Chinese reference computational human phantoms and multi-scale computational dosimetry

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Multi-scale dosimetry with multi-scale phantoms

**Effective dose, equivalent dose**

**Organ dose distribution, cell dose**

- Detailed lung model
- Detailed skeleton model
- Detailed breast model
- Detailed eye model
- Nucleus model

**DSB, Chromosomes aberration**

**Model**
- CRAM and Craf
- Chinese reference pediatric phantoms

**Quantities**
- Effective dose, equivalent dose
- Organ dose distribution, cell dose
- DSB, Chromosomes aberration

**Scale**
- m
- mm
- μm
- nm
Content

- Latest Development of the Chinese Reference Phantoms
  - Chinese mesh-type adult phantom
  - Chinese adult phantom library
  - Chinese pediatric reference phantoms
  - Detailed organ models (skeletal, breast, eyes and respiratory tract)
  - DNA model

- Applications of the Chinese Multi-scale Phantoms
  - Application in radiation protection
  - Application in medical health physics

- Summary
Development of computational human phantom

Stylized phantom

MIRD phantom

ORNL "Family" phantom

VIP-man

Voxel- type ICRP reference phantom (ICRP110)

Hybrid phantom

UF Family

ICRP task group 103: Mesh-type phantom for ICRP reference phantom
Chinese reference adult voxel phantoms

- Mass of individual organ has been adjusted to the Chinese reference data
- Including all organs required in ICRP 2007 recommendation
- Site-specific skeleton voxel models

CRAM: 170 cm/60 kg
1.741 mm × 1.741 mm × 1 mm (voxel)

CRAF: 160 cm/57.7 kg
0.613 mm × 0.613 mm × 1.98 mm (voxel)

Liye Liu et al. PHYSICS IN MEDICINE AND BIOLOGY, 54 (21): 6645-6673 NOV 7 2009
Liye Liu et al. PHYSICS IN MEDICINE AND BIOLOGY, 54 (21): 6675-6690 NOV 7 2009
Chinese mesh-type adult phantom

- Chinese reference adult male and female polygon surface phantom (CRAM_S and CRAF_S) was built.
- Posture change: from standing to sitting (CRAM_Ssit).
Referring to the weight and height distributions of the Chinese adult, a phantom library containing 84 male phantoms and 48 female phantoms were constructed.

- Male phantoms: 7 heights (155 cm to 185 cm), 12 weights in each height
- Female phantoms: 8 heights (145 cm to 175 cm), 6 weights in each height

Mesh-type Chinese pediatric reference phantoms

- A series of Mesh-type Chinese pediatric reference phantoms were constructed based on the CT medical images of children at different ages.
- Each phantom consists of 125 different organs and tissues.
- Height and weight: exactly the same with the Chinese reference value.
- The differences of the organ mass with the Chinese reference value are less than 2%.

Pediatric phantoms for 3 month, 1 year, 5 year, 10 year, and 15 year male and female
Phantoms with different postures

Dynamic phantom bending to pick up a radiation source
Phantoms with different postures

Dynamic phantom playing Taichi
Microscopic skeletal model

- Skeletal model is important: red bone marrow (RBM) and bone endosteum (BE) are associated with radiogenic leukemia and bone cancer.
- A set of microscopic skeletal dosimetry models of Chinese adult based on micro-CT images was built. (Resolution:19 μm)

Detailed organ models

- Detailed breast voxel model
  - Female breast is a radiosensitive organ and its tissue weighting factor has been increased from 0.05 to 0.12 (ICRP 2007).
  - The detailed breast model contains retromammary fat, lactiferous duct and lobule, intraglandular fat, glandular tissue, subcutaneous fat, Cooper’s ligament, and skin.
  - Voxelization: voxel size of 0.2 mm.

Front and side views of 3D detailed breast model

Detailed structures in the breast model

Detailed organ models

- Detailed human respiratory tract model

As radon is one of the most important natural radiation sources, its radiation hazard has been concerned. Detailed respiratory tract model need to be built and dose distribution in the respiratory tract should be studied.

The respiratory tract model in CRAM

The BB & bb region built in the present work

The voxel model of 16-generation bronchial tree, with voxel size of 0.2 mm × 0.2 mm × 0.2 mm, total voxel number of 1149 × 905 × 1036

Hongyu Zhu et al, CP2017 (Best student paper award)
ICRP commends to reduce the occupational equivalent dose limit for the lens of the eye from 150 mSv/y to 20 mSv/y, averaged over 5 y, based on some epidemiological studies (ICRP118).

Seven main structures: scleral, choroid, lens, iris, cornea, vitreous body and aqueous humor.

The lens was divided into sensitive volume and insensitive volume.

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**Detailed organ models**

**Detailed eye model of Chinese adult male**

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- Seven main structures: scleral, choroid, lens, iris, cornea, vitreous body and aqueous humor.
- The lens was divided into sensitive volume and insensitive volume.

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**Table 1. The characteristic parameters of Chinese adult male and value in literature.**

<table>
<thead>
<tr>
<th>Structure</th>
<th>Parameter type</th>
<th>Reference value of adult Chinese male (mm)</th>
<th>Eye model adopted in ICRP-116</th>
<th>Eye model built by Nogueira</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eye ball</td>
<td>Anteroposterior</td>
<td>24</td>
<td>25.389</td>
<td>24.15</td>
</tr>
<tr>
<td></td>
<td>diameter</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Vertical diameter</td>
<td>23</td>
<td>24.2</td>
<td>23.48</td>
</tr>
<tr>
<td></td>
<td>Horizontal diameter</td>
<td>23.5</td>
<td>24.2</td>
<td>23.48</td>
</tr>
<tr>
<td>Cornea</td>
<td>Curvature of external surface</td>
<td>7.8</td>
<td>7.75</td>
<td>7.75</td>
</tr>
<tr>
<td></td>
<td>Curvature of internal surface</td>
<td>6.8</td>
<td>7.2</td>
<td>7.2</td>
</tr>
<tr>
<td>Scleral</td>
<td>Thickness</td>
<td>0.3–1.0</td>
<td>0.589</td>
<td>0.55</td>
</tr>
<tr>
<td>Choroid</td>
<td>Thickness</td>
<td>0.2946(^{12})</td>
<td>—</td>
<td>0.48(^{12})</td>
</tr>
<tr>
<td>Iris</td>
<td>Thickness</td>
<td>0.2946(^{12})</td>
<td>—</td>
<td>0.5</td>
</tr>
<tr>
<td>Aqueous humor</td>
<td>Depth</td>
<td>2.860(^{13})</td>
<td>2.761</td>
<td>2.75</td>
</tr>
<tr>
<td>Lens</td>
<td>Curvature of anterior surface</td>
<td>10</td>
<td>12.5</td>
<td>12.5</td>
</tr>
<tr>
<td></td>
<td>Curvature of posterior surface</td>
<td>6</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>Diameter</td>
<td>9</td>
<td>10</td>
<td>10</td>
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<tr>
<td></td>
<td>Thickness</td>
<td>4</td>
<td>4.199</td>
<td>4.2</td>
</tr>
</tbody>
</table>

*All the values are taken from *Ophthalmology*\(^{12}\) except the data of Choroid and Aqueous humor.

\(^{12}\)The thickness here refers to the maximum thickness.

\(^{13}\)The thickness of iris is assumed to be same as the thickness of choroid.
DNA model

- Atomic nucleus model for DNA
  - 11 μm diameter
  - 46 chromatins and 2 nucleoli
  - Genomic length ~ 6.2 Gbp.
DNA model

Nanodosimetry biophysics Monte Carlo code NASIC

- Geometric module, DNA damage module, DNA repair module and cell death module have been developed.

Physical stage (0 ~ 10^{-15} s)  Chemical stage (10^{-15} ~ 10^{-6} s)  Biological stage (Long time)

Li, J., Li, C., Qiu, R., Yan, C., Xie, W., Wu, Z. Tung, C. DNA strand breaks induced by electrons simulated with nanodosimetry Monte Carlo simulation code: NASIC[J]. Radiation Protection Dosimetry, 2015, 166(1-4):38
Xie, W. Z., Friedland, W., Li, W. B., Li, C. Y., Oeh, U., Qiu, R., Hoeschen, C. Simulation on the molecular radiosensitization effect of gold nanoparticles in cells irradiated by x-rays[J]. Physics in medicine and biology, 2015, 60(16): 6195..
Applications

Application in radiation protection
- Breast dose conversion coefficients in external exposure using detailed breast model
- Conversion coefficients at neutron exposure with detailed Chinese eye model
- Radon progeny caused dose with respiratory tract model
- Dose reconstruction for radiation accident

Application in medical health physics
- Dose estimation for CT
- Dose estimation for X-ray radiography
- Personalized nuclear medicine dosimetry
Breast dose conversion coefficients in external photon exposure using detailed breast model

Comparison with the ICRP values:

- In intermediate energy range, the differences are below 20%.
- CRAF values are lower than ICRP values by up to ~91% below 30 keV, and significantly larger (35–70%) than ICRP values above 4 MeV.

Relative deviation of dose conversion coefficients of breast gland calculated with the detailed breast model compared with that of the old breast model in CRAF under AP photon irradiation

Structure of the detailed breast model of CRAF (lactiferous ducts and lobules, adipose tissue and gland from the left to the right).

Dose conversion coefficients of breast gland for the detailed breast model and ICRP reference adult female voxel phantom in AP geometry

Conversion coefficients at neutron exposure with detailed Chinese eye model

From $1 \times 10^{-7}$ to 1 MeV, the maximum difference between this work and ICRP 116 was:

- 52.36% at $1 \times 10^{-4}$ MeV for AP geometry,
- 42.20% at $1 \times 10^{-5}$ MeV for LAT geometry,
- 97.47% at $2 \times 10^{-3}$ MeV for PA geometry.

Dose coefficients (pGy·cm²) for eye lens for neutron exposures at (a) AP, (b) LAT, and (c) PA irradiation geometries.

Electron absorbed fractions calculated with microscopic skeletal models

- The values of $\phi(BE \leftarrow S)$ in this paper are significantly higher than the UFHADM and MASH.

Gao, Shenshen; Ren, Li; Qiu, Rui; Wu, Zhen; Li, Chunyan; Li, Junli, Radiation protection dosimetry, 10 Jan 2017
Radon progeny caused dose with respiratory tract model

Non-uniform energy deposition in respiratory tract is significant:
- Maximum voxel dose could be **30 times higher** than average voxel dose.
- Maximum dose in the target nuclei is up to more than **40 times higher** than the average dose in one voxel.

Application— in radiation protection

- Physical Dosimetric Reconstruction of Accidental Exposure from Radiological Source $^{192}$Ir in NanJing China

Radiography equipment


Local dose distribution of the legs

- Whole body dose by physical dosimetric reconstruction: 1.18~2.20 Gy;
- Consistent with the biological dosimetry: 1.40~1.61 Gy (95% confidence)

Lu, W., R. Qiu, J. Li, etc Health Physics, 2017 Nov., Cover Article
Dose estimation in CT

- A series of organ dose conversion coefficients for dose estimation in CT scanning were calculated for different tube potentials, beam thickness, filters and phantoms.

Web-based software for CT scan dose estimation (applied in the epidemiology study by Chinese CDC)

### Dose estimation in X-Ray radiography

- A series of organ dose conversion coefficients for dose estimation in X-Ray radiology were calculated with the Chinese adult and pediatric reference phantoms. The current national standard data was calculated based on the stylized phantom.

<table>
<thead>
<tr>
<th>Tube Potential (kVp)</th>
<th>CRAM LP AP</th>
<th>CRAM LP RL</th>
<th>CRAM CH AP</th>
<th>CRAM CH RL</th>
<th>CRAM LH AP</th>
<th>CRAM LH RL</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>39.2</td>
<td>39.2</td>
<td>39.2</td>
<td>39.2</td>
<td>39.2</td>
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<tr>
<td>70</td>
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<tr>
<td>80</td>
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<tr>
<td>90</td>
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<tr>
<td>100</td>
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<td>39.2</td>
<td>39.2</td>
<td>39.2</td>
<td>39.2</td>
<td>39.2</td>
</tr>
</tbody>
</table>

Simulation results for different tube potentials, beam thickness and filters

- These data will be adopted by the revised national standard for the estimation of the examinee's organ doses generated by X-ray diagnosis in China.
Application—in medical health physics

Dose estimation in Mammography
- A table of glandular tissue dose conversion factors for X-ray spectra with different target/filter, different HVL, different compressed thickness and different glandularity.
- A difference of 5.4%~45.4% is found comparing with the results calculated by Dance et al. These data will be adopted by the revised national standard.
Dose estimation in Mammography

- Validation of the Monte Carlo simulation with TLD measurements

Equipment used for measurements: the GE Senographe DS MAMMOMAT (left), the CIRS breast phantom (upper right), and the TLD GR200A (lower right)

The values obtained from simulations were well consistent with those obtained from measurements.

Dose estimation for Nuclear medicine

- Activity distribution of the radiopharmaceuticals is obtained by the SPECT images.
- Personalized phantom is developed based on the CT images.
- Monte Carlo simulation are processed to obtain the organ dose and the voxelized dose distribution.

I-131 distribution at different time

Personalized phantom

Organ dose distribution

Voxelized dose distribution

Ruiyao Ma et al., CP2019
Summary

- A Chinese male phantom library was constructed with 7 different heights ranging from 155 cm to 185 cm and 12 phantoms with different total body masses in each height.
- Chinese pediatric reference phantoms were constructed for 3 months, 1 year, 5 years, 10 years, and 15 based on the CT medical images of different ages.
- A series of detailed organ models were established, including microscopic skeletal models, detailed breast models, detailed respiratory tract models and detailed eye models.
- The phantoms were applied in health physics studies, including dose estimation for external exposure and internal exposure, in normal situations and in accidental situations.
- Organ dose conversion coefficients for CT scanning and X-Ray radiography as well as glandular tissue dose conversion coefficients for mammography were calculated. Related results have been adopted by the revision of the national standard.
Thank you!

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