TG246 On Patient Dose From Diagnostic Radiation

Format Types and Morphometric Categories of Computational Phantoms

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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

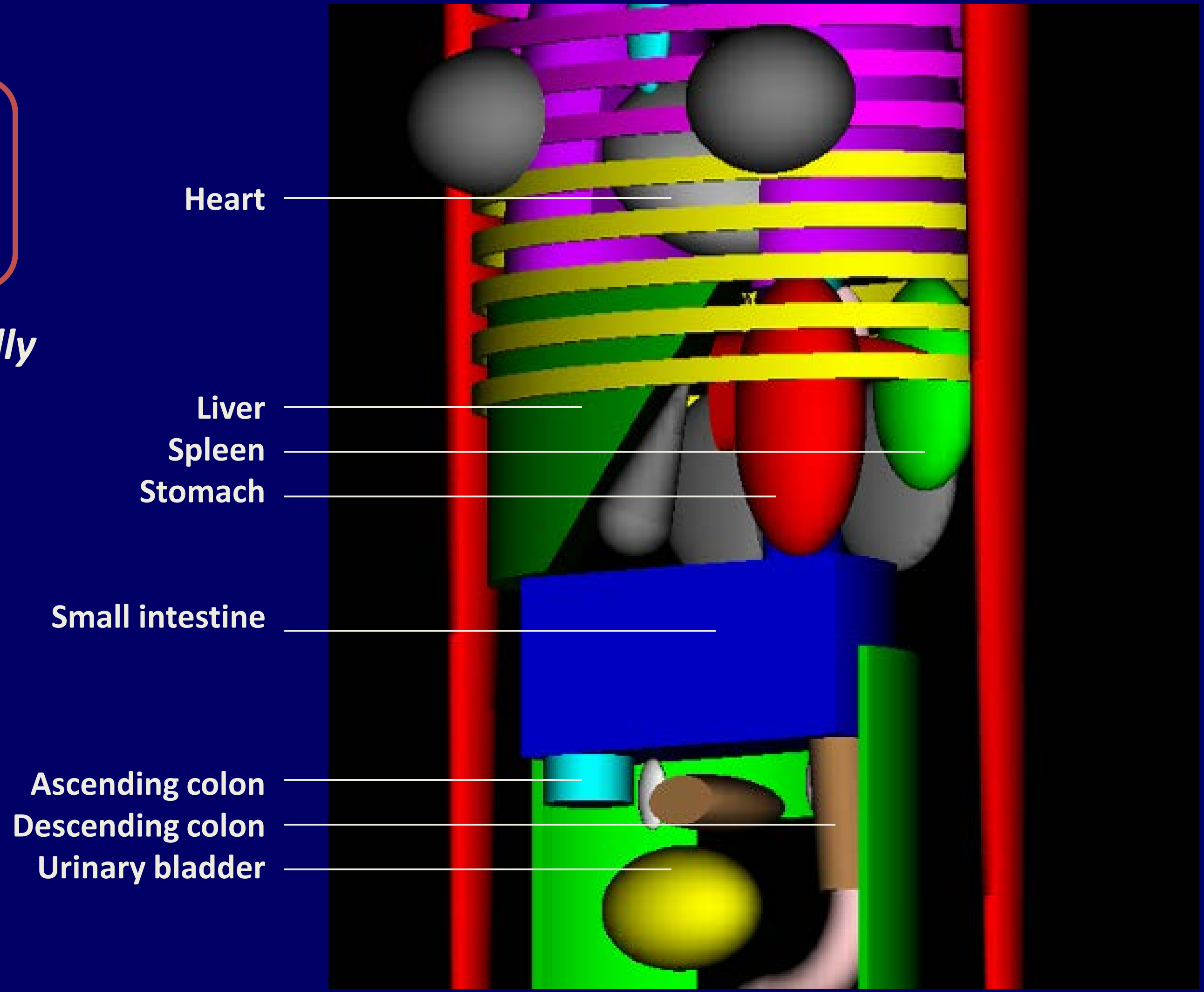
Phantom Types and Morphometric Categories

- *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

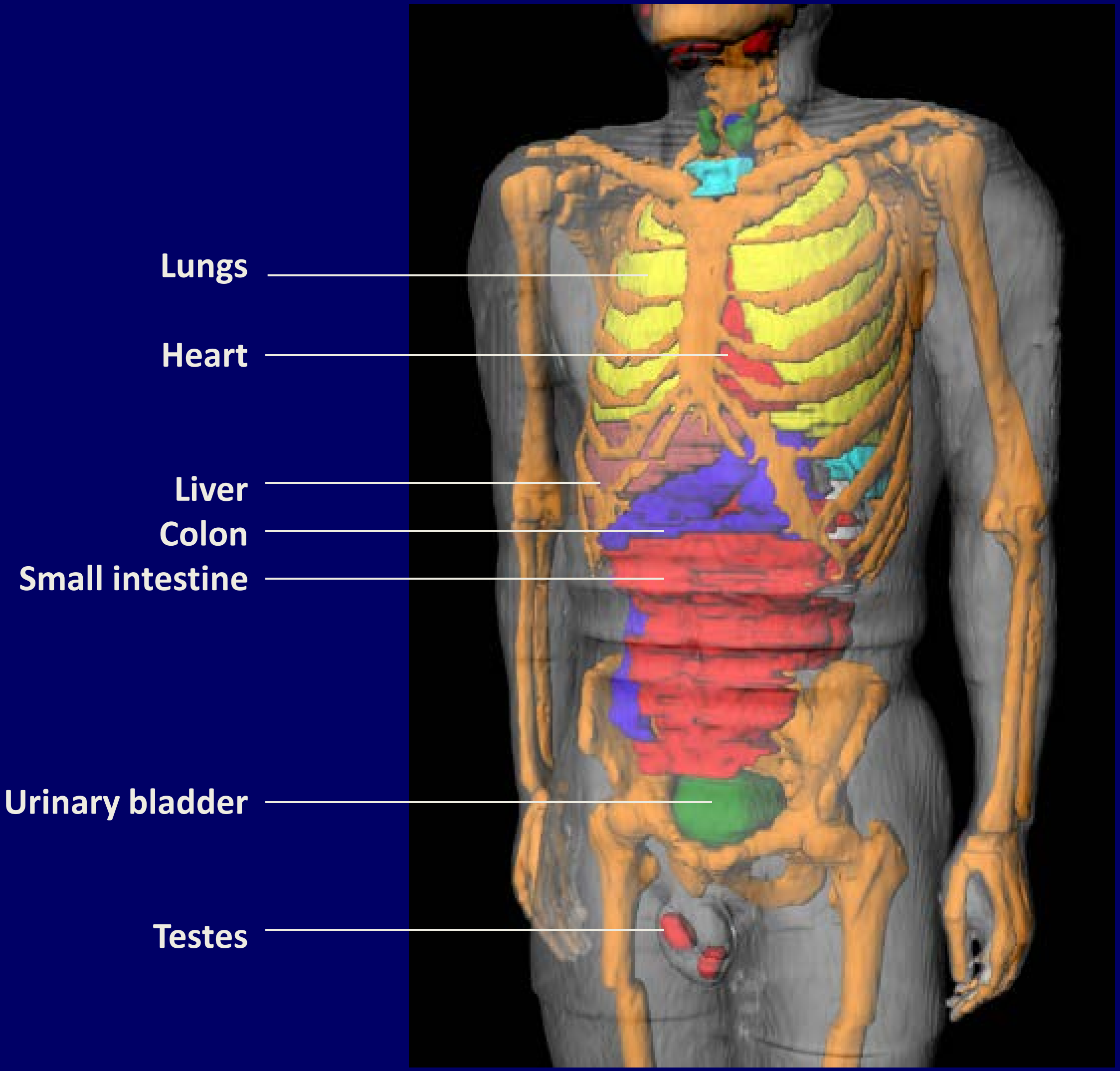
Selective History of Stylized Phantoms

Developer	*Nomenclature*	*Data Types*	*Human Subjects*	*References*
ORNL, USA	Fisher-Synder Phantom	Quadric Equations	Caucasian NB, 1y, 5y, 10y, 15y, and adult	Fisher and Snyder 1966, 1967
NASA, USA	CAM	Quadric Equations	Caucasian adult male	Bilings and Yucker 1973
ORNL, USA	ORNL Pediatric Phantoms	Quadric Equations	Caucasian NB, 1y, 5y, 10y, and 15y	Deus and Poston 1976, Hwang et al 1976
GSF, Germany	ADAM and EVA	Quadric Equations	Caucasian adult male and female	Kramer *et al* 1982
ORNL, USA	ORNL Family of Stylzied Phantoms	Quadric Equations	Based on previous ORNL phantoms	Cristy 1980, Cristy and Eckerman 1987
ORNL, USA	Pregnant Female Phantoms	Quadric Equations	Caucasian pregnant females at 3 preg stages	Stabin *et al* 1995
Johns Hopkins University	MCAT	Quadric Equations	Caucasian adult male	Pretorius *et al* 1997, Tsui *et al* 1993, 1994
Radiation Protection Bureau, Canada	Embryo and Fetus (4 models)	Quadric Equations	Cacausian females at 8, 13, 26, 38 wk	Chen 2004
Hanyang University, Korea	KMIRD	Quadric Equations	Korean adult male	Park *et al* 2006
Nagoya Institute of Technology, Japan	Japanese Infants	Quadric Equations	Japanese 3-year-old	Hirata *et al* 2008
Key Laboratory, Beijing	CMP	Quadric Equations	Chinese adult male	Qiu *et al* 2008
Catholic University of Pusan, Bugok	Korean Male	Quadric Equations	Korean male	Kim *et al* 2010
Bhaba Atomic Research Centre, India	BARC WBC Phantoms	Quadric Equations	Indian adult male	Bhati *et al* 2011
ITN, Porugal	ITN WBC Phantom	Quadric Equations	Caucasian adult male	Bento *et al* 2012

Format Types - Voxel Phantoms

1980s
Voxel
Phantom

Anatomically Realistic but not very flexible



Anatomy of Korean male voxel phantom

Selective History of Voxel Phantoms

Developer	Nomenclature	Data Types	Human Subjects	References
Vanderbilt Univeristy, USA	Gibbs Phantoms	Radiography	Caucasian female cadaver	Pujol and Gibbs 1982 Gibbs *et al* 1984, 1987
GSF / HMGU, Munich	BABY	CT	Caucasian 8wk female cadaver	Williams *et al* 1986 Zankl *et al* 1988
GSF / HMGU, Munich	CHILD	CT	Caucasian 7y female patient	Williams *et al* 1986 Zankl *et al* 1988
Yale University	Zubal Phantom	CT	Caucasian adult male	Zubal *et al* 1994
Public Health England (formerly HPA / NRPB)	NORMAN	MRI	Caucasian adult male	Dimbylow 1996, 1997 Jones 1997
Yale University	MANTISSUE	CT	Caucasian adult male	Dawson *et al* 1997
Univerisity of Utah, USA	No Name	MRI	Caucasian adult male	Tinniswood *et al* 1998
Brooks Air Force Base, USA	Visible Man	Color Photos	Caucasian 39y male	Mason *et al* 2000, Wang *et al* 2004
Rensselaer Polytechnic Institute (RPI), USA	VIP-Man	Color Photos	Caucasian 39y male	Xu *et al* 2000
Japanese Atomic Energy Agency, Japan	OTOKO	CT	Japanese adult male volunteer	Saito *et al* 2001
Yale University	VOXTISS	CT	Caucasian adult male	Sjogreen *et al* 2001
GSF / HMGU, Munich	GOLEM	CT	Caucasian 38y male patient	Zankl *et al* 2002
GSF / HMGU, Munich	VISIBLE HUMAN	CT	Caucasian 39y male cadaver	Zankl *et al* 2002
University of Florida, USA	UF Newborn	CT	Caucasian 6-day female	Nipper *et al* 2002

Selective History of Voxel Phantoms

Developer	*Nomenclature*	*Data Types*	*Human Subjects*	*References*
GSF / HMGU, Munich	DONNA	CT	Caucasian 40y female patient	Petoussi et al 2002 Fill *et al* 2004
GSF / HMGU, Munich	FRANK	CT	Caucasian 48y male patient	Petoussi *et al* 2002
GSF / HMGU, Munich	HELGA	CT	Caucasian 26y female patient	Petoussi et al 2002 Fill *et al* 2004
GSF / HMGU, Munich	IRENE	CT	Caucasian 32y female patient	Petoussi et al 2002 Fill *et al* 2004
FCS Department, Italy	DAM	MRI	34-year male volunteer	Mazzurana *et al* 2003
Federal University of Pernambuco, Brazil	MAX	CT	Caucasian adult male	Kramer *et al* 2003
Federal University of Pernambuco, Brazil	FAX	CT	Caucasian adult female	Kramer *et al* 2004
Hanyang University, South Korea	KORMAN	MRI	Korean 30y male	Lee *et al* 2004
NIICT, Japan	HANAKO	MRI	Japanese 22y female	Nagaoka et al 2004 Lee *et al* 2006
Rensselaer Polytechnic Institute (RPI), USA	RANDO CT Phantom	CT	Adult male	Wang *et al* 2004
GSF / HMGU, Munich	LAURA	CT	Caucasian 43y female patient	Zankl *et al* 2005
Hanyang University, South Korea	KORWOMAN	MRI	Korean 35y female	Lee et al 2005
Hanyang University, South Korea	KTMAN-1	MRI	Korean 25y male volunteer	Lee et al 2005
University of Florida, USA	UF Series A	CT	9m, 11y, 14y males 4y, 8y females	Lee *et al* 2005

Selective History of Voxel Phantoms

Developer	*Nomenclature*	*Data Types*	*Human Subjects*	*References*
Public Health England (formerly HPA / NRPB)	NAOMI	MRI	Caucasian adult female	Dimbylow 2005
Public Health England (formerly HPA / NRPB)	NORMAN-05	MRI	Caucasian adult male	Ferrari and Gualdrini 2005
Federal University of Pernambuco, Brazil	MAX06 and FAX06	CT	Caucasian adult male and female	Kramer *et al* 2006
Hanyang University, South Korea	KTMAN-2	PET/CT	Korean 35y male volunteer	Lee et al 2006
Hanyang University, South Korea	HDRK-Man	Color Photos	Korean 35y male cadaver	Choi *et al* 2006 Kim *et al* 2008
Public Health England (formerly HPA / NRPB)	Pregnat Females - 4 Models	Quadric Equations / MRI	Pregnat females at 8, 13, 26, and 38 wk	Dimbylow 2006
Korea Atomic Energy Research Inst, SK	Photographic voxel phantoms	Color Photos	Korean adult volunteers	Kim *et al* 2006
NIICT, Japan	TARO	MRI	Japanese 22y male	Lee *et al* 2006
NIICT, Japan	Pregnant Females	MRI	Japanese 26wk pregnant female	Nagaoka et al 2006, 2007
University of Florida, USA	UF Series B	CT	9m, 11y, 14y males 4y, 8y females	Lee *et al* 2006
China Institute for Radiation Protection	CNMAN	Color Photos	Chinese adult male cadaver	Zhang *et al* 2007
GSF / HMGU, Munich	KATJA	MRI	Caucasian pregnant female at 24 weeks	Becker *et al* 2007
GSF / HMGU, Munich	REGINA (ICRP RF)	CT	Caucasian 43y female patient	Schlattl *et al* 2007
GSF / HMGU, Munich	REX (ICRP RM)	CT	Caucasian 38y male patient	Schlattl *et al* 2007

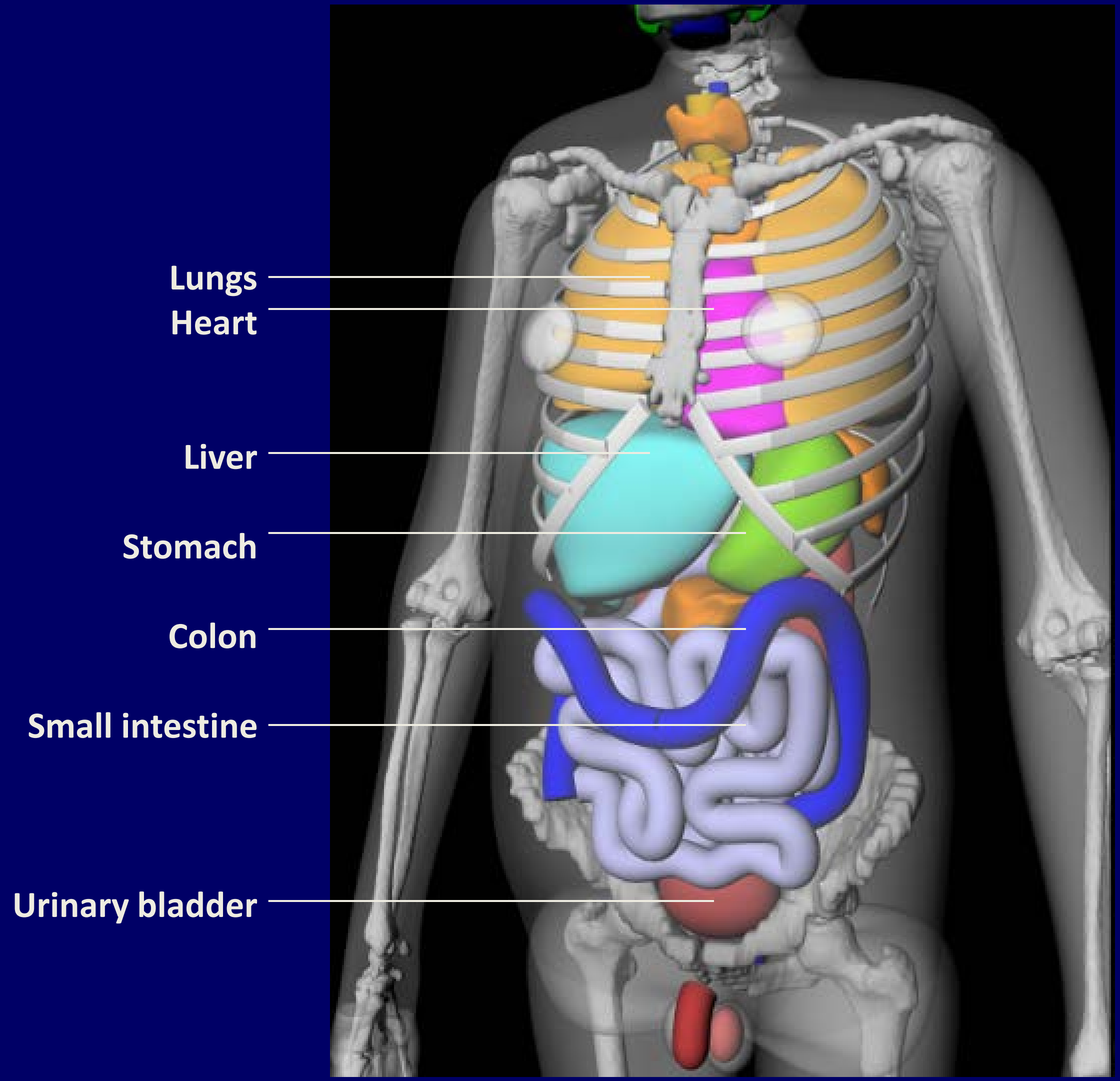
Selective History of Voxel Phantoms

Developer	*Nomenclature*	*Data Types*	*Human Subjects*	*References*
Graz University of Technology, Austria	SILVY	MRI and CT	Caucasian pregnant females at 30 weeks	Chech *et al* 2007, 2008
Japanese Atomic Energy Agency, Japan	JM and JM2	CT	Japanese 54y male	Sato *et al* 2007
University of Karlsruhe, Germany	MEET Mans	Color Photos	Caucasian 38y adult male cadaver	Doerfel & Heide 2007
Japanese Atomic Energy Agency, Japan	ONAGO	CT	Japanese adult female volunteer	Saito *et al* 2008
NIICT, Japan	Deformed Children	MRI	Japanese 3y, 5y, and 7y children	Nagaoka et al 2008
ORNL, USA	VOXMAT	CT and Quadric Eqs	Caucasian adult male	Akkrut 2008
University Hospital of Leuven, Belgium	Phantom 1	MRI	33wk stillborn male	Smans *et al* 2008
University Hospital of Leuven, Belgium	Phantom 2	CT	22wk stillborn male	Smans *et al* 2008
Huazhong University, China	VCH	Color Photos	Chinese adult male cadaver	Zhang *et al* 2008 Sun *et al* 2013
INSERM, France	WBPM - 4 Phantoms	CT	27y male, 52y female, two 3y males	Alziar *et al* 2009
University of Houston USA	No Name	CT	10y male	Taddei *et ali* 2009
Japanese Atomic Energy Agency, Japan	JF	CT	Japanese adult female volunteer	Sato *et al* 2009
ENEA, Italy	NUDEL	CT	Caucasian male	Ferrari 2010
Institute of Technology, Austria	MATSIM head and MATSIM torso	CT	ISS Astronaut	Beck *et al* 2011

Format Types – Hybrid Phantoms

2000s
Hybrid
Phantom

Realistic and flexible



Anatomy of UF hybrid adult male phantom

Selective History of Hybrid Phantoms

Developer	Nomenclature	Data Types	Human Subjects	References
Duke University	NCAT	NURBS	Caucasian 39y male and 59y female	Segars 2001
Rensselaer Polytechnic Institute (RPI)	4D VIP Man - Chest	NURBS	Caucasian 39y male	Xu and Shi 2005 Zhang et al 2008
University of Houtson, USA	Pregnant Female	NURBS / CAD	Pregnant female at 34 weeks	Wu et al 2006
Rensselaer Polytechnic Institute (RPI)	RPI Pregnant Females	Polygon Mesh	3, 6, 9 months of pregnancy	Xu et al 2007
Duke University	MOBY / ROBY	NURBS	Mouse and Rate phantoms	Segars and Tsui 2007
Vanderbilt University, USA	Adult and Pediatric Phantoms - 7 models	NURBS	Newborn, 1y, 5y, 10y, 15y, and Adults	Stabin et al 2008
Rensselaer Polytechnic Institute (RPI)	Adult Breast Phantoms - 8 models	Polygon Mesh	Based on RPI-AF	Hegenbart et al. 2008
Rensselaer Polytechnic Institute (RPI)	RPI-AM and RPI-AF	Polygon Mesh	Reference adult male and adult female	Zhang 2009 Na et al 2010
Federal University of Penambuco, Brazil	FASH and MASH	Polygon Mesh	Adult male and female	Cassola et al 2010 Kramer et al 2010
IRSN, France	Thoracic Female Torso - 34 phantoms	Polygon Mesh / NURBS	Variations of the ICRP Adult Female	Farah et al 2010 Farah et al 2011
IT IS, Switzerland	Virtual Family - 4 phantoms	Polygon Mesh	Caucasian volunteers - adult and pediatric	Christ et al 2010
University of Florida, USA	UF Hybrid Reference Series	NURBS / Polygon Mesh	Newborn, 1y, 5y, 10y, 15y, and Adults	Lee et al 2010
Duke University	XCAT - 47 phantoms	NURBS	Scaled adult males and females	Fung et al 2011
Federal University of Penambuco, Brazil	FASH and MASH Phantom Series	Polygon Mesh	Adult males and females at 10th, 50th, 90th	Cassola et al 2011

Selective History of Hybrid Phantoms

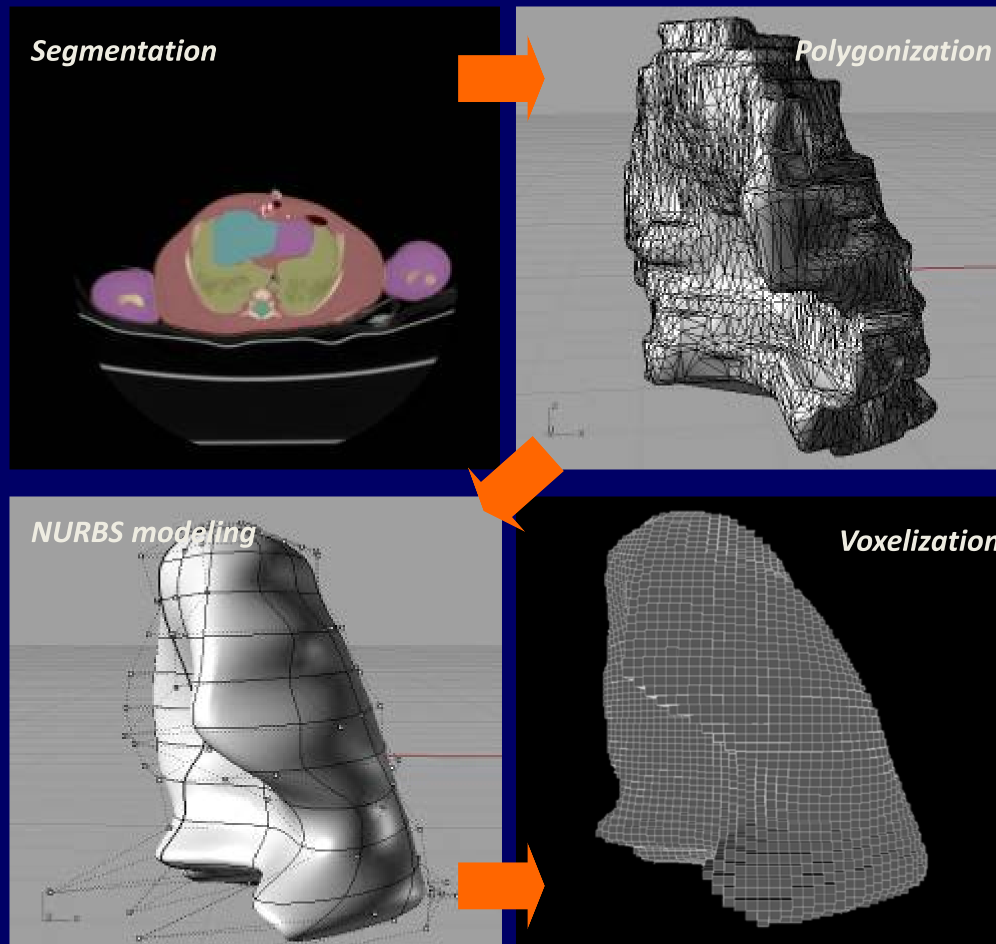
Developer	*Nomenclature*	*Data Types*	*Human Subjects*	*References*
Federal University of Penambuco, Brazil	Pediatric Phantoms	Polygon Mesh	5-year and 10-year males and females	de Melo Lima et al 2011
Hanyang University, Korea	PSRK-Man	Polygon Mesh	Korean male	Kim et al 2011
IRSN, France	Adult Male - 25 phantoms	Polygon Mesh / NURBS	25 whole-body male phantoms	Broggio et al 2011
University of Florida, USA	UF Hybrid Fetal Series	NURBS / Polygon Mesh	8, 10, 15, 20, 25, 30, 35, and 38 weeks	Maynard et al 2011
IT IS, Switzerland	Extended Virtual Family	Polygon Mesh	Caucasian volunteers - different gender/ages	IT IS 2011
Johns Hopkins University	Pediatric XCAT - 24 phantoms	NURBS	Rescaled from 39y male	Tward et al 2011
Rensselaer Polytechnic Institute (RPI)	Obese Adults	Polygon Mesh	Overweight, Obese, Morbidly Obese Adults	Ding et al 2012
Duke University	XCAT Library	NURBS	58 phantoms (35 male and 23 female)	Segars et al 2013
University of Florida, USA	UF Hybrid Phantom Library - 351 models	NURBS / Polygon Mesh	193 adults and 158 children	Geyers et al (2014)
University of Florida, USA	UF Hybrid Pregnant Female Series	NURBS / Polygon Mesh	8, 10, 15, 20, 25, 30, 35, and 38 weeks	Maynard et al (2014)

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™



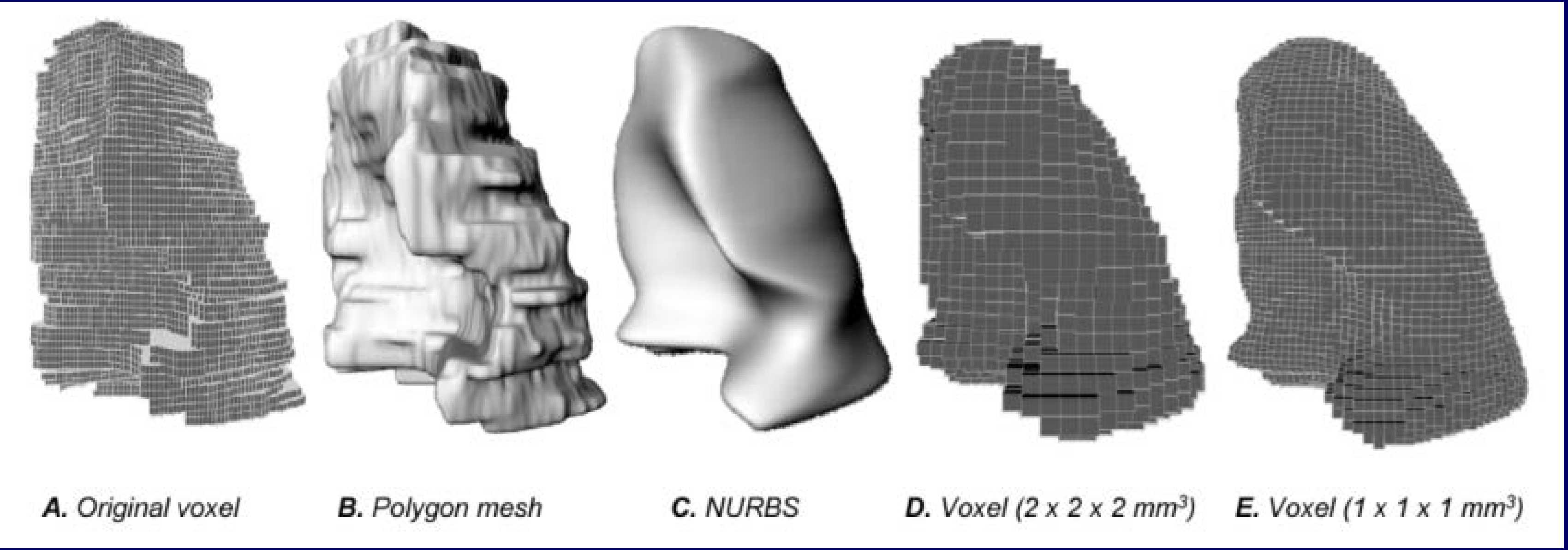
Make NURBS model from polygon mesh using Rhinoceros™

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 (50th 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).**

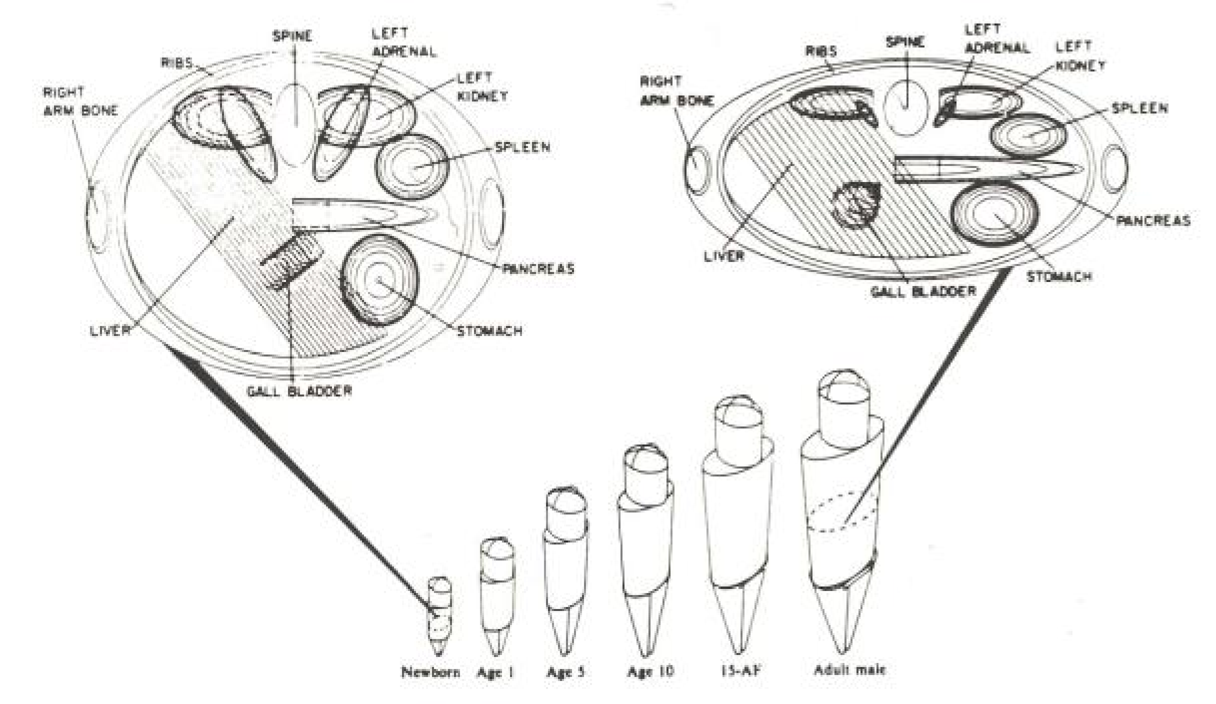
Table 2.9. Reference values for height, mass, and surface area of the total body

	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* ***are specified*** *in an ICRP reference phantom, organ shape, depth, position within the body* ***are not defined*** *by reference values*

Reference Phantoms Used by the ICRP

Essentially all dose coefficients published to date by the ICRP are based on computational data generated using the ORNL stylized phantom series.



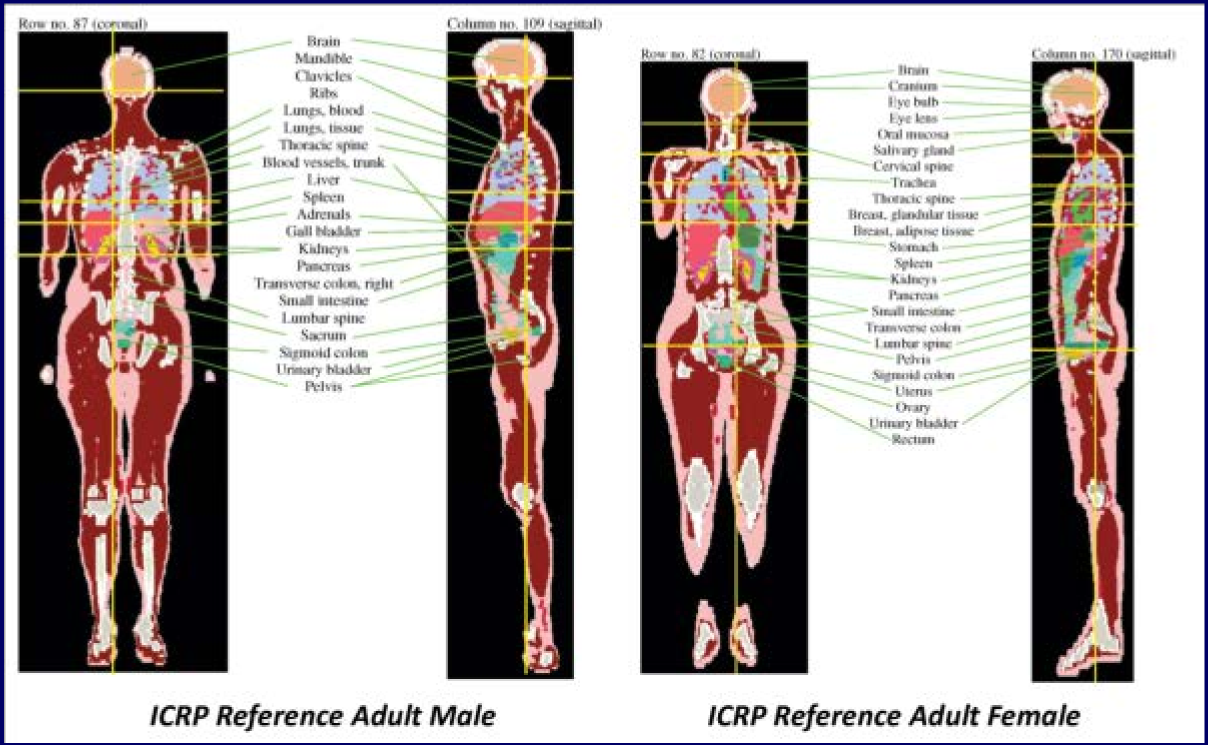
ORNL TM-8381
Cristy & Eckerman

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

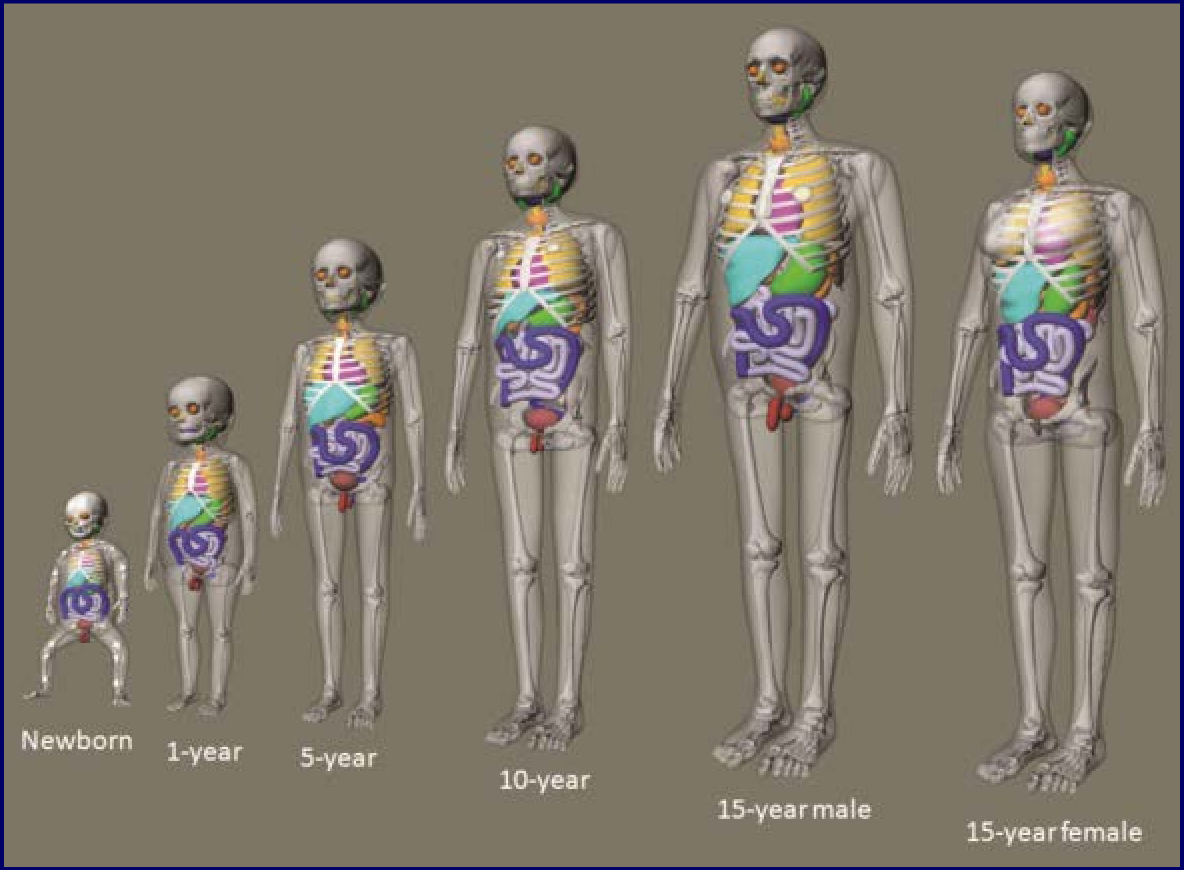


Upcoming Publications from ICRP using the Publication 110 Phantoms

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

Reference Phantoms Adopted by the ICRP

In April 2014, ICRP established that its future reference phantoms for pediatric individuals would be based upon the UF 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

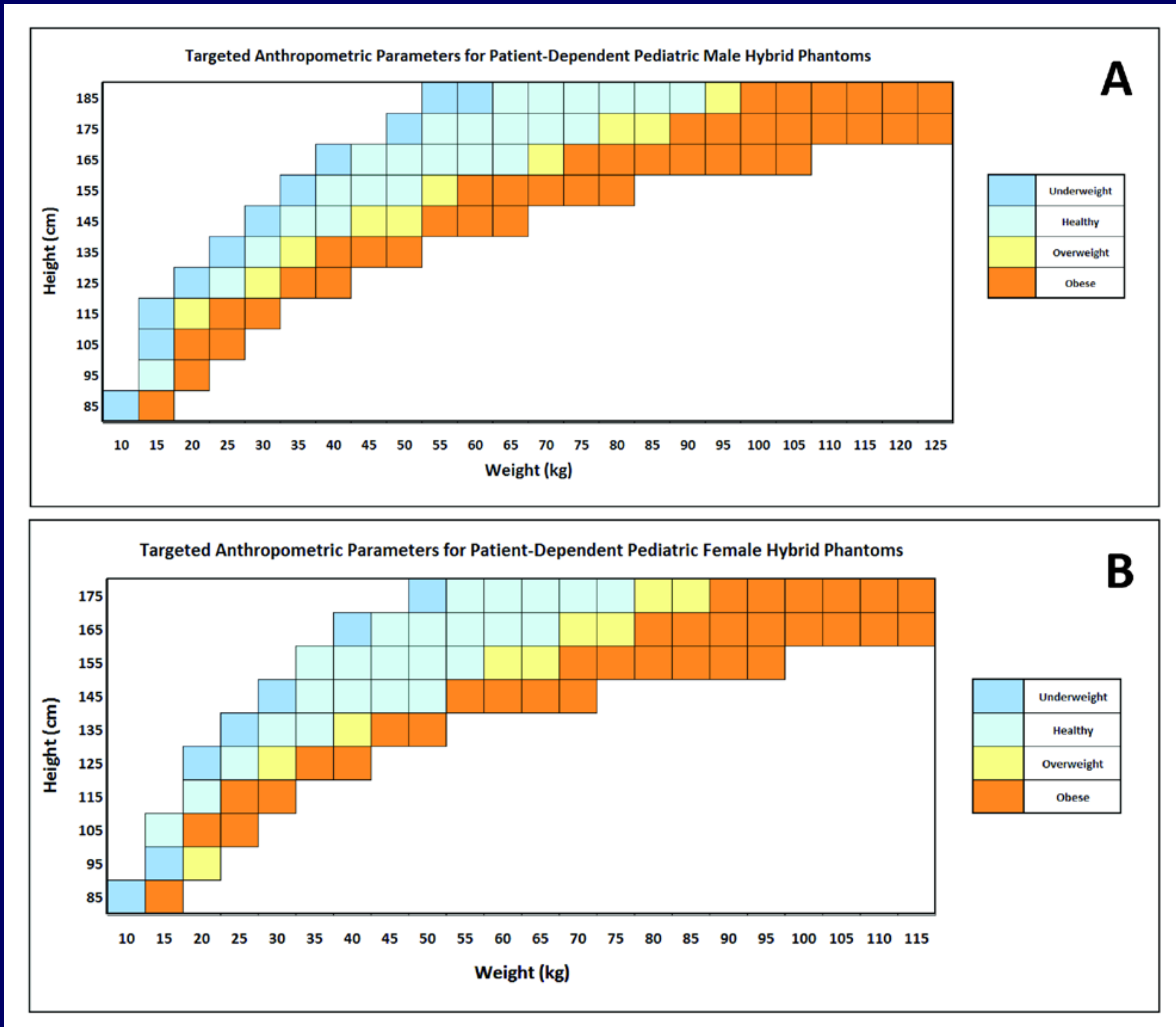
Patient-Dependent Hybrid Phantoms – UF Series

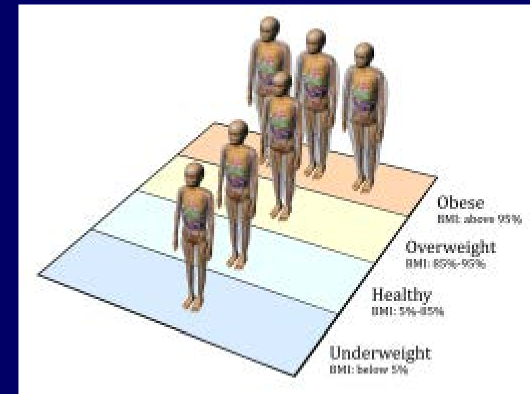
Phantom Height	Pediatric		Phantom Height	Adult	
(cm)	*Males*	*Females*	(cm)	*Males*	*Females*
185	UFHADM ↑		190	UFHADM ↑	
175	UFHADM ↓	UFHADF ↑	185	UFHADM ↑	
165	UFH15M ↓	UFHADF ↑	180	UFHADM ↑	
155	UFH15M ↓	UFH15F ↓	175	UFHADM ↓	UFHADF ↑
145	UFH10M ↑	UFH10F ↑	170	UFH15M ↑	UFHADF ↑
135	UFH10M ↓	UFH10F ↓	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)

New UF/NCI Phantom Library - Children

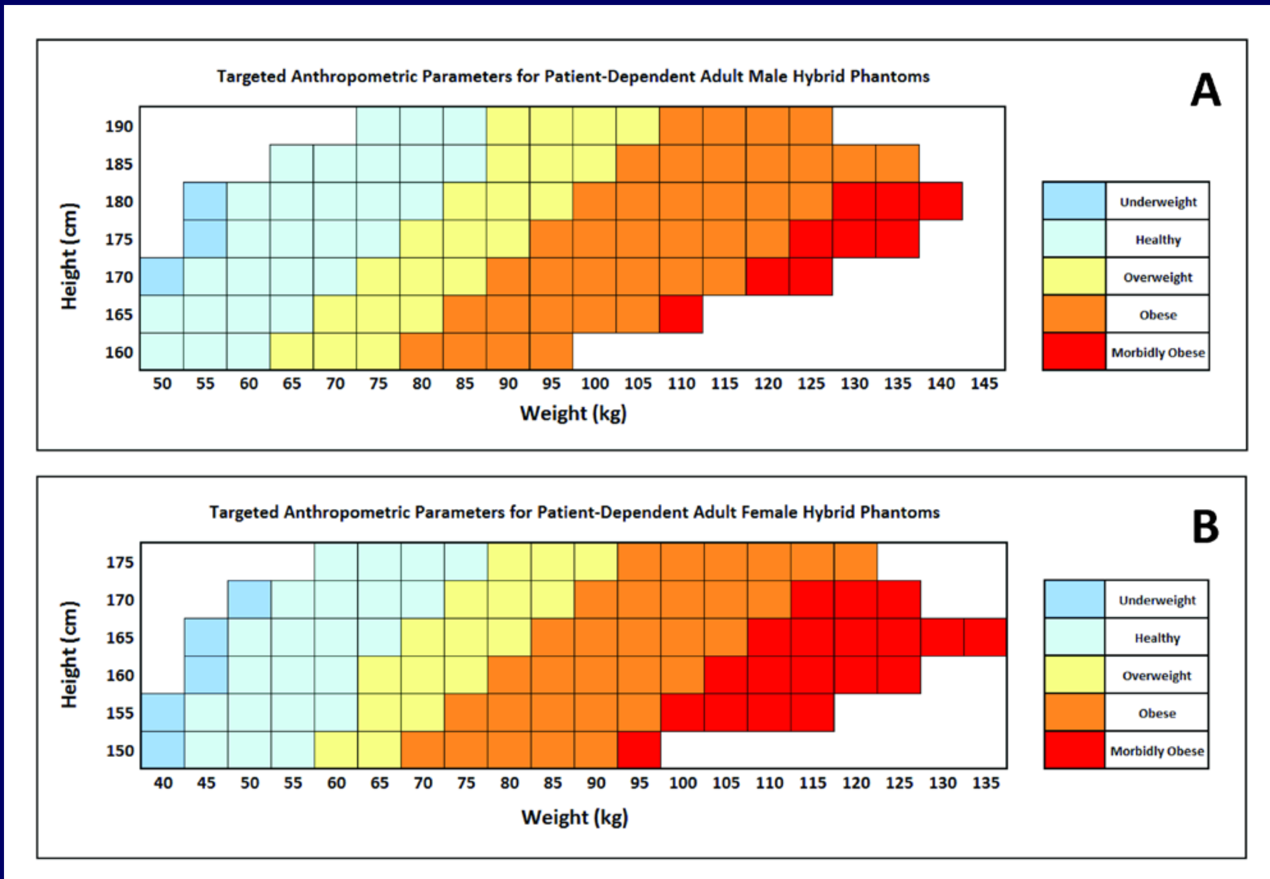


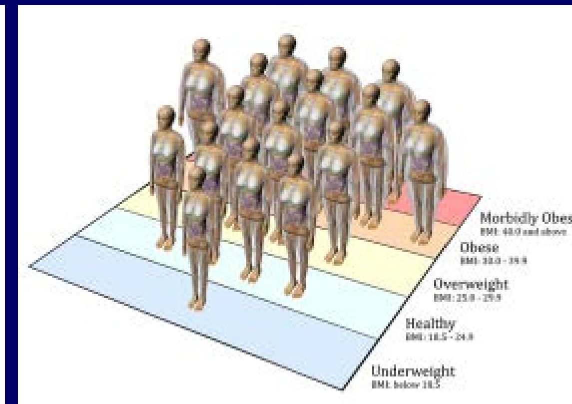


Phantom for each height/weight combination further matching average values of body circumference from CDC survey data

85 pediatric males
73 pediatric females

New UF/NCI Phantom Library - Adults

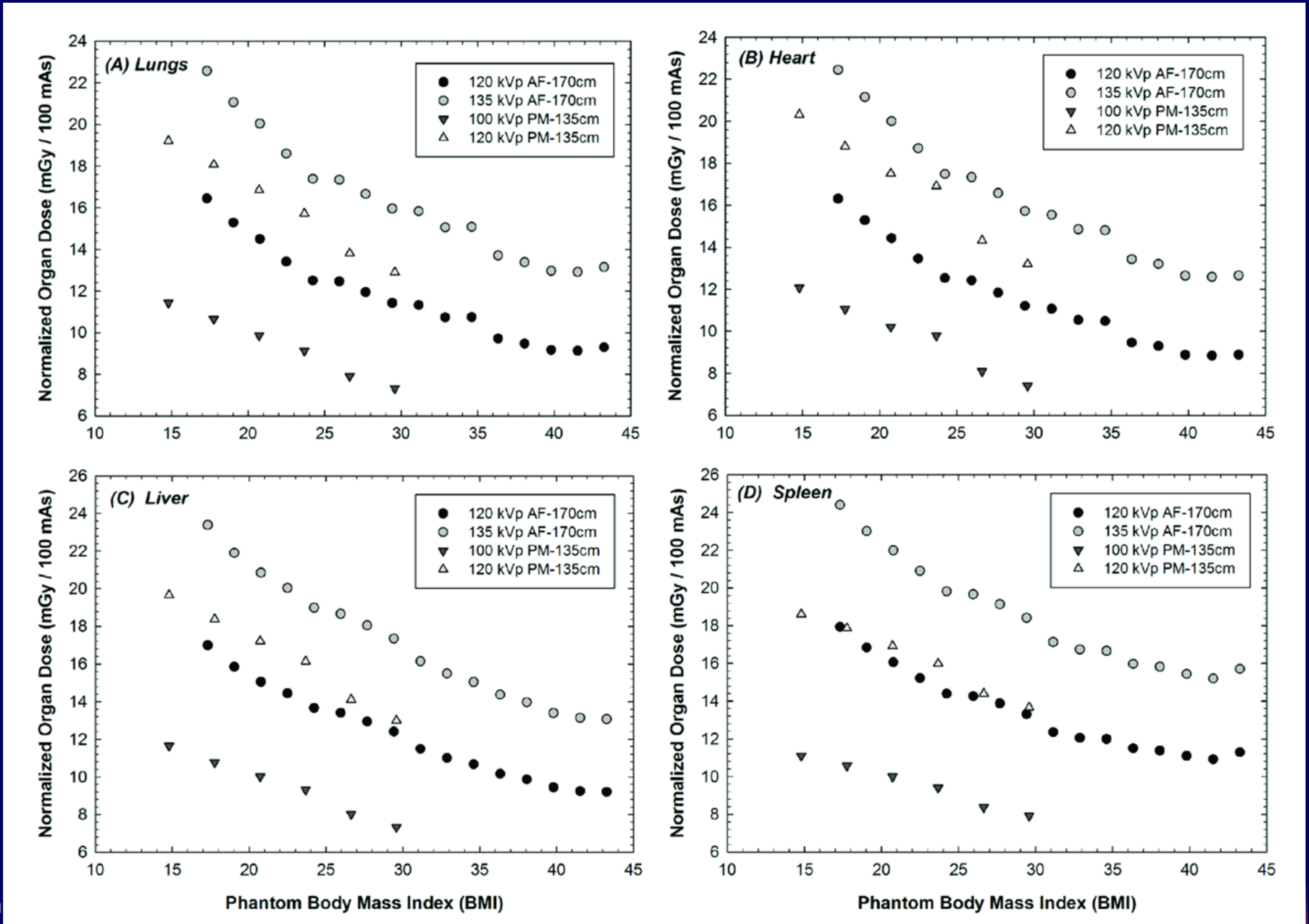




Phantom for each height/weight combination further matching average values of body circumference from CDC survey data

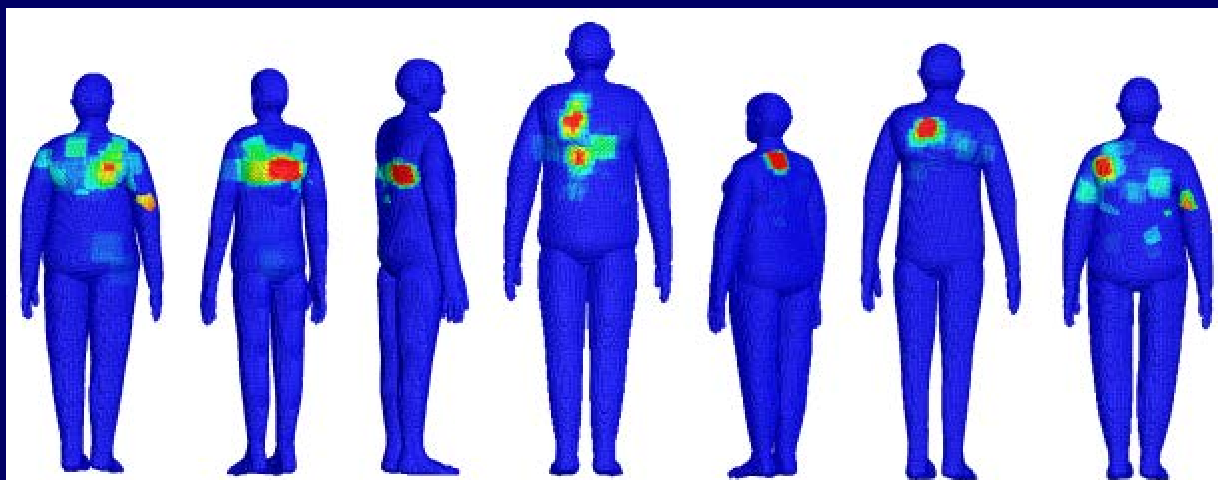
100 adult males
93 adult females

Variations in CT organ dose with BMI



Applications to Skin Dose Mapping

$$D_{skin} = \left(K_{a,r}\right) \cdot (CF) \cdot \left(\frac{d_{ref}}{d_{skin}}\right)^2 \cdot (BSF) \cdot \left(\frac{\mu_{en}}{\rho}\right)_{air}^{skin} \cdot e^{-\mu d}$$

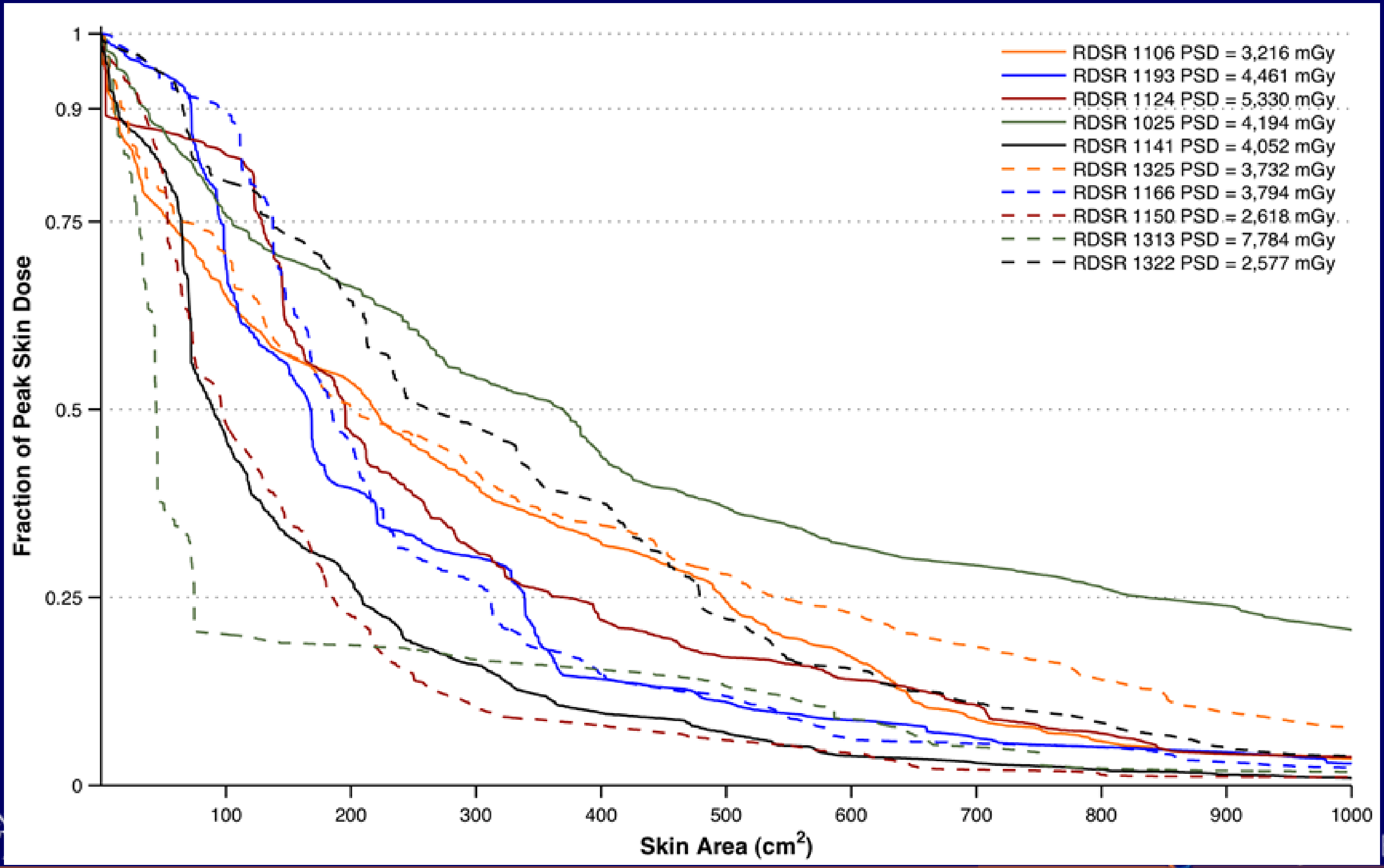


Skin Dose Maps on Morphometry Matched Hybrid Phantom

Med. Phys. 38 (10), October 2011

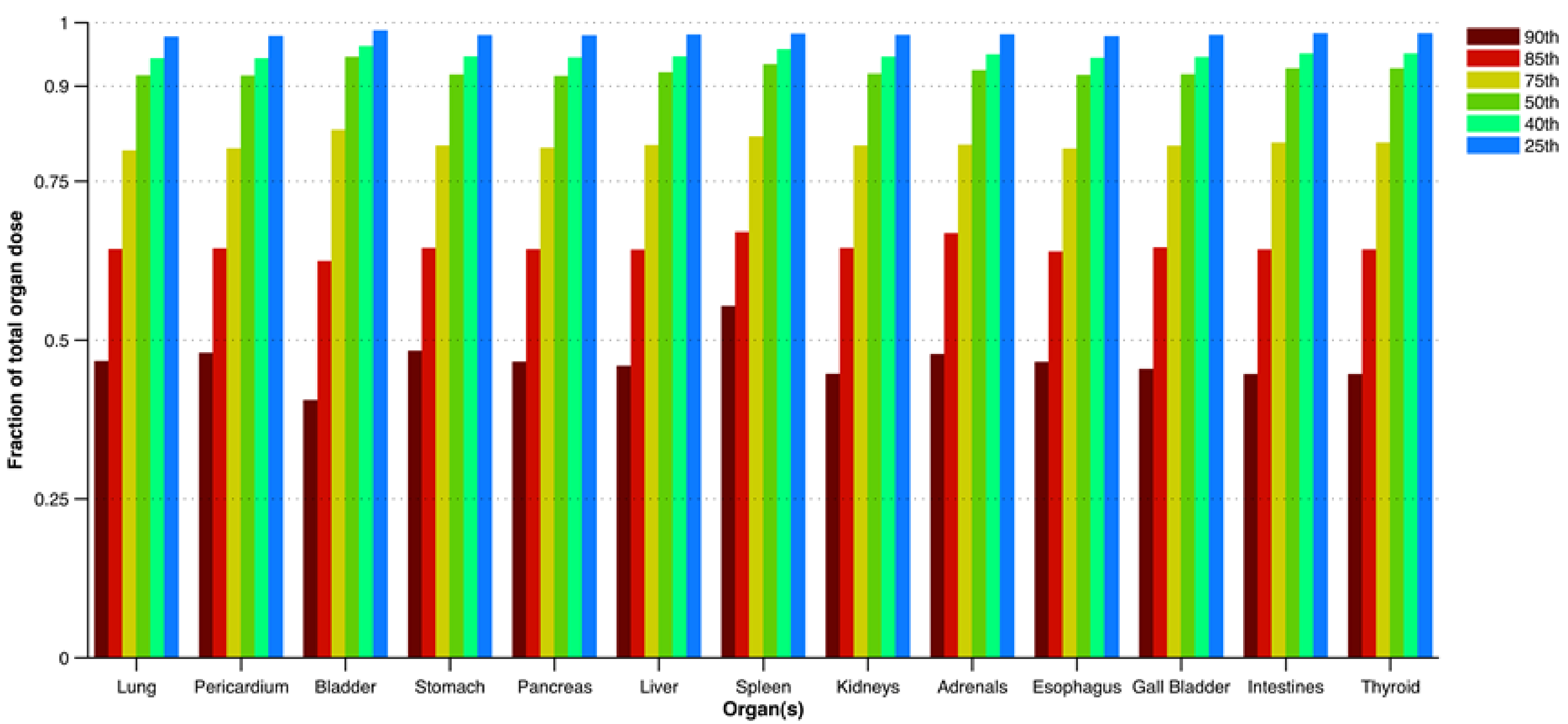
Applications to Skin Dose Mapping

$$D_{skin} = (K_{a,r}) \cdot (CF) \cdot \left(\frac{d_{ref}}{d_{skin}}\right)^2 \cdot (BSF) \cdot \left(\frac{\mu_{en}}{\rho}\right)_{air}^{skin} \cdot e^{-\mu d}$$



Applications to Organ Dosimetry

Fraction of total organ doses when considering only irradiation events that register a cumulative reference air kerma in the 90, 85, 75, 50, 40, and 25th percentile and above. Total number of irradiation events was 117.



Morphometric Categories – Patient-Sculpted Phantoms

- *The goal is to reshape the outer body contour of your reference or patient-dependent phantom to uniquely match that of the individual patient*
- *By definition, no individual changes are made to internal organs – both in terms of their relative shapes and positions.*
- *However, as the torso or sitting height is adjusted to higher or lower values, the collection of internal organ volumes in the torso are increased or decreased, accordingly. This scaling can be 1D (z), 2D (xy), or 3D (xyz)*
- *Arms and legs can be adjusted separately if the phantom is designed as such. Thus, patient total height and sitting height can be matched together.*
- *Once the sitting or torso height is matched, body thicknesses can be adjusted to uniquely match those seen in the individual patient. The additional phantom tissue volumes below the skin are then typically assigned to…*
    - ⇨ *Subcutaneous fat – OR –*
    - ⇨ *Residual soft tissues – combination of subcutaneous fat, muscle, connective tissue*

Morphometric Categories – Patient-Sculpted Phantoms

- ***Possible methods of obtaining targeted outer body contour***
  - ⇨ ***Visual coupling of patient body contour to those of an extensive phantom library. Example – patient "looks" like UF phantom 129, and so we will use that phantom for assigning organ doses in CT.***
  - ⇨ ***Make tape measurements of arm, thigh, head, chest, abdomen, pelvis circumferences. Next, one would manually or possibility automatically through Rhino script files, "rescale" the closest matched phantom from an existing library.***
  - ⇨ ***Sculpt the patient phantom using existing CT image or perhaps a IR scanning systems as used in radiotherapy. Use that body contour image to "adjust" the body contour of the closest matched phantom from an existing library. For skin dosimetry in FGI, the contour image is all that is needed for skin dose mapping.***

Morphometric Categories – Patient-Specific Phantoms

Holy Grail of Radiation Dosimetry!

- ***Cannot be done if you don't have the patient image!***

- ***Even if you have these images, the problem is <u>partial body coverage</u> and <u>segmentation</u>!***
  - ⇨ ***No global automation algorithms presently available***
  - ⇨ ***Specialized algorithms have been developed for select organs as part of TPS***

- ***However, one needs to ask the question – "How patient specific does my organ doses have to be?" In other words, what am I going to do with that dose?***

- ***If it is to be used to estimate cancer incidence risks, you need to appreciate from where these risk coefficients are derived.***
  - ⇨ ***Radiation epidemiology studies in which organ doses are crudely estimated by combinations of air kerma estimates and dose coefficients from ORNL stylized phantoms.***
  - ⇨ ***In conclusion, perhaps patient-specific phantoms are not needed, and patient-dependent libraries, with optional exterior sculpting, may be sufficient***

Thank you for your attention!