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

- Heart
- Liver
- Spleen
- Stomach
- Small intestine
- Ascending colon
- Descending colon
- Urinary bladder

Anatomy of ORNL stylized adult phantom
## Selective History of Stylized Phantoms

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Format Types - Voxel Phantoms

1980s Voxel Phantom

Anatomically Realistic but not very flexible

- Lungs
- Heart
- Liver
- Colon
- Small intestine
- Urinary bladder
- Testes

Anatomy of Korean male voxel phantom
# Selective History of Voxel Phantoms

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Format Types – **Hybrid Phantoms**

2000s
Hybrid
Phantom

Realistic and flexible

Anatomy of UF hybrid adult male phantom
## Selective History of Hybrid Phantoms

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# Selective History of Hybrid Phantoms

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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

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>
<thead>
<tr>
<th>Age</th>
<th>Height (cm)</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Male</td>
<td>Female</td>
</tr>
<tr>
<td>Newborn</td>
<td>51</td>
<td>51</td>
</tr>
<tr>
<td>1 year</td>
<td>76</td>
<td>76</td>
</tr>
<tr>
<td>5 years</td>
<td>109</td>
<td>109</td>
</tr>
<tr>
<td>10 years</td>
<td>138</td>
<td>138</td>
</tr>
<tr>
<td>15 years</td>
<td>167</td>
<td>161</td>
</tr>
<tr>
<td>Adult</td>
<td>176</td>
<td>163</td>
</tr>
</tbody>
</table>

*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.

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.
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
### Morphometric Categories – Patient Dependent Phantoms

#### Patient-Dependent Hybrid Phantoms – UF Series

<table>
<thead>
<tr>
<th>Phantom Height (cm)</th>
<th>Pediatric Males</th>
<th>Pediatric Females</th>
<th>Phantom Height (cm)</th>
<th>Adult Males</th>
<th>Adult Females</th>
</tr>
</thead>
<tbody>
<tr>
<td>185</td>
<td>UFHADM</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>175</td>
<td>UFHADM</td>
<td>UFHADF</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>165</td>
<td>UFH15M</td>
<td>UFHADF</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>155</td>
<td>UFH15M</td>
<td>UFH15F</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>145</td>
<td>UFH10M</td>
<td>UFH10F</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>135</td>
<td>UFH10M</td>
<td>UFH10F</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>125</td>
<td>UFH10M</td>
<td>UFH10F</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>115</td>
<td>UFH05M</td>
<td>UFH05F</td>
<td></td>
<td></td>
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<tr>
<td>105</td>
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<td>UFH05F</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>95</td>
<td>UFH05M</td>
<td>UFH05F</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>85</td>
<td>UFH01M</td>
<td>UFH01F</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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

(A) Lungs

(B) Heart

(C) Liver

(D) Spleen
Applications to Skin Dose Mapping

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

Skin Dose Maps on Morphometry Matched Hybrid Phantom

Med. Phys. 38 (10), October 2011
Applications to Skin Dose Mapping

\[ D_{\text{skin}} = \left( K_{a,r} \right) \cdot (CF) \cdot \left( \frac{d_{\text{ref}}}{d_{\text{skin}}} \right)^2 \cdot (BSF) \cdot \left( \frac{\mu_{en}}{\rho} \right)^{\text{skin}}_{\text{air}} \cdot e^{-\mu d} \]
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 25\textsuperscript{th} 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 partial body coverage and segmentation!**
  - 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!