Herbert Wertheim College of Engineering
UNIVERSITY of FLORIDA

Modern Computational Phantoms and Their Applications

Joint ICRP-RERF-JHPS Workshop
Recent Progress on Radiation Dosimetry for Epidemiology and Radiological Protection
Sunday, December 2, 2017

Wesley Bolch, University of Florida
ICRP Committee 2

POWERING THE NEW ENGINEER TO TRANSFORM THE FUTURE

Presentation Objectives

1. *Review of different phantom format types – stylized, voxel, and hybrid*
2. *Current series of phantoms used and adopted by ICRP – adult, pediatric, and pregnant female*
3. *Review of different phantom morphometric categories – phantom libraries & individual-specific*
4. *Example application of phantom libraries – pediatric CT radiation epidemiology*
5. *Future phantoms from the ICRP – polygon mesh formats & tools for voxel-to-mesh conversion*

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 across areas of radiological protection**
  - *Establishing dose coefficients for internal radiation exposure*
    - *Specific absorbed fractions for both self-dose and cross-dose to internal organs are computed using computational phantoms. These SAF values are then used, along with biokinetic models and radionuclide decay schemes, to compute dose coefficients - organ equivalent dose or effective dose per activity ingested or inhaled*
  - *Establishing dose coefficients for external radiation exposure*
    - *Either occupational or environmental fields of radiation or radionuclide emissions*
  - *Computing organ doses in radiological accidents – retrospectively / prospectively*

Computational Anatomic Phantoms

Essential tool for organ dose assessment

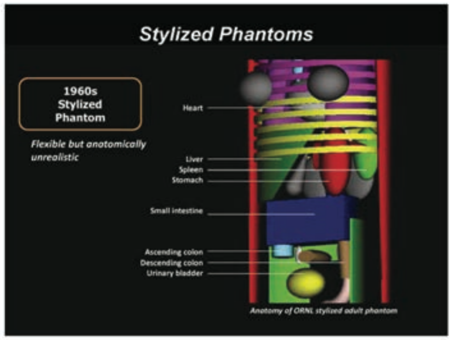
- ***Definition*** - ***Computerized representation of human anatomy for use in radiation transport simulation of the medical imaging or radiation therapy procedure***

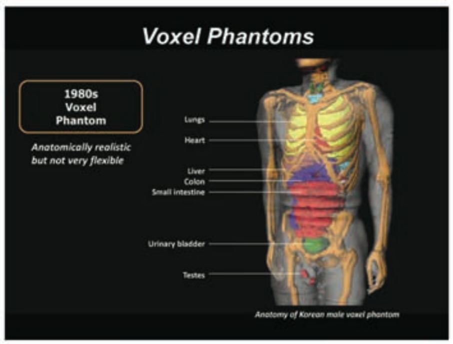
- ***Need for phantoms vary with the medical application***
  - ***Nuclear Medicine***
    - ***3D patient images generally not available, especially for children***
  - ***Diagnostic radiology and interventional fluoroscopy***
    - ***No 3D image***
  - ***Computed tomography***
    - ***3D patient 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***

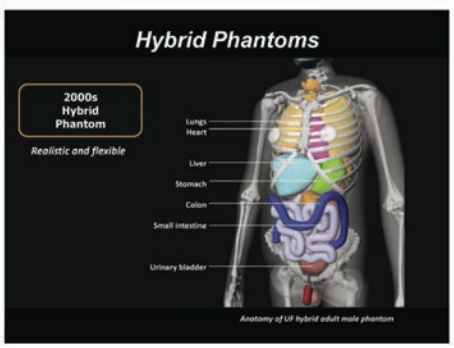
Computational Anatomic Phantoms

Phantom Types and Morphometric Categories

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







Stylized (mathematical) phantoms

Flexible but anatomically unrealistic

Voxel (tomographic) phantoms

Anatomically realistic but not very flexible

Hybrid (NURBS/Polygon Mesh) phantoms

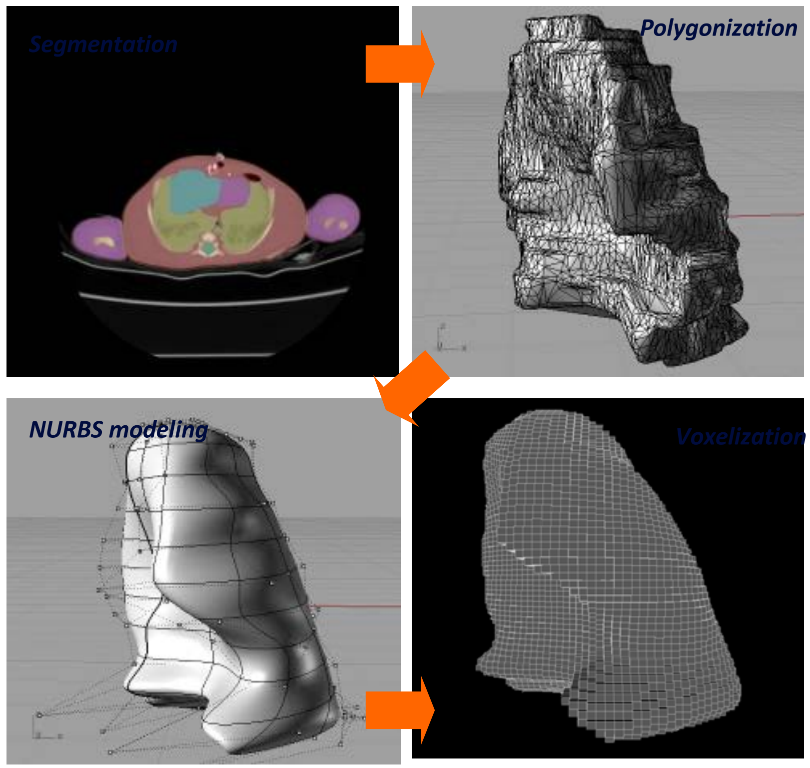
Both anatomically realistic and flexible

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)

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).***

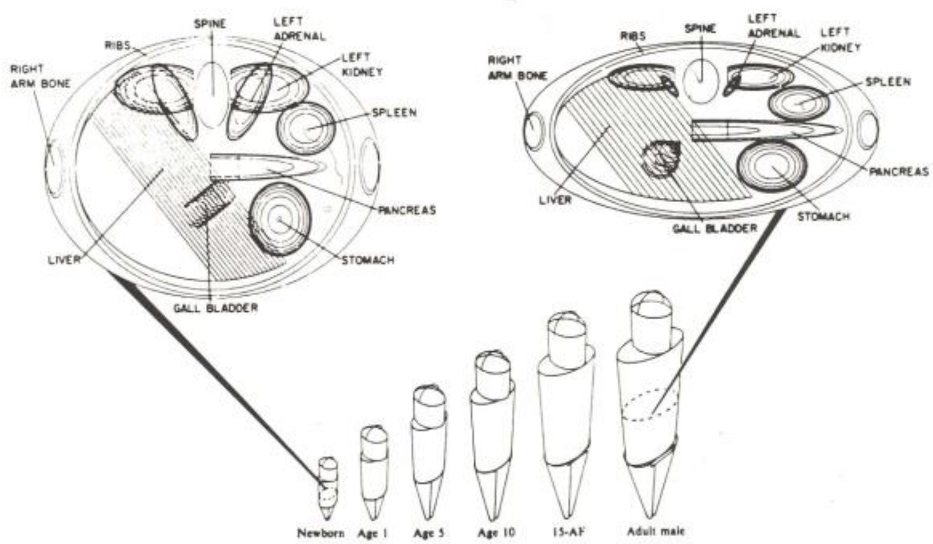
Table 2.9. Reference values for height, mass, and surface area of the total body

	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* ***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

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



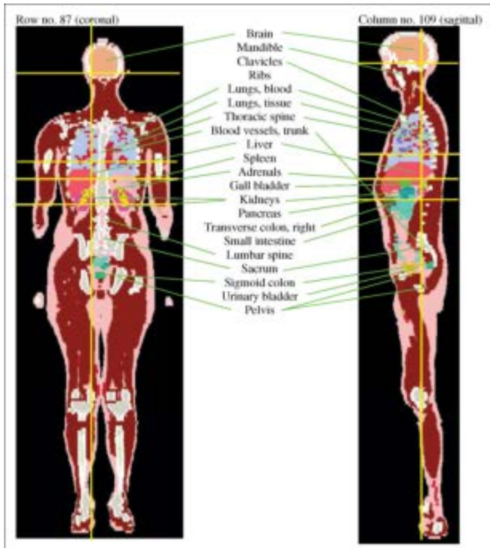
ORNL TM-8381
Cristy & Eckerman

Publications from ICRP using the Publication 110 Phantoms

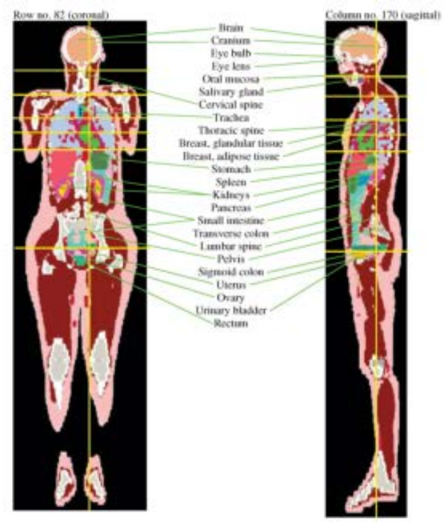
- ***ICRP Publication 116 – External Dose Coefficients (2010)***
- ***ICRU Report 84 – Cosmic Radiation Exposure to Aircrew (2010)***
- ***ICRP Publication 123 – Assessment of Radiation Exposure of Astronauts in Space (2013)***

Reference Phantoms Adopted by the ICRP

ICRP Publication 110 – Adult Reference Computational Phantoms



ICRP Reference Adult Male



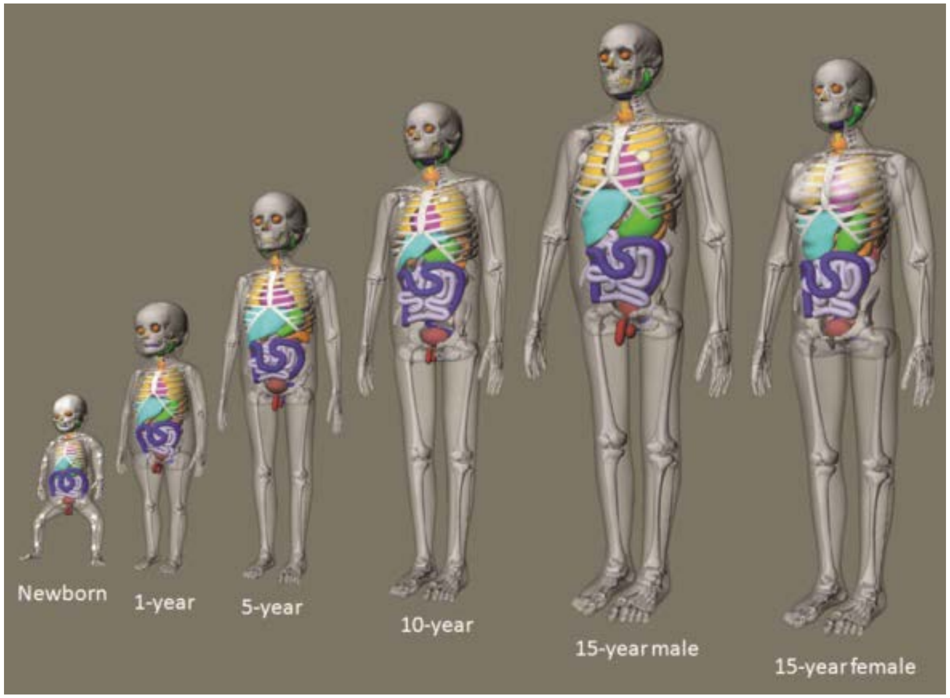
ICRP Reference Adult Female

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



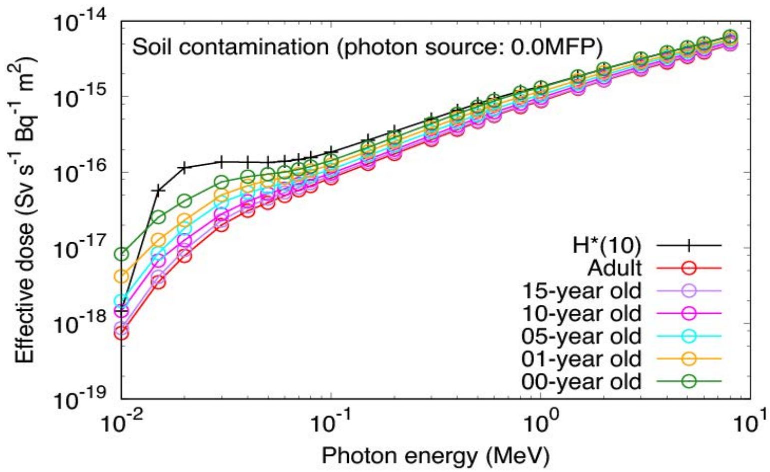
IOP Publishing
Phys. Med. Biol. 55 (2010) 339–363

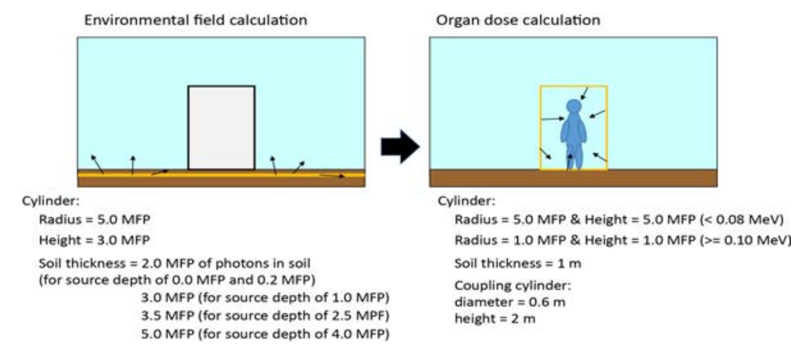
Current Publications Under Development in ICRP Committee 2 Using Pediatric Phantoms

Task Group 90
Dose Coefficients for Environmental External Exposures

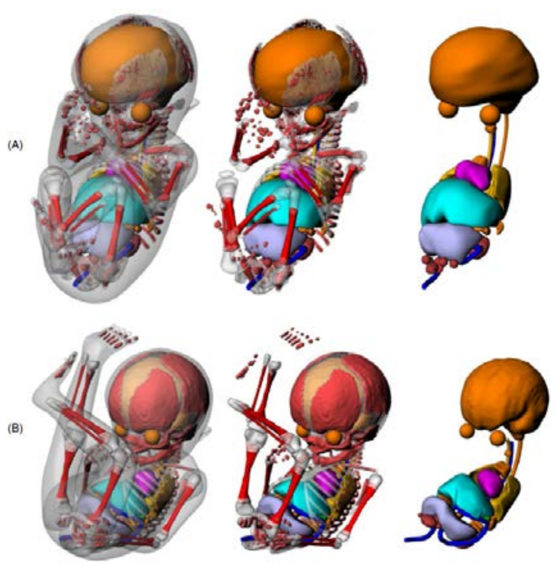
Task Group 95
Dose Coefficients for Environmental Internal Exposures

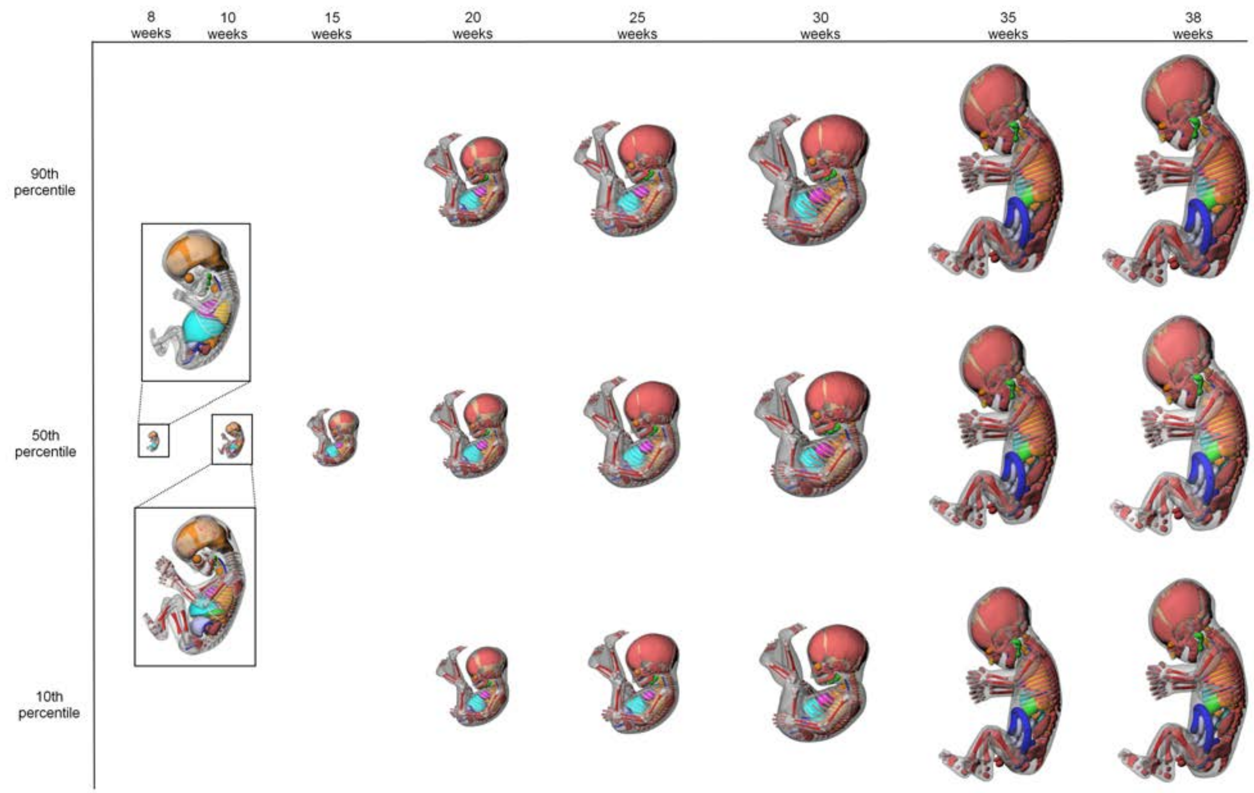
Task Group 96
Specific Absorbed Fractions for Internal Exposures



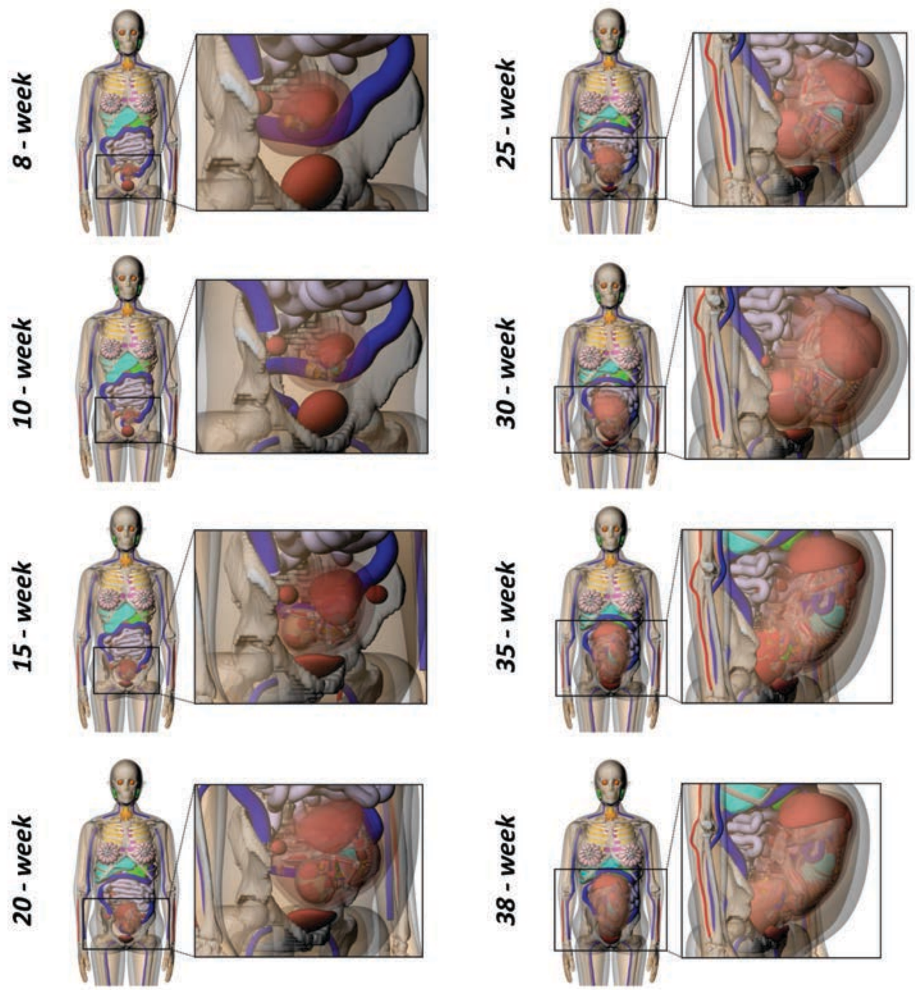


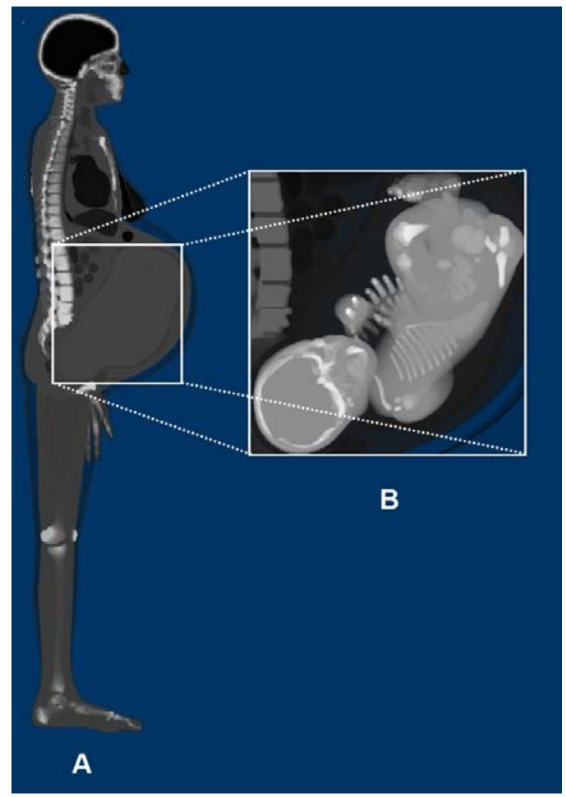
ICRP Series of Reference Fetal Models





ICRP Series of Reference Pregnant Female Models





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

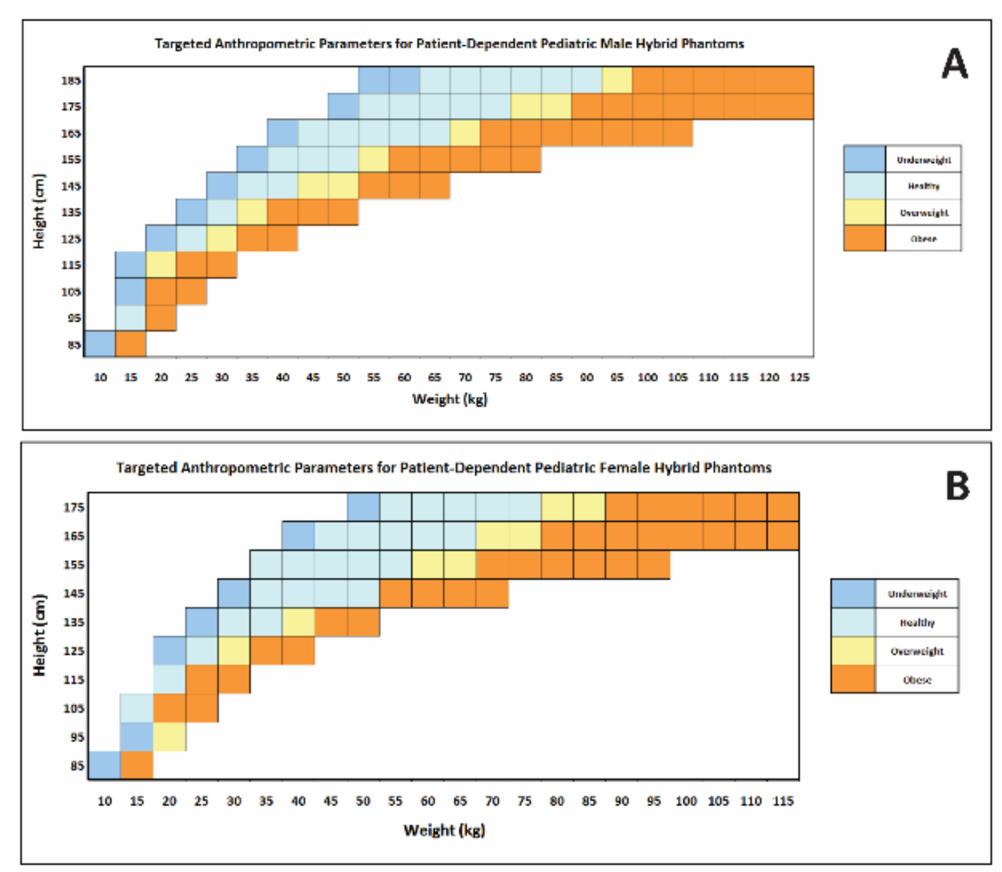
Patient-Dependent Hybrid Phantoms – UF Series

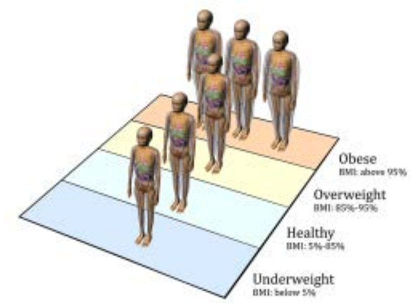
Phantom Height	Pediatric		Phantom Height	Adult	
(cm)	*Males*	*Females*	(cm)	*Males*	*Females*
185	UFHADM ⬆		190	UFHADM ⬆	
175	UFHADM ⬇	UFHADF ⬆	185	UFHADM ⬆	
165	UFH15M ⬇	UFHADF ⬆	180	UFHADM ⬆	
155	UFH15M ⬇	UFH15F ⬇	175	UFHADM ⬇	UFHADF ⬆
145	UFH10M ⬆	UFH10F ⬆	170	UFH15M ⬆	UFHADF ⬆
135	UFH10M ⬇	UFH10F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

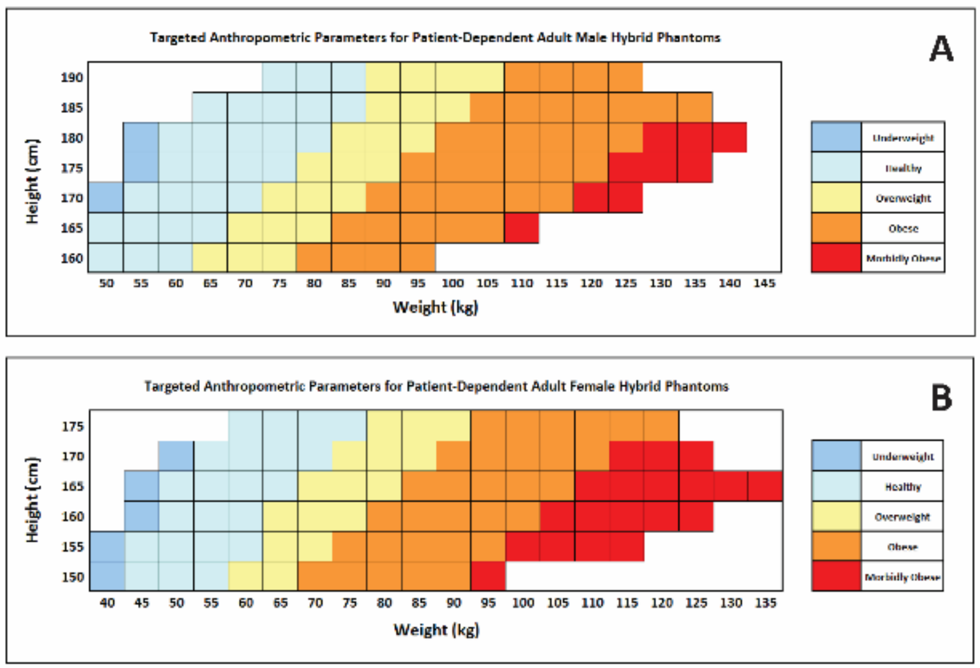


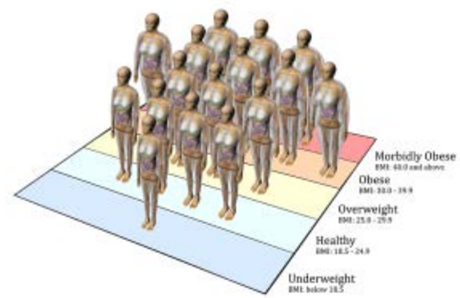


Phantom for each height/weight combination further matching average values of body circumference from CDC survey data

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

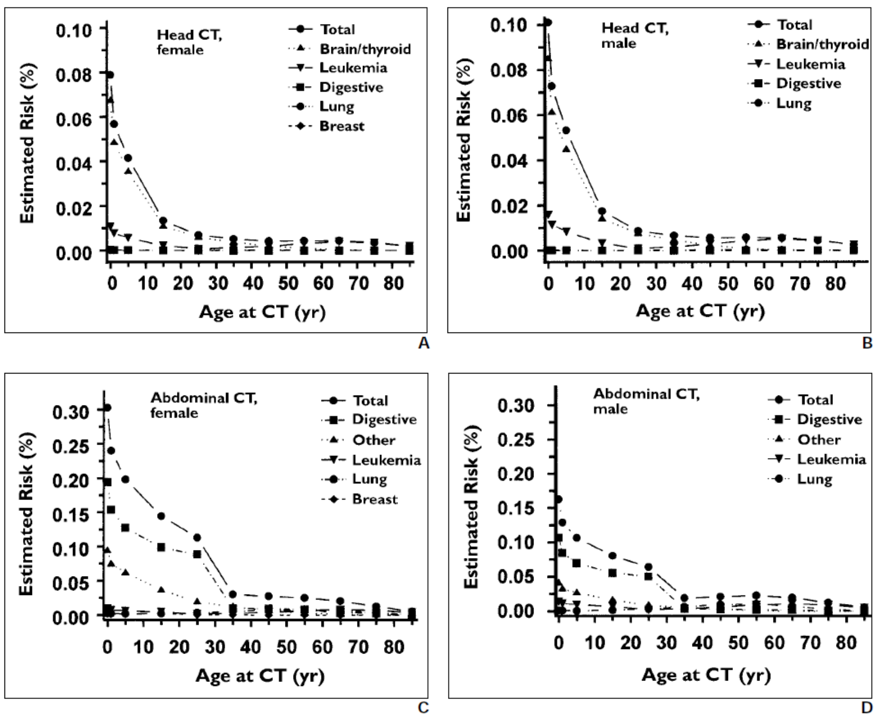
100 adult males
93 adult females

Article from Brenner et al. 2001 which changed CT imaging practice worldwide

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

The Image Gently Alliance

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.

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

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 computational methodology – Fixed Tube Current

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
Department of Medical Physics, Memorial Sloan Kettering Cancer Center, 1275 York Avenue, New York, NY 10065, USA

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

Med. Phys. 44 (10), October 2017

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

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

CT computational methodology – Modulated Tube Current

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

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

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

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

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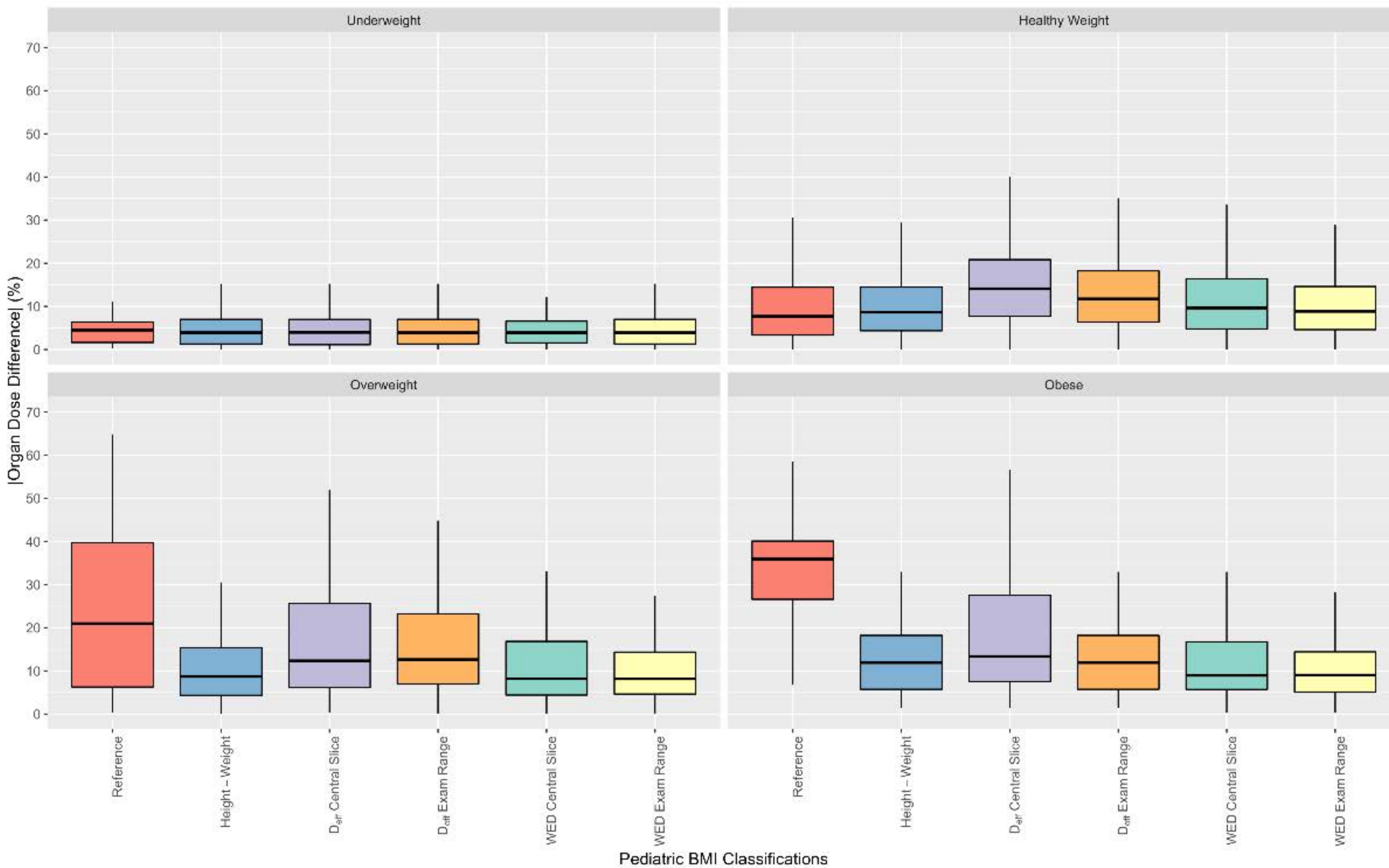
Daniel J. Long
Department of Medical Physics, Memorial Sloan Kettering Cancer Center, 1275 York Avenue, New York, NY 10065, USA

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

Med. Phys. 44 (10), October 2017

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.



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*

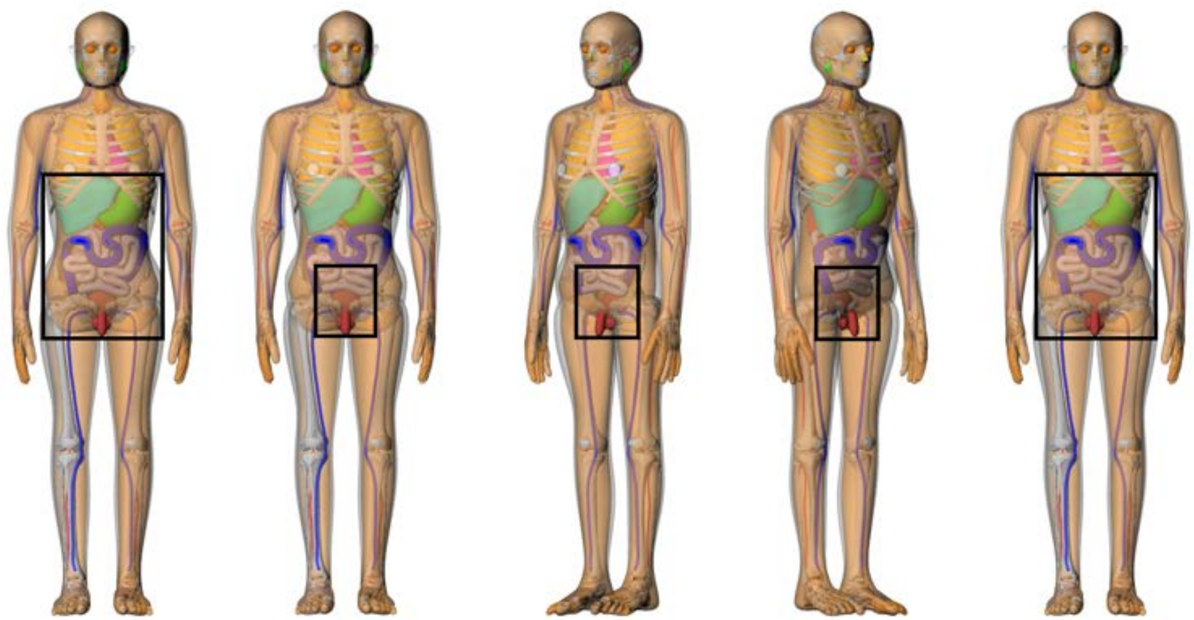


Image 1: 5% Time: 6 s	Image 2: 9% Time: 10.8 s	Image 3: 8% Time: 9.6 s	Image 4: 8% Time: 9.6 s	Image 5: 16% Time: 19.2 s
Contrast: None	**Contrast:** 50% concentration bladder	**Contrast:** 50% concentration bladder	**Contrast:** 50% concentration bladder	**Contrast:** 100% concentration bladder

Iodine Contrast →

3. Organ Dose Reconstruction in Diagnostic Nuclear Medicine

Data Collection – 2006 to 2017
Data Collection – 1996 to 2006

Radimetrics
Data Abstraction

Patient Data
Study ID
Age
Gender
Height
Weight

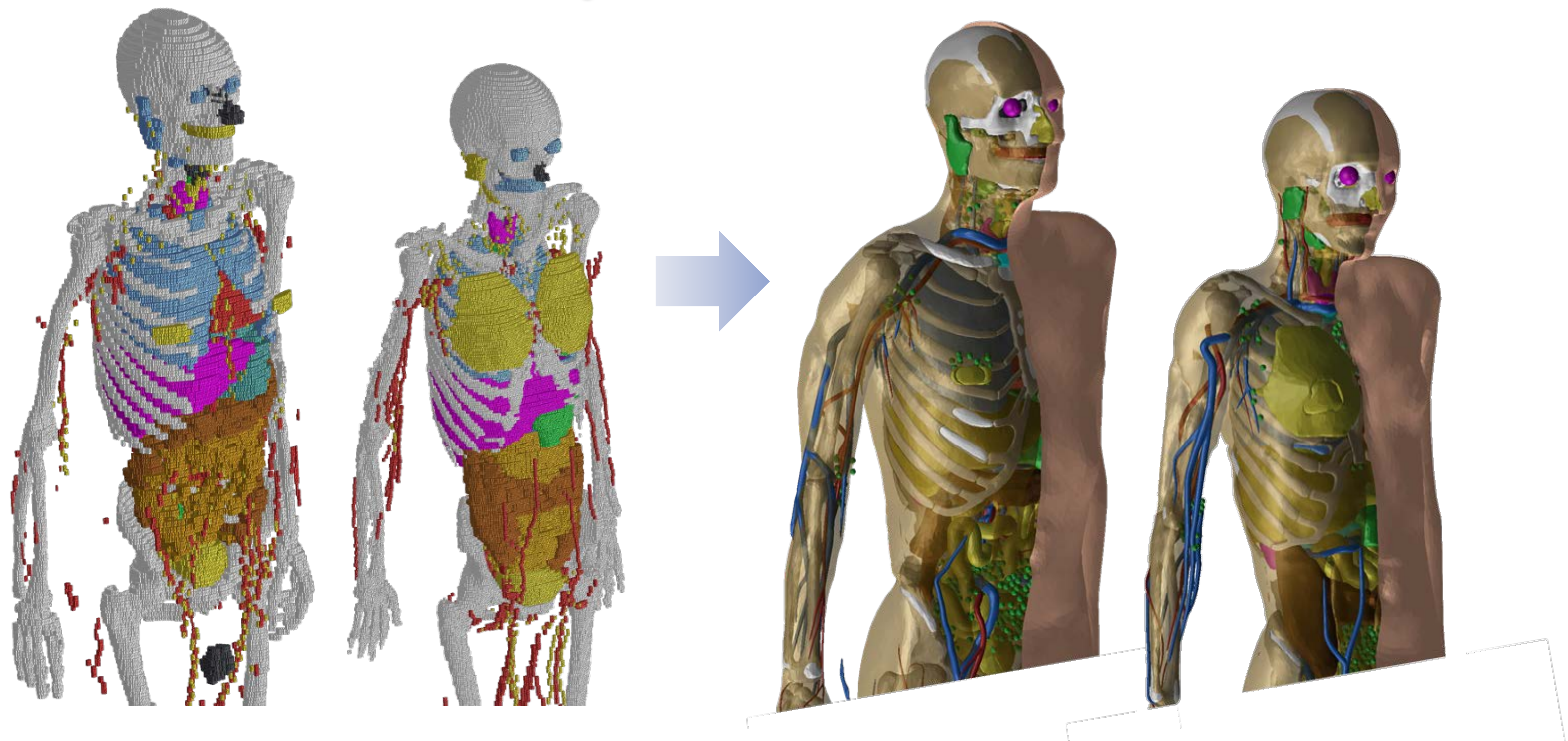
NM Procedure Details
Procedure type (1 to 6)
Administered Activity

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*

Committee 2 Task Group 103



VRCPs
(Voxel-type Reference Computational Phantoms)
(ICRP Publication 110)

MRCPs
(Mesh-type Reference Computational Phantoms)

Figure courtesy of CH Kim – TG 103 Chair

Computation Speed - PHITS

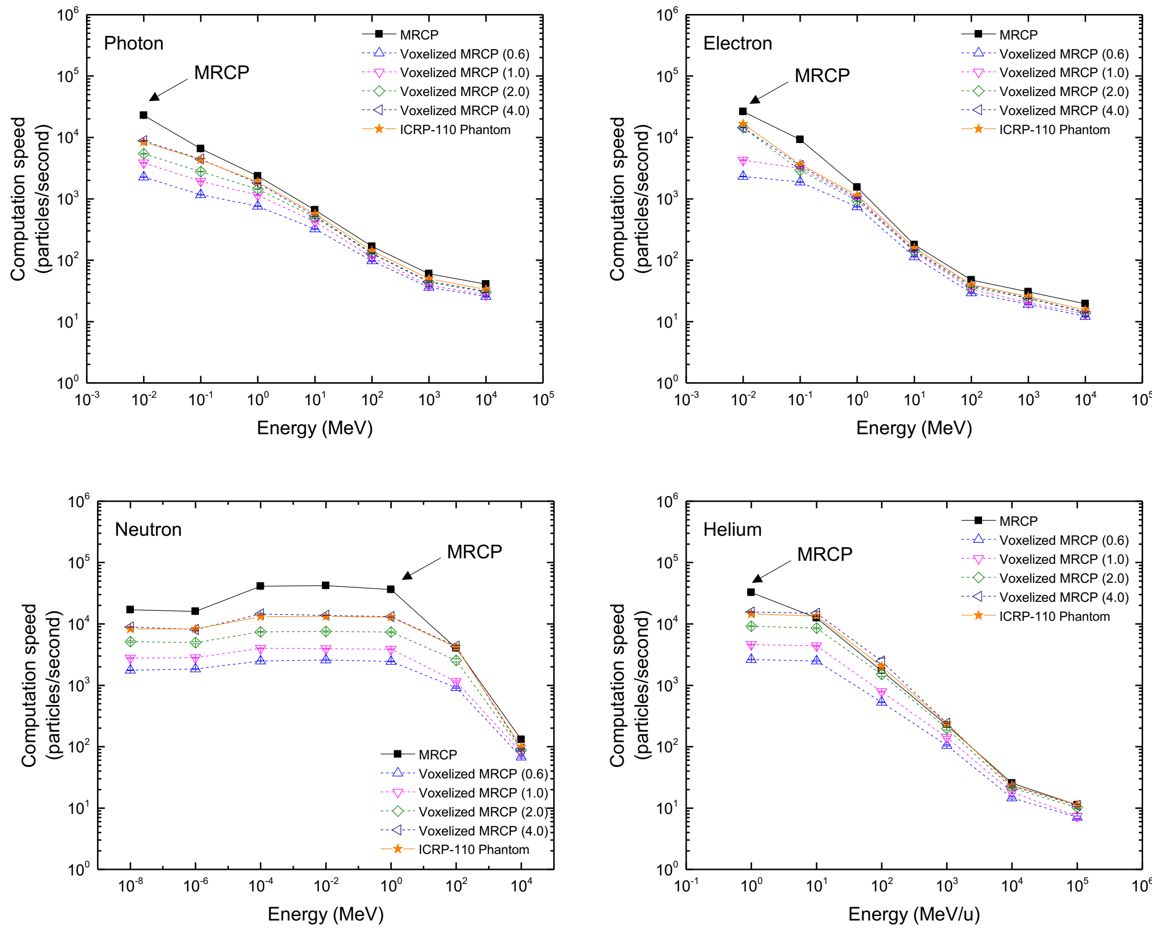
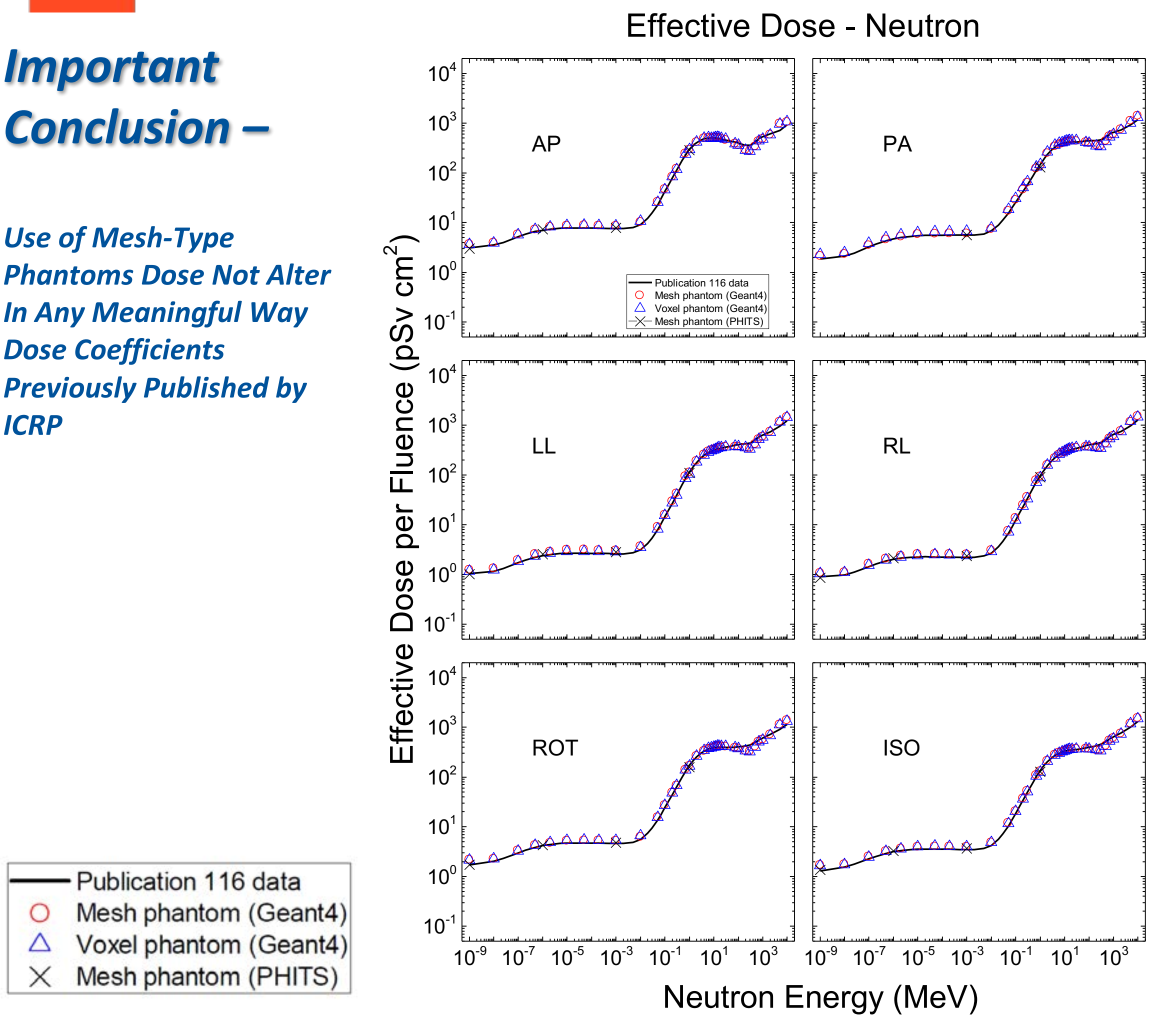
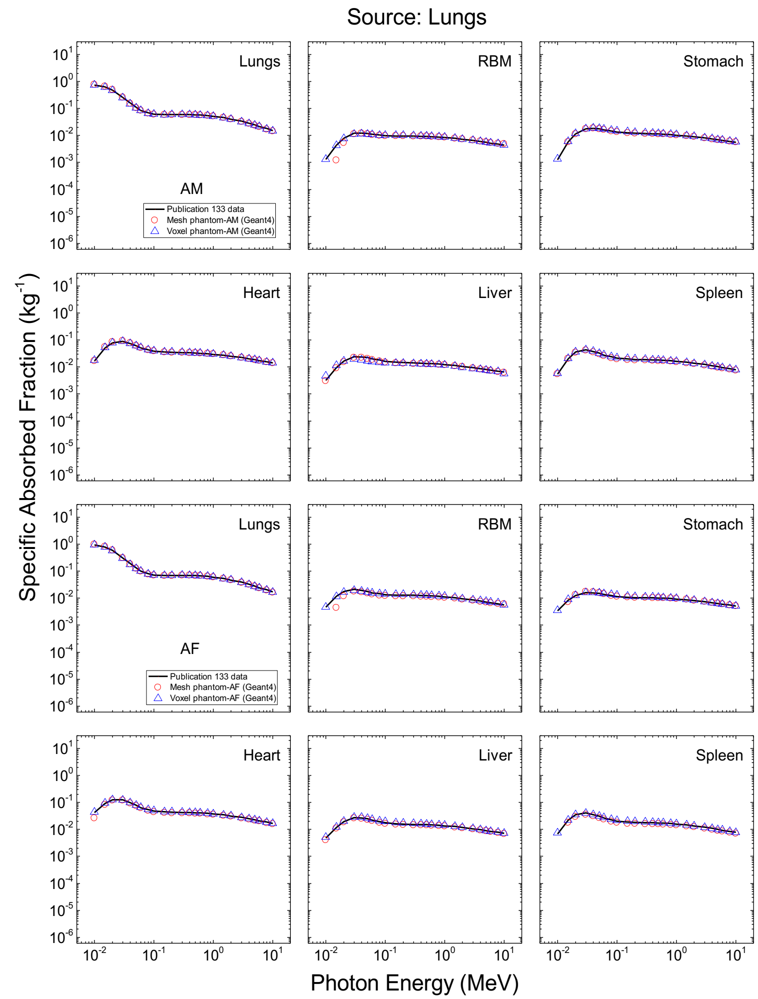


Figure courtesy of CH Kim – TG 103 Chair

Important Conclusion –

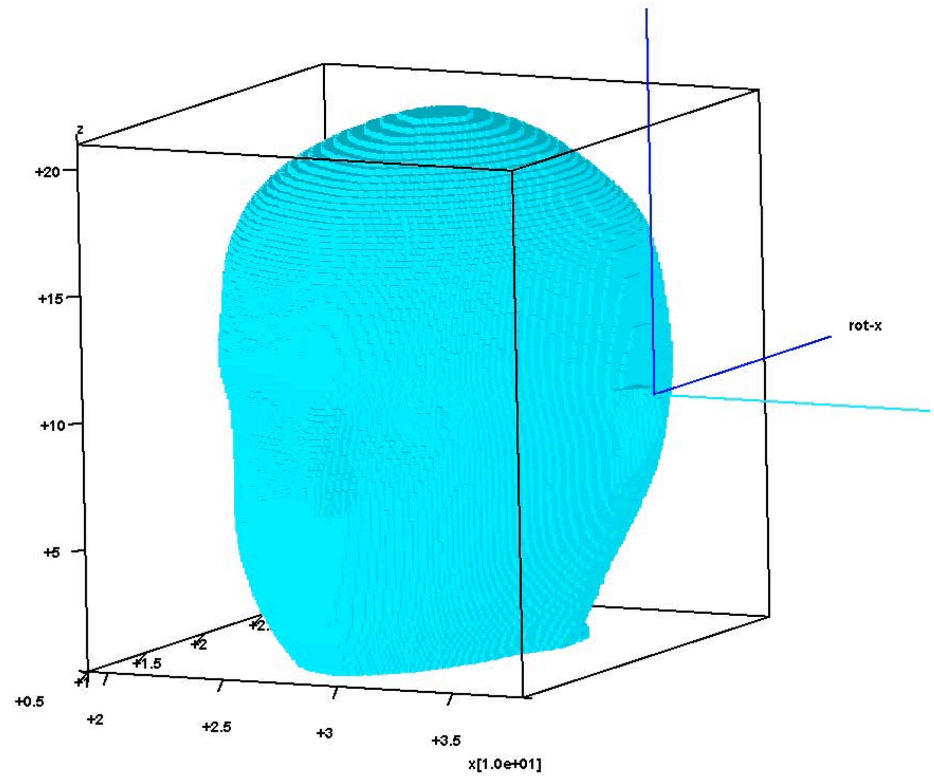
Use of Mesh-Type Phantoms Dose Not Alter In Any Meaningful Way Dose Coefficients Previously Published by ICRP





Recently Developed Voxel to TM Algorithm

- *Successful conversion of voxel phantom to surface meshed phantom with unique vertices*
- *Surface mesh ready for Tetgen™ to generate tetrahedral mesh*
- *Joint collaboration between UF and JAEA (manuscript in preparation)*



Thank you for your attention!

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