ICRP Mesh-type Reference Computational Phantoms (MRCPs)

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Computational Human Phantoms

“VRCPs”
Voxel-type Reference Computational Phantoms

ORNL/TM 8381
(1987)

ICRP Publication 110
(2009)
**VRCPs - Limitations**

**Male phantom**
(Voxel size: 2.137 × 2.137 × 8 mm³)

**Female phantom**
(Voxel size: 1.775 × 1.775 × 4.8 mm³)

Limitations:
1. Stepped surfaces
2. Alimentary, respiratory organs
3. Skin
4. Eyes

→ The ICRP had to use 12 additional stylized phantoms.
Limitations (Cont’d)

- **Organ masses** don’t match the ICRP reference masses inclusive of blood content.
- Some tissue masses do not match the ICRP-89 data.
- Some spongiosa is not fully covered by cortical bone.
- Some cartilage is included in spongiosa.
- The sacrum of the female phantom does not have cortical bone.
- The female phantom has toe-standing feet.
- The additional stylized model is used for assessing the equivalent dose specified for localized skin exposure.
- The phantoms are **not deformable**.
- **Sub-organ modeling** for emergency dosimetry is not feasible.
The committee decided to convert the current voxel-type ICRP reference computational phantoms into a high-quality mesh format to address these problems.

**Excerpt from ICRP C2 meeting minutes (Abu Dhabi, 2013)**

15. **Presentation by new C2 member Chan Kim**  
   The meeting concluded with a presentation by new member Chan Hyeong Kim. His research group has been pioneering efforts to incorporation NURBS/polygon mesh phantoms directly within the radiation transport codes GEANT4 and MCNP6. Of interest to C2 is the conversion of the ICRP Publication 110 adult male and adult female voxel phantoms into a hybrid phantom format. The result of the preliminary study, which has been published in a journal article, has shown that it is feasible to convert the ICRP voxel phantoms to a hybrid format. **The conversion of the ICRP male and female voxel phantoms will be started within the coming year and will be completed within about 3 years.**

[#11 - Kim – ICRP Phantom Conversion]
Working Group / Review Committee

• **Working group** established at Hanyang University in Korea (December 2013)
  - Chan Hyeong Kim (Hanyang University, ICRP C2)
  - Yeon Soo Yeom (Ph.D. student)
  - Tat Thang Nguyen (Ph.D. student)
  - Zhao Jun Wang (M.S. student)
  - Han Sung Kim (M.S. student)
  - Min Cheol Han (Ph.D. student, 20%)

• **Review committee** established (May 2014)
  - Maria Zankl (HMGU)
  - Nina Petoussi-Henss (HMGU, ICRP C2)
  - Jai Ki Lee (Hanyang University, ICRP MC)
  - Wesley Bolch (University of Florid, ICRP C2)
  - Chan Hyeong Kim (Hanyang University, ICRP C2)
  - Choonsik Lee (NCI)
  - Bum Sun Chung (Ajou University) - anatomist
Task Group 103
Mesh-type Reference Computational Phantoms (MRCP)

The mandate for this Task Group - Mesh-type Reference Computational Phantoms (MRCP) - will be focused on converting the current voxel-type reference computational phantoms into a high-quality mesh format to address the limitations of the voxel-type phantoms in some dose coefficient calculations. Specific work will include:

1. development of mesh-type ICRP reference computational phantoms which have all source and target tissues including the details of the eyes and skin and the thin target tissues (10-300 micron) of the alimentary and respiratory tract organs,
2. use of these mesh-type phantoms to calculate external and internal dose coefficients to estimate the uncertainties of the current reference dose coefficients, especially for the dose coefficients calculated with stylized phantoms (eye lenses, skin, and alimentary and respiratory tract organs) for weekly penetrating radiations, and
3. demonstration of phantom posture change and related dose coefficient calculations.

Chair
Prof Chan Hyeong Kim
TG 103 Members

• Full members
  • Chan Hyeong Kim (Hanyang Univ., Korea, ICRP C2) - Chair
  • Yeon Soo Yeom (NCI, U.S.A.)
  • Maria Zankl (HMGU, Germany)
  • Nina Petoussi-Henss (HMGU, Germany, ICRP C2)
  • Wesley Bolch (Univ. of Florid, U.S.A., ICRP C2)
  • Choonsik Lee (NCI, U.S.A.)

• Corresponding members
  • Keith Eckerman (ORNL, U.S.A.)
  • Riu Qiu (Tsinghua University, China)
  • Bum Sun Chung (Ajou Univ., Korea) – M.D./anatomist
  • Chansoo Choi (Hanyang Univ., Korea)
  • Min Cheol Han (INFN, Italy)
  • Han Sung Kim (KIRAMS, Korea)
  • Tat Thang Nguyen (Hanoi Institute of Technology, Vietnam)
Construction Method

"MRCPs"

Mesh-type Reference Computational Phantoms
Simple Organs – Direct Conversion

Conversion to primitive polygon-surface model

Decrease in the number of polygons

Smoothness of boundary of polygon-surface model

Increase in the number of polygons

Adjustment of organ mass to reference value
Spine – Fitting

Voxel model

High-quality mesh model

Detailed eye model (Behrens et al. 2009)

Conversion to polygonal model

Randomly generate **1000** small intestine (SI) models and select the **best model** considering both geometric and dosimetric similarities with the original voxel model.

Lung Airways – Modeling

- Tawhai’s method (2000) to produce the airway passages.
- ‘Inverted-Y branch’ model to produce the volumetric airways with multiple source and target layers.


Other Complex or Thin Organs

- Blood in large arteries and veins
  - Modeling
  - Fitted to the blood model in VRCPs
- Muscle
  - Direction conversion
  - Refinement and correction
- Lymphatic nodes
  - Modeling
  - UF/NCI approach
- Micron-scale target layers
  - Skin (50 μm), alimentary and respiratory tract organs
  - Modeling based on ICRP-89, 66, and 100
- Hands and feet
  - High-quality mesh model
  - Fitted to the MRCPs
Results
**MRCPs** *(Mesh-type Reference Computational Phantoms)*

**VRCPs** *(ICRP Publication 110)*

**MRCPs** *(Mesh-type Reference Computational Phantoms)*
Male MRCP
## Numerical Data

<table>
<thead>
<tr>
<th>Properties</th>
<th>Male MRCP</th>
<th>Female MRCP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height / Weight</td>
<td>176 cm / 73 kg</td>
<td>163 cm / 60 kg</td>
</tr>
<tr>
<td>Number of organs</td>
<td>48</td>
<td>48</td>
</tr>
<tr>
<td>Deviation from ICRP 89*</td>
<td>&lt; 0.1%</td>
<td>&lt; 0.1%</td>
</tr>
<tr>
<td>Number of tetrahedrons</td>
<td>8,232,811</td>
<td>8,596,890</td>
</tr>
<tr>
<td>Avg. volume of tetrahedron</td>
<td>8.64 mm(^3)</td>
<td>6.89 mm(^3)</td>
</tr>
<tr>
<td>File size (ASCII)</td>
<td>436 MB</td>
<td>457 MB</td>
</tr>
</tbody>
</table>

* Organ mass deviation from the ICRP-89 reference values inclusive of blood content.
Skin

Male

Female

Target layer
Depth: 50-100 μm
Thickness: 50 μm
Respiratory Tract Organs

Target region
Depth: 40-50 μm, Thickness: 10 μm

Source region
Sequestered
Bound
Fast

Male

Lungs

ET₁

ET₂
Airway Model of Lungs

Male

Secretory cells

8 μm

Target region

Source region

AI

5 μm

Sequestered

20 μm

Bound

6 μm

Fast & slow mucus

“Turn ON/OFF”

Bronchiolar (bb)
Eyeballs

Male

Behrens’ eye model (2009)

Converted to mesh format

Installed
Blood in Large Arteries and Veins

Male

Female
Muscle

Male

Female
Lymphatic Nodes

Male

Female
MRCPs – Complete

Male

Female
Dosimetry Impact
Effective Dose Coefficient – Photon

- AP direction
- PA direction
- RLAT direction
- ISO direction

ICRP Publication 116 data
Mesh phantom (Geant4)
Effective dose per fluence (pSv cm$^2$)
Photon energy (MeV)

Mesh phantoms, entire lens (Geant4)
ICRP Publication 116 data, entire lens
Effective Dose Coefficient – Neutron

- AP direction
- PA direction
- RLAT direction
- ISO direction

Mesh phantoms, entire lens (Geant4)
ICRP Publication 116 data, entire lens

Effective dose per fluence (pSv cm$^2$)
Neutron energy (MeV)
Effective Dose Coefficient – Electron

Electron energy (MeV) vs. Effective dose per fluence (pSv cm\(^2\))

- AP direction
- PA direction
- ISO direction

ICRP-116 (VRCP)

MRCP

VRCP

Skin (voxel) ~2 mm thick

Radiosensitive target layer (50 µm)
Effective Dose Coefficient – Helium Ion

LAT (not given in ICRP-116)
Calculation of DCs for Industrial Radiography Sources
Why Industrial Radiography Sources?

- Industrial radiography sources account for ~50% of all the reported accidents in the nuclear related industry (IAEA, 1998).

- Dose coefficients for -
  - red bone marrow (RBM), brain, lungs, and small and large intestines
  - effective dose (for comparison purpose)
Different Body Sizes

• Non-reference phantoms:
  • 10\textsuperscript{th} percentile phantom (H10M10)
  • 90\textsuperscript{th} percentile phantom (H90M90)

• Procedure (3 steps)
  1. Height & weight (standing height, weight, sitting height, head height): PeopleSize 2008 software
  2. Organ mass (adjustment in planar direction): lean body mass (LBM) equation (Deurenberg et al. 1991)
  3. Detailed dimensions
    • Head breadth, head length: ANSUR II (2010-2012)
Male phantoms

10\textsuperscript{th} percentile

MRCP

90\textsuperscript{th} percentile
Female phantoms

10th percentile

MRCP

90th percentile
Non-standing phantoms

- 5 arbitrary postures produced with a motion capture device.
Total 60 source locations

- Level: ground, middle thigh, lower torso, middle torso, and upper torso
- Direction: front, back, right, and left
- Distance: 0.5, 10, 30, 100, 150, and 300 cm
Development of Pediatric MRCPs
The pediatric VRCPs were produced from the UF/NCI pediatric phantoms through voxelization. After the voxelization, some organs/tissues (e.g., muscle, breasts, colon, ureter, lymphatic nodes…) were modified or added in the phantoms.
First, we had to decide which phantoms we will use to produce the pediatric MRCPs.

Decision

• Use both UF/NCI phantoms and pediatric reference phantoms
  ✓ Convert UF/NCI phantoms to polygon-mesh format with refinement
  ✓ Adjust the polygon-mesh phantoms to the pediatric VRCPs for each organ/tissue

→ *polygon-mesh replica of pediatric VRCPs*

✓ Adjust the organs/tissues of the polygon-mesh phantoms to the reference masses inclusive of blood content.

✓ Add complex organ/tissue models, including micron-scale tissue structures.
Constructed Phantoms – Newborn

Male

Female
Constructed Phantoms – 1 Year

Male

Female
_constructed phantoms – 5 years

male

female
Constructed Phantoms – 10 Years
Constructed Phantoms – 15 Years

Male

Female
Steps of Development for Pediatric MRCPs

Step 1 – Production of PM replica of pediatric reference phantoms
- Convert the UF/NCI phantoms to PM format with refinement
- Adjust the PM phantoms to the pediatric reference phantoms

Step 2 – Inclusion of blood content in organs/tissues
- Calculate organ/tissue data inclusive of blood content
- Adjust the PM phantoms to match the new organ/tissue masses

Step 3 – Construction of complex organs/tissues
- Develop models for eyes, teeth, colon, liver, fontanelle cartilage, …
- Install the models + lung airways, muscle, LNs, blood in large vessels, …

Step 4 – Characterization of the constructed phantoms
- Calculate DIs, CDs, ODDs, and CLDs
- Calculate dose coefficients (DCs) for external and internal exposure
Conclusion
Conclusion

- We are now developing mesh-type reference computational phantoms (MRCPs) for adults, children, and pregnant females.

- The MRCPs will include:
  - *continuous and fully-closed* surfaces for the skin, stomach, gall bladder, and urinary bladder;
  - *thin target layers (8-300 μm)* in the respiratory and alimentary tract organs and in the urinary bladder; and
  - *detailed and more accurate models* for skeletal system, eyes, lymphatic nodes, blood vessels, hands, and feet.

- These phantoms can be directly used in general-purpose Monte Carlo codes, including Geant4, PHITS, and MCNP.
The MRCPs will provide -

- **very similar dose values** with the current voxel-type reference phantoms (VRCPs) for highly-penetrating radiations (photons ≥ 0.03 MeV, neutrons), and

- **more accurate** or **correct dose values** for weakly-penetrating radiations (electrons, ions, low-energy photons)

The MRCPs will be **deformable**, and we can easily produce phantoms with different body sizes and different postures.

The adult MRCPs will be distributed early next year with a full description of the phantoms and the **input files** for Geant4, MCNP, and PHITS.
Schedule

- Adult MRCPs
  - Public consultation ~2018 Q4
  - ICRP Publication ~2019 Q2

- Pediatric MRCPs
  - Phantom completion ~2019 Q4
  - ICRP Publication ~2020 Q4

- Pregnant-female MRCPs
  - Phantom completion ~2021 Q4
  - ICRP Publication ~2022 Q4
Thank you!