Voluntary versus Mandatory Standards
Education, Standardization, Regulation

Wesley Bolch, PhD, PE, DABHP
University of Florida, Department of Biomedical Engineering

2011 Annual Meeting of the AAPM
Vancouver, British Columbia, August 2, 2011

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 – Hybrid Phantoms**

- **Segmentation**
- **Polygonization**
- **NURBS modeling**
- **Voxelization**

Segment patient CT images using 3D-DOCTOR
Convert into polygon mesh using 3D-DOCTOR
Make NURBS model using Rhinoceros
Convert NURBS model into voxel model using MATLAB code

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

**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**

<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 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.

**Definition**

Expanded library of reference phantoms covering a range of height/weight percentiles

**ICRP-based UFHADM**

- Reference weights @ 1 or more fixed anthropometric parameter(s)

**NHANES-based UFHADM**

- Reference heights @ 1 or more fixed anthropometric parameter(s)

**Morphometric Categories – Patient Dependent Phantoms**

- Patient Dependent Phantoms
  - Adult Males
    - Same height/different weights
    - Same weight/different heights

**Patient Dependent Phantoms – Adult Males**

<table>
<thead>
<tr>
<th>Standing Height</th>
<th>Weight</th>
<th>Avg. Sitting Height</th>
<th>Arm Circumference</th>
<th>Waist Circumference</th>
<th>Thigh Circumference</th>
</tr>
</thead>
<tbody>
<tr>
<td>57.0% (10%)</td>
<td>27.7</td>
<td>79.2</td>
<td>87.2</td>
<td>44.5</td>
<td></td>
</tr>
<tr>
<td>60.0% (25%)</td>
<td>28.6</td>
<td>88.9</td>
<td>96.7</td>
<td>47.2</td>
<td></td>
</tr>
<tr>
<td>68.4% (50%)</td>
<td>29.9</td>
<td>95.9</td>
<td>106.0</td>
<td>47.5</td>
<td></td>
</tr>
<tr>
<td>75.9% (75%)</td>
<td>30.5</td>
<td>100.0</td>
<td>107.4</td>
<td>48.2</td>
<td></td>
</tr>
<tr>
<td>80.3% (90%)</td>
<td>31.0</td>
<td>105.6</td>
<td>105.8</td>
<td>52.6</td>
<td></td>
</tr>
<tr>
<td>73.7% (10%)</td>
<td>29.4</td>
<td>81.4</td>
<td>99.9</td>
<td>45.3</td>
<td></td>
</tr>
<tr>
<td>68.7% (25%)</td>
<td>30.1</td>
<td>87.4</td>
<td>102.0</td>
<td>47.1</td>
<td></td>
</tr>
<tr>
<td>75.9% (50%)</td>
<td>30.6</td>
<td>94.2</td>
<td>105.5</td>
<td>48.5</td>
<td></td>
</tr>
<tr>
<td>78.6% (75%)</td>
<td>31.4</td>
<td>101.1</td>
<td>108.4</td>
<td>54.6</td>
<td></td>
</tr>
<tr>
<td>76.2% (90%)</td>
<td>32.0</td>
<td>105.1</td>
<td>105.8</td>
<td>59.6</td>
<td></td>
</tr>
<tr>
<td>64.1% (10%)</td>
<td>28.9</td>
<td>82.6</td>
<td>98.3</td>
<td>48.0</td>
<td></td>
</tr>
<tr>
<td>74.7% (25%)</td>
<td>29.9</td>
<td>87.8</td>
<td>103.5</td>
<td>48.6</td>
<td></td>
</tr>
<tr>
<td>77.1% (50%)</td>
<td>31.3</td>
<td>94.6</td>
<td>106.0</td>
<td>50.5</td>
<td></td>
</tr>
<tr>
<td>87.1% (75%)</td>
<td>33.4</td>
<td>101.2</td>
<td>106.1</td>
<td>55.0</td>
<td></td>
</tr>
<tr>
<td>92.7% (90%)</td>
<td>35.2</td>
<td>104.8</td>
<td>107.9</td>
<td>59.4</td>
<td></td>
</tr>
<tr>
<td>77.1% (10%)</td>
<td>28.9</td>
<td>91.1</td>
<td>91.7</td>
<td>47.0</td>
<td></td>
</tr>
<tr>
<td>87.1% (25%)</td>
<td>31.5</td>
<td>97.4</td>
<td>98.0</td>
<td>50.4</td>
<td></td>
</tr>
<tr>
<td>98.4% (50%)</td>
<td>33.9</td>
<td>102.2</td>
<td>102.2</td>
<td>52.7</td>
<td></td>
</tr>
<tr>
<td>95.9% (75%)</td>
<td>36.3</td>
<td>104.2</td>
<td>108.8</td>
<td>59.0</td>
<td></td>
</tr>
<tr>
<td>99.3% (90%)</td>
<td>38.0</td>
<td>110.1</td>
<td>112.1</td>
<td>59.7</td>
<td></td>
</tr>
</tbody>
</table>
**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/organisms 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

\[ D(r_s, t) = \sum_{r_a} A(r_a, t) S(r_a \leftarrow r_s, t) \]

where \( r_s \) is the target tissue region
\( r_a \) is the source tissue region

\[ A(r_a, t) \] - radiopharmaceutical activity in \( r_a \) at time \( t \)

\[ S(r_a \leftarrow r_s, t) \] - radionuclide S value at time \( t \)

\( r_s / r_a \) 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
  - WinDose
  - ImPACT

**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

**Streaming RDSR**

Would provide 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.