Hybrid Computational Phantoms for Medical Dose Reconstruction

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NCI Conference on Late Health Effects of Ionizing Radiation
Georgetown University, Washington, DC
May 4, 2009
**NCRP Report 160**

**Ionizing Radiation Exposure of the US Population**

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**Early 1980s**

- ~15% medical
- 0.53 out of 3.6 mSv

**2006**

- ~48% medical
- 3.0 out of 6.2 mSv

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*Example Pie Chart*

- Radon (55%)
- Medical (48%)
- Other background (13%)
- Interventional (7%)
- Radiographic / Fluoroscopic (5%)
- Nuclear medicine (12%)
- Diagnostic (11%)

---

*Example 2 Pie Chart*

- Radon (37%)
- Other background (13%)
- Consumer / Occupational / Industrial (2%)
- Radiographic / Fluoroscopic (5%)
- Interventional (7%)
- Nuclear medicine (12%)
- Diagnostic (11%)

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*Embedding Kartik Image for University of Florida*

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*Embedding Kartik Image for Nuclear and Radiological Engineering*
The report does not, however, "attempt to quantify the associated health risks nor specify the actions that should be taken in light of these latest data," and AAPM experts are cautioning that these data do not necessarily indicate that the U.S. population is at any higher risk due to this increased use of medical imaging. They caution that the new report should not deter patients from getting medically-appropriate imaging exams. The NCRP findings on average population dose could be easily misinterpreted if applied to an individual patient’s medical situation.
Impetus from NCRP 160 on Medical Dosimetry

Retrospective Dosimetry Studies

• Radiation epidemiological studies
• Quantifying past exposures and construction of dose-response correlations
• Emphasis on pediatric exposures

• Examples - NCI Radiation Epidemiological Branch
  ➤ Study of pediatric CT imaging
    • Retrieval of pediatric imaging records in the UK
    • Phase I – Cohort study of 200,000 individuals (1985 to 2002)
    • Phase II – Nested case control study of 1000 individuals
    • Leukemia, brain, thyroid, breast cancers
  ➤ Childhood Cancer Survivor Study (CCSS)
Impetus from NCRP 160 on Medical Dosimetry

Prospective Dosimetry Studies

• Assignment of organ doses under specific imaging protocols
• Optimization of patient dose versus image quality

• Example – Pediatric Nuclear Medicine Imaging
  → Survey of 13 major pediatric hospitals (JNM 2008; 49:1024–1027)
    • 16 radiopharmaceutical examinations were surveyed
    • Minimum / maximum activity
    • Activity per unit body mass or body surface area
  → Conclusions
    • Maximum variations – factor of 8.5 in amount administered
    • Average variation – factor of 3

• Recording of individual doses in electronic medical records
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 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 (generally limited to those defined in ICRP 89)
  - Patient-specific (phantom uniquely matching patient morphometry)
  - Patient-dependent (expanded library of reference phantoms)
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
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
Hybrid Phantoms

2000s Hybrid Phantom

Realistic and flexible

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

Anatomy of UF hybrid adult male phantom

Nuclear and Radiological Engineering
Hybrid Phantoms

Stylized phantom
Mathematical Flexibility (NURBS surface)

Control Point
Control Polygon
Non-Uniform Rational B-Spline

Hybrid phantom

Tomographic phantom
Anatomical Realism (CT images of patient)
Hybrid Phantoms

Reference organ mass
(ICRP Publication 89)

Reference organ composition
(ICRU Report 46 & ICRP Publication 89)

Reference intestine
(ICRP Publication 100)

Reference anthropometry
(NHANES data)
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

Segmentation

Polygonization

NURBS modeling

Voxelization
Hybrid Phantoms

(a) Original Voxel  (b) Polygon Mesh  (c) NURBS  (d) Revoxelized (2x2x2 mm³)  (e) Revoxelized (1x1x1 mm³)

Realism  Flexibility
## Hybrid Phantoms

Creation of ICRP pediatric reference series

<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>

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

Newborn Male  Newborn Female
1-year Male  1-year Female
5-year Male  5-year Female
10-year Male  10-year Female
15-year Male  15-year Female
Adult Male  Adult Female
UF Newborn Phantoms
UF Newborn Phantoms
Voxel-Based Computational Phantoms

Created by segmentation in 2D and stacking resulting slices
UF Newborn Phantoms

A. Coronal cross-sections

B. Sagittal cross-sections
UF 15-year Phantoms
Hybrid versus Voxel Phantoms

Problems with tissue continuity in 3D

Voxel adult male  Voxel adult female
Hybrid versus Voxel Phantoms

Utility of hybrid phantoms for fine anatomic adjustments
Hybrid versus Voxel Phantoms

Utility of hybrid phantoms for fine anatomic adjustments
Hybrid versus Voxel Phantoms

A

Brain
Cranium
Eye Lens
Optic Nerve
Salivary Glands
Mandible
Cervical Vertebrae
Thyroid

B
## Examples of Phantom Types/Categories

<table>
<thead>
<tr>
<th>Type / Category</th>
<th>Reference</th>
<th>Patient-Dependent</th>
<th>Patient-Specific</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stylized</td>
<td>ORNL Series</td>
<td>Body Builder™</td>
<td>N/A</td>
</tr>
<tr>
<td>Voxel</td>
<td>ICRP 110 (in press)</td>
<td>GSF Family</td>
<td>VIP-Man KTMAN2</td>
</tr>
<tr>
<td>Hybrid</td>
<td>UF Series</td>
<td>UF (in development)</td>
<td>UF (future development)</td>
</tr>
</tbody>
</table>
Hybrid Phantoms

Patient-Dependent Series

Purpose -

Design criterion for a new class of reference phantoms based on a US population.

ICRP - based

UHFADM

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

UHFADM

Nuclear and Radiological Engineering
Hybrid Phantoms
Patient-Dependent Series

170 cm

50% 75% 90%

Weight

174 cm

50% 75% 90%

Variable sitting height

178 cm

50% 75% 90%

Standing height

Adult Phantoms
Hybrid Phantoms
Patient-Dependent Series

Weight vs Standing and Sitting Height

Height (cm)

Weight (kg)
### Patient-Dependent Series - Adults

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

Frontal and lateral views of patient-dependent adult male phantoms at 50th percentile standing height and 10th, 25th, 50th, 75th, and 90th percentile body mass
Patient-Dependent Series – Adults
Same weights / different heights

Frontal and lateral views of patient-dependent adult male phantoms at 50th percentile body mass and 10th, 25th, 50th, 75th, and 90th percentile standing height
Patient-Dependent Series - Children
### Patient-Dependent Series - Children

<table>
<thead>
<tr>
<th>UF Anchor Phantom Age</th>
<th>Standing Height</th>
<th>Weight</th>
<th>Avg Sitting Height</th>
<th>Arm Circumference</th>
<th>Waist Circumference</th>
<th>Buttocks Circumference</th>
<th>Thigh Circumference</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>years</td>
<td>cm</td>
<td>kg</td>
<td>cm</td>
<td>cm</td>
<td>cm</td>
<td>cm</td>
</tr>
<tr>
<td>124.89</td>
<td>10</td>
<td>65.2</td>
<td>21.5 (10%)</td>
<td>17.36</td>
<td>51.75</td>
<td>59.47</td>
<td>32.19</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>22.7 (25%)</td>
<td>18.03</td>
<td>52.77</td>
<td>61.54</td>
<td>32.89</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>24.8 (50%)</td>
<td>19.19</td>
<td>55.56</td>
<td>63.78</td>
<td>34.41</td>
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<tr>
<td></td>
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<td>28.1 (75%)</td>
<td>20.83</td>
<td>59.84</td>
<td>67.81</td>
<td>37.70</td>
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<td></td>
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<td>22.91</td>
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<td>73.12</td>
<td>40.95</td>
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<td>135.62</td>
<td>10</td>
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<td>26.2 (10%)</td>
<td>18.24</td>
<td>54.49</td>
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<td>19.53</td>
<td>56.69</td>
<td>67.30</td>
<td>35.89</td>
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<td>30.9 (50%)</td>
<td>20.61</td>
<td>59.45</td>
<td>69.67</td>
<td>38.10</td>
</tr>
<tr>
<td></td>
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<td></td>
<td>36.1 (75%)</td>
<td>22.84</td>
<td>64.56</td>
<td>75.18</td>
<td>40.94</td>
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<tr>
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<td>41.3 (90%)</td>
<td>24.95</td>
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<td>80.46</td>
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</tr>
<tr>
<td>146.35</td>
<td>10</td>
<td>75.5</td>
<td>32.0 (10%)</td>
<td>19.56</td>
<td>57.39</td>
<td>70.65</td>
<td>37.69</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>35.8 (25%)</td>
<td>21.07</td>
<td>60.65</td>
<td>73.99</td>
<td>39.26</td>
</tr>
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<td>40.9 (50%)</td>
<td>23.46</td>
<td>67.05</td>
<td>79.46</td>
<td>42.26</td>
</tr>
<tr>
<td></td>
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<td>46.6 (75%)</td>
<td>25.24</td>
<td>73.09</td>
<td>84.36</td>
<td>45.15</td>
</tr>
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<td></td>
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<td>51.8 (90%)</td>
<td>26.86</td>
<td>76.91</td>
<td>89.78</td>
<td>48.15</td>
</tr>
</tbody>
</table>

### Pediatric Phantoms - subset

*Univ of Florida - Nuclear and Radiological Engineering*
Patient-Dependent Series - Children

- NHANES III data
- Parameterization
de la Grandmaison, G.L., Clairand, I., and Durigon, M.
Organ weight in 684 adult autopsies: new tables for a Caucasoid population
Patient-Dependent Series - Adults

de la Grandmaison, G.L., Clairand, I., and Durigon, M.
Organ weight in 684 adult autopsies: new tables for a Caucasoid population
Dosimetry Applications of Hybrid Phantoms
Nuclear Medicine Imaging

Comparison of UFH15F to ORNL Stylized 15-year
## Dosimetry Applications of Hybrid Phantoms

**Nuclear Medicine Imaging**

### Ratio of $S_{\text{value}_{\text{OLINDA}}}/S_{\text{value}_{\text{NURBS}}}$

<table>
<thead>
<tr>
<th>Target Organs</th>
<th>Heart</th>
<th>Kidneys</th>
<th>Liver</th>
<th>Lungs</th>
<th>Skeleton</th>
<th>Spleen</th>
<th>UB Cont</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active Marrow</td>
<td>2.4</td>
<td>0.8</td>
<td>1.4</td>
<td>0.9</td>
<td>1.4</td>
<td>1.4</td>
<td>0.8</td>
</tr>
<tr>
<td>Brain</td>
<td>1.8</td>
<td>0.3</td>
<td>0.8</td>
<td>1.2</td>
<td>6.2</td>
<td>1.2</td>
<td>0.6</td>
</tr>
<tr>
<td>Breasts</td>
<td>2.5</td>
<td>0.9</td>
<td>1.0</td>
<td>1.6</td>
<td>22.7</td>
<td>1.5</td>
<td>3.6</td>
</tr>
<tr>
<td>Liver</td>
<td>2.3</td>
<td>0.9</td>
<td>1.3</td>
<td>1.3</td>
<td>10.0</td>
<td>1.0</td>
<td>2.7</td>
</tr>
<tr>
<td>Lungs</td>
<td>1.1</td>
<td>0.4</td>
<td>0.6</td>
<td>0.8</td>
<td>1.3</td>
<td>0.7</td>
<td>1.1</td>
</tr>
<tr>
<td>Ovaries</td>
<td>52.0</td>
<td>1.8</td>
<td>5.9</td>
<td>3.6</td>
<td>2.6</td>
<td>6.5</td>
<td>0.3</td>
</tr>
<tr>
<td>Skin</td>
<td>3.8</td>
<td>0.8</td>
<td>1.6</td>
<td>1.7</td>
<td>11.7</td>
<td>1.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Stomach Wall</td>
<td>2.2</td>
<td>0.7</td>
<td>0.6</td>
<td>1.0</td>
<td>6.2</td>
<td>1.1</td>
<td>2.7</td>
</tr>
<tr>
<td>Thyroid</td>
<td>1.0</td>
<td>0.3</td>
<td>0.6</td>
<td>0.6</td>
<td>4.4</td>
<td>0.8</td>
<td>1.2</td>
</tr>
<tr>
<td>Urinary Bladder Wall</td>
<td>9.1</td>
<td>1.3</td>
<td>2.7</td>
<td>2.6</td>
<td>3.1</td>
<td>2.6</td>
<td>2.6</td>
</tr>
</tbody>
</table>

**Difference due to (1) mass changes, (2) inter-organ spacing**
Dosimetry Applications of Hybrid Phantoms
Radionuclide Therapy of Lymphoma

(A)

(B)
Dosimetry Applications of Hybrid Phantoms
Radionuclide Therapy of Lymphoma

I-131 Source in Left Mesentery Lymphatic Nodes

S-value (mGy/MBq-s)

0.0
5.0e-7
1.0e-6
1.5e-6
2.0e-6
2.5e-6
3.0e-6
3.5e-6

Right Colon Wall
Left Colon Wall
Lung Left
Lung Right
Stomach Wall
Urinary Bladder Wall
Testes
Esophagus
Liver
Thyroid
Brain
Salivary Glands
Bone Surface
Bone marrow

Nuclear and Radiological Engineering
Dosimetry Applications of Hybrid Phantoms
Radionuclide Therapy of Lymphoma

I-131 Source in Right Inguinal Lymphatic Nodes

B

S-value (mGy/MBq-s)

0
1e-7
2e-7
3e-7
4e-7
5e-7
6e-4

Extrathoracic
Cervical
Thoracic Upper
Thoracic Lower
Breast Right
Breast Left
Mesentery Right
Mesentery Left
Axillary Right
Axillary Left
Cubital Right
Cubital Left
Inguinal Right
Inguinal Left
Popliteal Right
Popliteal Left
Dosimetry Applications of Hybrid Phantoms

Pediatric CT
Dosimetry Applications of Hybrid Phantoms

Pediatric CT

- **Chest CT --> Thyroid D (F)**
  - Organ Dose (mGy/100 mAs)
  - Age at Exposure (Year) 0 5 10 15 Adult

- **Chest CT --> BM Dose (F)**
  - Organ Dose (mGy/100 mAs)
  - Age at Exposure (Year) 0 5 10 15 Adult

- **Chest CT --> Breast D (F)**
  - Organ Dose (mGy/100 mAs)
  - Age at Exposure (Year) 0 5 10 15 Adult

These graphs illustrate the dosimetry applications of hybrid phantoms for pediatric CT, focusing on thyroid, bone marrow, and breast doses. The data shows how dose varies with age at exposure.
### Dosimetry Applications of Hybrid Phantoms

#### Adult Cardiac Catheterization

<table>
<thead>
<tr>
<th></th>
<th>60 kVp</th>
<th>90 kVp</th>
<th>120 kVp</th>
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<tbody>
<tr>
<td></td>
<td>UFHADM mass percentile</td>
<td>UFHADM mass percentile</td>
<td>UFHADM mass percentile</td>
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<tr>
<td></td>
<td>10%</td>
<td>90%</td>
<td>10%</td>
</tr>
<tr>
<td><strong>AP</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heart</td>
<td>-14.8%</td>
<td>112.9%</td>
<td>-13.0%</td>
</tr>
<tr>
<td>Liver</td>
<td>-24.0%</td>
<td>59.7%</td>
<td>-20.9%</td>
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<tr>
<td>Stomach</td>
<td>-20.6%</td>
<td>68.4%</td>
<td>-16.4%</td>
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<tr>
<td>Lung</td>
<td>-39.7%</td>
<td>95.5%</td>
<td>-35.2%</td>
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<tr>
<td>Esophagus</td>
<td>-31.1%</td>
<td>102.7%</td>
<td>-25.1%</td>
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<tr>
<td>Effective dose</td>
<td>-43.0%</td>
<td>43.2%</td>
<td>-37.4%</td>
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<tr>
<td><strong>PA</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heart</td>
<td>-34.1%</td>
<td>4.8%</td>
<td>-29.3%</td>
</tr>
<tr>
<td>Liver</td>
<td>-48.1%</td>
<td>2.7%</td>
<td>-39.5%</td>
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<td>-31.5%</td>
<td>5.8%</td>
<td>-26.2%</td>
</tr>
<tr>
<td>Lung</td>
<td>-34.1%</td>
<td>3.4%</td>
<td>-31.4%</td>
</tr>
<tr>
<td>Esophagus</td>
<td>-33.4%</td>
<td>3.9%</td>
<td>-25.7%</td>
</tr>
<tr>
<td>Effective dose</td>
<td>-34.5%</td>
<td>6.8%</td>
<td>-30.7%</td>
</tr>
<tr>
<td><strong>LAO</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heart</td>
<td>-30.8%</td>
<td>4.8%</td>
<td>-27.4%</td>
</tr>
<tr>
<td>Liver</td>
<td>-22.9%</td>
<td>8.3%</td>
<td>-19.3%</td>
</tr>
<tr>
<td>Stomach</td>
<td>-45.5%</td>
<td>4.5%</td>
<td>-39.3%</td>
</tr>
<tr>
<td>Lung</td>
<td>-19.8%</td>
<td>5.4%</td>
<td>-18.4%</td>
</tr>
<tr>
<td>Esophagus</td>
<td>-26.1%</td>
<td>4.7%</td>
<td>-21.9%</td>
</tr>
<tr>
<td>Effective dose</td>
<td>-23.2%</td>
<td>6.6%</td>
<td>-22.0%</td>
</tr>
<tr>
<td><strong>RAO</strong></td>
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<td></td>
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</tr>
<tr>
<td>Heart</td>
<td>-23.8%</td>
<td>6.5%</td>
<td>-20.6%</td>
</tr>
<tr>
<td>Liver</td>
<td>-39.3%</td>
<td>6.0%</td>
<td>-35.6%</td>
</tr>
<tr>
<td>Stomach</td>
<td>-18.4%</td>
<td>8.6%</td>
<td>-14.8%</td>
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<tr>
<td>Lung</td>
<td>-17.3%</td>
<td>5.5%</td>
<td>-16.5%</td>
</tr>
<tr>
<td>Esophagus</td>
<td>-30.6%</td>
<td>5.0%</td>
<td>-27.4%</td>
</tr>
<tr>
<td>Effective dose</td>
<td>-21.5%</td>
<td>7.9%</td>
<td>-20.6%</td>
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</tbody>
</table>
Dosimetry Applications of Hybrid Phantoms
Fetal Skeletal Dosimetry

Specimen Sources
Courtesy of Brad Smith PhD and the Multi-Dimensional Human Embryo Project
Courtesy of John Aris PhD and the UF Department of Anatomy and Cell Biology
Image scans courtesy of Roger Shifrin MD and SHANDS Radiology Department

- NMR microscopy images of 8 week embryo (BS)

- MR and CT scans of specimens (JA & RS):
  - 10.5 weeks
  - 14 weeks
  - 20 weeks
  - 22 weeks
Dosimetry Applications of Hybrid Phantoms
Fetal Skeletal Dosimetry

Two-Region Skeleton
- Spongiosa
- Cartilage

Structures from CT
ossified portions of:
- Cranium
- Mandible
- Spine
- Ribs
- Hands & Feet

Structures from MR
ossified & unossified portions of:
- Long bones
- Os Coxae
- Scapulae
- Clavicles
- Sternum
- Soft tissue
Dosimetry Applications of Hybrid Phantoms
Fetal Skeletal Dosimetry
## Dosimetry Applications of Hybrid Phantoms

**ICRP Series of Reference Fetal Models**

<table>
<thead>
<tr>
<th>Foetal Age (wks)</th>
<th>Foetal Mass (g)</th>
<th>Source Specimen (wks)</th>
<th>Imaging Sources</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>4.7</td>
<td>10.5</td>
<td>MR / CT images</td>
<td>New model under SOLO</td>
</tr>
<tr>
<td>10</td>
<td>21</td>
<td>10.5</td>
<td>MR / CT images</td>
<td>Replace scaled SOUL provisional model</td>
</tr>
<tr>
<td>15</td>
<td>160</td>
<td>14</td>
<td>MR / CT images</td>
<td>New model under SOLO</td>
</tr>
<tr>
<td>20</td>
<td>480</td>
<td>22</td>
<td>MR / CT images</td>
<td>Add tissues within existing SOUL model</td>
</tr>
<tr>
<td>25</td>
<td>990</td>
<td>22</td>
<td>MR / CT images</td>
<td>New model under SOLO</td>
</tr>
<tr>
<td>30</td>
<td>1700</td>
<td>22</td>
<td>MR / CT images</td>
<td>Add tissues within existing SOUL model</td>
</tr>
<tr>
<td>35</td>
<td>2700</td>
<td>6-day newborn</td>
<td>Scaled NB Phantom</td>
<td>New model under SOLO</td>
</tr>
<tr>
<td>38</td>
<td>3500</td>
<td>6-day newborn</td>
<td>UF NB Phantom</td>
<td>Completed model under SOUL</td>
</tr>
</tbody>
</table>

Table 2.1. Reference values for masses of organs and tissues in the developing fetus (g) (Section 3.3)

<table>
<thead>
<tr>
<th>Organ/tissue</th>
<th>8</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>25</th>
<th>30</th>
<th>35</th>
<th>38</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brain</td>
<td>3.9</td>
<td>0.7</td>
<td>23</td>
<td>62</td>
<td>120</td>
<td>200</td>
<td>300</td>
<td>370</td>
</tr>
<tr>
<td>Thyroid</td>
<td>0.011</td>
<td>0.022</td>
<td>0.077</td>
<td>0.18</td>
<td>0.36</td>
<td>0.63</td>
<td>1.0</td>
<td>1.3</td>
</tr>
<tr>
<td>Heart</td>
<td>0.068</td>
<td>0.15</td>
<td>1.1</td>
<td>3.0</td>
<td>6.0</td>
<td>9.9</td>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td>Adrenals (2)</td>
<td>0.016</td>
<td>0.06</td>
<td>0.38</td>
<td>0.98</td>
<td>1.9</td>
<td>3.0</td>
<td>4.6</td>
<td>6.0</td>
</tr>
<tr>
<td>Marrow, active</td>
<td>0.070</td>
<td>0.30</td>
<td>2.4</td>
<td>6.9</td>
<td>14</td>
<td>24</td>
<td>38</td>
<td>50</td>
</tr>
<tr>
<td>Kidneys (2)</td>
<td>0.024</td>
<td>0.13</td>
<td>1.3</td>
<td>3.8</td>
<td>7.6</td>
<td>13</td>
<td>20</td>
<td>25</td>
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<tr>
<td>Liver</td>
<td>0.71</td>
<td>0.87</td>
<td>6.5</td>
<td>19</td>
<td>38</td>
<td>63</td>
<td>100</td>
<td>130</td>
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<tr>
<td>Lungs</td>
<td>0.096</td>
<td>0.63</td>
<td>5.8</td>
<td>15</td>
<td>26</td>
<td>38</td>
<td>51</td>
<td>60</td>
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<tr>
<td>Pancreas</td>
<td>0.39</td>
<td>0.69</td>
<td>1.5</td>
<td>2.3</td>
<td>3.1</td>
<td>3.8</td>
<td>4.5</td>
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<tr>
<td>Spleen</td>
<td>0.00049</td>
<td>0.0035</td>
<td>0.060</td>
<td>0.36</td>
<td>1.1</td>
<td>2.7</td>
<td>5.8</td>
<td>9.5</td>
</tr>
<tr>
<td>Thymus</td>
<td>0.011</td>
<td>0.022</td>
<td>0.45</td>
<td>1.5</td>
<td>3.2</td>
<td>5.8</td>
<td>9.7</td>
<td>13</td>
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</table>
Acknowledgments

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US Department of Energy (DE-FG07-06ID14773)

European Commission (FP6-516478)