Voluntary versus Mandatory Standards

Education, Standardization, Regulation

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Radiation Dosimetry Standards

Two aspects to consider in standardization of patient dosimetry

- *Anatomic model of the patient*
  - *Outer body contour*
  - *Organ sizes / masses*
  - *Organ shapes, depths, and positions within the body*
- *Geometric model of the patient examination*
  - *External radiation sources – Computed Tomography and Fluoroscopy*
  - *Internal radiation sources – Source Tissues for Radiopharmaceuticals*

Anatomic Models

Ideal situation…

Use the diagnostic image of the patient as the anatomic model to estimate the doses received by the diagnostic image!

Such "patient-specific" anatomic models can and are used…

- *Research-level nuclear medicine codes where the CT portion of the SPECT/CT or PET/CT is used for radiation transport simulation.*
- *Same can be used for diagnostic CT imaging, although this is not common*
- *Problems of image-based patient-specific models include…*
- *Lack of whole-body coverage in many cases*
- *Need to segment those images to quantify organ doses*

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 typically 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

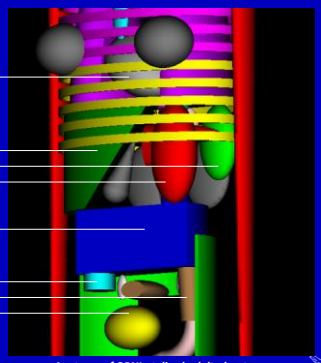
Phantom Types and Categories

- ***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)*

Format Types - Stylized Phantoms

1960s Stylized Phantom

Flexible but anatomically unrealistic

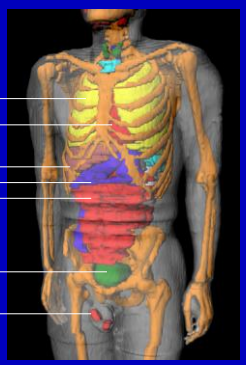


Anatomy of ORNL stylized adult phantom

Format Types - Voxel Phantoms

1980s Voxel Phantom

Anatomically realistic but not very flexible

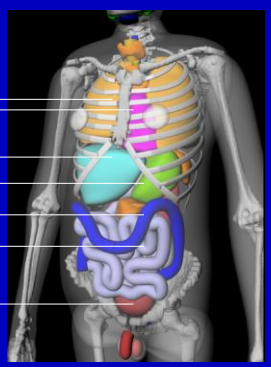


Anatomy of Korean male voxel phantom

Format Types – Hybrid Phantoms

2000s Hybrid Phantom

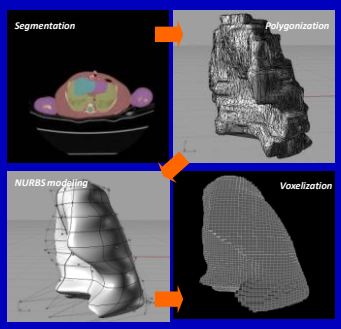
Realistic and flexible



Anatomy of UF hybrid adult male phantom

Format Types – Hybrid Phantoms

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

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).

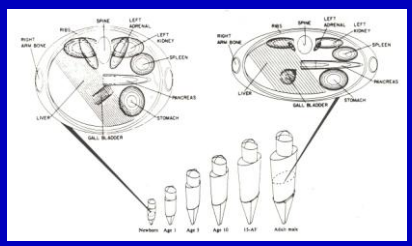
Table 2.9. Reference values for height, mass, and surface area of the total body

	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

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

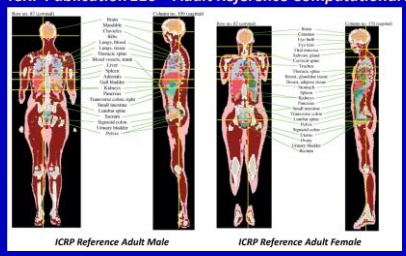


ORNL TM-8381
Cristy & Eckerman

One exception is ICRP Publication 74 on external dose coefficients
Reference data taken from a variety of both stylized and voxel phantoms

Reference Phantoms Adopted by the ICRP

ICRP Publication 110 – Adult Reference Computational Phantoms

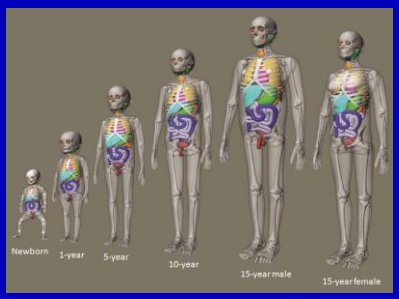


Upcoming Publications from ICRP using the Publication 110 Phantoms

- Reference dose conversion coefficients (DCC) for external radiations (revision of ICRP 74)
- Reference DDC for space radiation environments
- Reference DCC for aircrew exposures
- Reference absorbed fractions (AF) for internal dose coefficients / nuclear medicine

Reference Phantoms Adopted by the ICRP

In September 2008, 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)

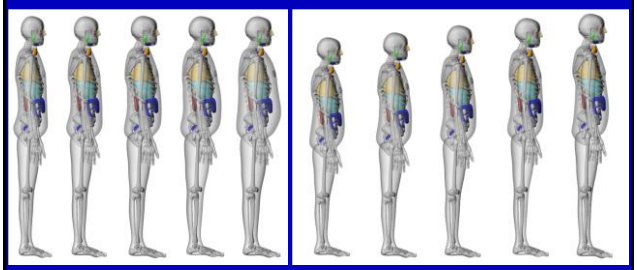
NHANES - based UFHADM

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

Patient Dependent Phantoms – Adult Males

Standing Height cm	Weight kg	Avg Sitting Height cm	Arm Circumference cm	Waist Circumference cm	Buttocks Circumference cm	Thigh Circumference cm
163.7 (10%)	57.6 (10%)	86.1	27.7	79.2	87.2	44.3
	62.9 (25%)		29.6	85.5	90.7	47.2
	69.4 (50%)		30.8	93.9	94.0	47.5
	76.9 (75%)		32.2	100.0	97.4	49.2
	85.0 (90%)		34.9	108.6	103.9	52.5
168.2 (25%)	60.8 (10%)	88.1	28.4	81.4	88.8	45.3
	66.7 (25%)		30.1	87.4	92.0	47.1
	74.3 (50%)		32.0	94.2	96.5	49.5
	82.9 (75%)		34.6	100.1	101.1	53.2
	91.6 (90%)		35.8	109.1	106.4	54.8
173.2 (50%)	64.1 (10%)	90.2	28.9	82.0	90.3	46.0
	70.7 (25%)		30.8	87.8	93.8	48.6
	78.4 (50%)		32.2	95.6	98.0	50.5
	87.0 (75%)		34.4	101.2	103.1	53.0
	97.3 (90%)		36.3	112.4	107.6	55.4
178.3 (75%)	67.9 (10%)	92.4	29.0	81.1	91.7	47.0
	74.8 (25%)		31.3	86.4	95.1	50.5
	82.3 (50%)		32.6	95.2	99.3	51.3
	92.9 (75%)		35.3	104.1	104.7	54.0
	102.0 (90%)		36.8	112.4	112.1	57.0
182.8 (90%)	69.8 (10%)	94.2	29.6	82.5	92.7	47.3
	77.1 (25%)		31.5	87.4	96.0	50.4
	87.0 (50%)		33.3	98.1	102.2	52.7
	98.3 (75%)		36.0	104.2	105.8	55.0
	109.9 (90%)		38.6	110.7	114.1	59.7

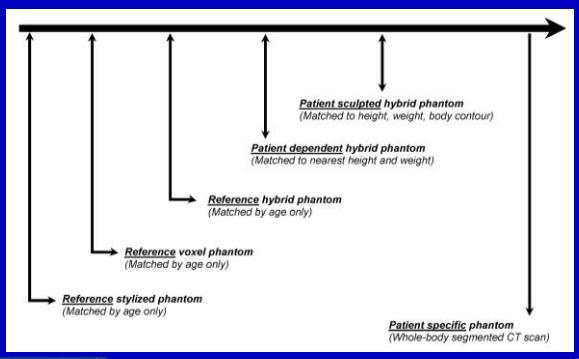
Patient Dependent Phantoms – Adult Males



Same height / different weights *Same weight / different heights*

Continuum of Anatomic Specificity

Pre-computed dose library ↔ *Patient-specific dose calculation*



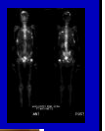
Geometric Models – Nuclear Medicine

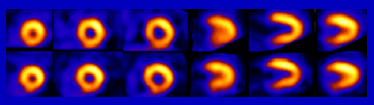
The radiation sources in nuclear medicine are the tissues / organs in which the radiopharmaceutical localizes.

The time-dependent amount of the radiopharmaceutical in a given source organ is determined almost exclusively by direct imaging and is thus patient specific

The imaging is either 2D or 3D..

- *Single or Dual Headed Gamma Cameras – 2D*
- *Single Photon Emission Computed Tomography – 3D*
- *Positron Emission Tomography – 3D*





MIRD Schema

Time-Dependent Mean Absorbed Dose Rate

Absorbed dose rate to a tissue region at time t post-administration

$$\dot{D}(r_T,t) = \sum_{r_S} A(r_S,t)\ S(r_T \leftarrow r_S,t)$$

where r_T *is the target tissue region*
r_S *is the source tissue region*

$A(r_S,t)$ - *radiopharmaceutical activity in* r_S *at time t*
(radionuclide decays per unit time at time t)

$S(r_T \leftarrow r_S,t)$ - *radionuclide S value at time t*
(absorbed dose to r_T *per decay in* r_S *at time t)*

r_S / r_T *may represent organ, suborgan tissue, image voxel, tumor, cell compartments*

Geometric Models – Computed Tomography

The radiation source in CT is a rotating fan / cone beam externally incident on the patient

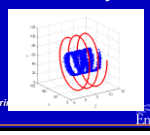
Typical exams include: Head, Chest, Abdomen, Pelvis, AP, and CAP

Source term models can be generated by measuring HVL and radial dose profiles at the isocenter – unique to each CT scanner make/model

Existing codes are based on pre-computed organ doses for 10-mm axial slices / user then "sums" the organ doses across the imaged anatomy

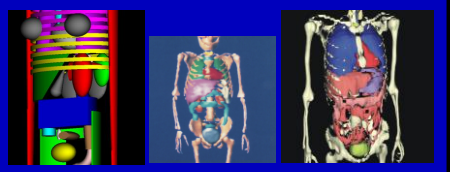
Important to scale these doses by some physical measurement – typically, the $CTDI_w$

Current research – development of algorithms to model modern-day tube current modulation schemes



Existing Organ Dose Databases for CT

- Two established in the early 1990s
  - National Radiation Protection Board (NRPB) in the UK
  - National Research Center for Environmental Health (GSF) in Germany
- NRPB Database – based upon ORNL stylized phantom series
- GSF Database – based upon two pediatric voxel phantoms and stylized adult phantoms
- Currently available software for CT organ dosimetry are primarily based upon one of these two organ dose databases
  - CT-Expo
  - CT Dosimetry
  - CT Dose
  - WinDose
  - ImPACT



ORNL Adult | GSF - BABY | GSF - CHILD

Geometric Models – Fluoroscopically Guided Interventions

The radiation sources in FGI are one or two projection x-ray fields that can change with the angulation, tube voltage, tube current, and field size.

Current practice –

- Organ doses assessed using dose conversion coefficients – organ dose per unit entrance skin dose or air kerma
- Skin doses assessed by using the reference point air kerma defined as the air kerma at 15 cm from isocenter on the x-ray tube side

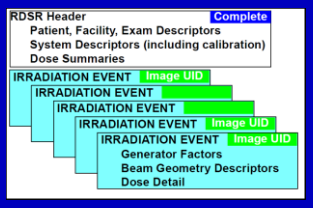
Future potential –

- Radiation Dose Structured Report – RDSR – a new DICOM standard file

Geometric Models – Fluoroscopically Guided Interventions

DICOM Radiation Dose Structured Report (RDSR)

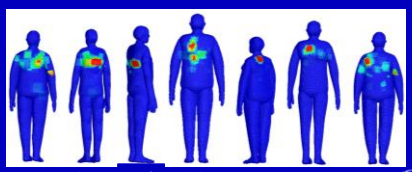
- DICOM object – independent of image
- Can be managed like other DICOM objects
- Expandable format with all public fields
- Near real-time streaming included in specification



Geometric Models – Fluoroscopically Guided Interventions

Streaming RDSR – Would provides for real-time monitoring of skin dose

Post-procedure RDSR – Would provide the geometric model for exam-specific organ doses via Monte Carlo simulation



Conclusions

- *Recent advances in computational phantoms – in particular, patient-dependent hybrid phantoms, provide a rich library of body morphometry models for which pre-computed organ dose databases can be constructed*
- *Techniques for implementing appropriate geometric models of organ irradiation for both nuclear medicine and CT imaging are well established*
- *The release of the new DICOM standard RDSR will soon permit standardized methods of organ dosimetry in fluoroscopically guided interventions*