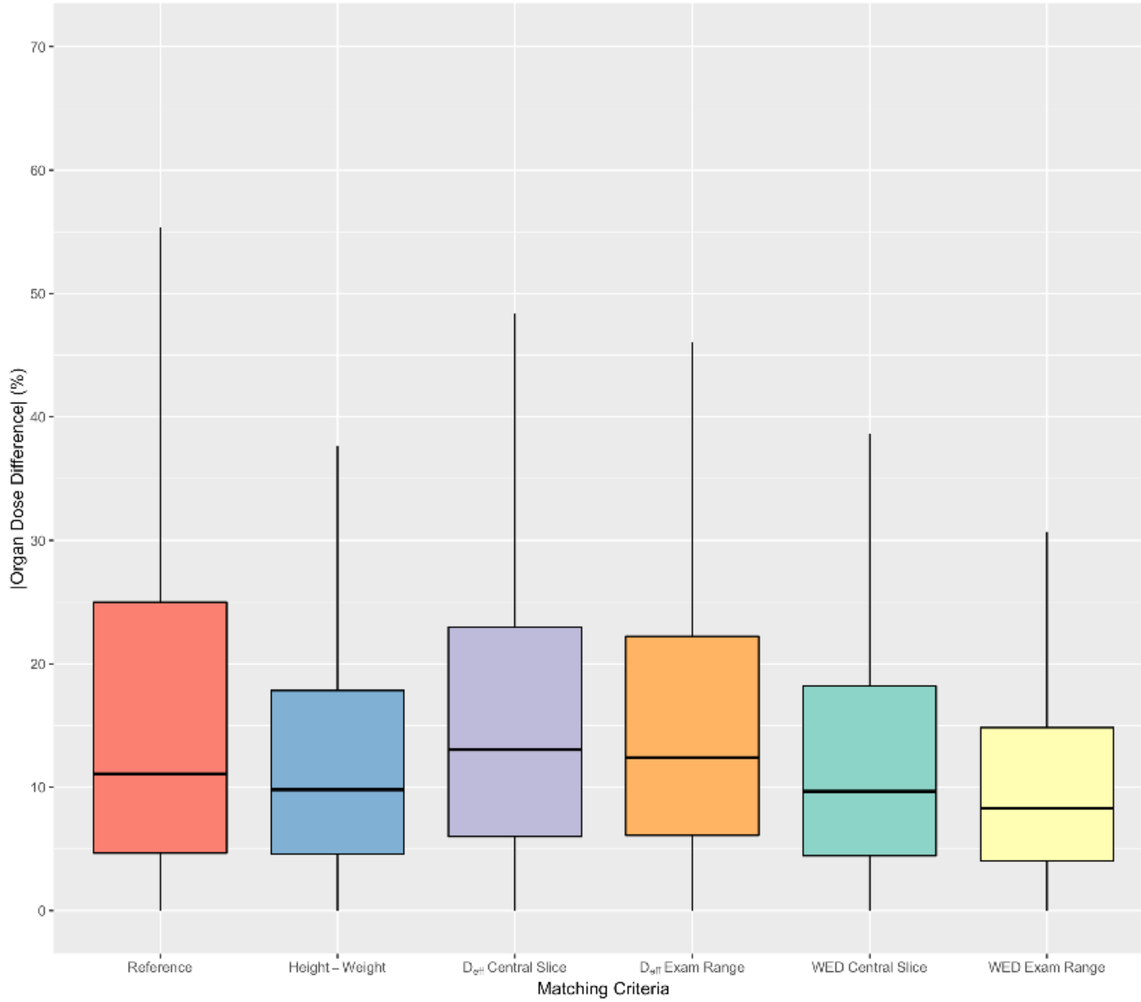
#No BMI classification for pediatric patients less than 2 years-old

‖Bladder could not be segmented

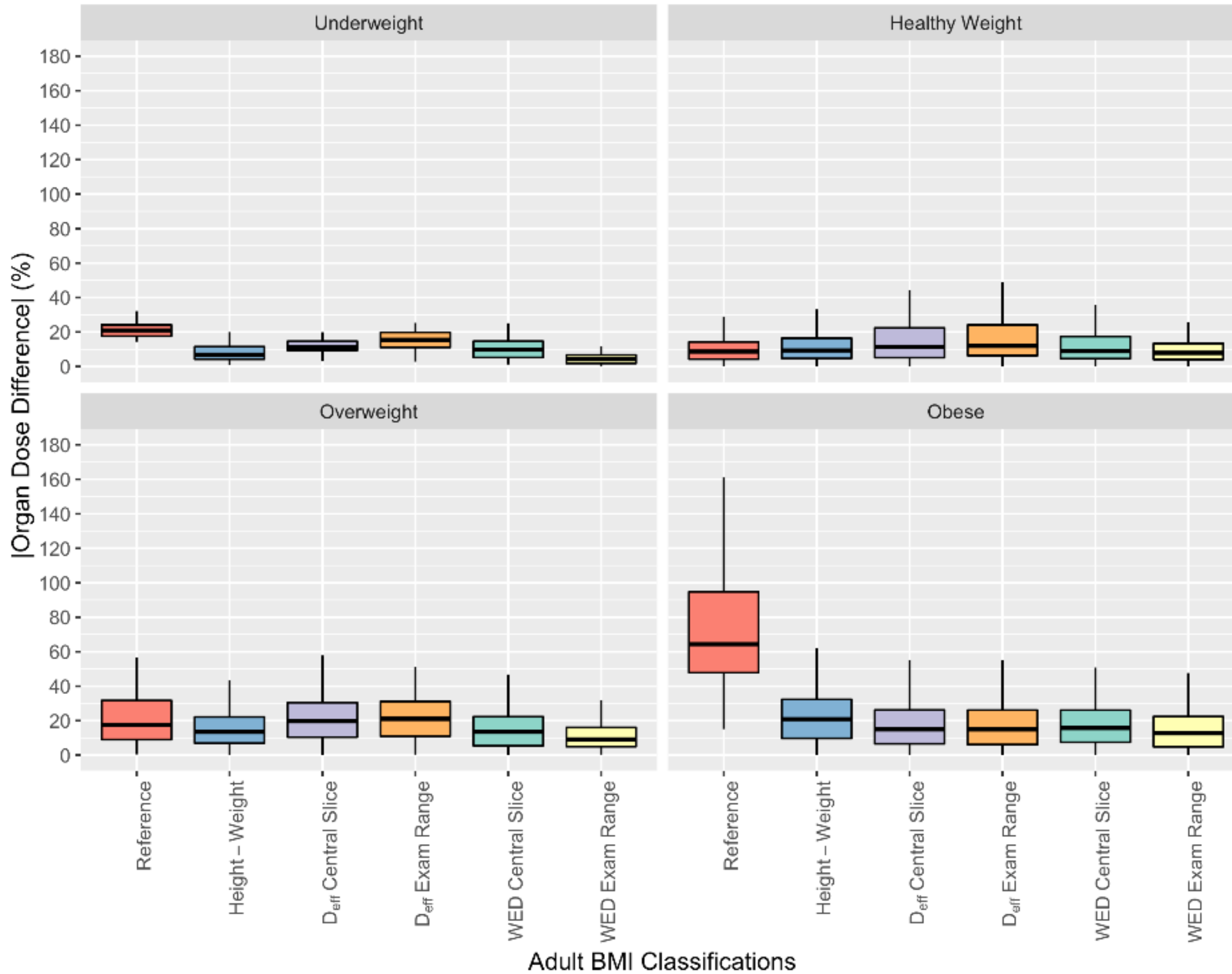
Summary of CT scan parameters in the patient-to-phantom matching study

Parameter	Chest-Abdomen-Pelvis	Chest-Abdomen	Abdomen-Pelvis	Chest	Abdomen	Pelvis
Tube Current Modulation	Yes	Yes	Yes	Yes	Yes	Yes
Collimation	0.5 mm x 64	0.5 mm x 64	0.5 mm x 64	0.5 mm x 64	0.5 mm x 64	0.5 mm x 64
Energy (kVp)	120	120	120	120	120	120
Exam Start	Thoracic Inlet	Thoracic Inlet	Dome of Diaphragm	Thoracic Inlet	Dome of Diaphragm	Illiac Crest
Exam End	Lesser Trochanter	2cm below Illiac Crest	Lesser Trochanter	Top of Kidneys	2cm below Illiac Crest	Lesser Trochanter
Filter	Large	Large	Large	Large	Large	Large
Gantry Tilt (°)	0	0	0	0	0	0
Average mA	300	300	300	300	300	300
mA (min, max)	(100, 500)	(100, 500)	(100, 500)	(100, 500)	(100, 500)	(100, 500)
Pitch	0.828	0.828	0.828	1.484	0.828	0.828
Rotation Time (s)	0.5	0.5	0.5	0.5	0.5	0.5

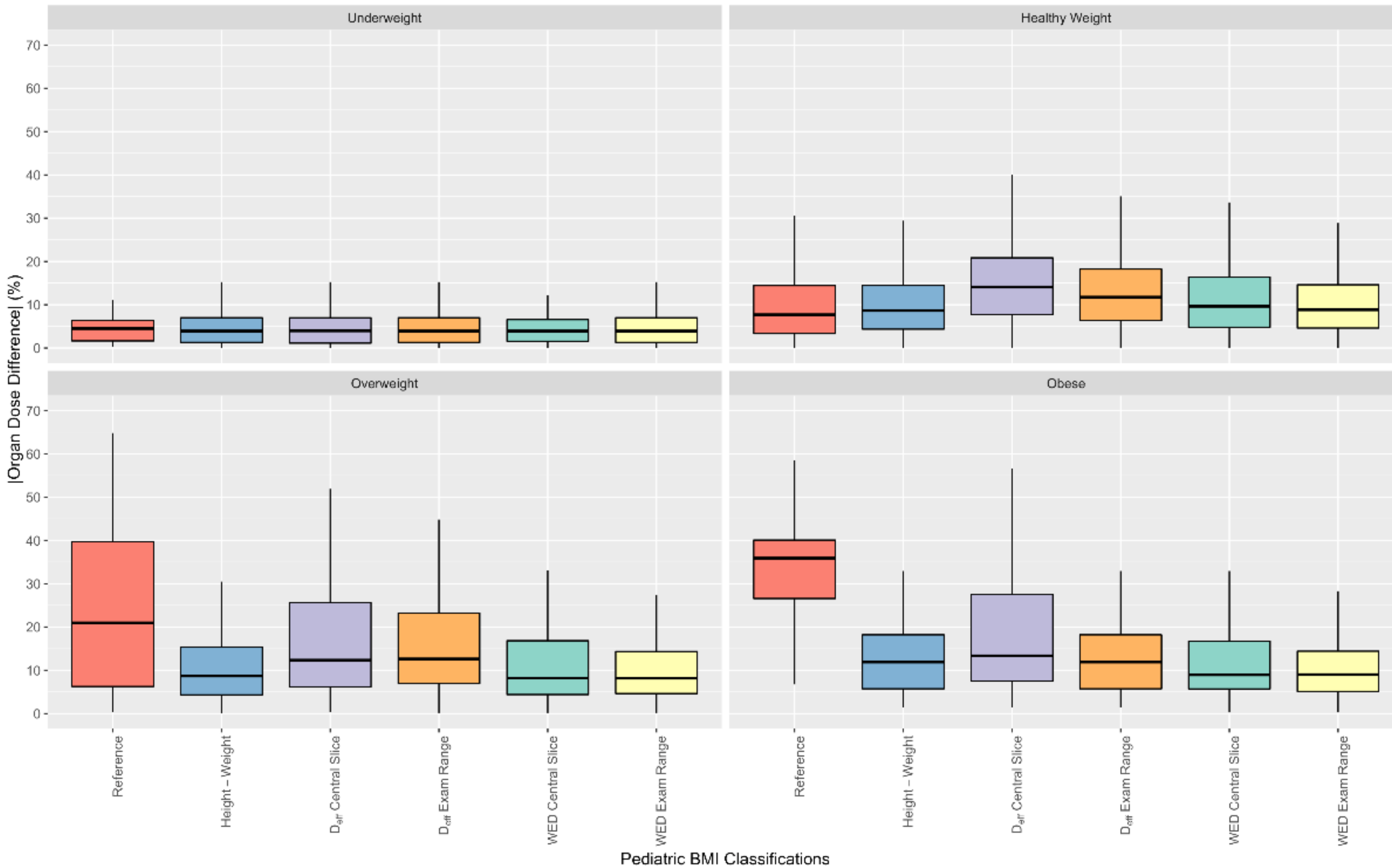
Boxplots comparing all organ dose percent differences for each of the six matching parameters. The vertical lines extend at most 1.5 times the interquartile.



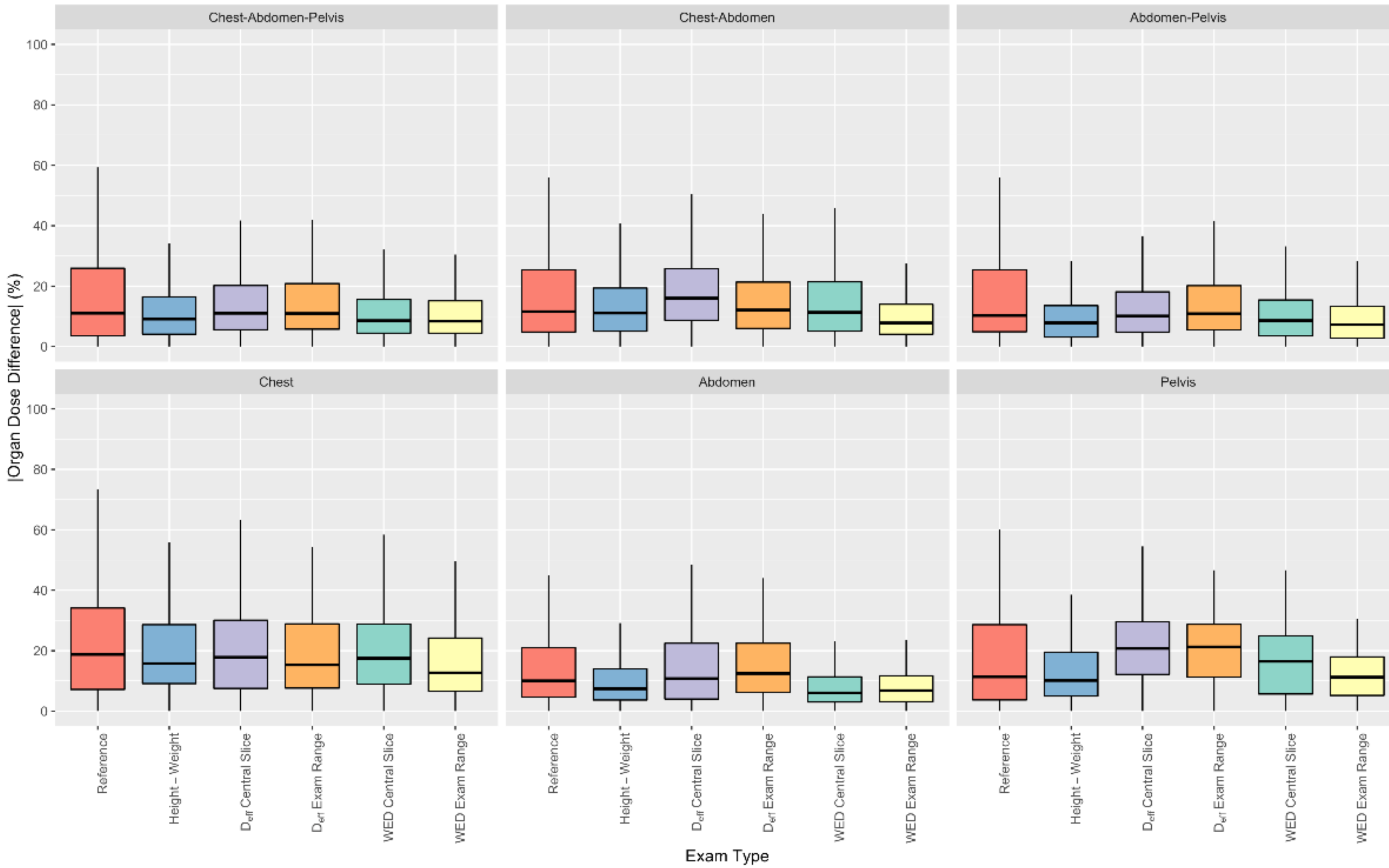
Boxplots comparing organ dose percent difference for each of the six matching parameters based on CDC BMI classifications for adult patients. The vertical lines extend at most 1.5 times the interquartile range.



Boxplots comparing organ dose percent difference for each of the six matching parameters based on CDC BMI classifications for pediatric patients. The vertical lines extend at most 1.5 times the interquartile range.



Boxplots comparing organ dose percent difference for each of the six matching parameters based on exam type. The vertical lines extend at most 1.5 times the interquartile range.



2. Organ Dose Reconstruction in Diagnostic Fluoroscopy

Data Collection – 2006 to 2017 — **Radimetrics**
Data Collection – 1996 to 2006 — **Data Abstraction**

Patient Data
Study ID
Age
Gender
Height
Weight

Fluoroscopy Procedure Details
Procedure type (1 to 6)
Cumulative fluoroscopy time
Cumulative reference air kerma
Cumulative kerma-area product

Reference Fluoroscopy Exams
1. *Upper Gastrointestinal Series (UGI)*
2. *Upper Gastrointestinal Series with Follow-Through (UGI-FT)*
3. *Voiding Cystourethrogram (VCUG)*
4. *Rehabilitation Swallow (RS)*
5. *Lower Gastrointestinal Series / Barium Enema (LGI)*
6. *Gastrostomy Tube Placement (G-Tube)*

Problem *– nearly all diagnostic fluoroscopy systems cannot generate RDSRs*
Solution *– create "reference" diagnostic exams and scale doses by FT, RAK, KAP*

Diagnostic Fluoroscopy Procedure Outlines - UF

VCUG *Procedure Duration: 120 seconds*

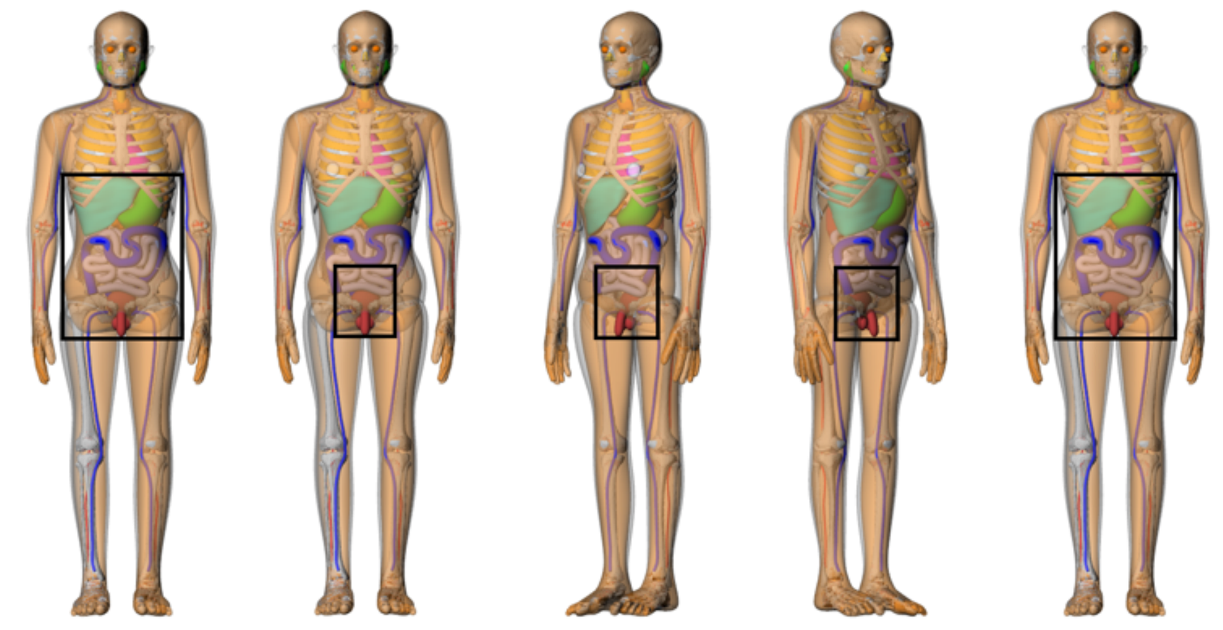
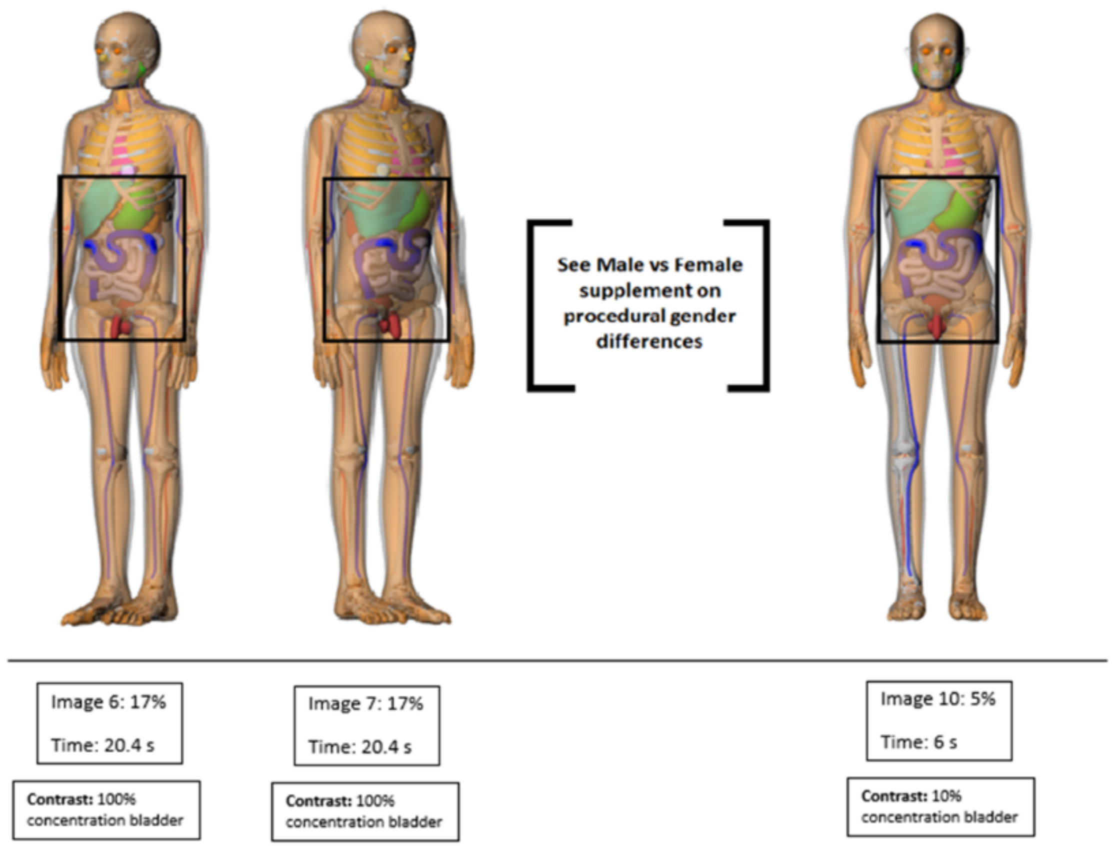


	Image 1: 5%	Image 2: 9%	Image 3: 8%	Image 4: 8%	Image 5: 16%
	Time: 6 s	Time: 10.8 s	Time: 9.6 s	Time: 9.6 s	Time: 19.2 s
Iodine Contrast →	**Contrast:** None	**Contrast:** 50% concentration bladder	**Contrast:** 50% concentration bladder	**Contrast:** 50% concentration bladder	**Contrast:** 100% concentration bladder

Diagnostic Fluoroscopy Procedure Outlines - UF

VCUG *Procedure Duration: 120 seconds*



Iodine Contrast

Diagnostic Fluoroscopy Procedure Outlines - UF

VCUG *Procedure Duration: 120 seconds*

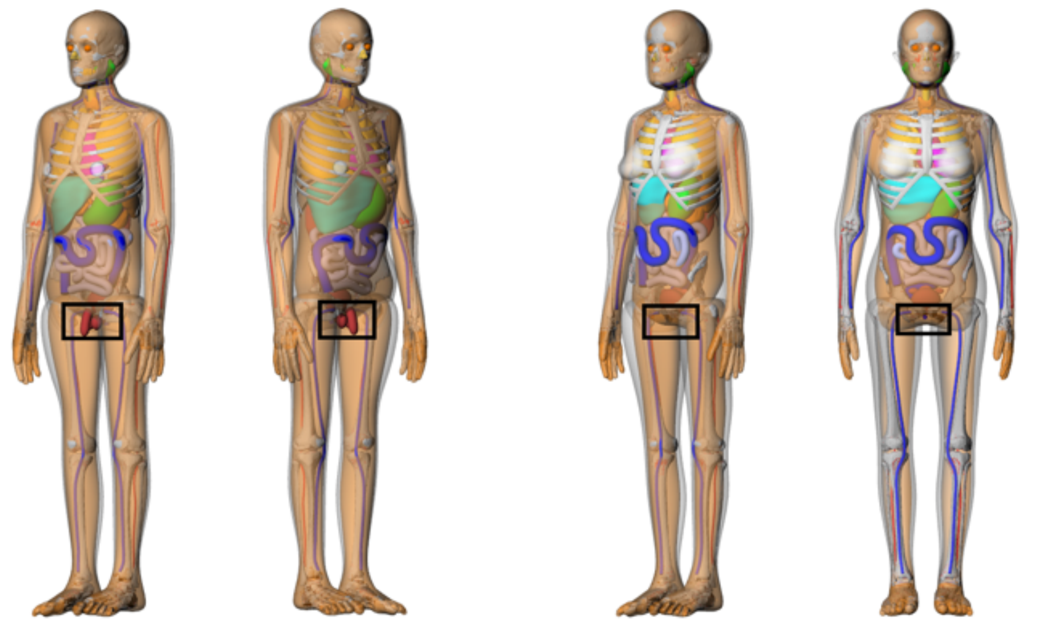


Image 8: 7.5%	Image 9: 7.5%	Image 8: 7.5%	Image 9: 7.5%
Time: 9 s	Time: 9 s	Time: 9 s	Time: 9 s
Contrast: 70% concentration bladder	**Contrast:** 50% concentration bladder	**Contrast:** 70% concentration bladder	**Contrast:** 50% concentration bladder

Iodine Contrast →

Automatic Brightness Control Modeling

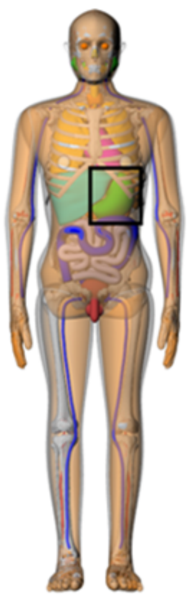


Image 1 –
G-Tube injection

Theoretical thickness calculation:

Energy (kVp)	Filter (mmCu)	Thickness (cm)
60	0.1	28.6
60	0.2	27.7
60	0.3	27.7
80	0.1	26.8
80	0.2	25.9
80	0.3	25.7
120	0.1	24.8
120	0.2	24.0
120	0.3	23.5

New thickness = 24.6 cm = 9.7 in

Average theoretical thickness
$\sum_{i=1}^{9} Thickness_i$ = 234.7

Divided by 9 possible combinations = 26.1 cm

Conversion to inches = 10.3 in

Clinical dose rate table – filter and energy extrapolation:

acrylic (inches)	kVp	filter (mmCu)	dose rate (µGy/min)
10	93	0.3	81
10.1	95.6	0.3	85.2
10.2	98.2	0.3	89.4
10.3	100.8	0.3	93.6
10.4	103.4	0.3	97.8
10.5	106	0.3	102
10.6	106.8	0.3	102.8
10.7	107.6	0.3	103.6
10.8	108.4	0.3	104.4
10.9	109.2	0.3	105.2

kVp = 100.8
Filter = 0.3

The iteration process begins again (completes at 100 times)

3. Organ Dose Reconstruction in Diagnostic Nuclear Medicine

Data Collection – 2006 to 2017 — ***Radimetrics***

Data Collection – 1996 to 2006 — ***Data Abstraction***

Patient Data
Study ID
Age
Gender
Height
Weight

NM Procedure Details
Procedure type (1 to 6)
Administered Activity

Reference NM Procedures
1. *Tc-99m DMSA*
2. *Tc-99m MDP*
3. *Tc-99m MAG3*
4. *F-18 FDG*
5. *Tc-99m Sulfur Colloid*
6. *I-123 MIBG*

Problem – *Injected activity might not be available*
Solution – *Use current guidelines or period-specific weight-based dosing schemes*

Biokinetics – *Assume ICRP reference models*
Radionuclide S values – *Assume values from the UF reference phantoms*

Summary

The UF/NCI pediatric (and possibly adult) phantom library will be used to reconstruct organ doses in a very large US/Canadian study of the association of medical imaging dose and pediatric cancer incidence.

Techniques are in place for batch-processing of several million cohort member data for reporting organ doses following computed tomography, diagnostic fluoroscopy, and diagnostic nuclear medicine examinations.

The project – currently at the beginning of Year 3 of 5 – will hopefully contribute a better understanding of the magnitude and uncertainties in cancer incidence risks following low-dose, low-LET radiation exposures associated with medical important and potentially life-saving imaging procedures.

Thank you for your attention!