

Compatibility of Next-Gen ICRP Reference Computational Phantoms with General- purpose Monte Carlo codes

Yeon Soo Yeom, Ph.D.

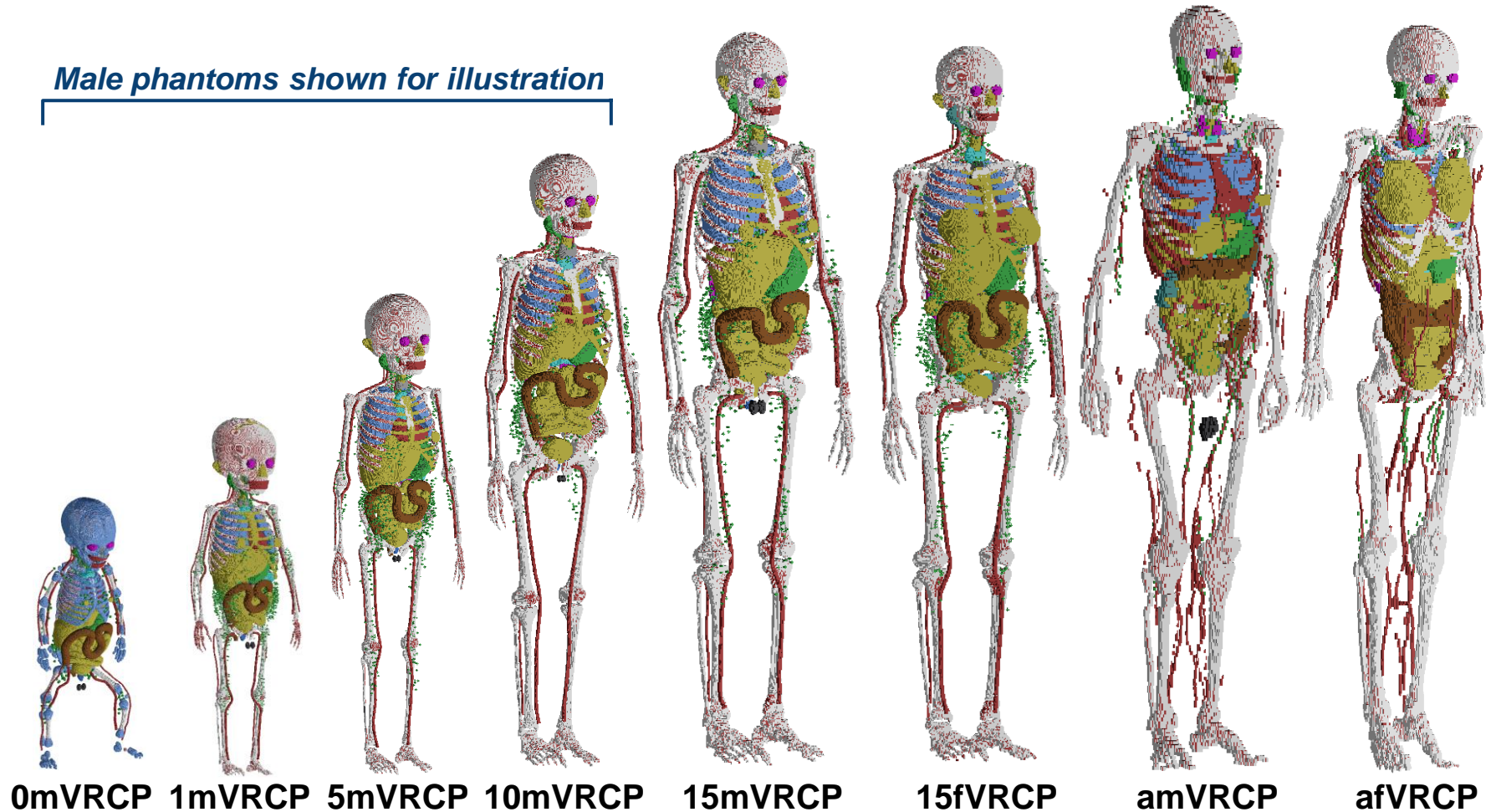
**Yonsei University
ICRP Task Group 103
ICRP Committee 2**

***11th International Geant4 Tutorial in Korea 2024
User Session, 2024-08-19***

Current ICRP Reference Phantoms - VRCPs

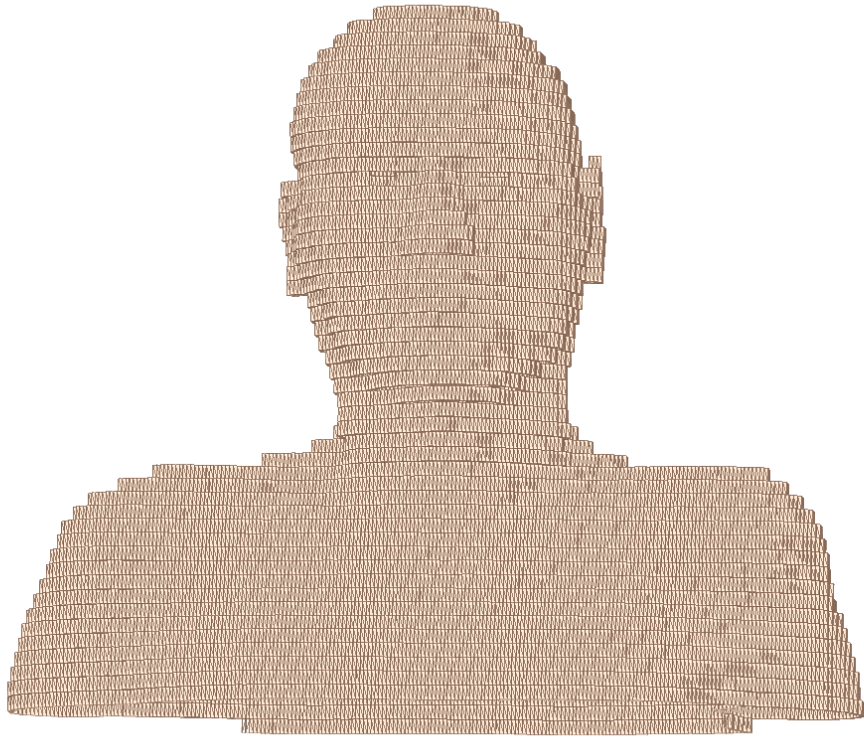
- **Adults (2)** – adult male/female (ICRP 110, 2009)
- **Children (10)** – newborn, 1, 5, 10, 15 years male/female (ICRP 143, 2020)

Male phantoms shown for illustration

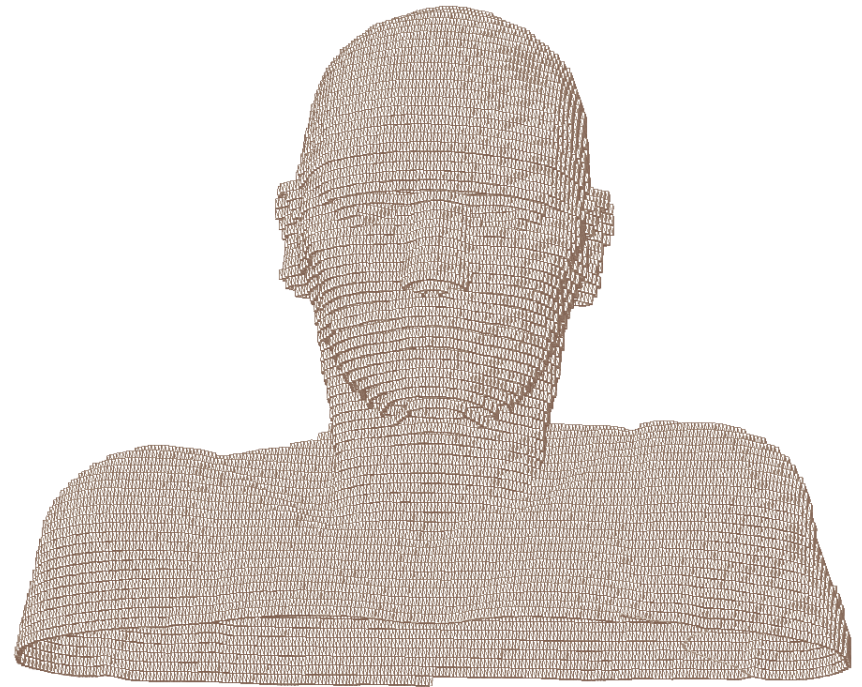


Voxel resolutions: 0.66 – 8.00 mm

VRCP Limitations (Skin)



**Adult male VRCP
($2.137 \times 2.137 \times 8 \text{ mm}^3$)**

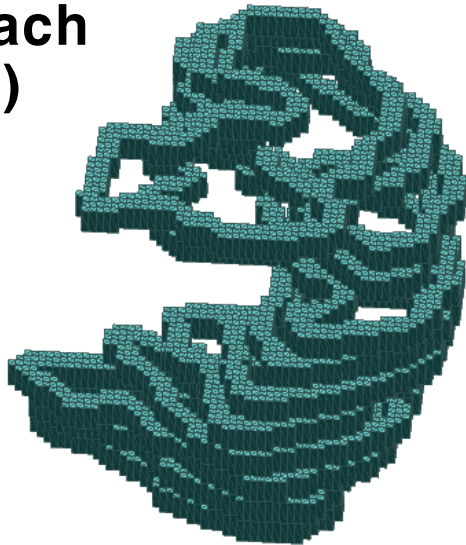


**Adult female VRCP
($1.775 \times 1.775 \times 4.8 \text{ mm}^3$)**

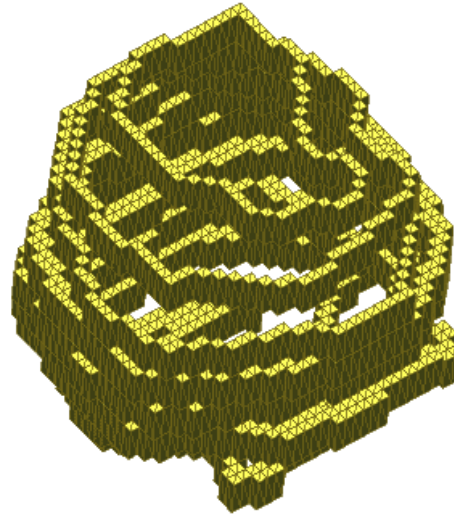
“Discontinuous”

VRCP Limitations (Hollow Organs)

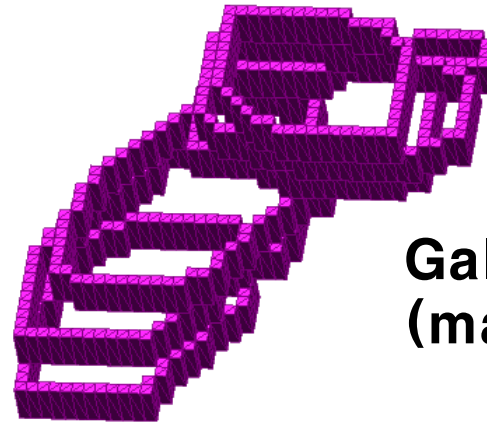
**Stomach
(male)**



**Urinary bladder
(male)**

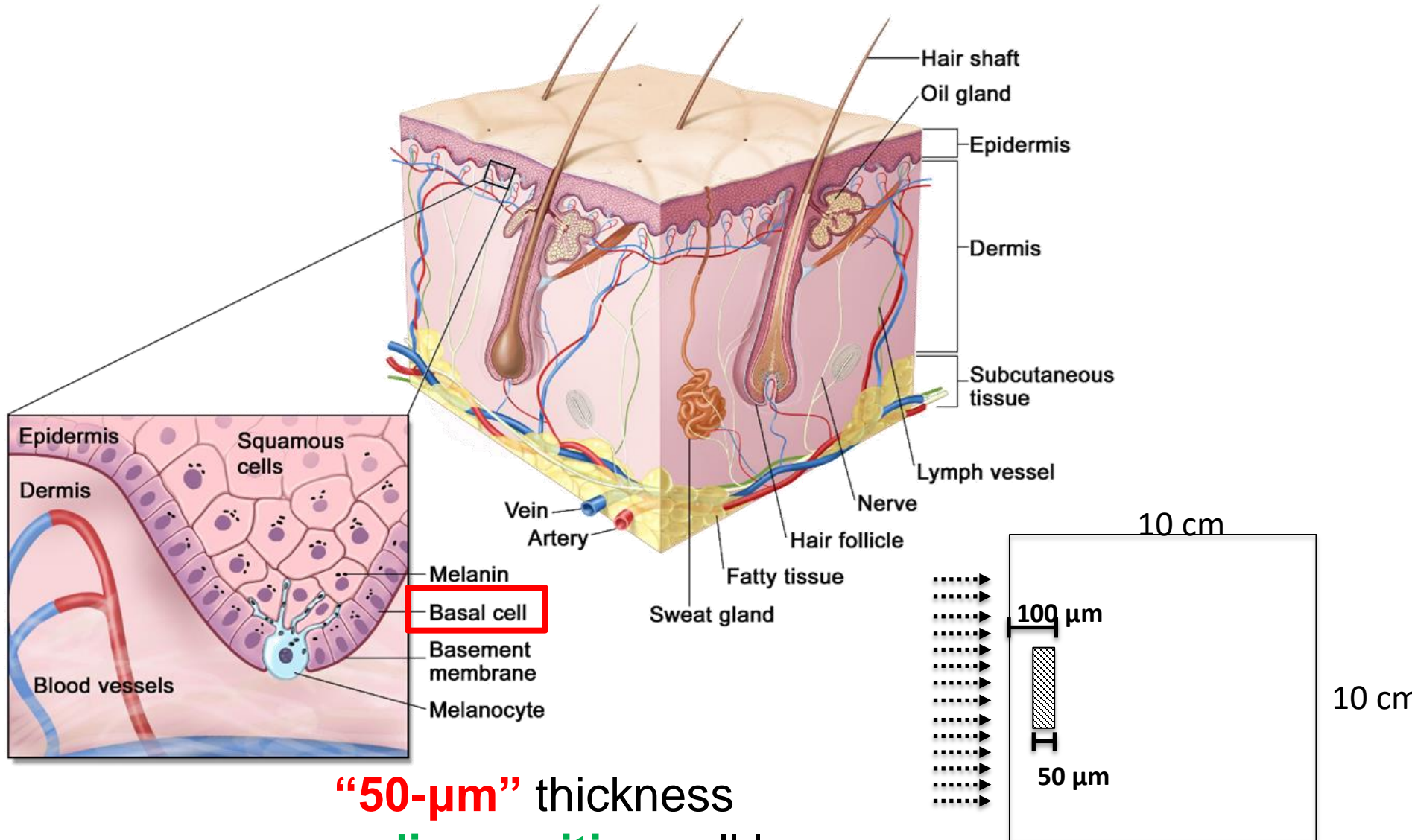


**Gall bladder
(male)**



“Discontinuous”

VRCP Limitations (Micron-thick target, Skin)

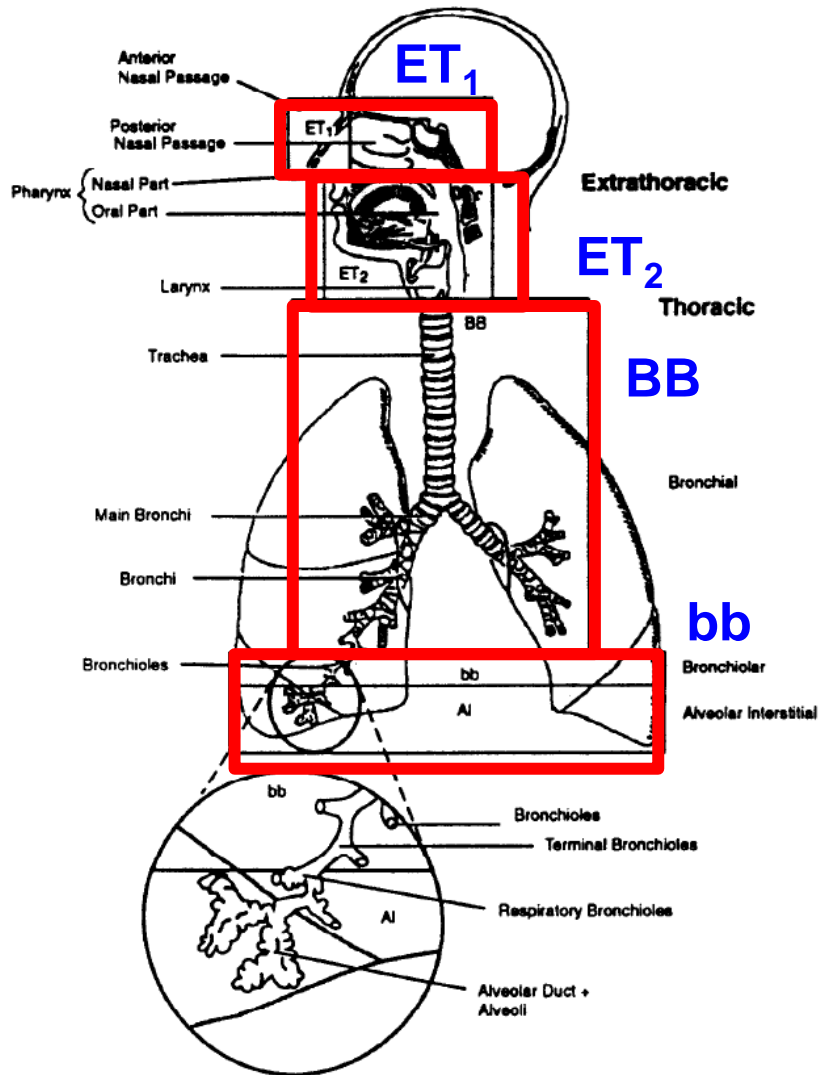


“50- μm ” thickness
radiosensitive cell layer

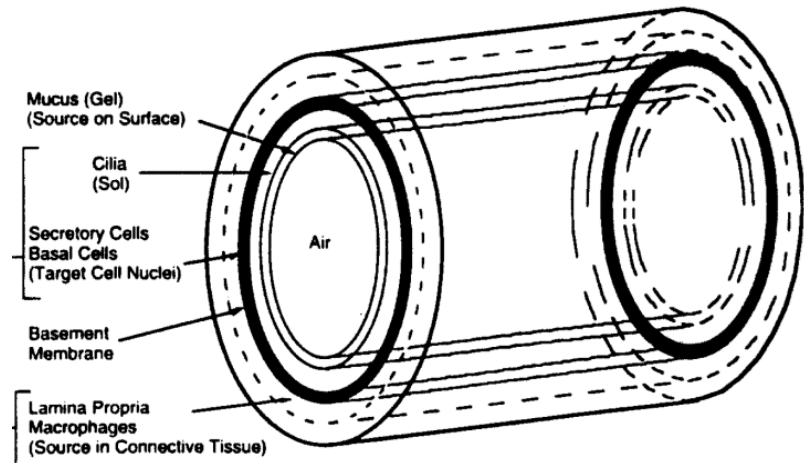
Voxel resolutions: 0.66 – 8.00 mm

ICRP-116 (2010)

VRCP Limitations (Micron-thick target, Respiratory)



Human Respiratory Tract Model (ICRP 66, 1994)

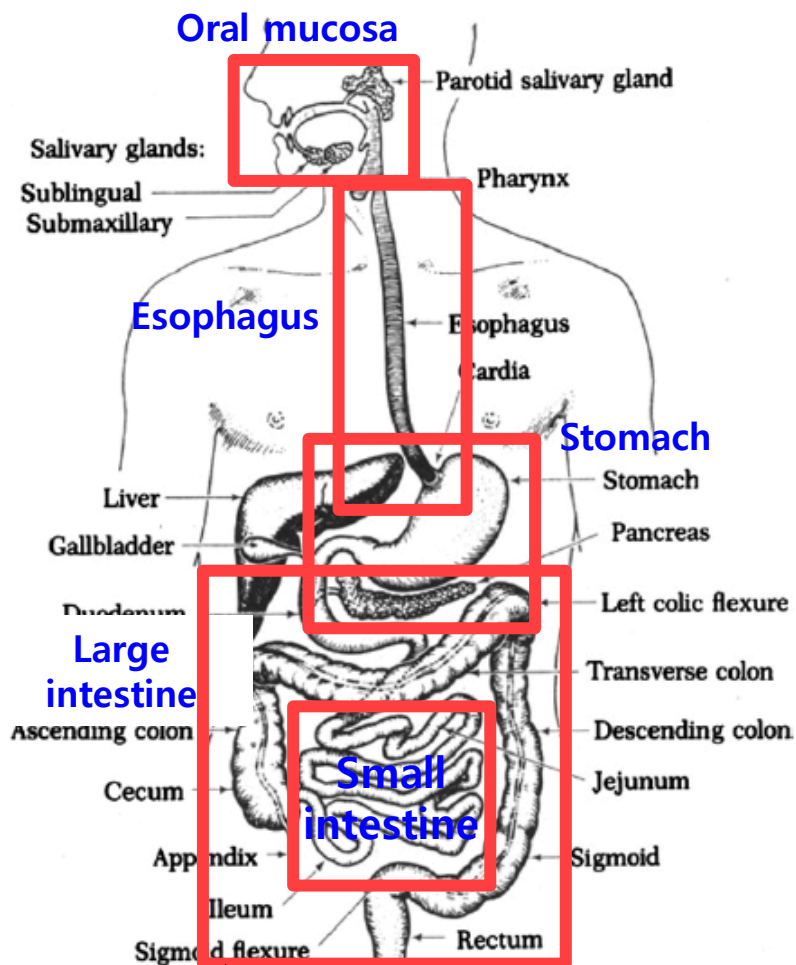


“8-15- μm ” thickness
radiosensitive cell layer

4 “additional” stylized model
used for adult SAF
calculations

Voxel resolutions: 0.66 – 8.00 mm

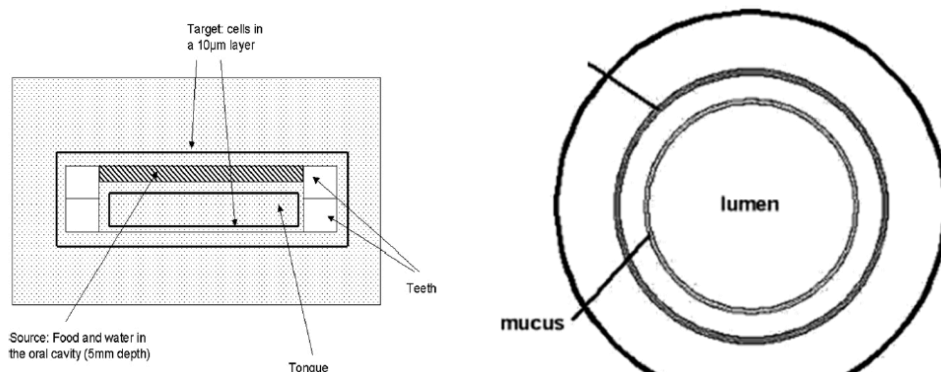
VRCP Limitations (Micron-thick target, Alimentary)



Note: 3 different stylized phantoms are used for large intestine.

Human Alimentary Tract Model
(ICRP 100, 2006)

“10-40- μm ” thickness
radiosensitive cell layers



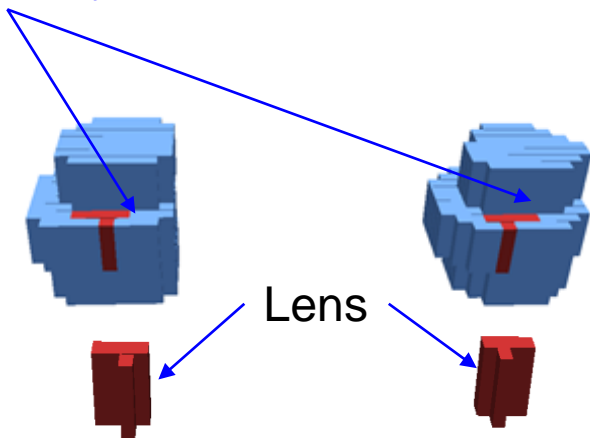
7 “additional” stylized model
used for adult SAF
calculations

Voxel resolutions: 0.66 – 8.00 mm

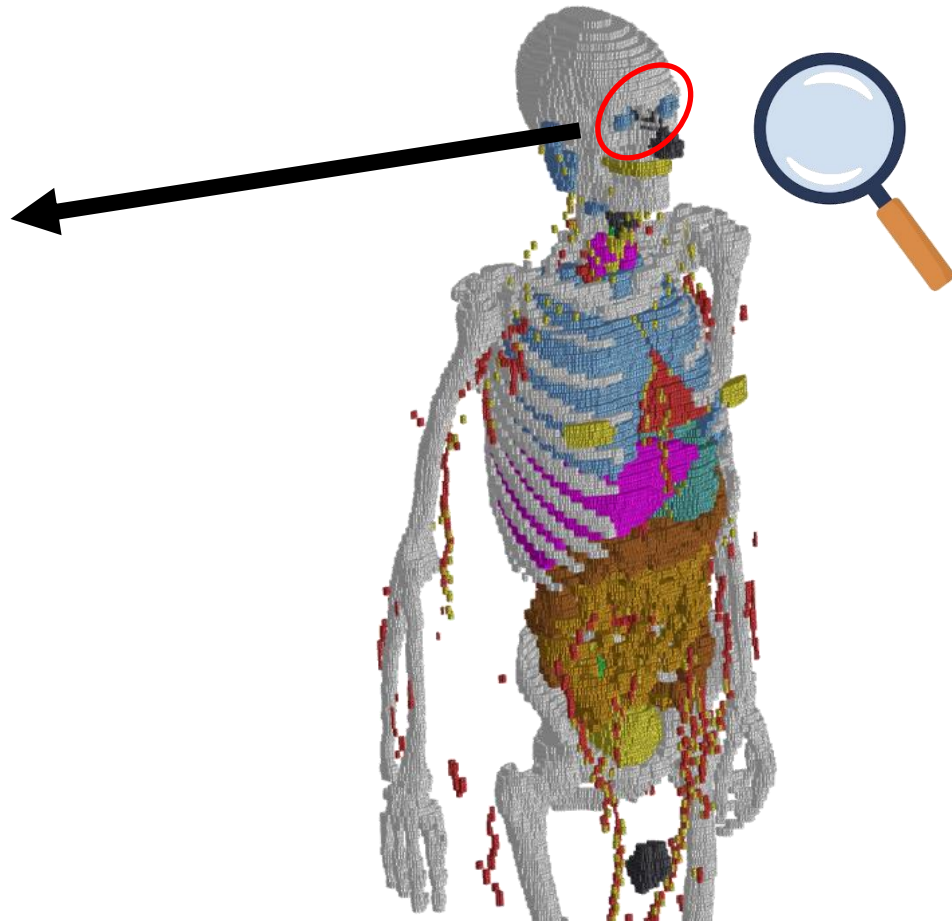
VRCP Limitations (Eye Lens)

- The lenses of the eyes are directly exposed to air, which is anatomically incorrect, resulting in significant overestimation in lens dose calculation for weakly-penetrating radiations.

Directly exposed to air



Eye models of adult male
VRCP

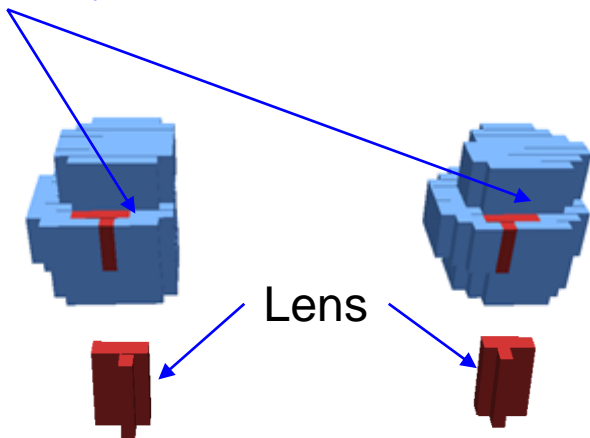


Adult male VRCP

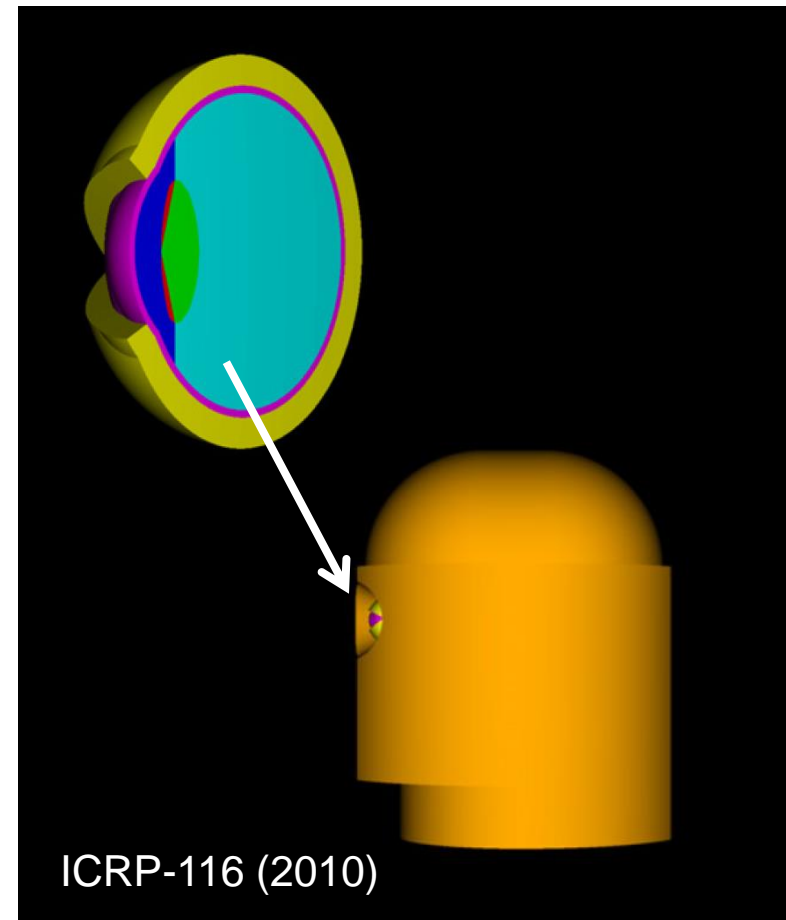
VRCP Limitations (Eye Lens)

- The lenses of the eyes are directly exposed to air, which is anatomically incorrect, resulting in significant overestimation in lens dose calculation for weakly-penetrating radiations.

Directly exposed to air



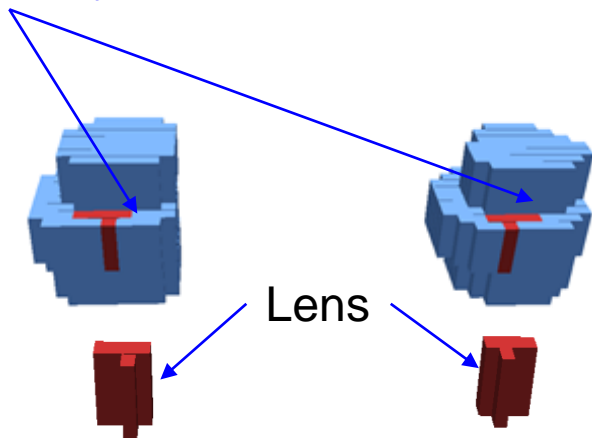
Eye models of adult male
VRCP



VRCP Limitations (Eye Lens)

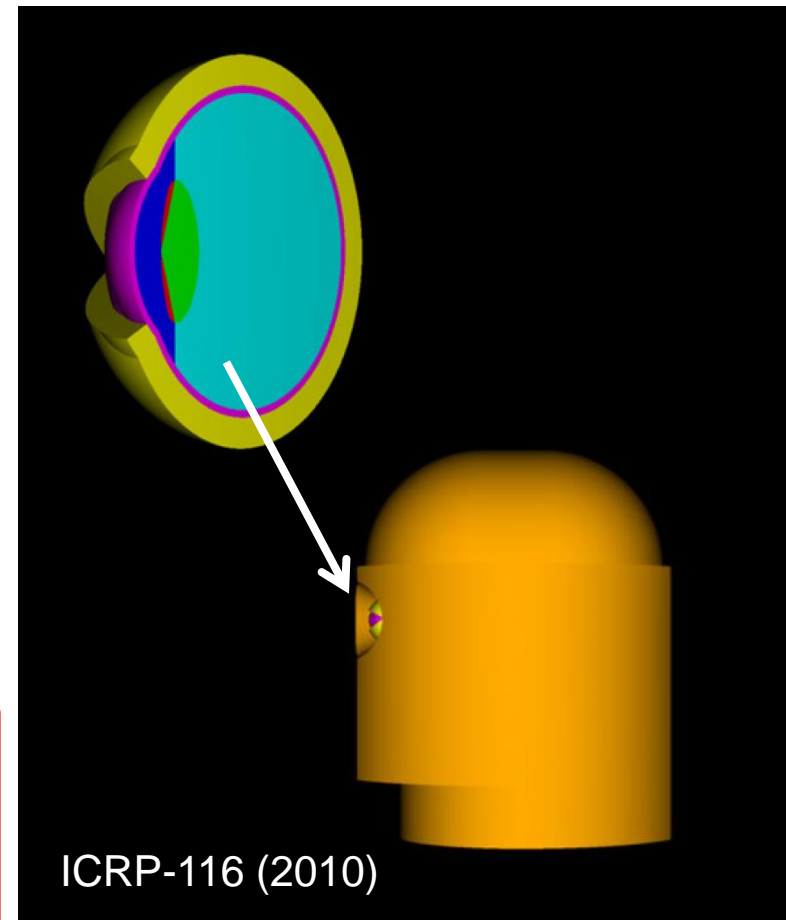
- The lenses of the eyes are directly exposed to air, which is anatomically incorrect, resulting in significant overestimation in lens dose calculation for weakly-penetrating radiations.

Directly exposed to air



Eye models of adult male
VRCP

“Using 13 additional stylized models for adults (~50 models including children)



Other Limitations

- The VRCs were matched to the reference organ masses **exclusive of blood content.**
 - Organs smaller than usual (i.e., by 3-20%)
 - Some neighboring organs not in contact
- These phantoms are **not deformable.**
- 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 distribution of lymphatic nodes in the phantoms are not symmetric.
- Some tissue masses do not match the ICRP-89 data

Advances in Phantom Technology

1950s~1960s

Simplified

1st Generation
(1960s~)

**Stylized
(Equations)**

2nd Generation
(1980s~)

**Voxel
(Volume Mesh)**

3rd Generation
(2000s~)

**NURBS/Polygon
Mesh
(Surface Mesh)**

4th Generation
(2010s~)

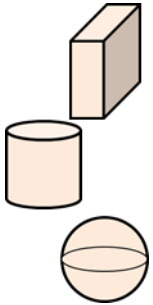
**Tetrahedron
(Volume Mesh)**



Advances in Phantom Technology

1950s~1960s

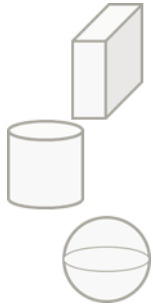
Simplified



Advances in Phantom Technology

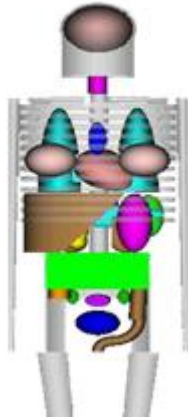
1950s~1960s

Simplified



1st Generation
(1960s~)

Stylized
(Equations)



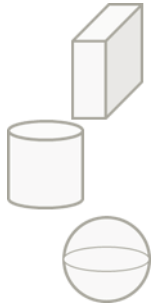
MIRD5,
ADAM/EVA,
KMIRD, ...

- Specific organs

Advances in Phantom Technology

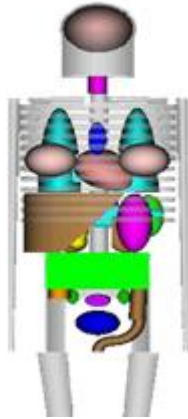
1950s~1960s

Simplified



1st Generation
(1960s~)

Stylized
(Equations)



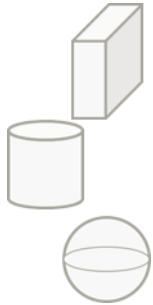
MIRD5,
ADAM/EVA,
KMIRD, ...

- Specific organs
- **Not realistic**

Advances in Phantom Technology

1950s~1960s

Simplified



1st Generation
(1960s~)

Stylized
(Equations)

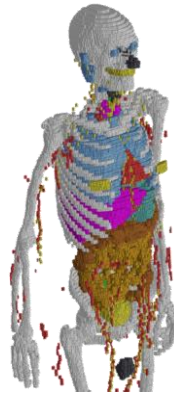


MIRD5,
ADAM/EVA,
KMIRD, ...

- Specific organs
- Not realistic

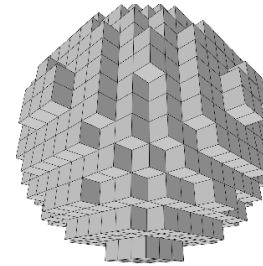
2nd Generation
(1980s~)

Voxel
(Volume Mesh)



ICRP 110,
VIP-MAN,
HDRKs, ...

- Realistic than stylized

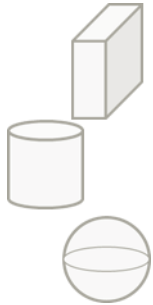


Voxel

Advances in Phantom Technology

1950s~1960s

Simplified



1st Generation
(1960s~)

Stylized
(Equations)

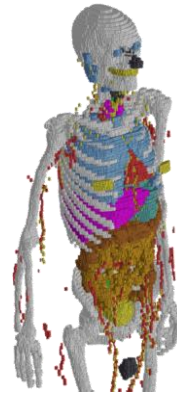


MIRD5,
ADAM/EVA,
KMIRD, ...

- Specific organs
- Not realistic

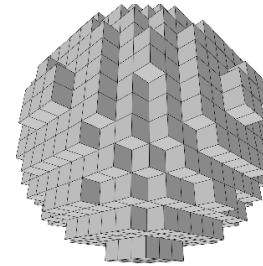
2nd Generation
(1980s~)

Voxel
(Volume Mesh)



ICRP 110,
VIP-MAN,
HDRKs, ...

- Realistic than stylized
- **Limited voxel resolutions (millimeter scale)**

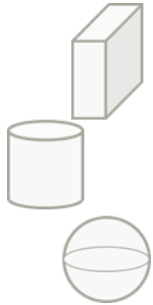


Voxel

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1950s~1960s

Simplified



1st Generation
(1960s~)

Stylized
(Equations)

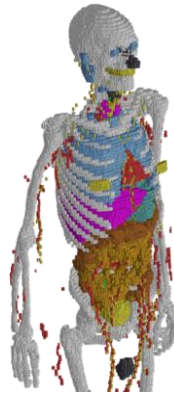


MIRD5,
ADAM/EVA,
KMIRD, ...

- Specific organs
- Not realistic

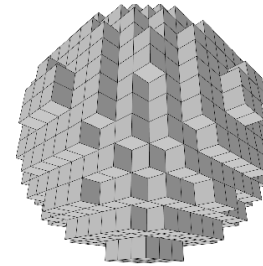
2nd Generation
(1980s~)

Voxel
(Volume Mesh)



ICRP 110,
VIP-MAN,
HDRKs, ...

- Realistic than stylized
- **Limited voxel resolutions (millimeter scale)**
- Not deformable
- Stair-stepped

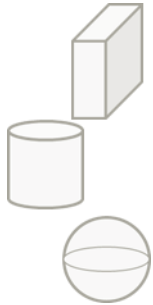


Voxel

Advances in Phantom Technology

1950s~1960s

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1st Generation
(1960s~)

Stylized
(Equations)



MIRD5,
ADAM/EVA,
KMIRD, ...

- Specific organs
- Deformable
- Not realistic

2nd Generation
(1980s~)

Voxel
(Volume Mesh)

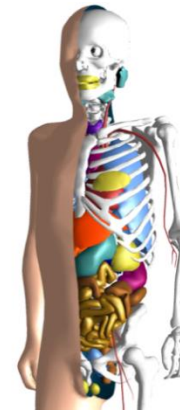


ICRP 110,
VIP-MAN,
HDRKs, ...

- Realistic than stylized
- Limited voxel resolutions (millimeter scale)
- Not deformable
- Stair-stepped

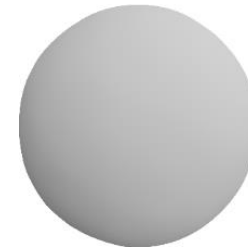
3rd Generation
(2000s~)

NURBS/Polygon
Mesh
(Surface Mesh)

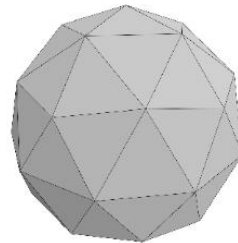


PSRKs,
UF Family,
RPI-AM,AF
4D XCAT, ...

- Smooth boundary



NURBS

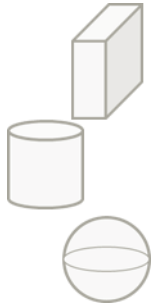


Polygon
Mesh

Advances in Phantom Technology

1950s~1960s

Simplified



1st Generation
(1960s~)

Stylized
(Equations)



MIRD5,
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KMIRD, ...

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- Deformable
- Not realistic

2nd Generation
(1980s~)

Voxel
(Volume Mesh)

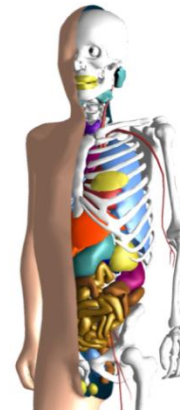


ICRP 110,
VIP-MAN,
HDRKs, ...

- Realistic than stylized
- Limited voxel resolutions (millimeter scale)
- Not deformable
- Stair-stepped

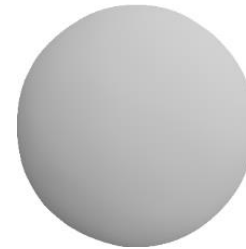
3rd Generation
(2000s~)

NURBS/Polygon
Mesh
(Surface Mesh)

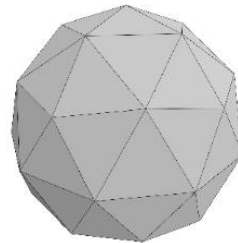


PSRKs,
UF Family,
RPI-AM,AF
4D XCAT, ...

- Smooth boundary
- Thin/small structures



NURBS

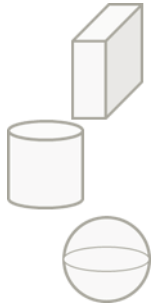


Polygon
Mesh

Advances in Phantom Technology

1950s~1960s

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1st Generation
(1960s~)

Stylized
(Equations)



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2nd Generation
(1980s~)

Voxel
(Volume Mesh)

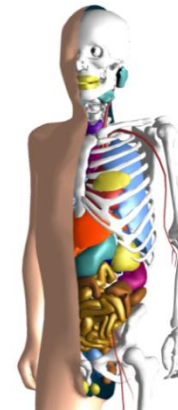


ICRP 110,
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- Realistic than stylized
- Limited voxel resolutions (millimeter scale)
- Not deformable
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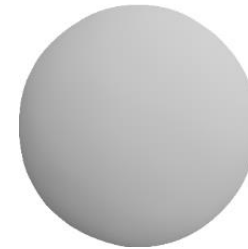
3rd Generation
(2000s~)

NURBS/Polygon
Mesh
(Surface Mesh)

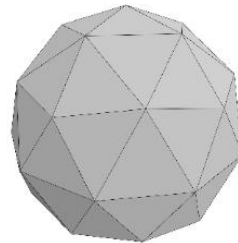


PSRKs,
UF Family,
RPI-AM,AF
4D XCAT, ...

- Smooth boundary
- Thin/small structures
- Deformable



NURBS



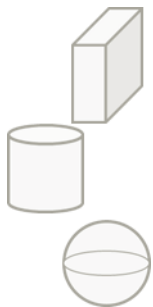
Polygon
Mesh



Advances in Phantom Technology

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(1960s~)

Stylized
(Equations)



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- Deformable
- Not realistic

2nd Generation
(1980s~)

Voxel
(Volume Mesh)

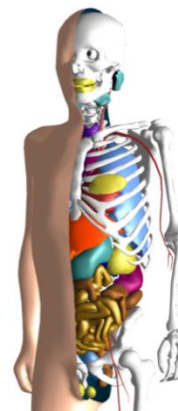


ICRP 110,
VIP-MAN,
HDRKs, ...

- Realistic than stylized
- Limited voxel resolutions (millimeter scale)
- Not deformable
- Stair-stepped

3rd Generation
(2000s~)

NURBS/Polygon
Mesh
(Surface Mesh)



PSRKs,
UF Family,
RPI-AM,AF
4D XCAT, ...

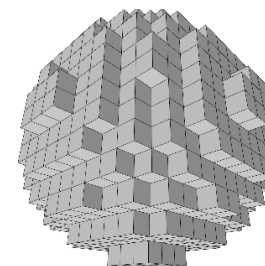
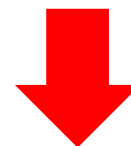
- Smooth boundary
- Thin/small structures
- Deformable
- **Voxelized for MC**



NURBS



Polygon
Mesh

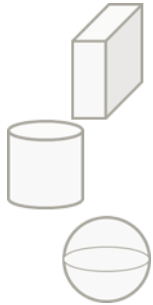


Voxel

Advances in Phantom Technology

1950s~1960s

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1st Generation
(1960s~)

Stylized
(Equations)



MIRD5,
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KMIRD, ...

- Specific organs
- Deformable
- Not realistic

2nd Generation
(1980s~)

Voxel
(Volume Mesh)

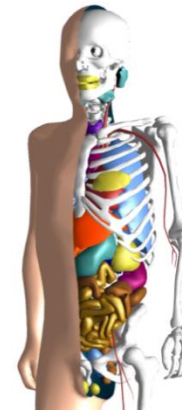


ICRP 110,
VIP-MAN,
HDRKs, ...

- Realistic than stylized
- Limited voxel resolutions (millimeter scale)
- Not deformable
- Stair-stepped

3rd Generation
(2000s~)

**NURBS/Polygon
Mesh
(Surface Mesh)**

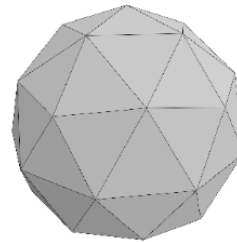


PSRKs,
UF Family,
RPI-AM,AF
4D XCAT, ...

- **Smooth boundary**
- **Thin/small structures**
- **Deformable**
- Voxelized for MC
- **Slow MC calc.**



NURBS

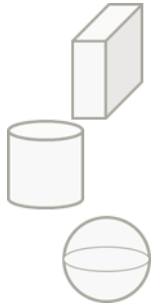


Polygon
Mesh

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(1960s~)

Stylized
(Equations)



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ADAM/EVA,
KMIRD, ...

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2nd Generation
(1980s~)

Voxel
(Volume Mesh)

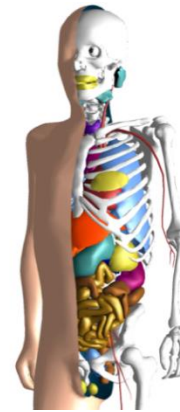


ICRP 110,
VIP-MAN,
HDRKs, ...

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3rd Generation
(2000s~)

NURBS/Polygon
Mesh
(Surface Mesh)

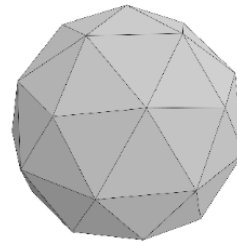


PSRKs,
UF Family,
RPI-AM,AF
4D XCAT, ...

- Smooth boundary
- Thin/small structures
- Deformable
- Voxelized for MC
- **Slow MC calc.**
- No sub-organ density variation



NURBS

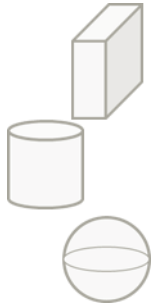


Polygon
Mesh

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(1960s~)

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(Equations)



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(2000s~)

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Mesh
(Surface Mesh)

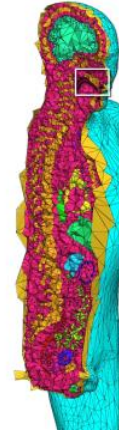


PSRKs,
UF Family,
RPI-AM,AF
4D XCAT, ...

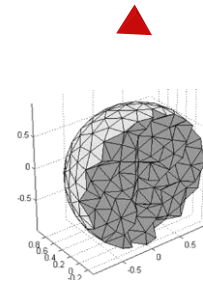
- Smooth boundary
- Thin/small structures
- Deformable
- Voxelized for MC
- Slow MC calc.
- No sub-organ density variation

4th Generation
(2010s~)

Tetrahedron
(Volume Mesh)



THRKs,
MRCPs,
MRKPs



Advances in Phantom Technology

1950s~1960s

1st Generation
(1960s~)

2nd Generation
(1980s~)

3rd Generation
(2000s~)

4th Generation
(2010s~)

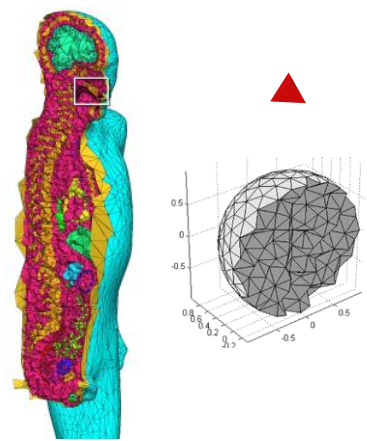
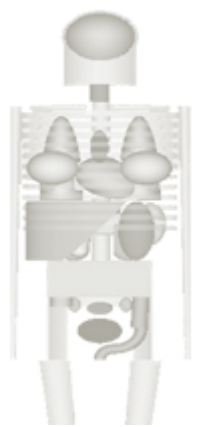
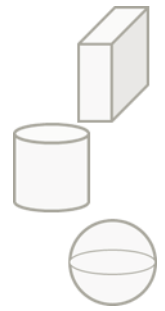
Simplified

Stylized
(Equations)

Voxel
(Volume Mesh)

NURBS/Polygon
Mesh
(Surface Mesh)

**Tetrahedron
(Volume Mesh)**



MIRD5,
ADAM/EVA,
KMIRD, ...

ICRP 110,
VIP-MAN,
HDRKs, ...

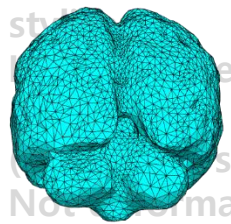
PSRKs,
UF Family,
RPI-AM,AF
4D XCAT, ...

THRKs,
MRCPs,
MRKPs

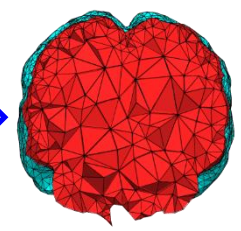
- Specific organs
- Deformable
- Not realistic

- Realistic than stylized
- Not deformable
- Stair-stepped

- Smooth boundary
- Thin/small structures



Polygon



Tetrahedron

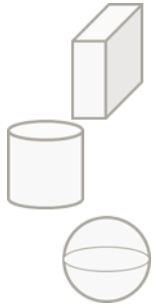
- Not deformable
- Slow MC calc.
- No sub-organ density variation

- voxelized for MC
- Slow MC calc.
- No sub-organ density variation

Advances in Phantom Technology

1950s~1960s

Simplified



1st Generation
(1960s~)

Stylized
(Equations)



MIRD5,
ADAM/EVA,
KMIRD, ...

- Specific organs
- Deformable
- Not realistic

2nd Generation
(1980s~)

Voxel
(Volume Mesh)

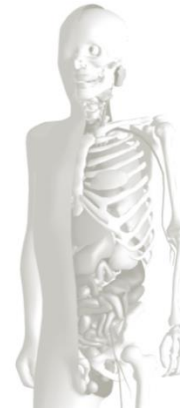


ICRP 110,
VIP-MAN,
HDRKs, ...

- Realistic than stylized
- Limited voxel resolutions (millimeter scale)
- Not deformable
- Stair-stepped

3rd Generation
(2000s~)

NURBS/Polygon
Mesh
(Surface Mesh)

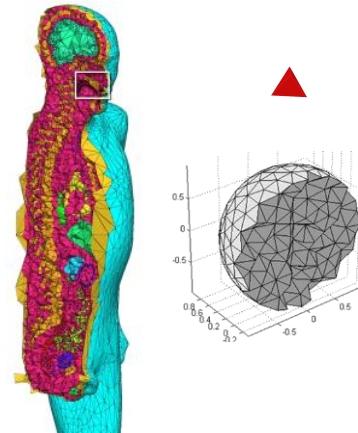


PSRKs,
UF Family,
RPI-AM,AF
4D XCAT, ...

- Smooth boundary
- Thin/small structures
- Deformable
- Voxelized for MC
- Slow MC calc.
- No sub-organ density variation

4th Generation
(2010s~)

Tetrahedron
(Volume Mesh)



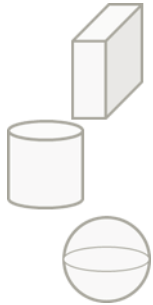
THRKs,
MRCPs,
MRKPs

- Smooth boundary
- Thin/small structures
- Deformable

Advances in Phantom Technology

1950s~1960s

Simplified



1st Generation
(1960s~)

Stylized
(Equations)



MIRD5,
ADAM/EVA,
KMIRD, ...

- Specific organs
- Deformable
- Not realistic

2nd Generation
(1980s~)

Voxel
(Volume Mesh)

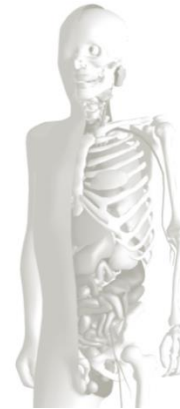


ICRP 110,
VIP-MAN,
HDRKs, ...

- Realistic than stylized
- Limited voxel resolutions (millimeter scale)
- Not deformable
- Stair-stepped

3rd Generation
(2000s~)

NURBS/Polygon
Mesh
(Surface Mesh)

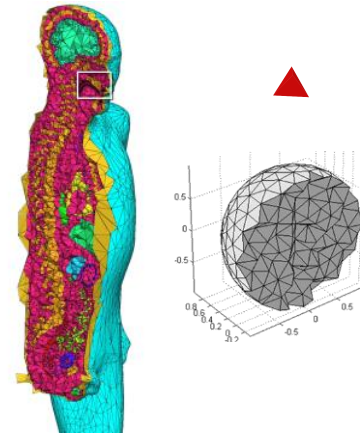


PSRKs,
UF Family,
RPI-AM,AF
4D XCAT, ...

- Smooth boundary
- Thin/small structures
- Deformable
- Voxelized for MC
- Slow MC calc.
- No sub-organ density variation

4th Generation
(2010s~)

Tetrahedron
(Volume Mesh)



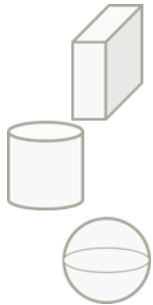
THRKs,
MRCPs,
MRKPs

- Smooth boundary
- Thin/small structures
- Deformable
- **Fast MC calc. (no voxelization)**

Advances in Phantom Technology

1950s~1960s

Simplified



1st Generation
(1960s~)

Stylized
(Equations)



MIRD5,
ADAM/EVA,
KMIRD, ...

- Specific organs
- Deformable
- Not realistic

2nd Generation
(1980s~)

Voxel
(Volume Mesh)

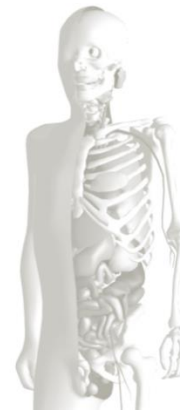


ICRP 110,
VIP-MAN,
HDRKs, ...

- Realistic than stylized
- Limited voxel resolutions (millimeter scale)
- Not deformable
- Stair-stepped

3rd Generation
(2000s~)

NURBS/Polygon
Mesh
(Surface Mesh)

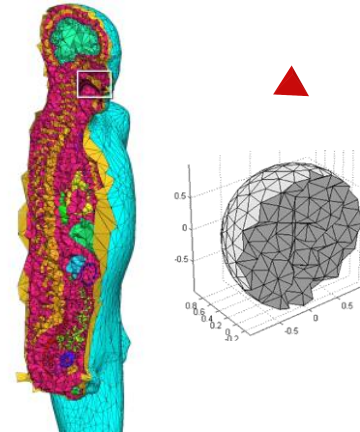


PSRKs,
UF Family,
RPI-AM,AF
4D XCAT, ...

- Smooth boundary
- Thin/small structures
- Deformable
- Voxelized for MC
- Slow MC calc.
- No sub-organ density variation

4th Generation
(2010s~)

Tetrahedron
(Volume Mesh)

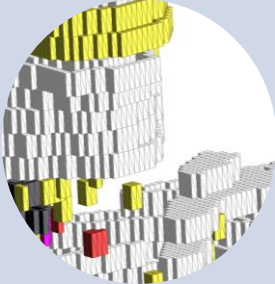
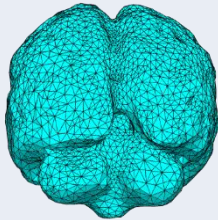
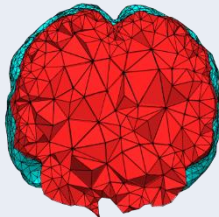


THRKs,
MRCPs,
MRKPs

- Smooth boundary
- Thin/small structures
- Deformable
- **Fast MC calc. (no voxelization)**
- Sub-organ density variation

Representation type

Mesh type

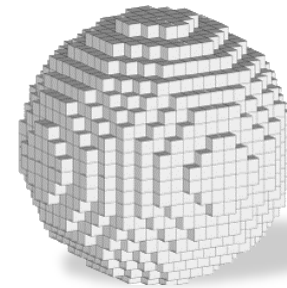
| | Surface mesh (B-Rep) | Volume mesh (V-Rep) |
|-------------------|--|--|
| Structured Mesh | | Voxel <ul style="list-style-type: none">- 2nd generation- Structured volume mesh <p><u>Advantages:</u></p> <ul style="list-style-type: none">• Fast simulation• Sub-organ density variation modeling  |
| Unstructured mesh | NURBS/Polygon <ul style="list-style-type: none">- 3rd generation- Unstructured surface mesh  <p><u>Advantages:</u></p> <ul style="list-style-type: none">• Flexibility (deformation)• Precision modeling | Tetrahedron <ul style="list-style-type: none">- 4th generation- Unstructured volume mesh  <p><u>Advantages:</u></p> <ul style="list-style-type: none">• Flexibility (deformation)• Precision modeling• Fast simulation (i.e., no voxelization)• Sub-organ density variation modeling |

VRCP Limitations Discussed in C2 Meeting, 2013

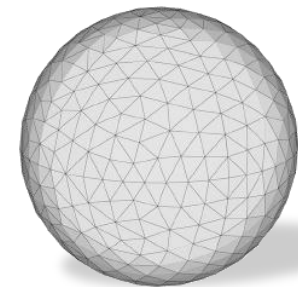
(Abu Dhabi, UAE October 2013)



- The committee decided to convert the voxel-type reference computational phantoms into a high-quality mesh format to address these problems of the voxel phantoms.
- The new phantoms will replace the current voxel-type reference phantoms from the next general recommendations.



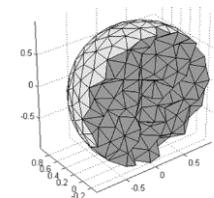
Voxel format



Mesh format



Tetrahedron



ICRP Task Group 103 (since 2016)

Task Group 103

Mesh-type Reference Computational Phantoms (MRCP)

Under Committee 2

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:

- The Task Group will develop the adult, paediatric and pregnant-female MRCPs. As a first step, the adult MRCPs will be developed by converting the existing voxel phantoms in Publication 110 into a high-quality mesh format. Then, the paediatric MRCPs will be developed from the paediatric voxel phantoms in Publication 143.
- Finally, the pregnant-female MRCPs will be newly developed. All the development processes will be discussed among TG members and the developed phantoms will be comprehensively reviewed by anatomists.

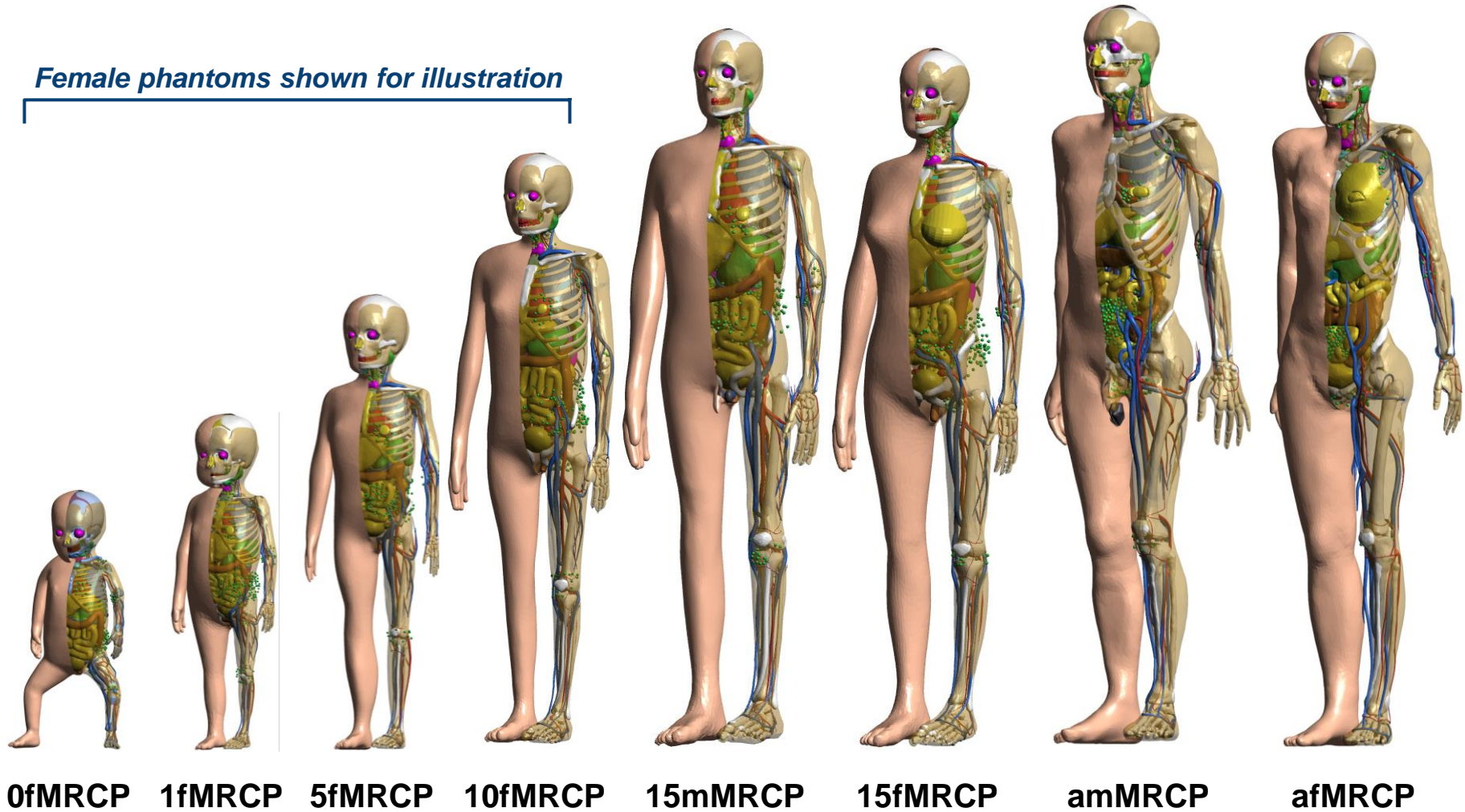
Work completed to date:

- The adult MRCPs were completely developed and released in Publication 145 - Adult Mesh-type Reference Computational Phantoms.
- The paediatric MRCPs were completely developed and the relevant report will be released soon as Publication 156 - Paediatric Mesh-type Reference Computational Phantoms.
- Recently, the pregnant-female MRCPs were completely developed and the report is currently under preparation. Public consultation is expected in 2025.

Adult and Pediatric MRCPs

- Adult MRCPs (ICRP 145, 2020)
- Pediatric MRCPs (ICRP 156, in press)

Female phantoms shown for illustration



0fMRCP

1fMRCP

5fMRCP

10fMRCP

15mMRCP

15fMRCP

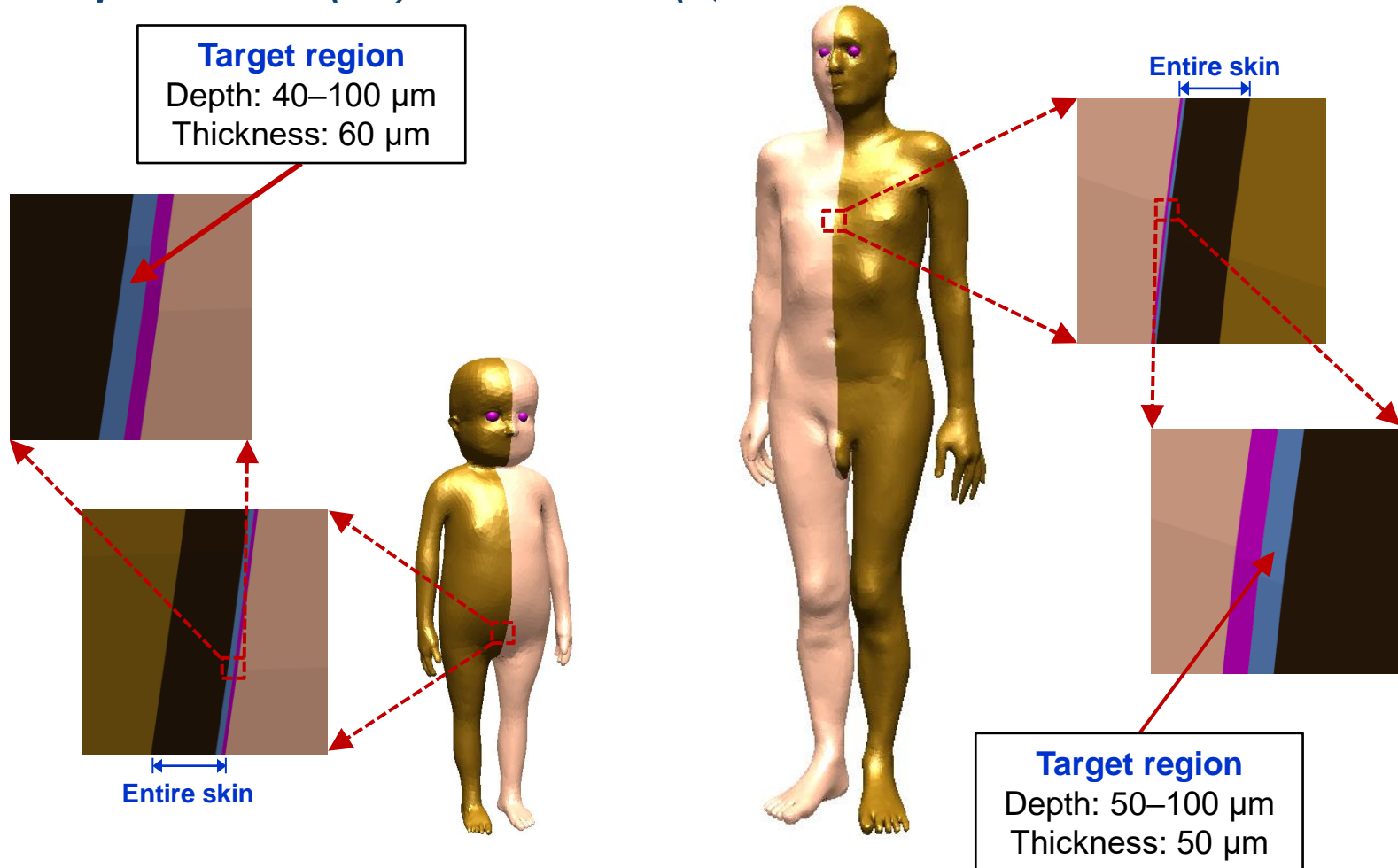
amMRCP

afMRCP

Skin

- The **micron-thick radiosensitive skin layer**.
 - 50- μm -thickness (≥ 15 -year)
 - 60- μm -thickness (≤ 10 -year)

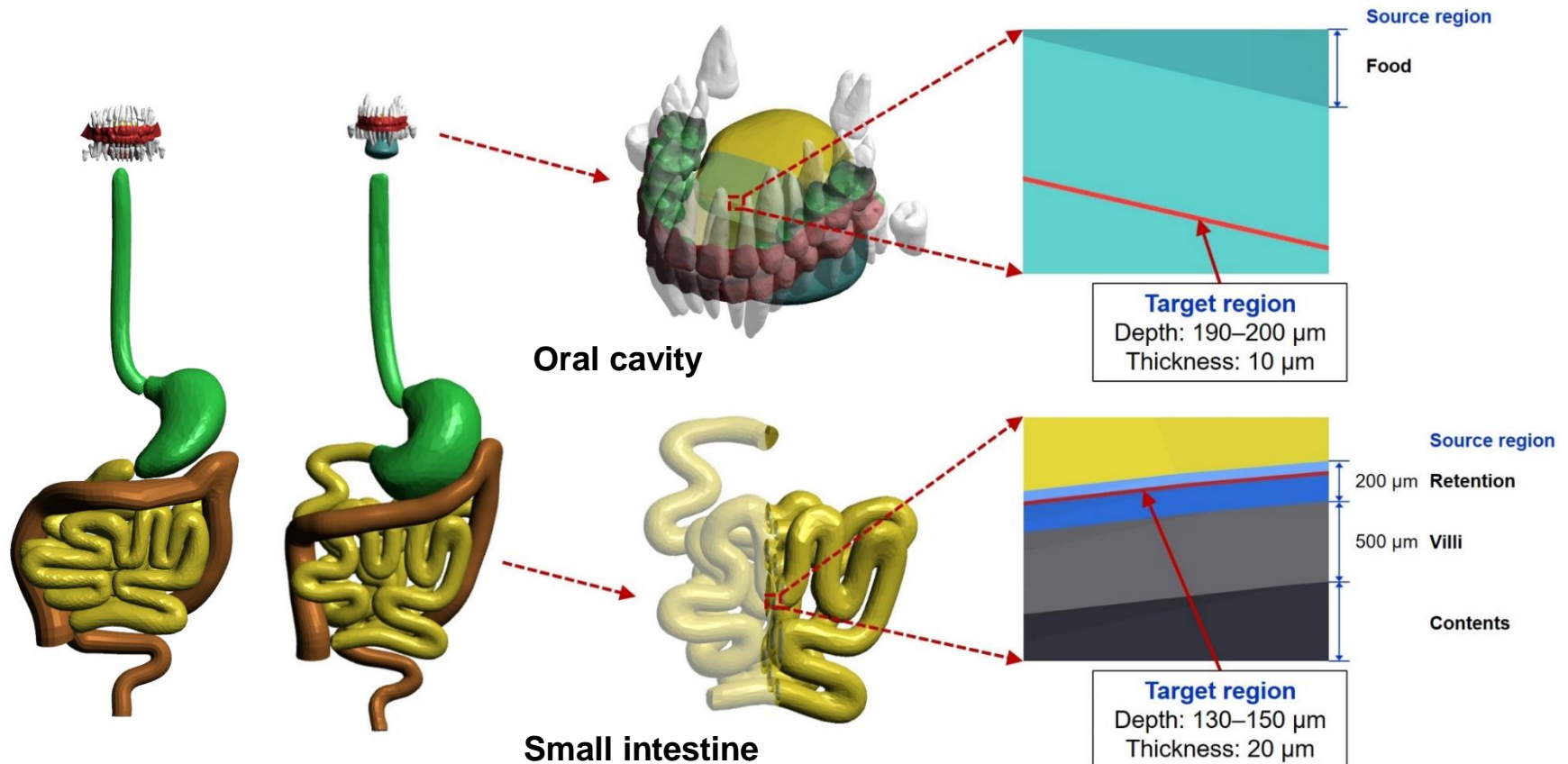
Example: 1fMRCP (left) and amMRCP (right)



Alimentary Tract Organs

- The **micron-thick radiosensitive target and source regions** in the alimentary tract organs (i.e., oral cavity, oesophagus, stomach, small intestine, ascending colon, transverse right colon, transverse left colon, descending colon, sigmoid colon, and rectum).

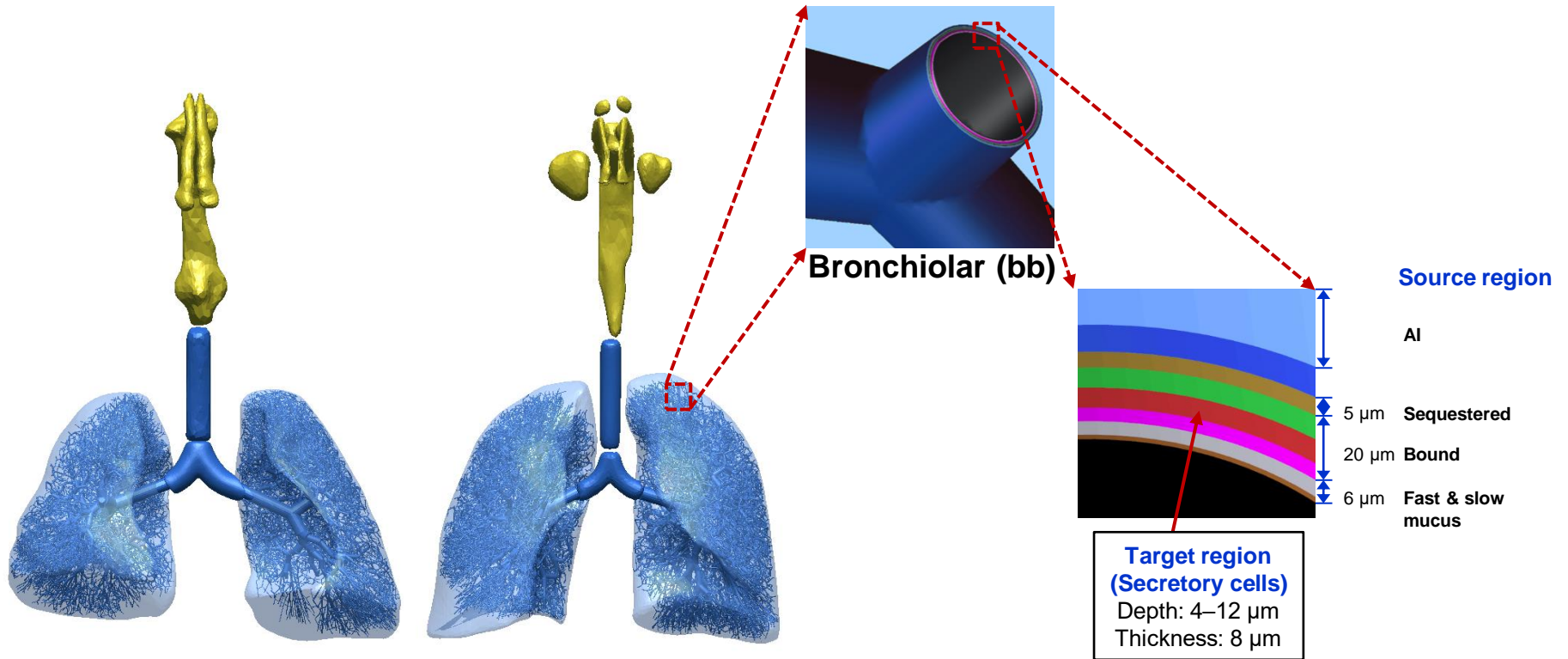
Example: 5fMRCP (left) and 15mMRCP (right)



Respiratory Tract Organs

- The **micron-thick radiosensitive target and source regions** in the respiratory tract organs (i.e., extrathoracic (ET₁ and ET₂) regions, bronchi (BB), bronchioles (bb)).

Example: 0mMRCP (left) and 10fMRCP (right)



BB / bb (Target & Source)

Male

Target region

Secretory cells

$8 \mu\text{m}$

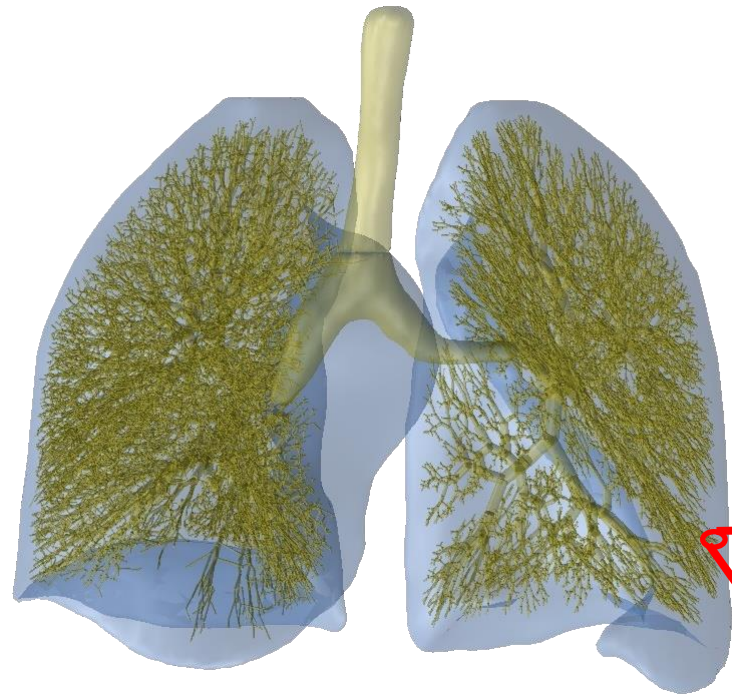
Source region

AI

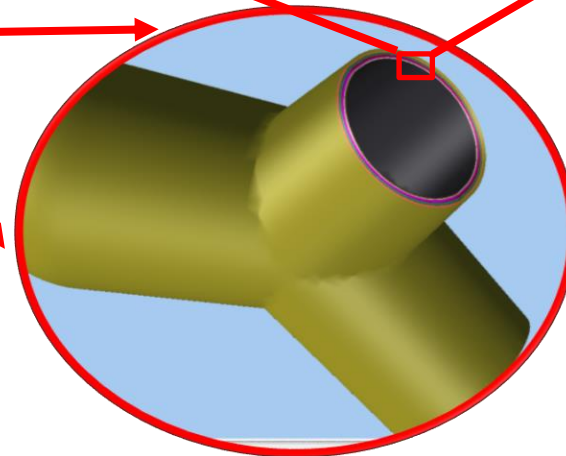
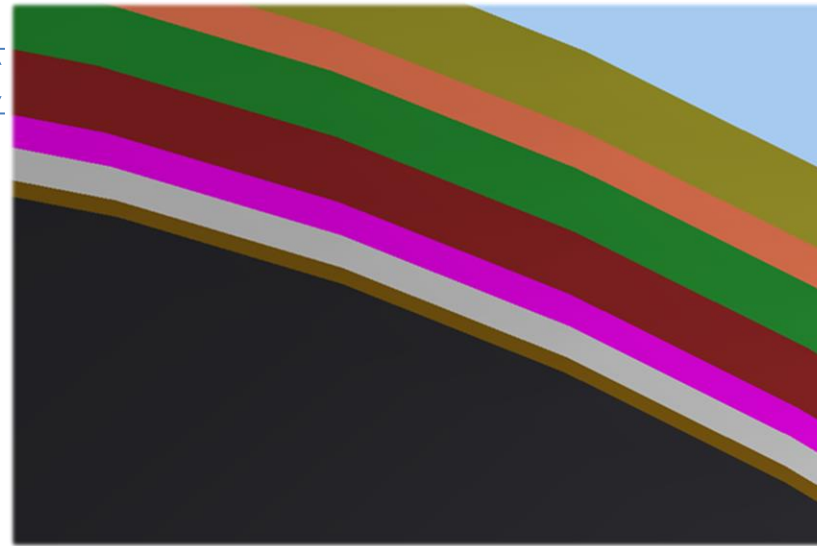
$5 \mu\text{m}$ Sequestered

$20 \mu\text{m}$ Bound

$6 \mu\text{m}$ Fast & slow mucus



“Turn ON/OFF”



Bronchiolar (bb)

Eyes

- The **detailed eye models** including **micron-thick** radiosensitive lens region.

Example: female phantoms



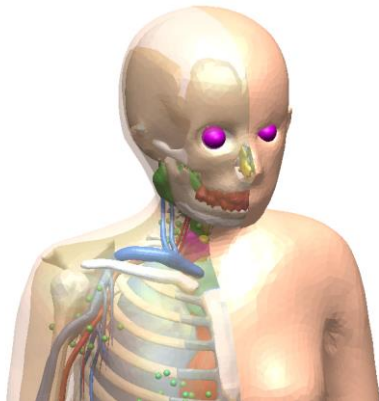
0fMRCP



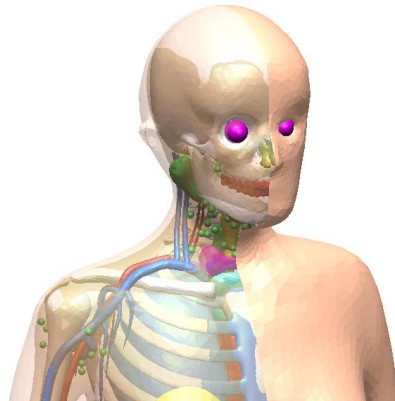
1fMRCP



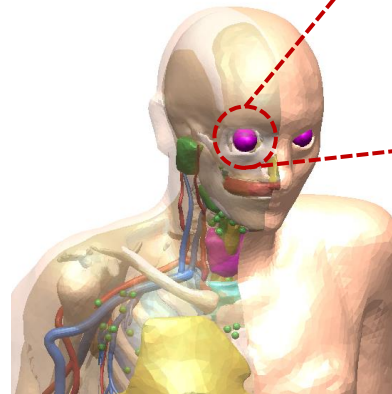
5fMRCP



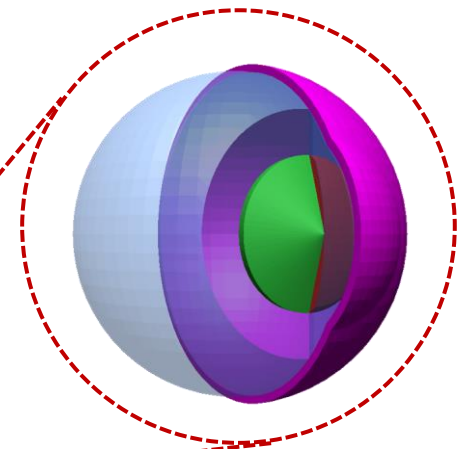
10fMRCP



15fMRCP



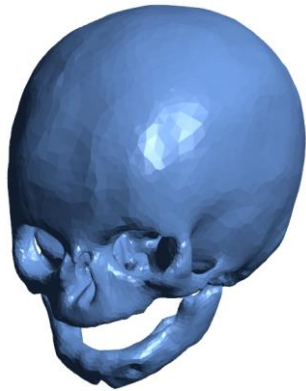
afMRCP



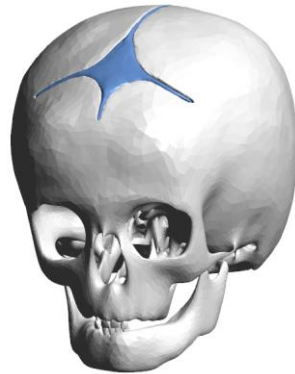
Teeth

- The **detailed teeth** installed in the MRCPs to support EPR dosimetry with tooth enamel.

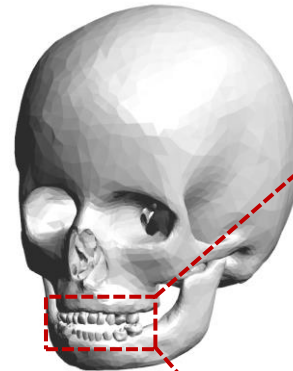
Example: male phantoms



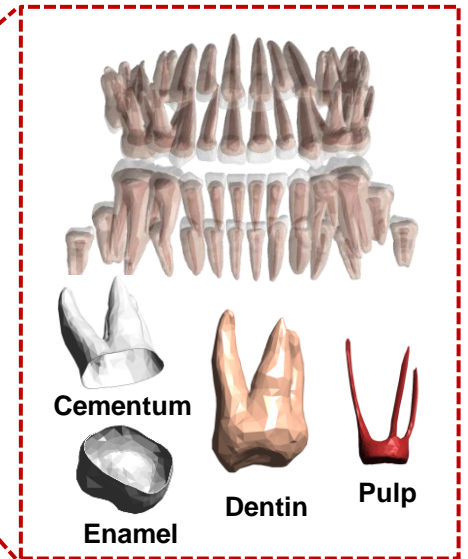
0mMRCP



1mMRCP



5mMRCP



10mMRCP

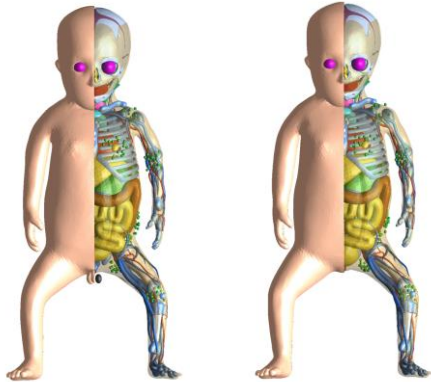


15mMRCP

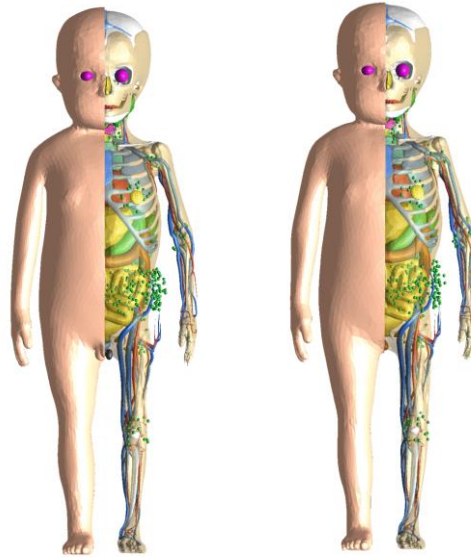


amMRCP

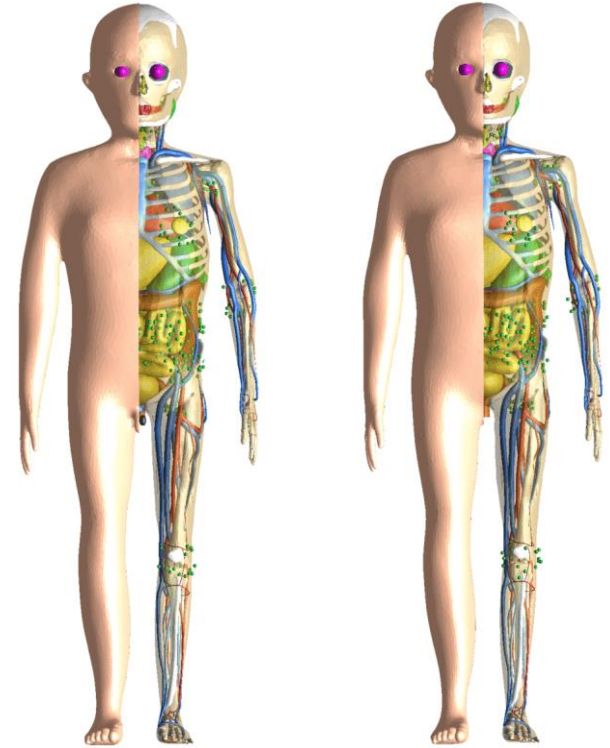
MRCPs – Rotational View (Cont'd)



0mMRCP / 0fMRCP

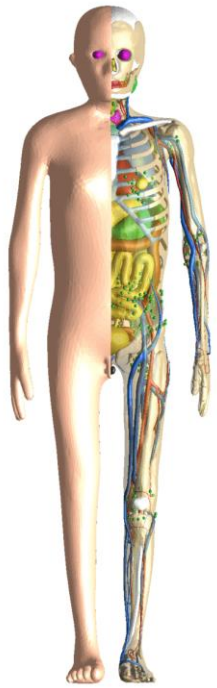


1mMRCP / 1fMRCP

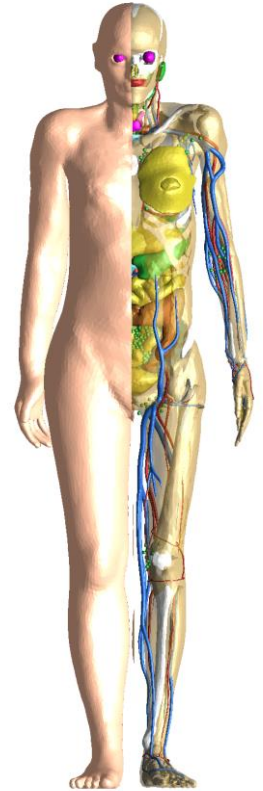
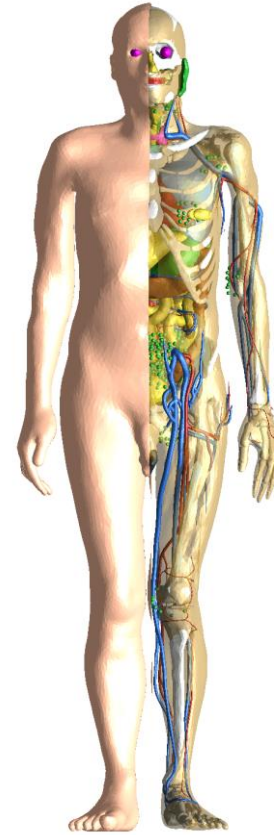
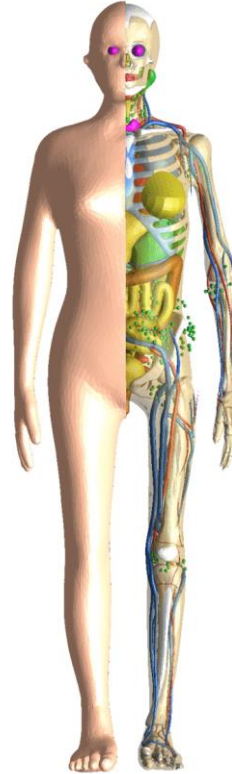
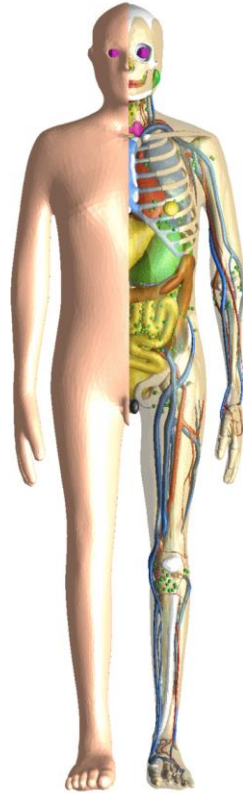
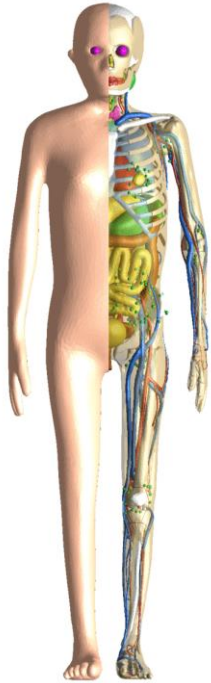


5mMRCP / 5fMRCP

MRCPs – Rotational View



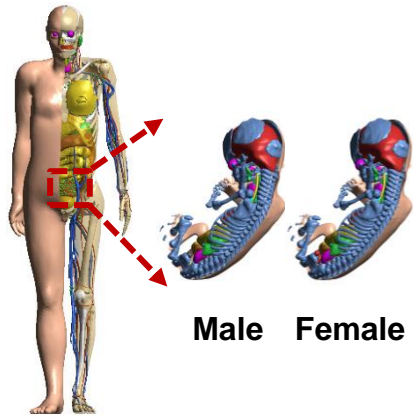
10mMRCP / 10fMRCP



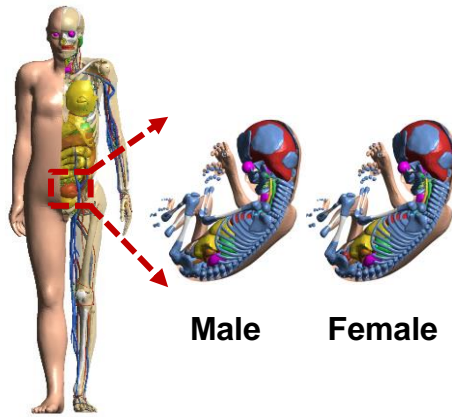
15mMRCP / 15fMRCP

amMRCP / afMRCP

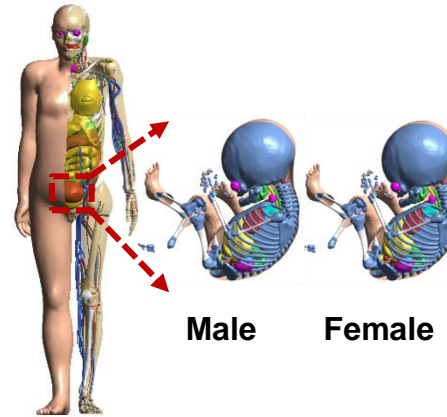
Pregnant-female MRCPs



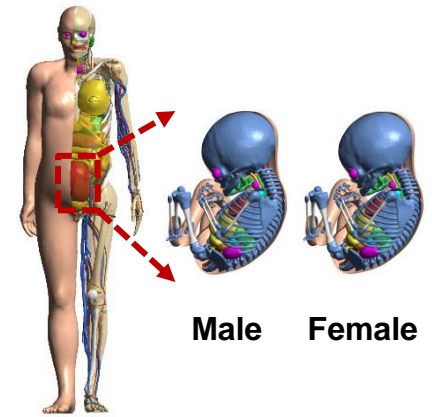
8-week pregnant-female MRCP



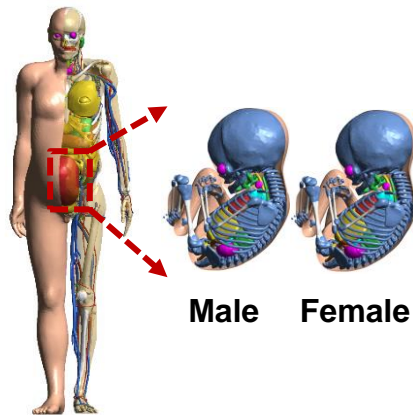
10-week pregnant-female MRCP



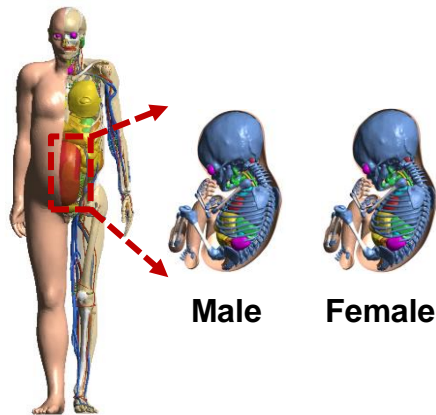
15-week pregnant-female MRCP



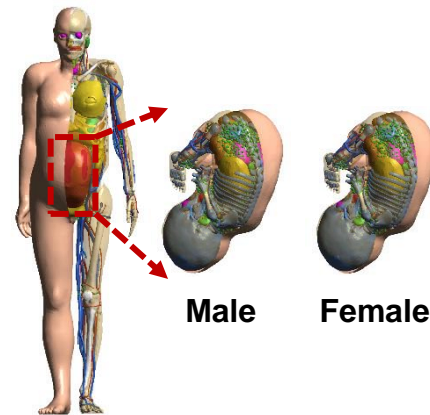
20-week pregnant-female MRCP



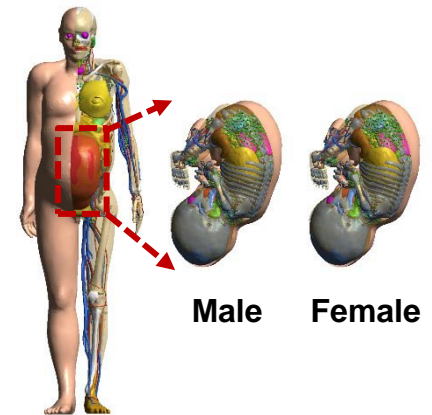
25-week pregnant-female MRCP



30-week pregnant-female MRCP



35-week pregnant-female MRCP



38-week pregnant-female MRCP

Maternal Phantoms – Rotational View



8-week maternal phantom



10-week maternal phantom

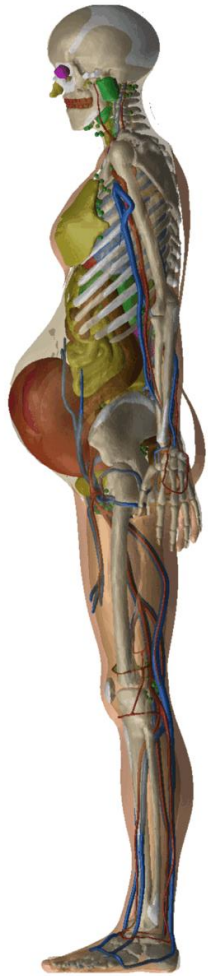


15-week maternal phantom

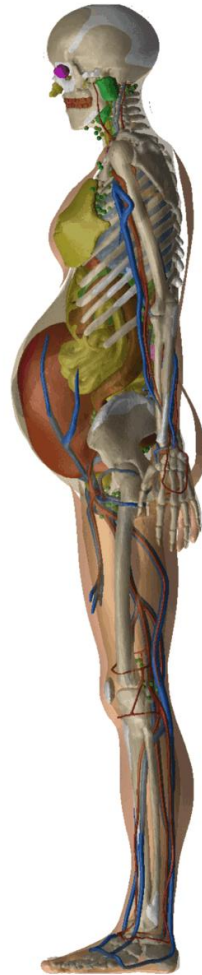


20-week maternal phantom

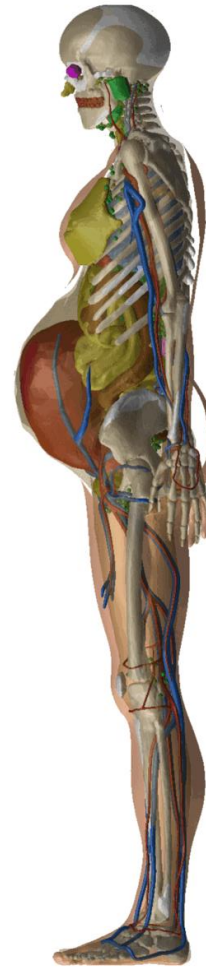
Maternal Phantoms – Rotational View (Cont'd)



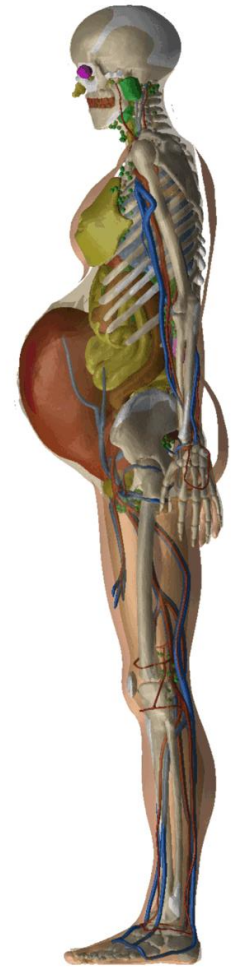
25-week maternal phantom



30-week maternal phantom



35-week maternal phantom



38-week maternal phantom

Fetal Phantoms – Rotational View



8-week male fetal phantom



10-week male fetal phantom



15-week male fetal phantom



20-week male fetal phantom



25-week male fetal phantom



30-week male fetal phantom



35-week male fetal phantom



38-week male fetal phantom

Compatibility with MC codes

Compatible MC codes

- Geant4
- PHITS
- MCNP
- EGSnrc
- FLUKA (from next version)

Performance Comparison between MC codes

Paper

COMPUTATION SPEEDS AND MEMORY REQUIREMENTS OF MESH-TYPE ICRP REFERENCE COMPUTATIONAL PHANTOMS IN GEANT4, MCNP6, AND PHITS

Yeon Soo Yeom,^{1,2} Min Cheol Han,^{2,3} Chansoo Choi,² Haegin Han,² Bangho Shin,² Takuya Furuta,⁴ and Chan Hyeong Kim²

Abstract—Recently, Task Group 103 of the International Commission on Radiological Protection completed the development of new adult male and female mesh-type reference computational phantoms, which are planned for use in future International Commission on Radiological Protection dose coefficient calculations. In the present study, the performance of major Monte Carlo particle transport codes, i.e., Geant4, MCNP6, and PHITS, were investigated for the mesh-type reference computational phantoms by performing transport simulations of photons, electrons, neutrons, and helium ions for some external and internal exposures, and simultaneously measuring the memory usage, initialization time, and computation speed of the adult male mesh-type reference computational phantom in the codes. The measured results were then compared with the values measured with the current adult male voxel-type reference computational phantom in Inter-

slower than that for the voxel-type reference computational phantom by up to ~50 times and slower than that for all of the voxelized phantoms by up to ~40 times. By contrast, PHITS showed the best performance for the mesh-type reference computational phantom, which was faster than that for the voxel-type reference computational phantom by up to ~3 times and faster than that for all of the voxelized phantoms by up to ~20 times. This high performance of PHITS is indeed encouraging considering that it is used nowadays by the International Commission on Radiological Protection for most dose coefficient calculations.

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Key words: computer calculations; International Commission on Radiological Protection; Monte Carlo; phantom

- Geant4 (ver. 10.3.1)
- PHITS (ver. 2.92)
- MCNP (ver. 6.2 pre)

Geant4 vs PHITS with recent versions

- **Used computer**

- ✓ CPU: Intel® Xeon® CPU E5-2698 v4 @ 2.20 GHz
- ✓ RAM: 256 GB DDR4 Memory
- ✓ SSD: Intel S3520 (480 GB)
- ✓ OS : CentOS 7 Linux

- **Geant4 (version 11.1.2)**

- ✓ Production cut value: 1 μm
- ✓ Physics library: FTFP_BERT_HP_LIV
- ✓ Photo-nuclear reaction is enabled.

- **PHITS (version 3.31)**

- ✓ Energy cut value: 1 keV
- ✓ Physics library: EGS5 algorithm, JENDL-4.0
- ✓ Event generator mode (version 2) is activated.
- ✓ Implicit capture is inactivated.
- ✓ Photo-nuclear reaction is enabled.

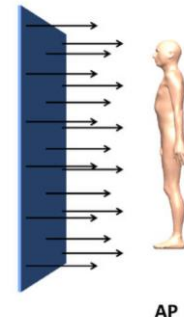
Memory Usage (GB)

| Phantom | gender | Geant4 (GB) | PHITS (GB) |
|-----------------|--------------|-------------|------------|
| Newborn | M | 13.3 | 1.46 |
| | F | 13.2 | 1.46 |
| 1-year-old | M | 13.5 | 1.37 |
| | F | 13.6 | 1.61 |
| 5-year-old | M | 13.2 | 1.56 |
| | F | 13.1 | 1.60 |
| 10-year-old | M | 12.4 | 1.47 |
| | F | 13.0 | 1.46 |
| 15-year-old | M | 12.4 | 1.50 |
| | F | 13.0 | 1.52 |
| Adult | M | 14.1 | 1.52 |
| | F | 13.3 | 1.56 |
| Pregnant-female | 8-week male | 13.7 | 1.86 |
| | 25-week male | 14.9 | 1.99 |
| | 38-week male | 19.5 | 2.91 |

Initialization Time (min)

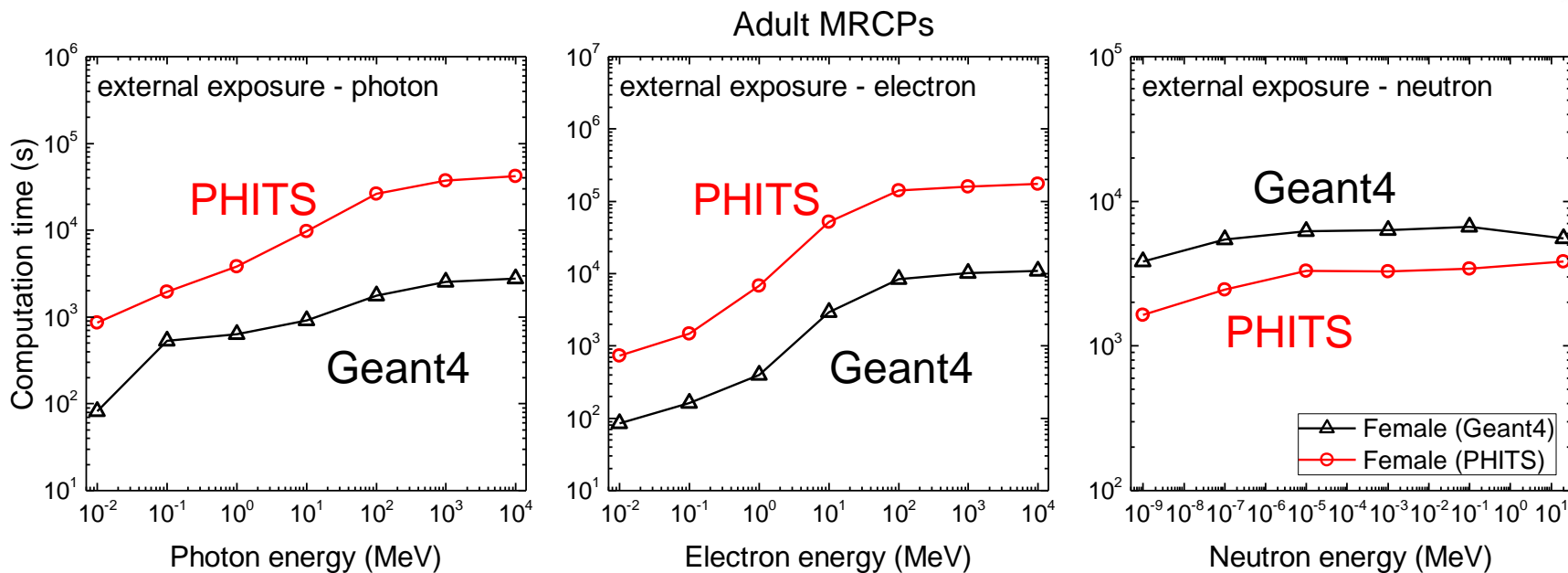
| Phantom | gender | Geant4 (min) | PHITS (min) |
|-----------------|--------------|--------------|-------------|
| Newborn | M | 3.89 | 0.603 |
| | F | 3.97 | 0.605 |
| 1-year-old | M | 4.30 | 0.624 |
| | F | 4.39 | 0.628 |
| 5-year-old | M | 4.08 | 0.679 |
| | F | 4.08 | 0.684 |
| 10-year-old | M | 4.07 | 0.678 |
| | F | 4.03 | 0.687 |
| 15-year-old | M | 3.93 | 0.670 |
| | F | 4.04 | 0.668 |
| Adult | M | 4.28 | 0.622 |
| | F | 4.37 | 0.629 |
| Pregnant-female | 8-week male | 7.65 | 1.10 |
| | 25-week male | 8.46 | 1.23 |
| | 38-week male | 11.0 | 1.92 |

Computation Time (s) – Adult MRCPs



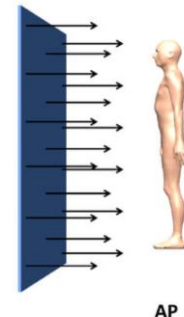
- Female

- NPS: 10^6
- Source: AP geometry

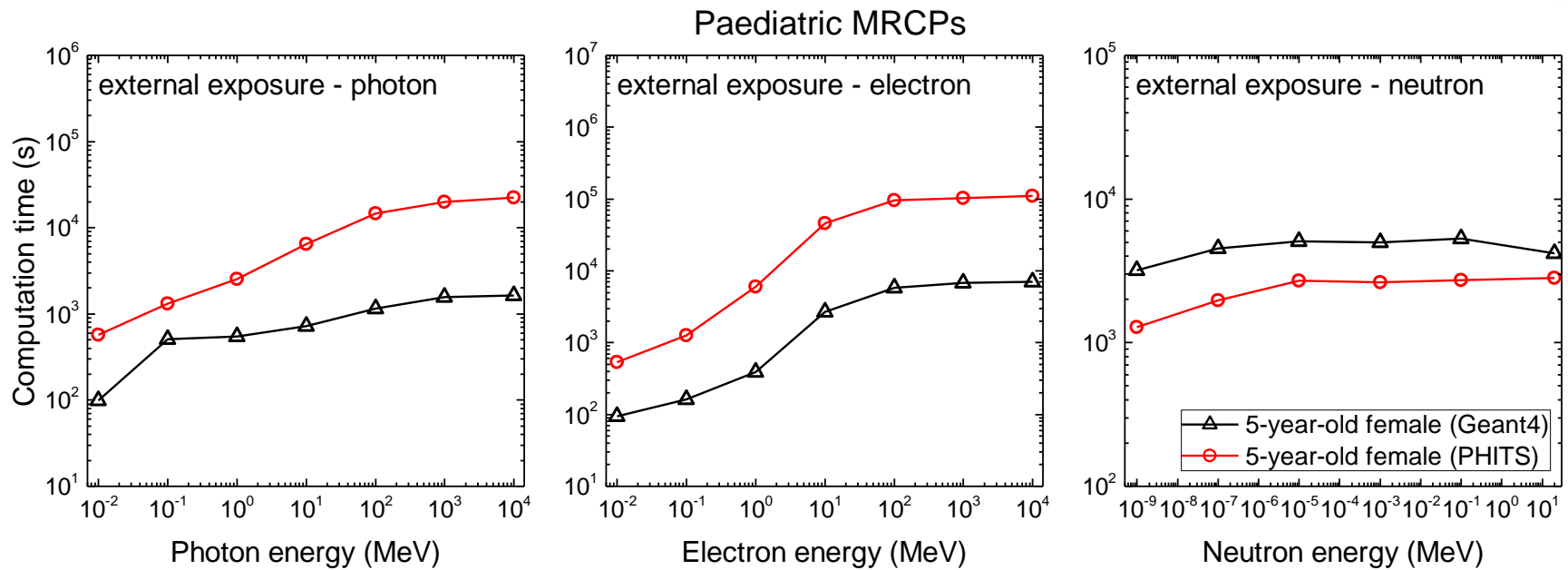


| | Photon energy (MeV) | | Electron energy (MeV) | | Neutron energy (MeV) | |
|--------|---------------------|-------------|-----------------------|-------------|----------------------|------------|
| Geant4 | 10^{-2} | 1m 22s | 10^{-2} | 1m 25s | 10^{-9} | 1h 03m 39s |
| | 10^{-1} | 8m 52s | 10^{-1} | 2m 42s | 10^{-7} | 1h 31m 04s |
| | 10^0 | 10m 34s | 10^0 | 6m 39s | 10^{-5} | 1h 43m 36s |
| | 10^1 | 15m 13s | 10^1 | 48m 58s | 10^{-3} | 1h 45m 19s |
| | 10^2 | 29m 27s | 10^2 | 2h 19m 53s | 10^{-1} | 1h 50m 34s |
| | 10^3 | 42m 36s | 10^3 | 2h 49m 12s | 2×10^1 | 1h 32m 40s |
| | 10^4 | 45m 53s | 10^4 | 3h 01m 48s | | |
| PHITS | 10^{-2} | 14m 24s | 10^{-2} | 12m 15s | 10^{-9} | 21m 22s |
| | 10^{-1} | 32m 46s | 10^{-1} | 24m 40s | 10^{-7} | 32m 51s |
| | 10^0 | 1h 03m 55s | 10^0 | 1h 52m 55s | 10^{-5} | 44m 59s |
| | 10^1 | 2h 40m 4s | 10^1 | 14h 22m 55s | 10^{-3} | 43m 54s |
| | 10^2 | 7h 17m 44s | 10^2 | 39h 30m 37s | 10^{-1} | 45m 23s |
| | 10^3 | 10h 21m 47s | 10^3 | 44h 12m 34s | 2×10^1 | 46m 56s |
| | 10^4 | 11h 36m 51s | 10^4 | 48h 13m 24s | | |

Computation Time (s) – Paediatric MRCPs



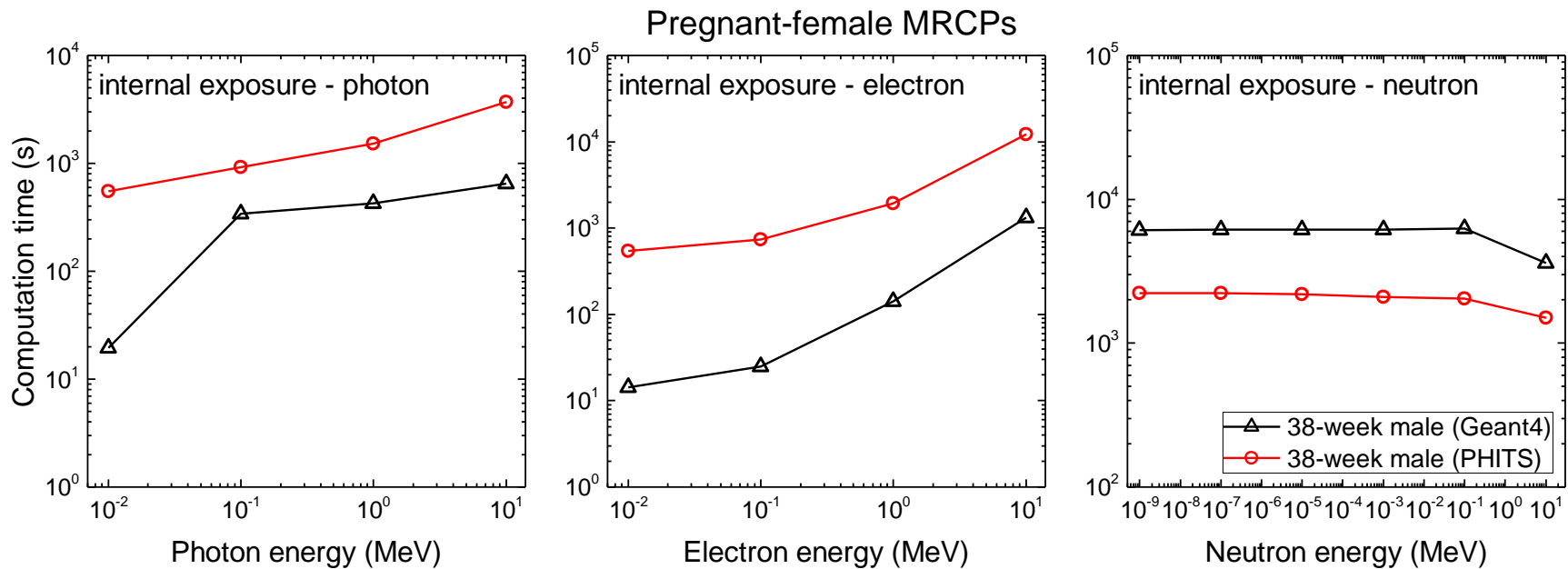
- 5-year-old female
 - NPS: 10^6
 - Source: AP geometry



| | Photon energy (MeV) | | Electron energy (MeV) | | Neutron energy (MeV) | |
|--------|---------------------|------------|-----------------------|-------------|----------------------|------------|
| Geant4 | 10^{-2} | 1m 38s | 10^{-2} | 1m 35s | 10^{-9} | 53m 07s |
| | 10^{-1} | 8m 26s | 10^{-1} | 2m 42s | 10^{-7} | 1h 15m 28s |
| | 10^0 | 9m 05s | 10^0 | 6m 28s | 10^{-5} | 1h 24m 56s |
| | 10^1 | 12m 01s | 10^1 | 44m 32s | 10^{-3} | 1h 23m 16s |
| | 10^2 | 19m 18s | 10^2 | 1h 36m 04s | 10^{-1} | 1h 28m 12s |
| | 10^3 | 26m 00s | 10^3 | 1h 53m 01s | 2×10^1 | 1h 09m 30s |
| | 10^4 | 27m 24s | 10^4 | 1h 57m 42s | | |
| PHITS | 10^{-2} | 9m 31s | 10^{-2} | 8m 57s | 10^{-9} | 27m 14s |
| | 10^{-1} | 21m 47s | 10^{-1} | 20m 54s | 10^{-7} | 40m 48s |
| | 10^0 | 42m 31s | 10^0 | 1h 41m 00s | 10^{-5} | 55m 18s |
| | 10^1 | 1h 47m 53s | 10^1 | 12h 49m 12s | 10^{-3} | 54m 41s |
| | 10^2 | 4h 05m 43s | 10^2 | 26h 35m 28s | 10^{-1} | 57m 00s |
| | 10^3 | 5h 34m 00s | 10^3 | 28h 26m 56s | 2×10^1 | 1h 04m 07s |
| | 10^4 | 6h 12m 59s | 10^4 | 30h 31m 19s | | |

Computation Time (s) – Pregnant-female MRCPs

- 38-week male
 - NPS: 10^5
 - Source: Urinary bladder contents



| | Photon energy (MeV) | | Electron energy (MeV) | | Neutron energy (MeV) | |
|--------|---------------------|------------|-----------------------|------------|----------------------|------------|
| Geant4 | 10^{-2} | 20s | 10^{-2} | 14s | 10^{-9} | 1h 41m 53s |
| | 10^{-1} | 5m 39s | 10^{-1} | 25s | 10^{-7} | 1h 42m 12s |
| | 10^0 | 7m 06s | 10^0 | 2m 21s | 10^{-5} | 1h 42m 36s |
| | 10^1 | 10m 48s | 10^1 | 21m 54s | 10^{-3} | 1h 42m 58s |
| | | | | | 10^{-1} | 1h 44m 27s |
| PHITS | 10^{-2} | 9m 12s | 10^{-2} | 9m 02s | 10^1 | 59m 60s |
| | 10^{-1} | 15m 18s | 10^{-1} | 12m 18s | 10^{-9} | 37m 04s |
| | 10^0 | 25m 16s | 10^0 | 32m 23s | 10^{-7} | 37m 16s |
| | 10^1 | 1h 01m 45s | 10^1 | 3h 23m 59s | 10^{-5} | 36m 24s |
| | | | | | 10^{-3} | 35m 01s |
| | | | | | 10^{-1} | 34m 09s |
| | | | | 10^1 | 25m 07s | |

Summary

- Next-Gen ICRP Reference Computational Phantoms
 - Adult phantoms (ICRP 145, 2020)
 - Pediatric phantoms (ICRP 156, in press)
 - Pregnant-female phantoms (report under preparation)
- Compatibility with MC codes
 - Geant4 – advanced example for ICRP-145 phantoms
 - PHITS
 - MCNP
 - EGSnrc
 - FLUKA (from next version)
- Performance comparison between Geant4 and PHITS
 - Memory usage: PHITS is better
 - Initialization time: PHITS is shorter
 - Computation speed for photons/electrons: Geant4 is faster (~ 10 times)
 - Computation speed for Neutrons: PHITS is faster (~2-3 times)

Thank you!