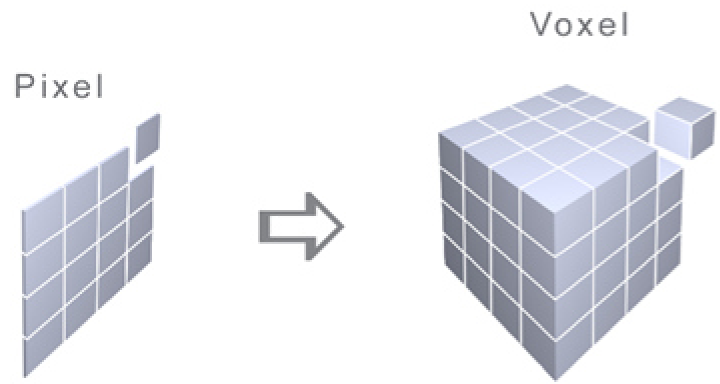
The Reference Phantoms: Voxel vs. Polygon

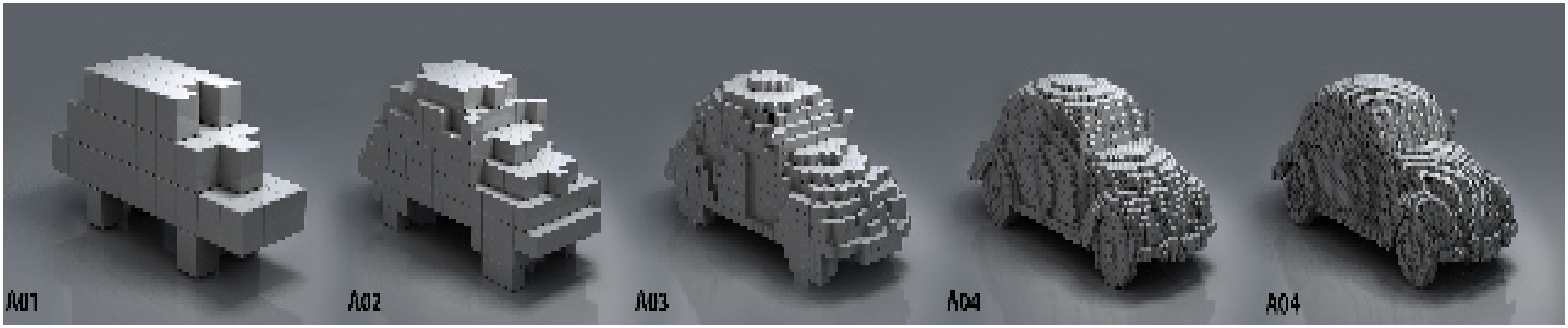
Seoul, October 21, 2015

Chan Hyeong Kim
ICRP Committee 2 / Hanyang University

What Is Voxel?

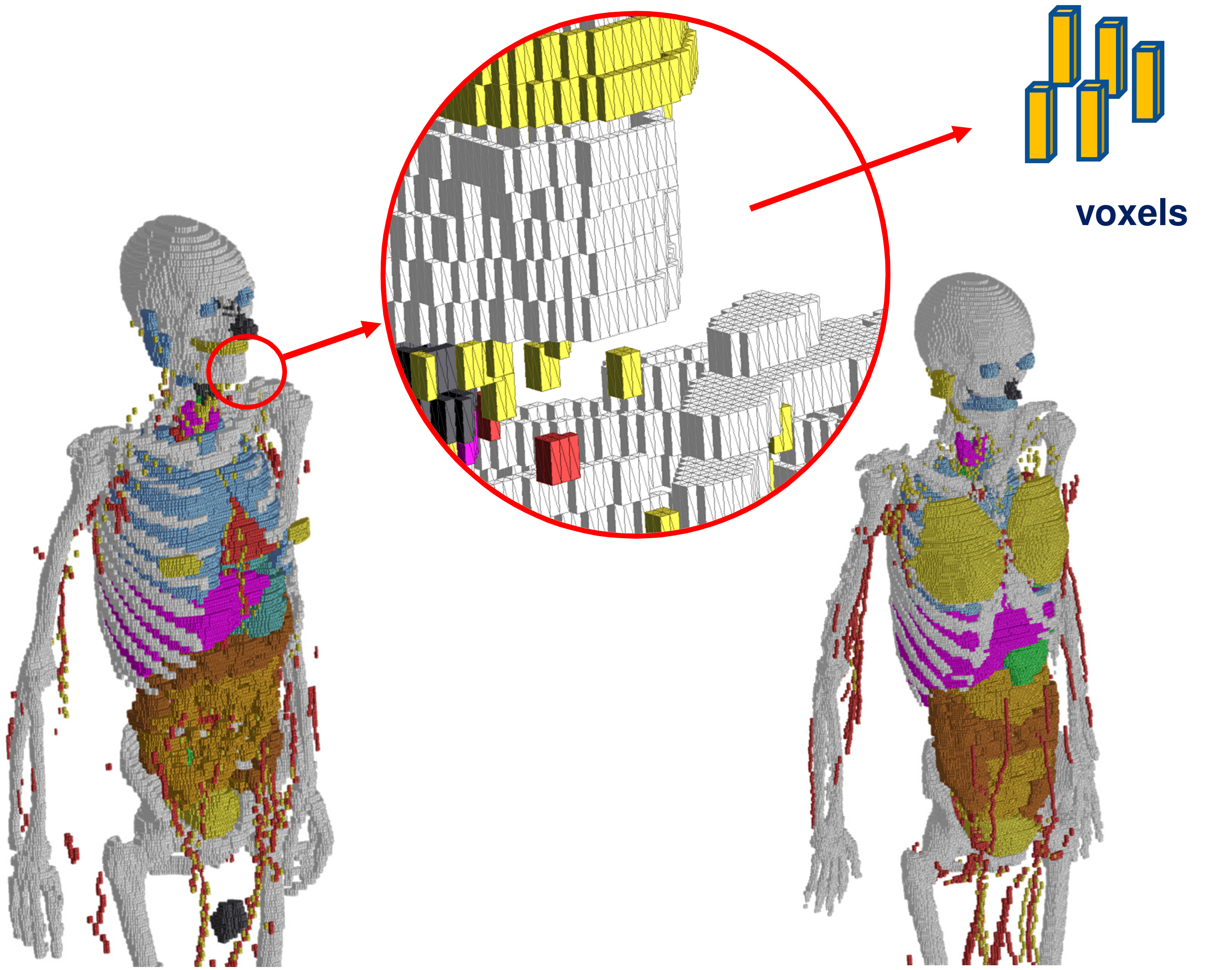


"Voxel" = "Volume" + "Pixel"



- Limitations:
  - Very difficult to construct a voxel model with <u>thin layers</u> or <u>small structures</u>
  - Not deformable

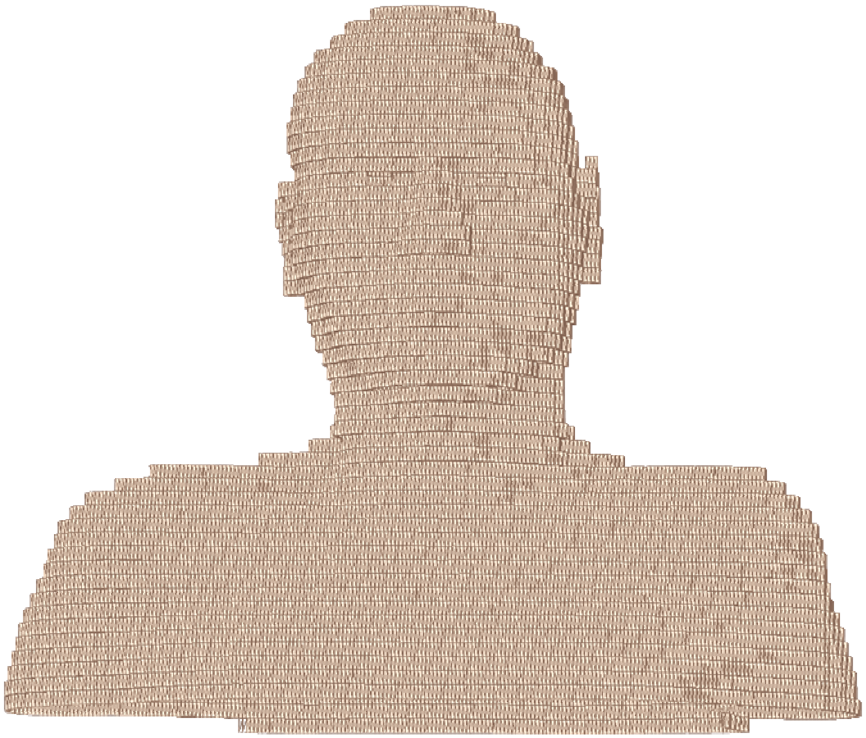
ICRP-110 Reference Phantoms



Male phantom
(Voxel size: 2.137×2.137×8 mm^3)

Female phantom
(Voxel size: 1.775×1.775×4.8 mm^3)

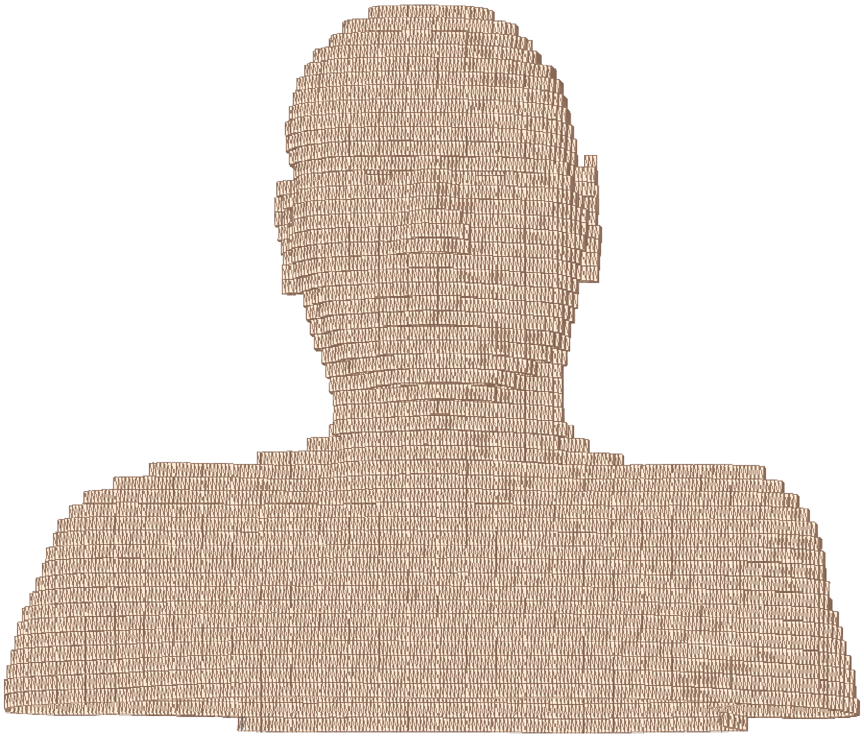
Problem #1 (Skin)



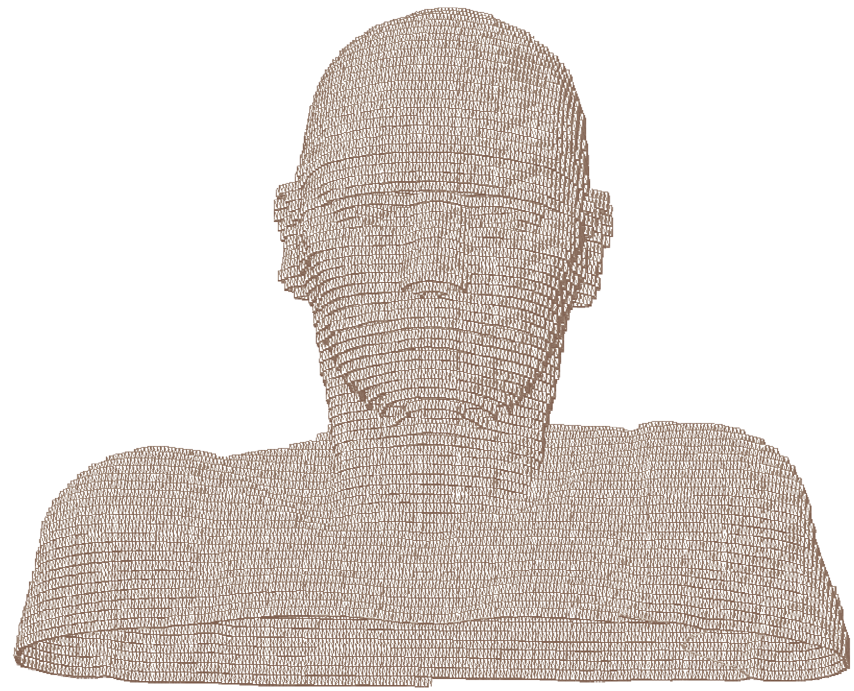
ICRP reference male phantom
(2.137 × 2.137 × 8 mm^3)

ICRP reference female phantom
(1.775 × 1.775 × 4.8 mm^3)

Problem #1 (Skin)



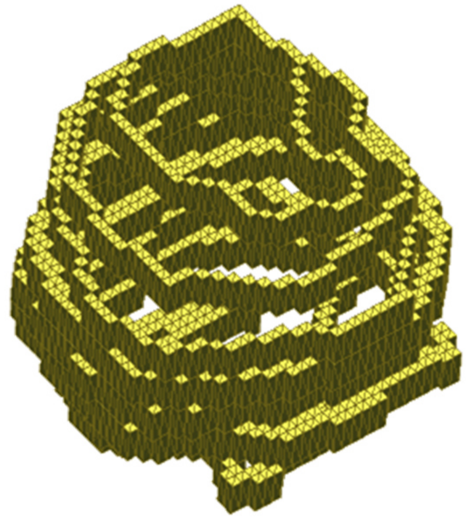
ICRP reference male phantom
($2.137 \times 2.137 \times 8$ mm^3)



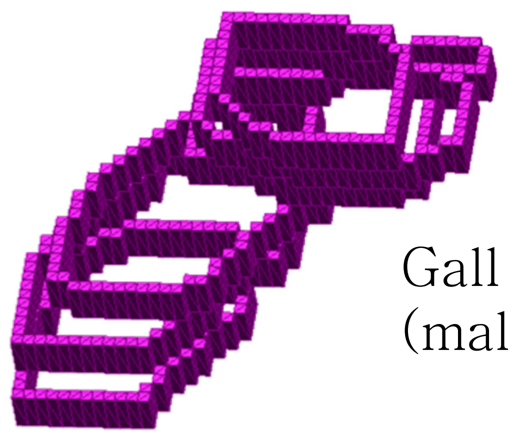
ICRP reference female phantom
($1.775 \times 1.775 \times 4.8$ mm^3)

Problem #2 (Hollow Organs)

Stomach
(male)

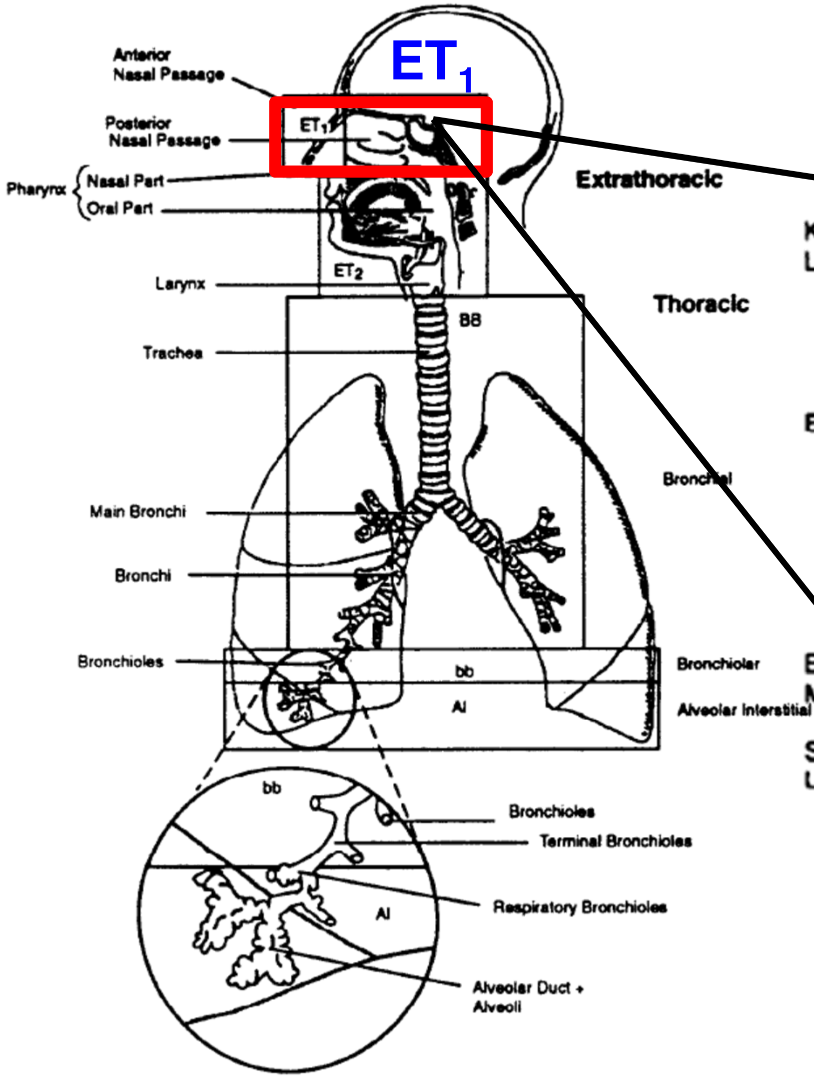


Urinary bladder
(male)

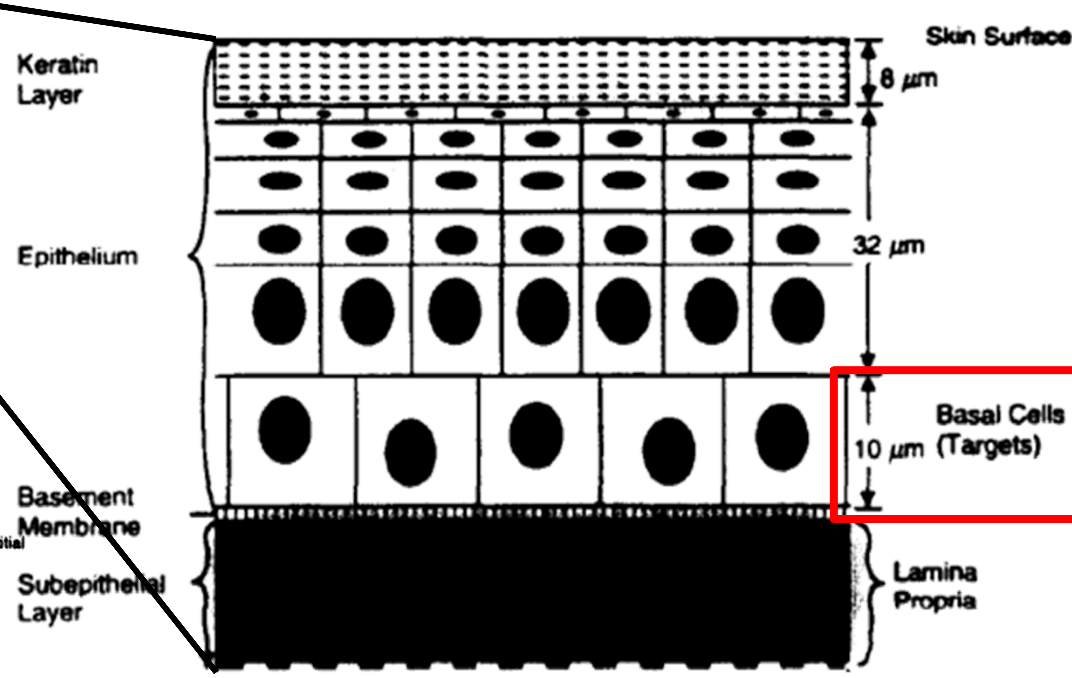


Gall bladder
(male)

Problem #3 (Respiratory Tract Organs)

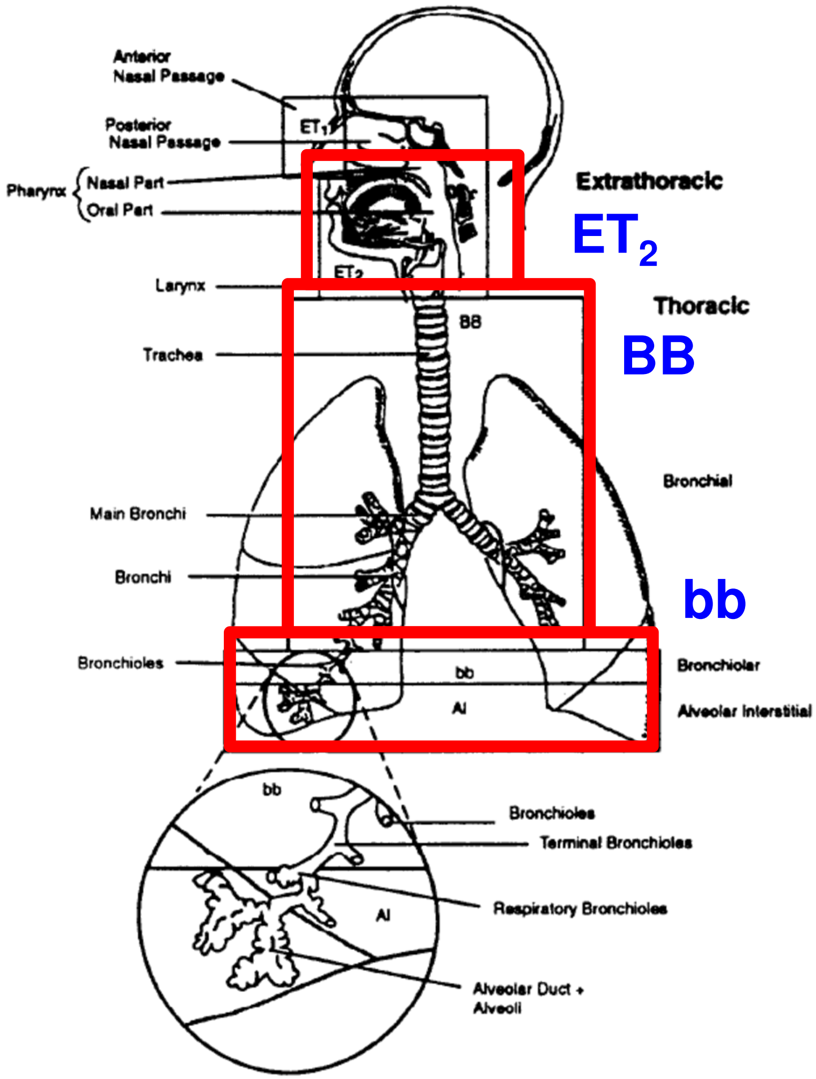


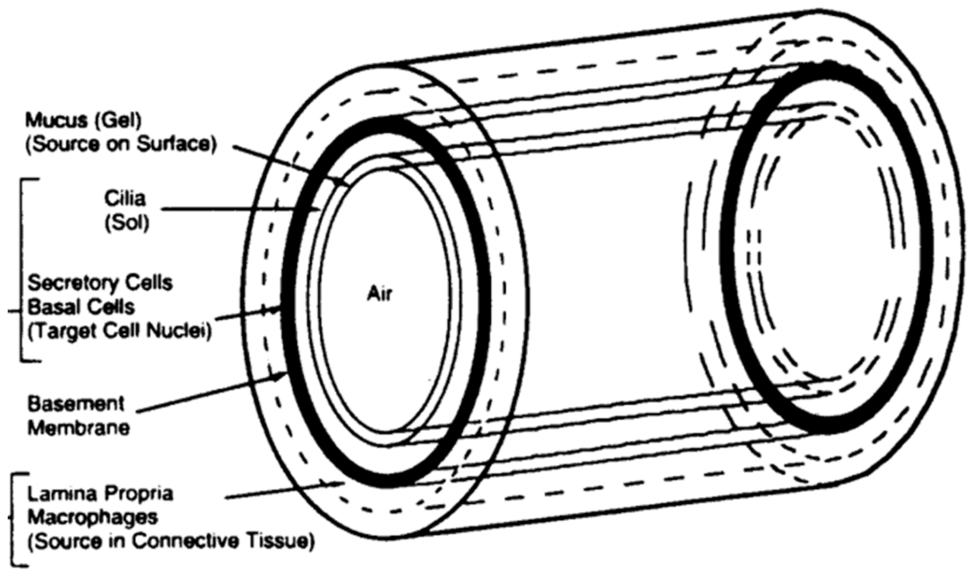
Human Respiratory Tract Model (ICRP 66, 1994)



an <u>additional</u> stylized phantom used for SAF calculations

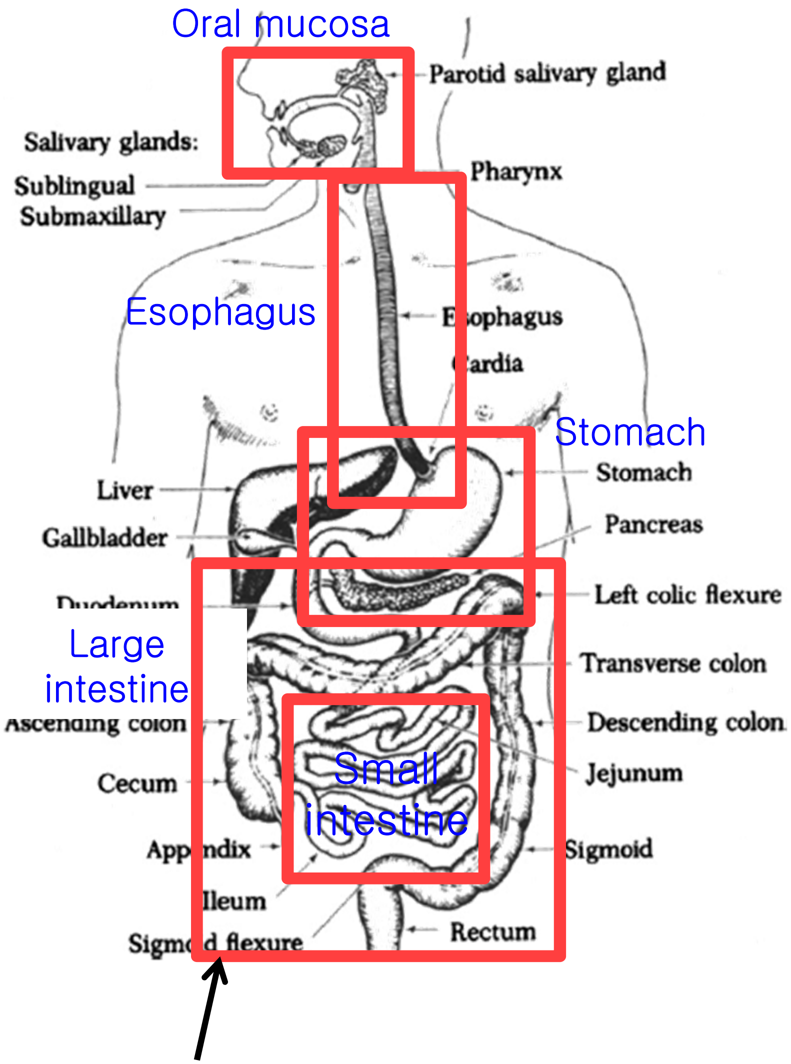
ICRP 66, 1994



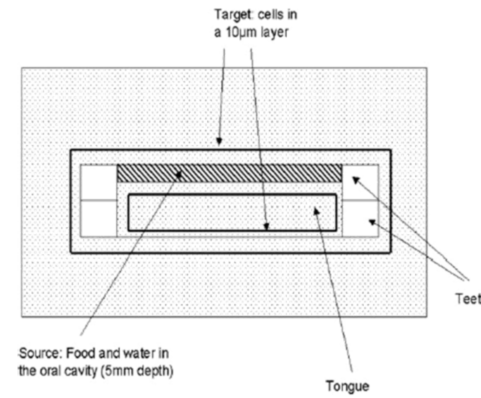


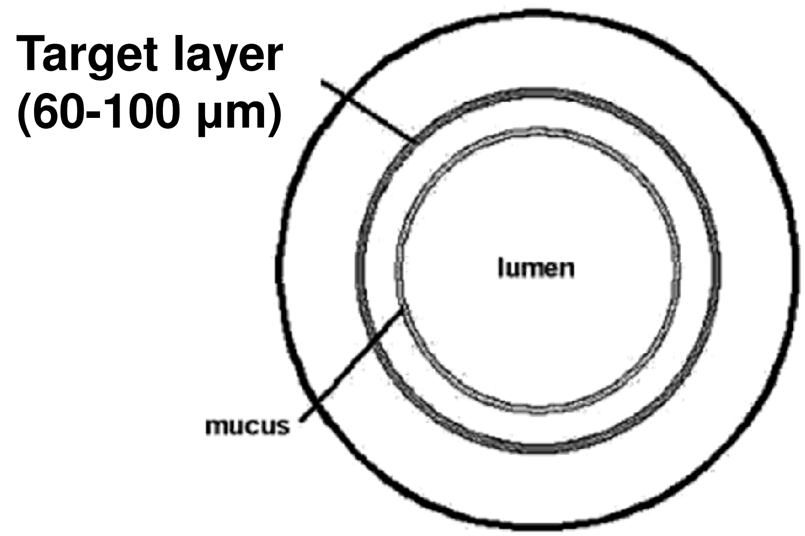
<u>3 additional</u> stylized phantoms used for SAF calculations

Problem #4 (Alimentary Tract Organs)



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



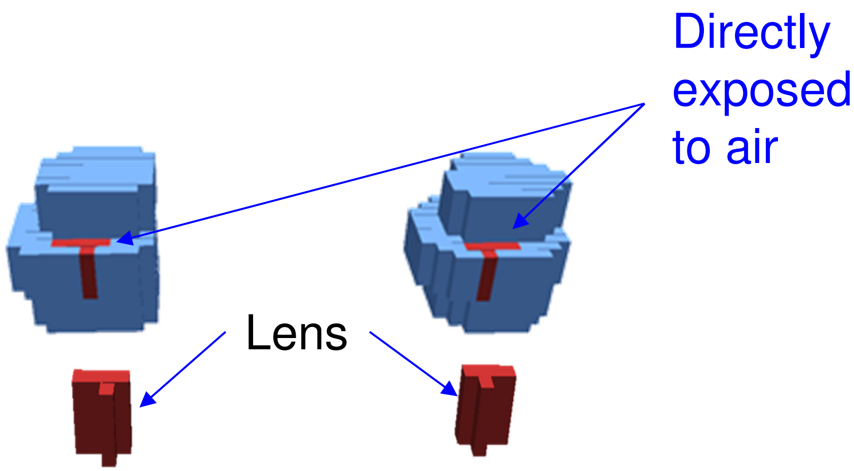


Human Alimentary Tract Model (ICRP 100, 2006)

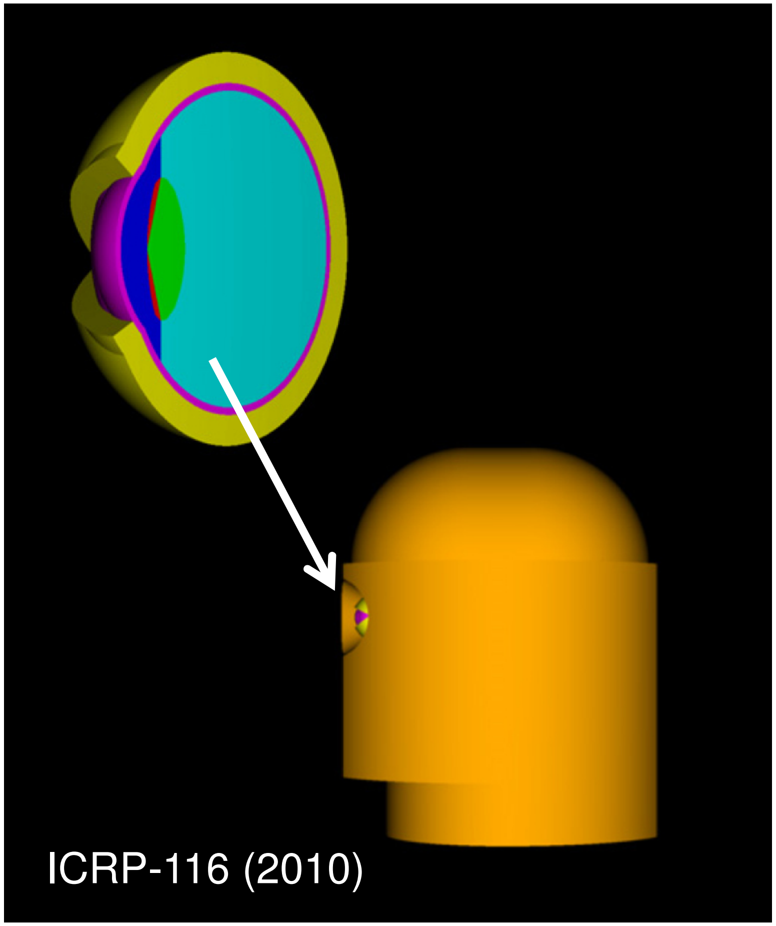
7 additional stylized phantoms used for SAF calculations

Problem #5 (Eye)

- 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.



Eye models of ICRP-110 male phantom



“Using *12 additional stylized phantoms*”

Other Limitations

- 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.
- The female phantom has a toe-standing feet.
- The 50-μm-thick sensitive layer of the skin is not defined, and an additional stylized phantom was used for assessing the equivalent dose specified for localized skin exposure.
- The tissue masses do not include blood content of the target tissue.
- Some tissue masses do not match the ICRP-89 data
- These phantoms are ***not deformable***.

Limitations Discussed in ICRP C2 Meeting

ICRP Committee 2 Meeting
(Abu Dhabi, UAE October 2013)

- The committee decided to start a research project to convert the ICRP-110 reference phantoms into a high-quality polygon-mesh format to address these problems.

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

15. Presentation by new C2 member Chan Kim *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

- <u>Working group</u> 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%)

Bimonthly report

- <u>Steering committee</u> 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)
  - Min Suk Chung (Ajou University) - anatomist

Research Fund

- Necessary research fund secured (December 2014)
  - Nuclear Safety and Security Commission (NSSC) / Korea Radiation Safety Foundation (KORSAFs).
  - Project period: December 2014 – November 2017 (3 years)
  - Research fund: $100,000 / year

Objective of Research Project

To produce “exact replica“ of ICRP-110 reference phantoms in a high-quality polygon-mesh (PM) format

- The developed phantoms will include ….
    1. continuous and fully-enclosed surfaces for skin, stomach, gall bladder, and urinary bladder;
    2. thin target layers (10-300 μm) in the alimentary and respiratory tract organs; and
    3. detailed and more accurate models for skeletal system, eyes, lymphatic nodes, blood vessels, hands, feet, etc.

Current Progress of Project

1. Construction of “Simple Organs”
2. Construction of “Skeletal Systems”
3. Construction of “Complex Organs”
4. Preliminary Results

1. Construction of “Simple Organs”

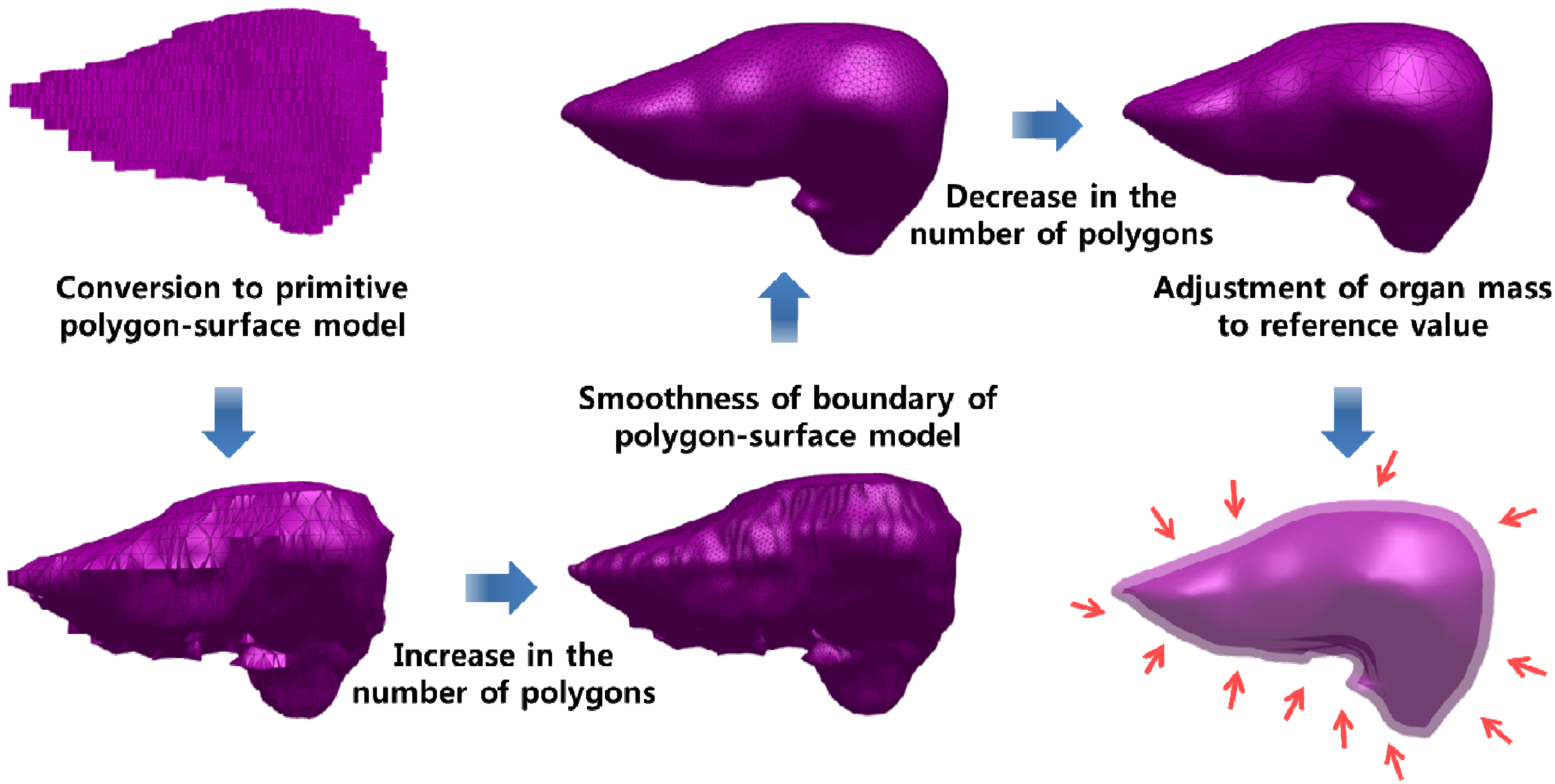
2. Construction of “Skeletal Systems”

3. Construction of “Complex Organs”

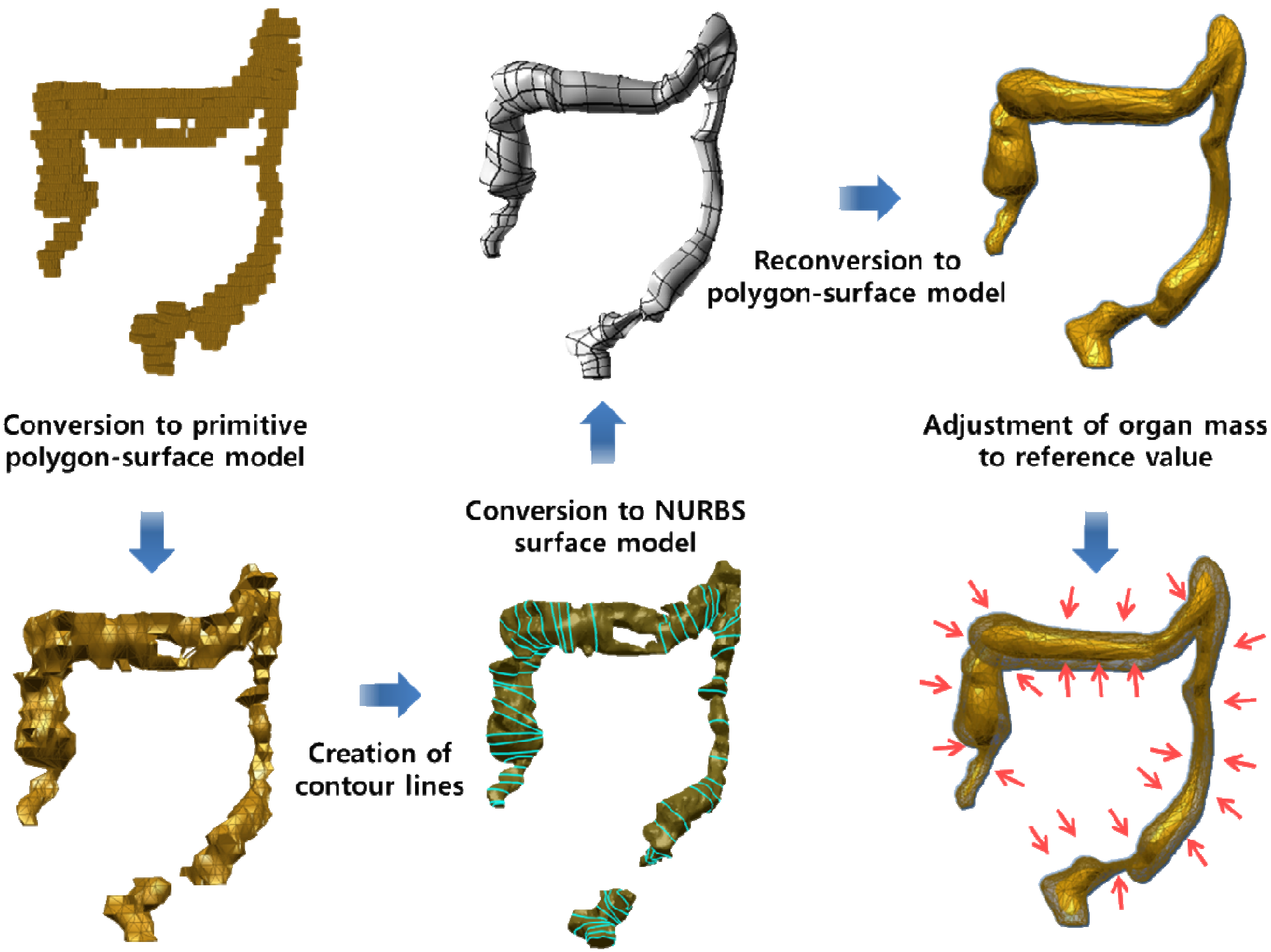
4. Preliminary Results

Conversion Methods

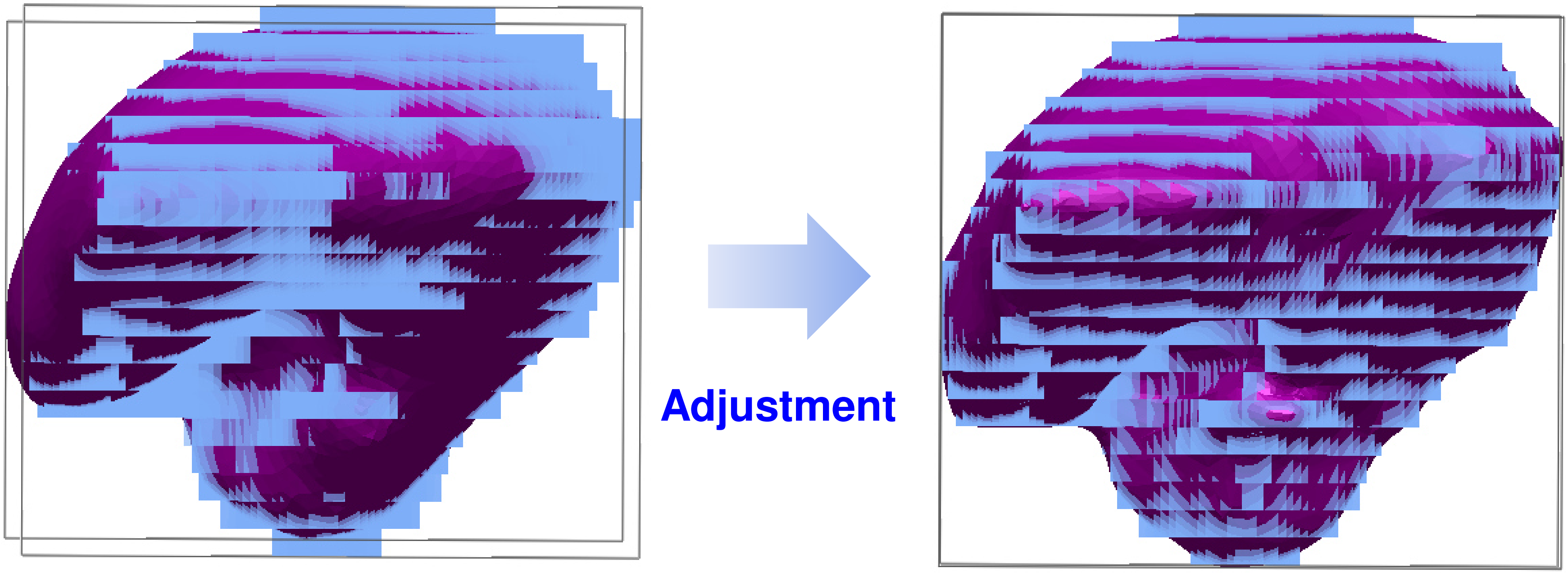
Method #1



Method #2


Conversion to primitive polygon-surface model
Creation of contour lines
Conversion to NURBS surface model
Reconversion to polygon-surface model
Adjustment of organ mass to reference value

Adjustment and Monitoring Methods

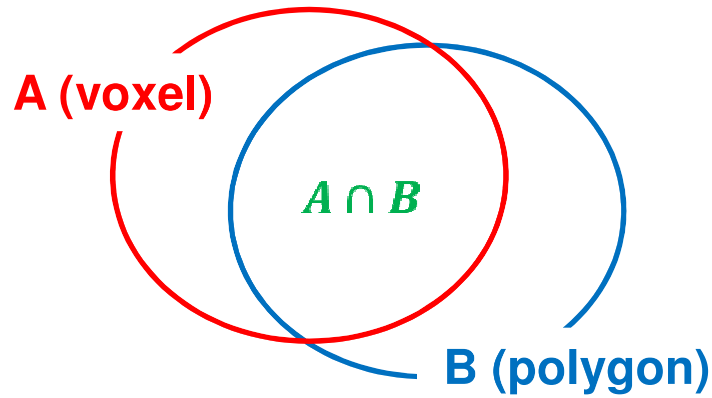


Before **After**

- Polygonal-mesh model is adjusted to original voxel models using the functions in ***Rapidform*** software:
  - ✓ *Deform by paint*
  - ✓ *Deform by trackball*
  - ✓ *Fit shell to function*
- In-house monitoring programs (DI, CD)

Acceptance Criteria for Adjustment

- **Dice index (DI)**
  - ✓ "Volume overlap fraction"
  - ✓ DI > 97% of maximally achievable volume overlap fraction (MAVOF)

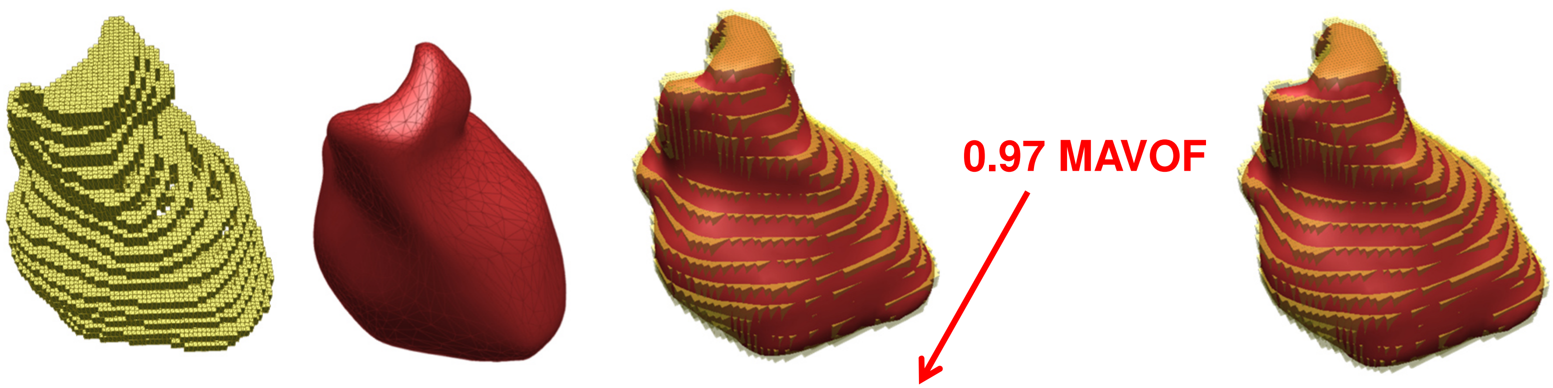


$$\mathbf{DI} = \frac{\mathbf{A} \cap \mathbf{B}}{(\mathbf{A} + \mathbf{B})/2}$$

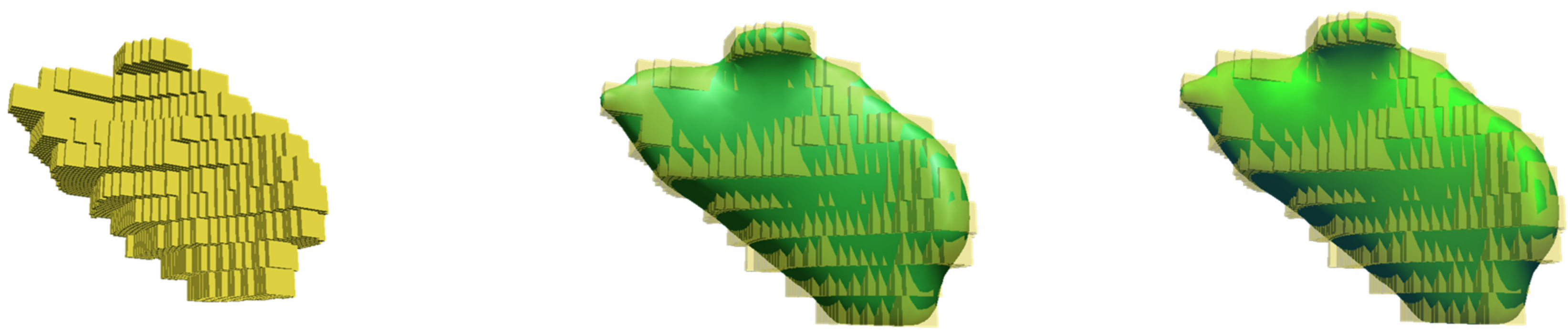
- **Centroid distance (CD)**
  - ✓ Distance between the centroids of the two models in comparison
  - ✓ CD < 0.5 mm

Examples

Voxel model → Conversion → Adjustment

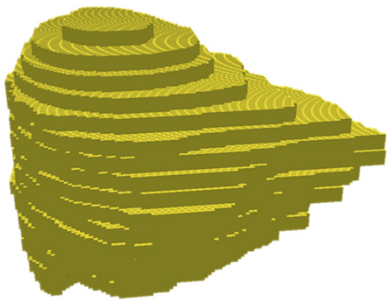


Heart (male)	**DI: 0.96 (ADI: 0.94)** **CD: 0.59 mm**	**DI: 0.96 (ADI: 0.94)** **CD: 0.47 mm**



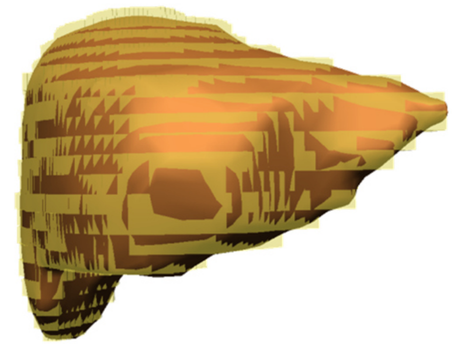
Spleen (male)	**DI: 0.91 (ADI: 0.92)** **CD: 0.76 mm**	**DI: 0.94 (ADI: 0.92)** **CD: 0.26 mm**

Voxel model	→	Conversion	→	Adjustment

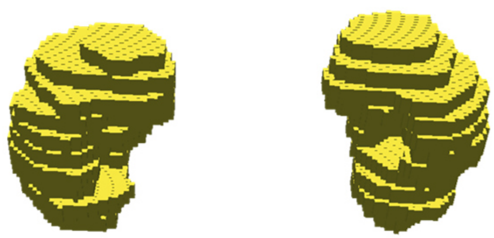


Liver
(male)

DI: 0.95 (ADI: 0.94)
CD: 0.66 mm



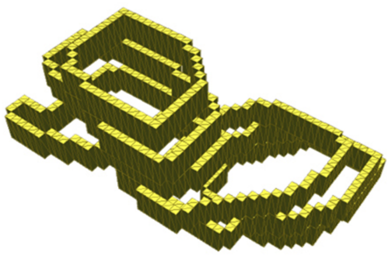
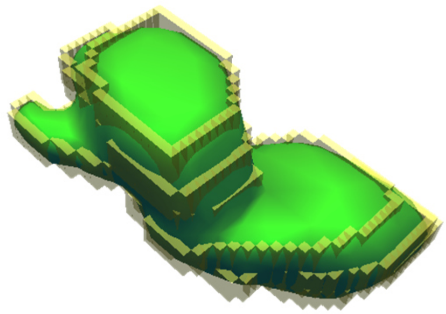
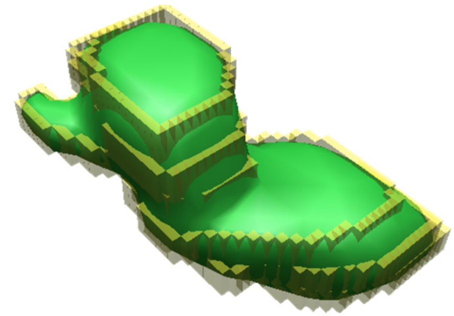
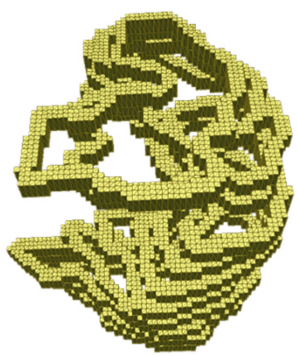
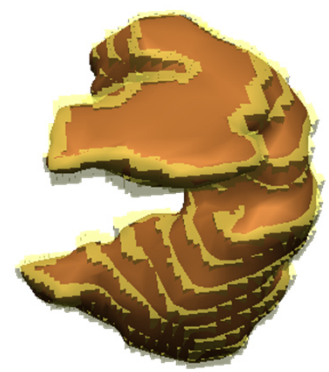
DI: 0.97 (ADI: 0.94)
CD: 0.33 mm



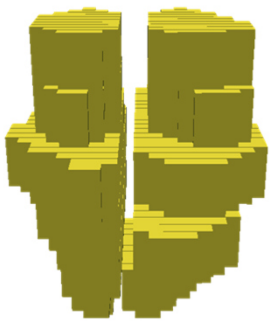
Kidneys
(male)

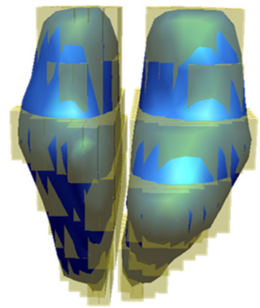
DI: 0.93 (ADI: 0.91)
CD: 1.22 mm

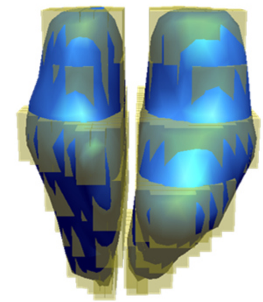
DI: 0.93 (ADI: 0.91)
CD: 0.50 mm

Voxel model	Conversion	Adjustment
		
Gall bladder (male)	**DI: 0.85 (ADI: 0.90)** **CD: 0.59 mm**	**DI: 0.91 (ADI: 0.90)** **CD: 0.23 mm**
		
Stomach (male)	**DI: 0.93 (ADI: 0.92)** **CD: 1.55 mm**	**DI: 0.93 (ADI: 0.92)** **CD: 0.49 mm**

Voxel model → **Conversion** → **Adjustment**



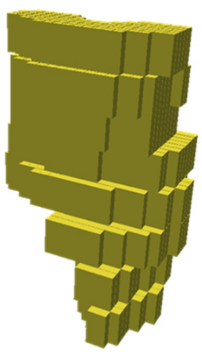




Testis (male)

DI: 0.87 (ADI: 0.88)
CD: 0.73 mm

DI: 0.90 (ADI: 0.88)
CD: 0.04 mm



Thymus (male)

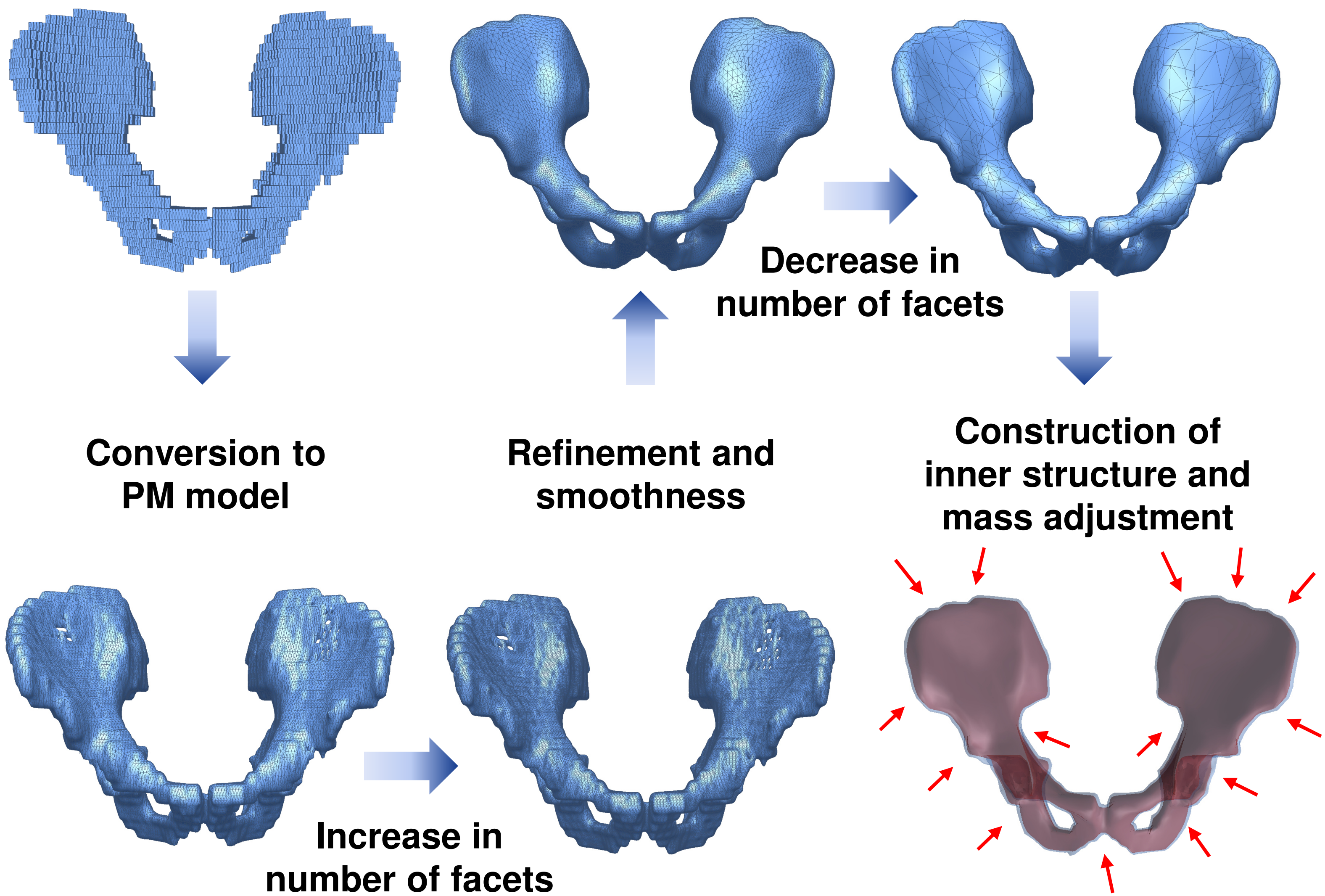
DI: 0.89 (ADI: 0.90)
CD: 0.65 mm

DI: 0.90 (ADI: 0.90)
CD: 0.30 mm

1. Construction of “Simple Organs”
2. Construction of “Skeletal Systems”
3. Construction of “Complex Organs”
4. Preliminary Results

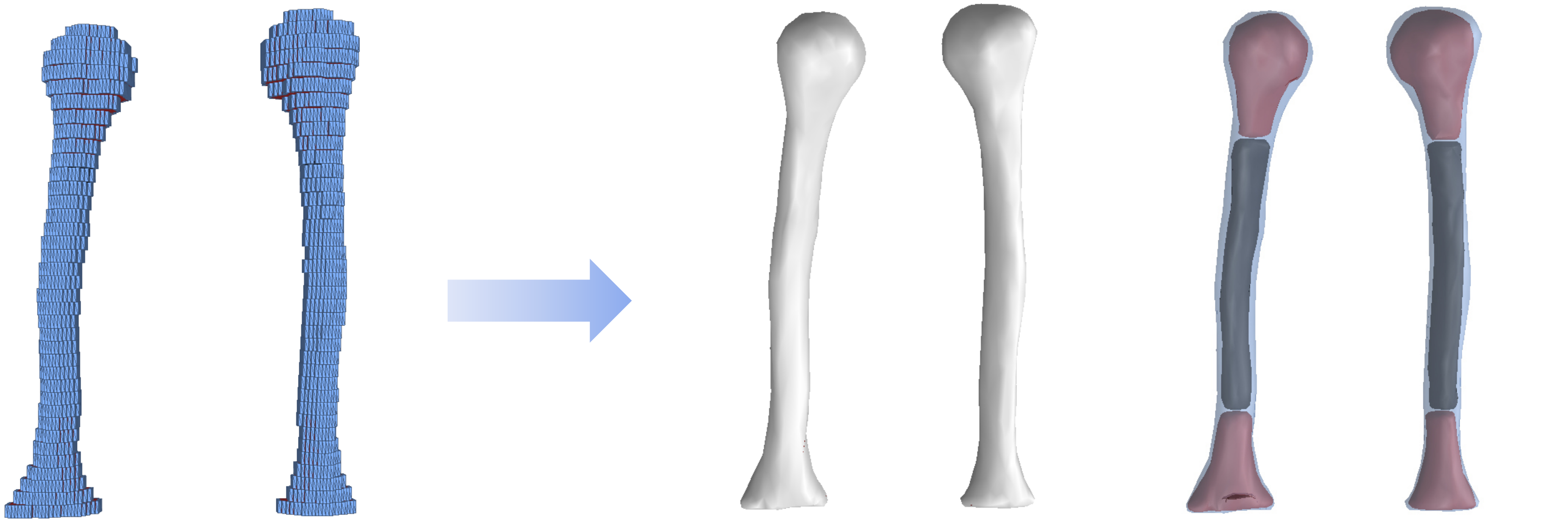
Construction of Simple Skeletons - Conversion

Humeri
Ulnae
Clavicles
Femora
Tibiae
Mandible
Pelvis
Scapulae
Sacrum
Sternum
Cranium
Ribs
Spines
Feet
Hands

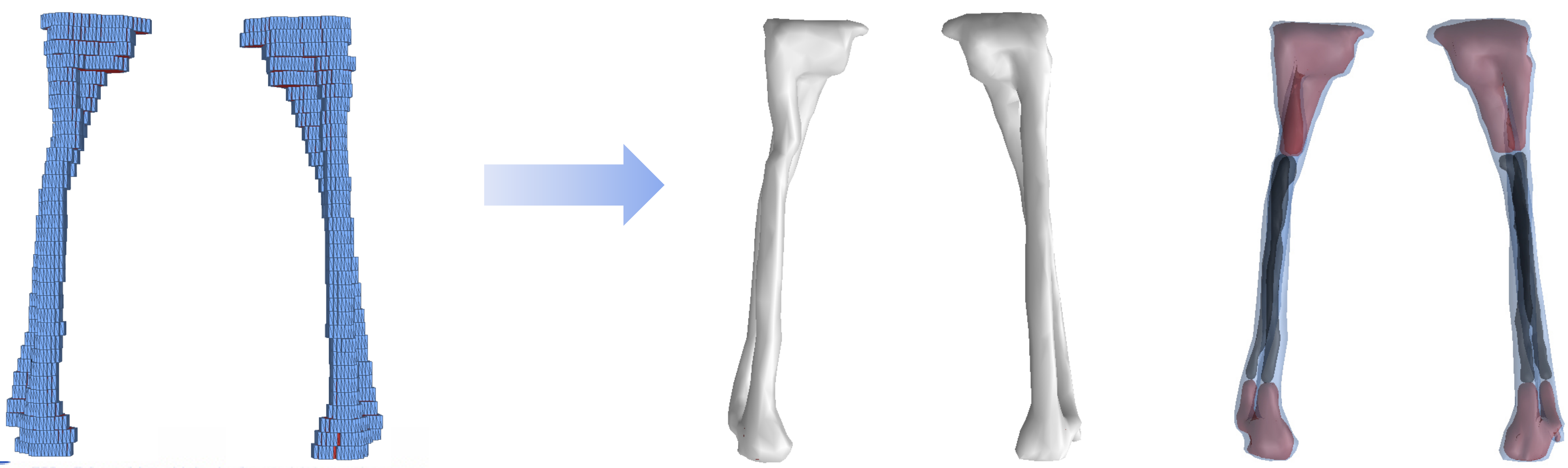


Examples

Humeri

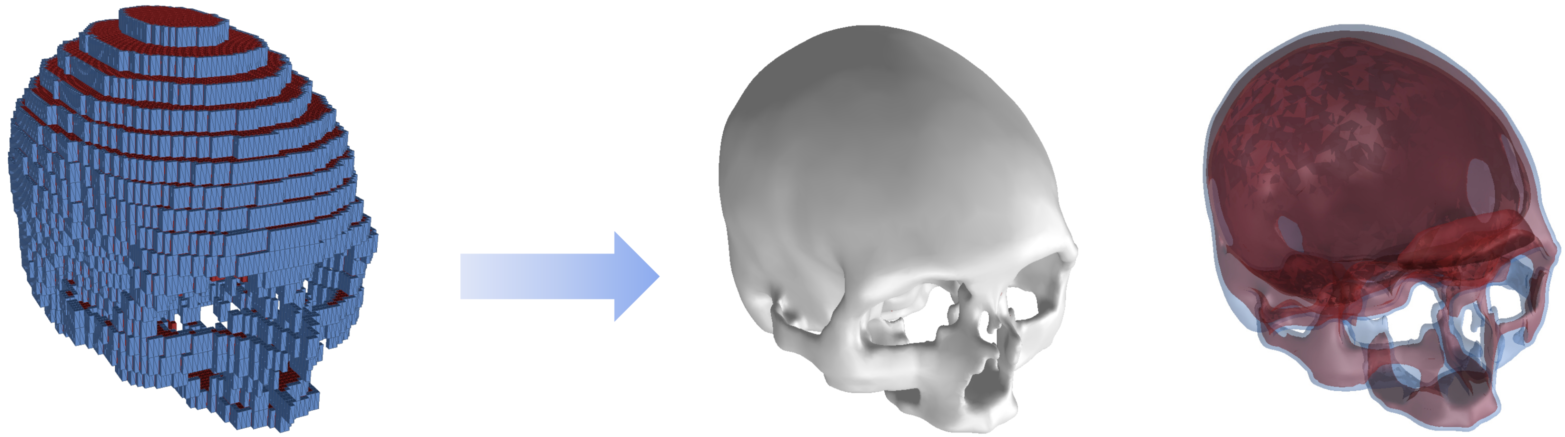


Ulnae and radii

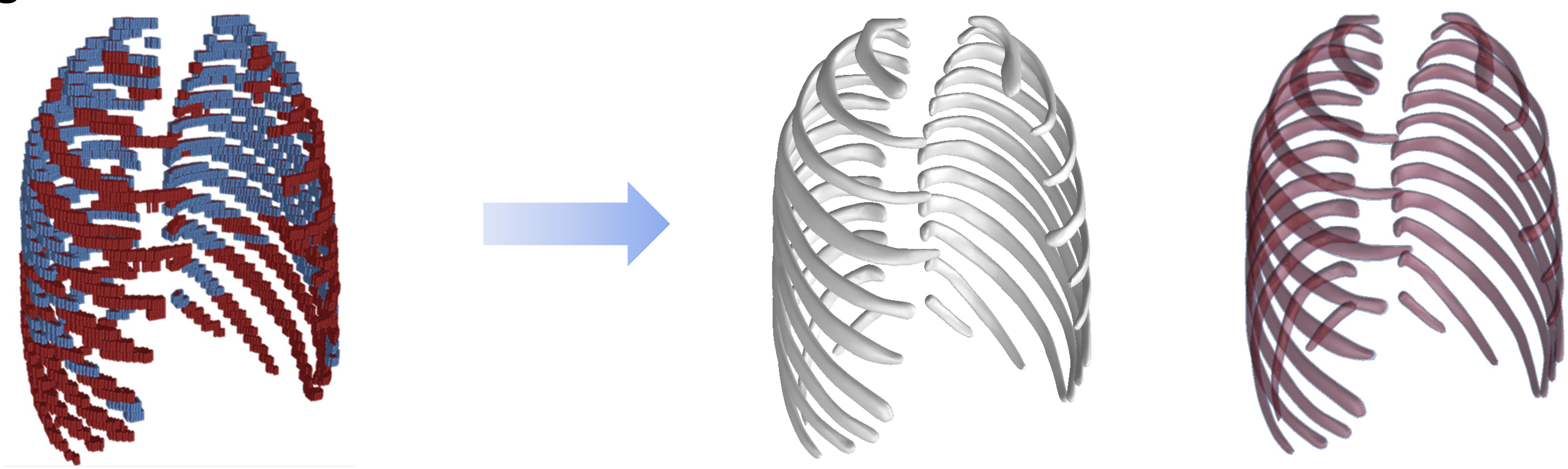


Examples

Cranium

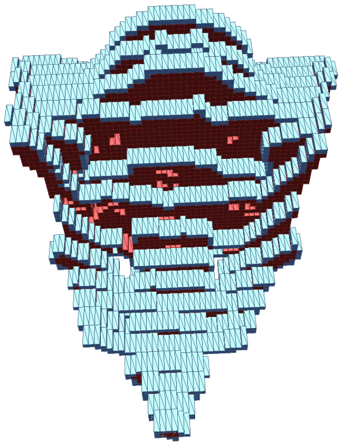


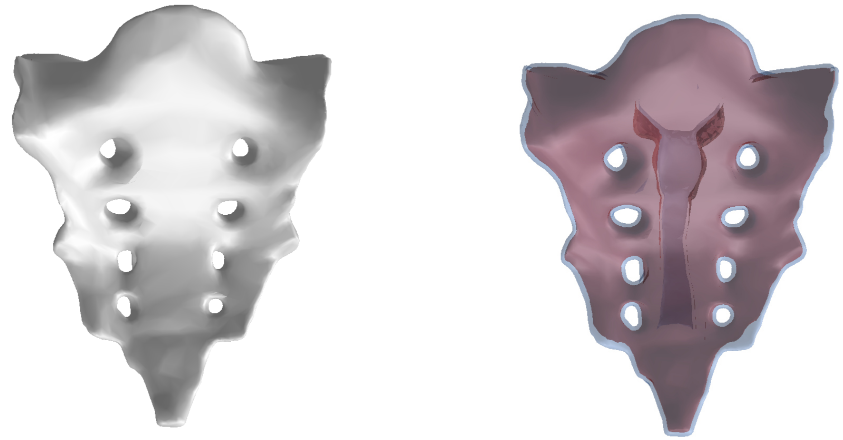
Ribs



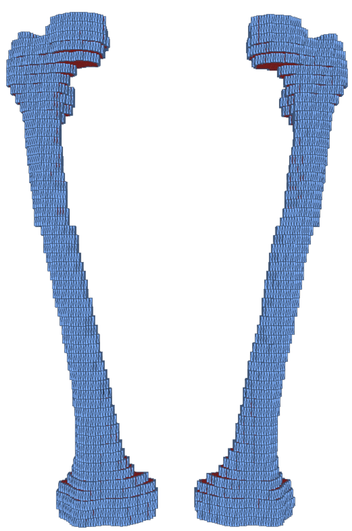
Examples

Sacrum

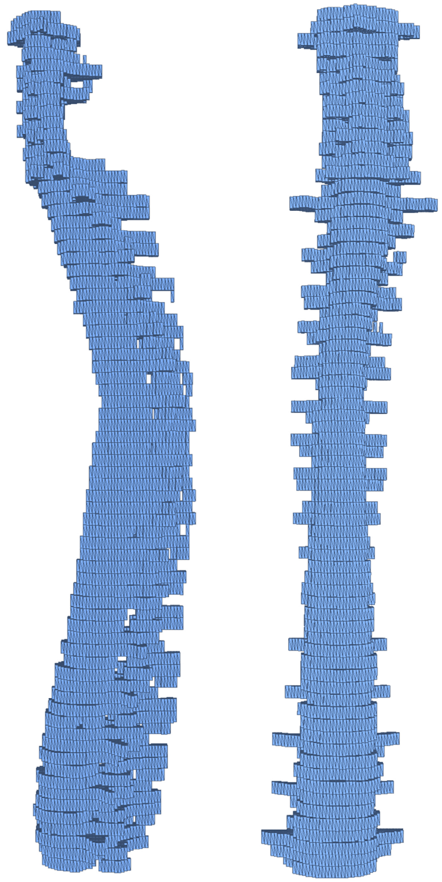




Femora



Construction of Spines – “Adjustment”

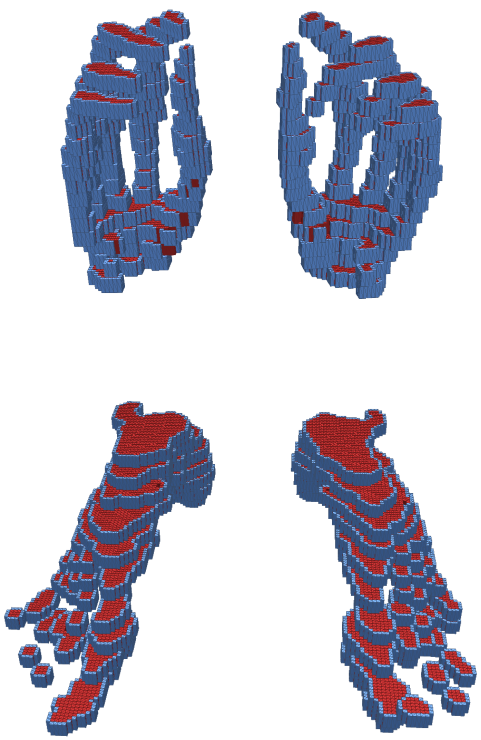


Adjustment

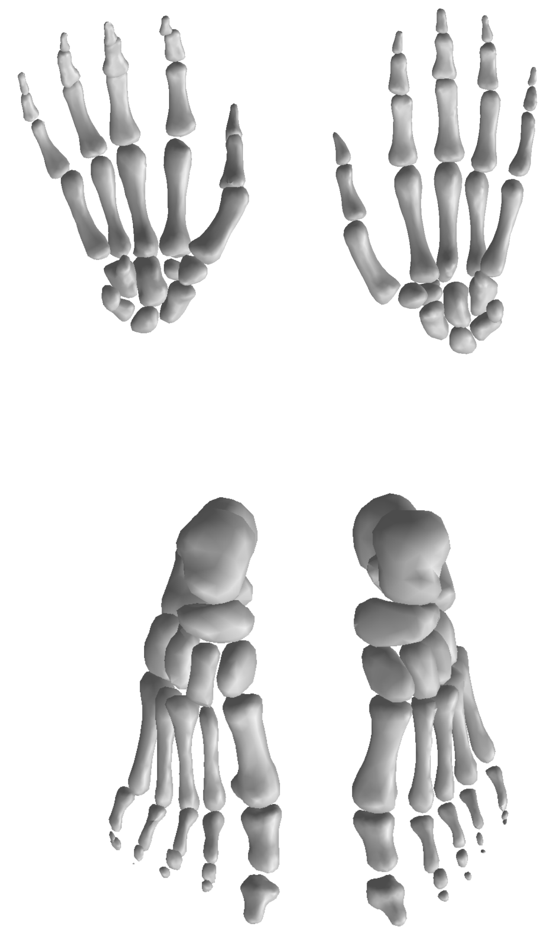
Voxel model

High-quality polygon-mesh model

Construction of Hands and Feet - “Adjustment”



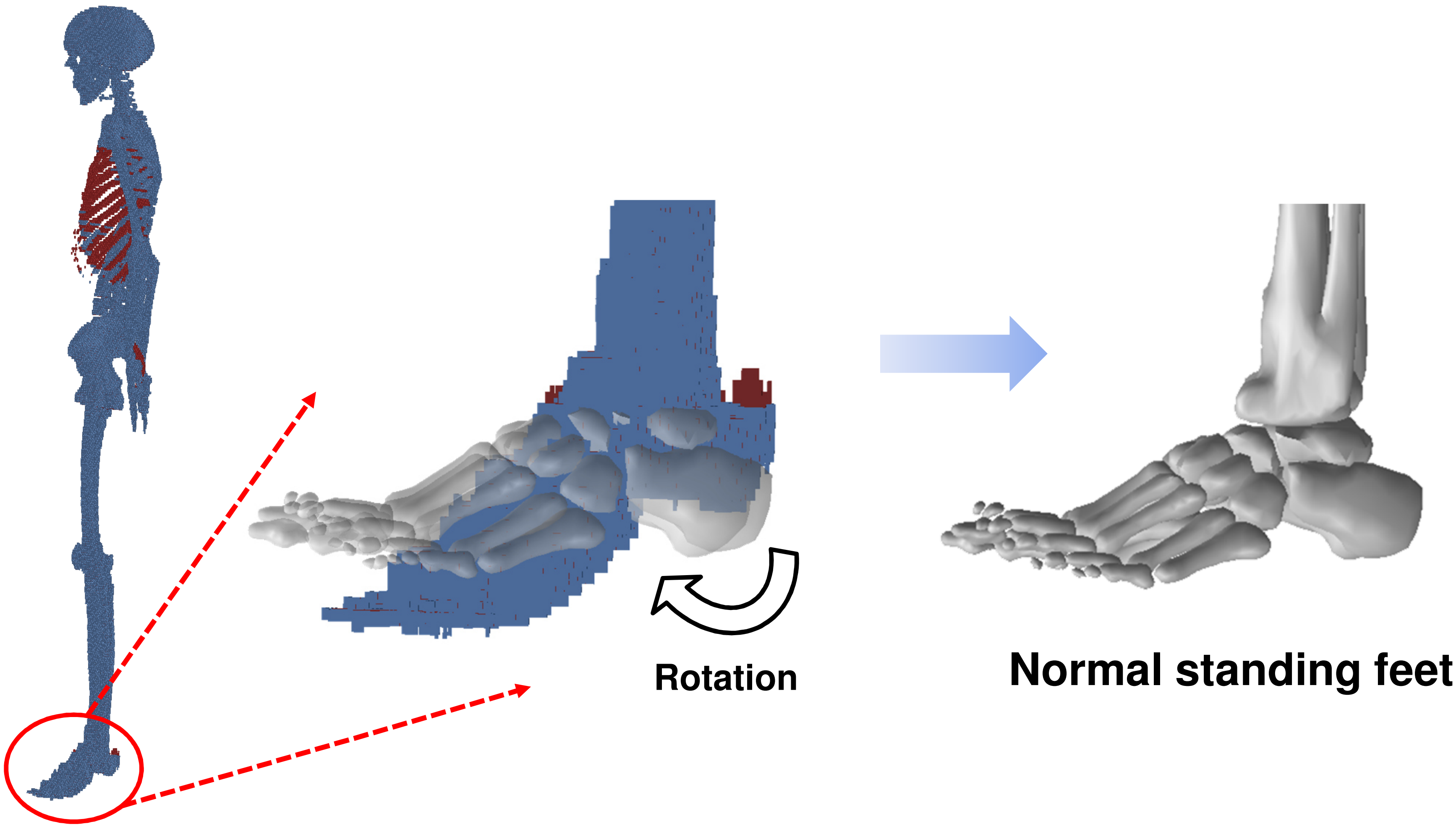
Adjustment



Voxel models

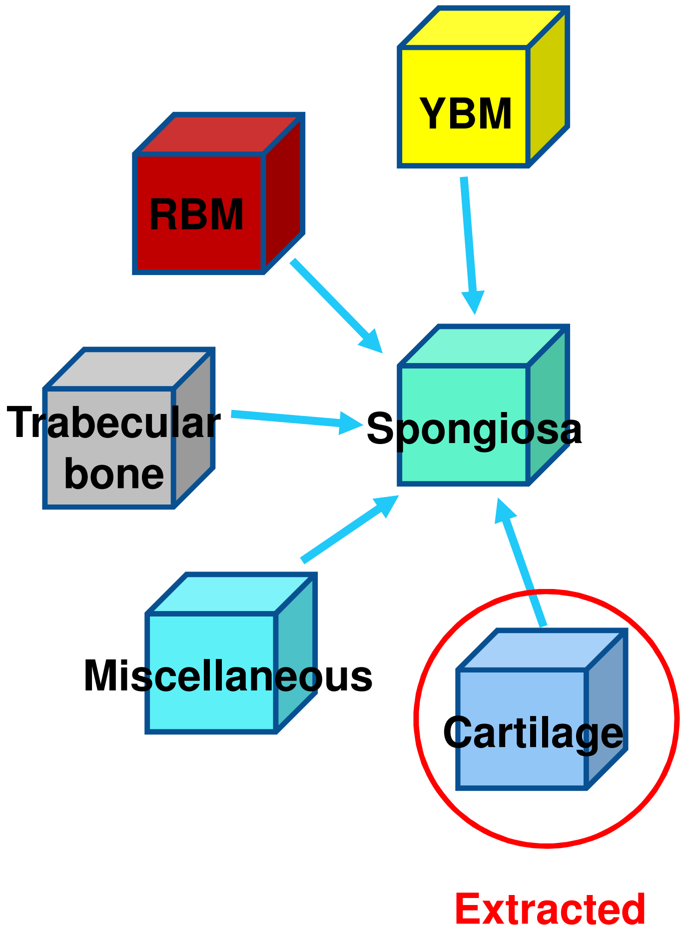
High-quality polygon model

Correction of Toe-standing Feet

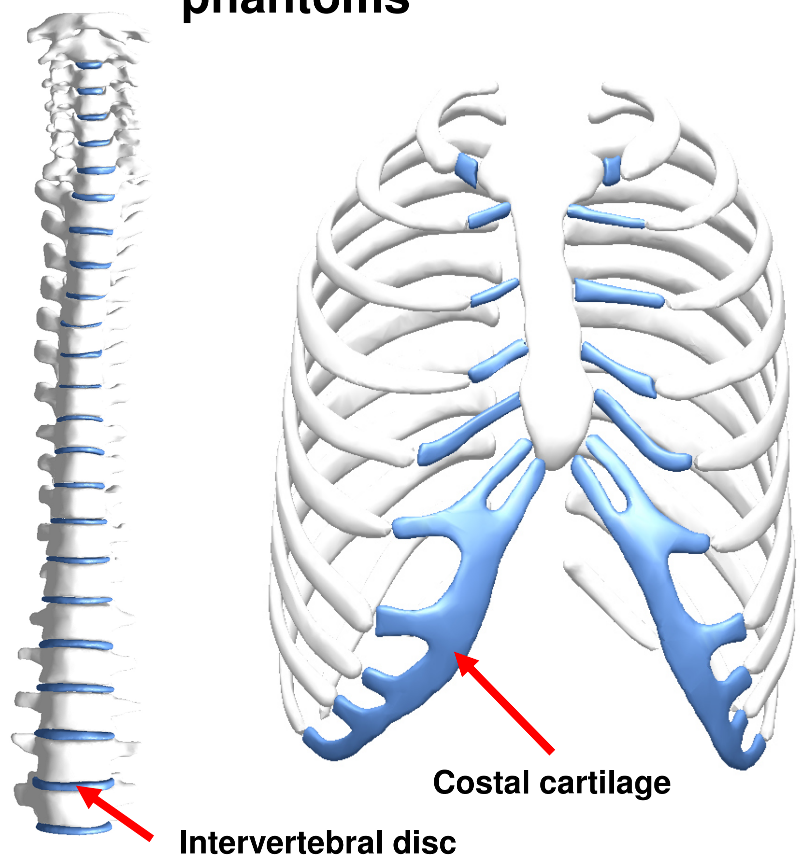


Toe-standing feet (female)

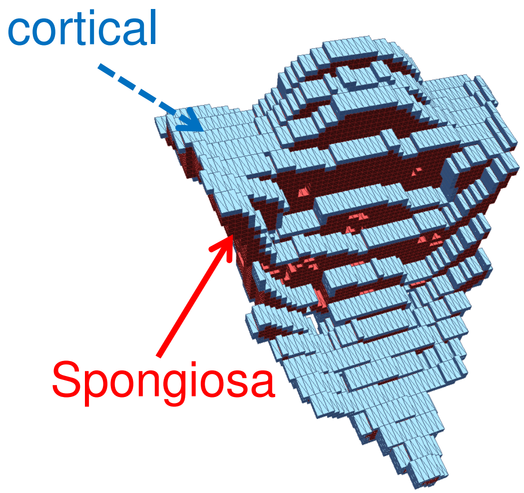
Extraction of Cartilage / Cartilage Modeling



Costal cartilage and intervertebral discs were modeled following UF/NCI phantoms

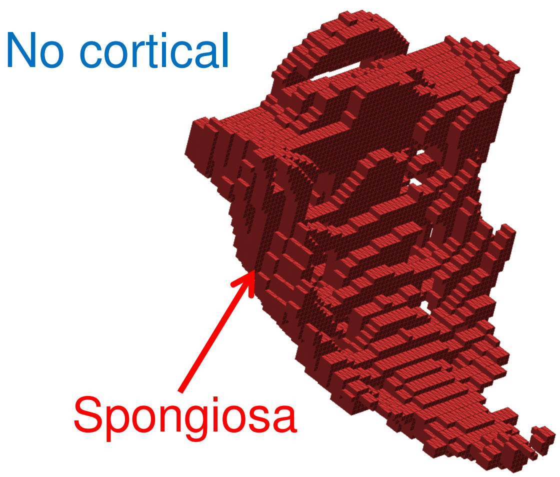


Correction of Female Sacrum

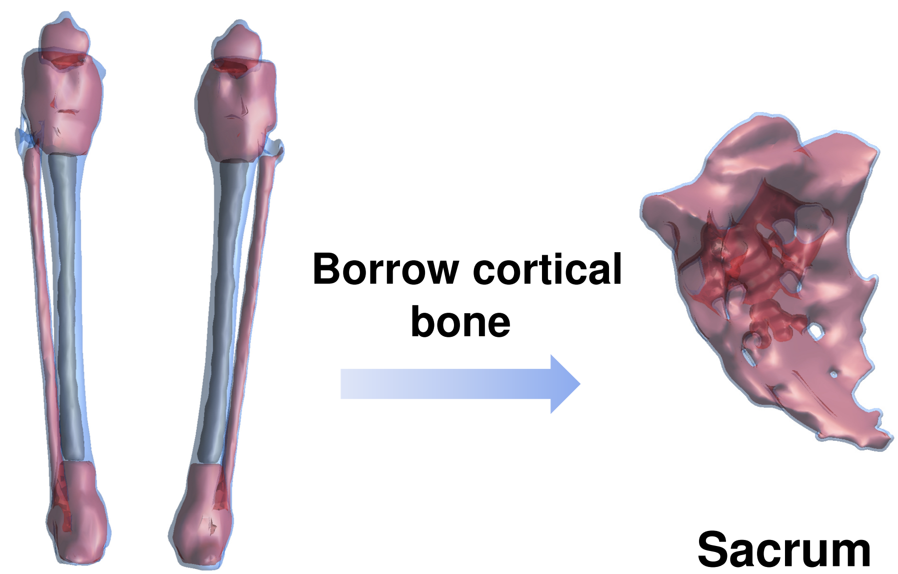


Male sacrum

Cortical bones	Male		Female (original)		Female (new)	
	Mass (g)	fraction	Mass (g)	fraction	Mass (g)	fraction
Humeri	263.29	5.98%	214.81	6.71%	214.81	6.71%
Ulnae and radii	270.80	6.15%	155.15	4.85%	155.15	4.85%
Hands	179.74	4.08%	104.08	3.25%	104.08	3.25%
Clavicles	47.78	1.09%	32.50	1.02%	32.50	1.02%
Cranium	562.85	12.79%	403.60	12.61%	403.60	12.61%
Femora	555.76	12.63%	480.22	15.01%	480.22	15.01%
Tibiae, fibulae and patellae	531.35	12.08%	618.85	19.34%	539.41	16.86%
Feet	232.56	5.29%	171.75	5.37%	171.75	5.37%
Mandible	76.12	1.73%	44.94	1.40%	44.94	1.40%
Pelvis	398.62	9.06%	259.84	8.12%	259.84	8.12%
Ribs	365.15	8.30%	162.87	5.09%	162.87	5.09%
Scapulae	221.13	5.03%	120.45	3.76%	120.45	3.76%
Cervical spine	102.92	2.34%	70.88	2.22%	70.88	2.22%
Thoracic spine	286.58	6.51%	203.78	6.37%	203.78	6.37%
Lumbar spine	186.19	4.23%	154.62	4.83%	154.62	4.83%
Sacrum	109.23	2.48%	0.00	0.00%	79.44	2.48%
Sternum	9.89	0.22%	1.67	0.05%	1.67	0.05%



Female sacrum



Sacrum

Lower leg bones

1. Construction of “Simple Organs”

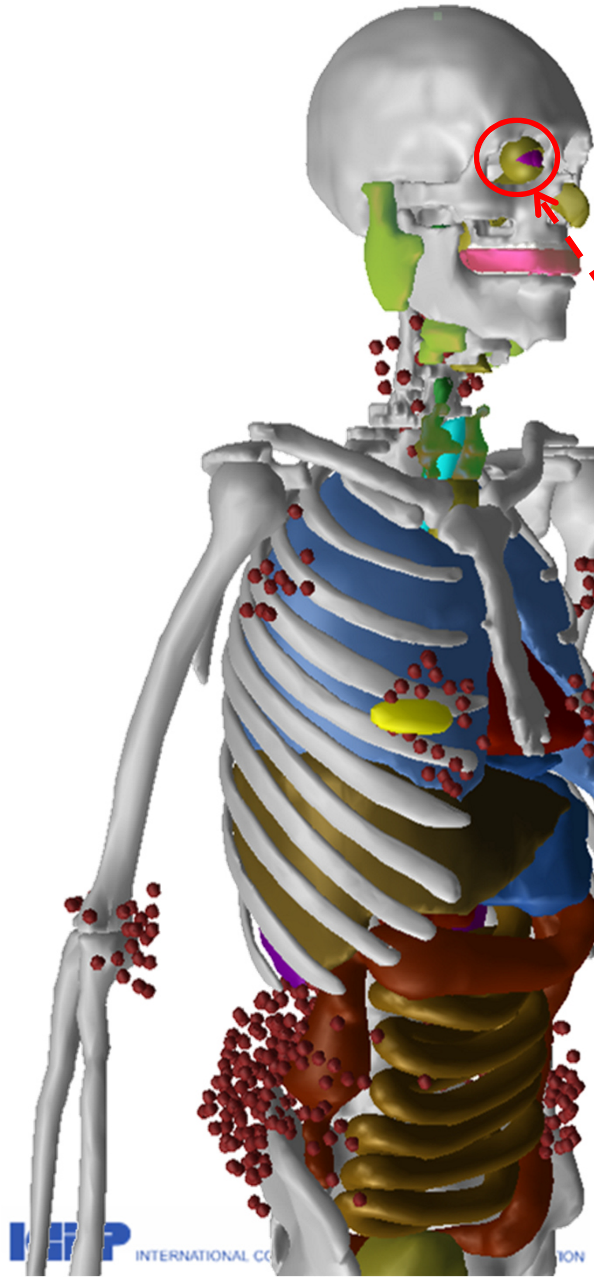
2. Construction of “Skeletal Systems”

3. Construction of “Complex Organs”

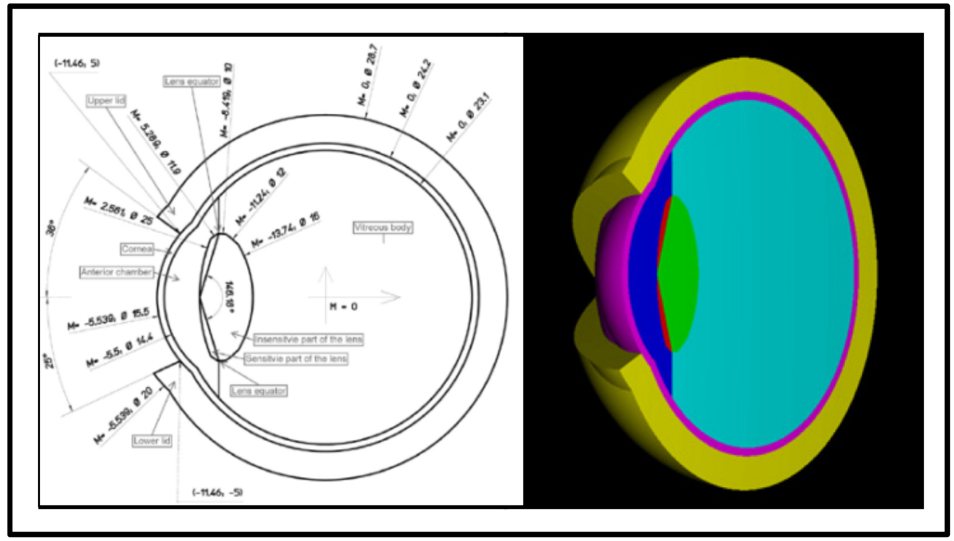
~50% completed

4. Preliminary Results

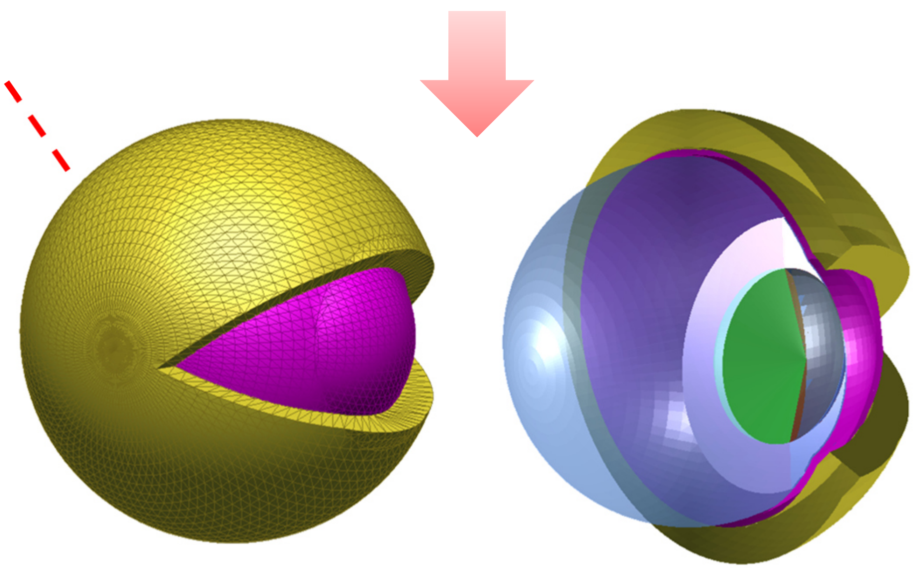
3-1. Eyes



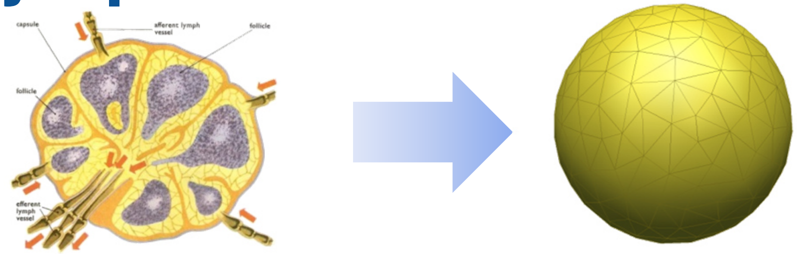
ICRP stylized eye model (ICRP-116)



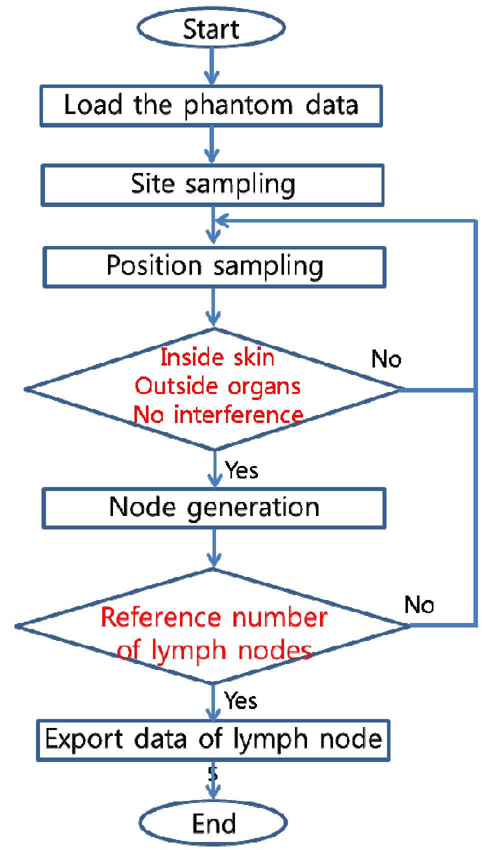
Conversion to polygonal model



3-2. Lymphatic Nodes

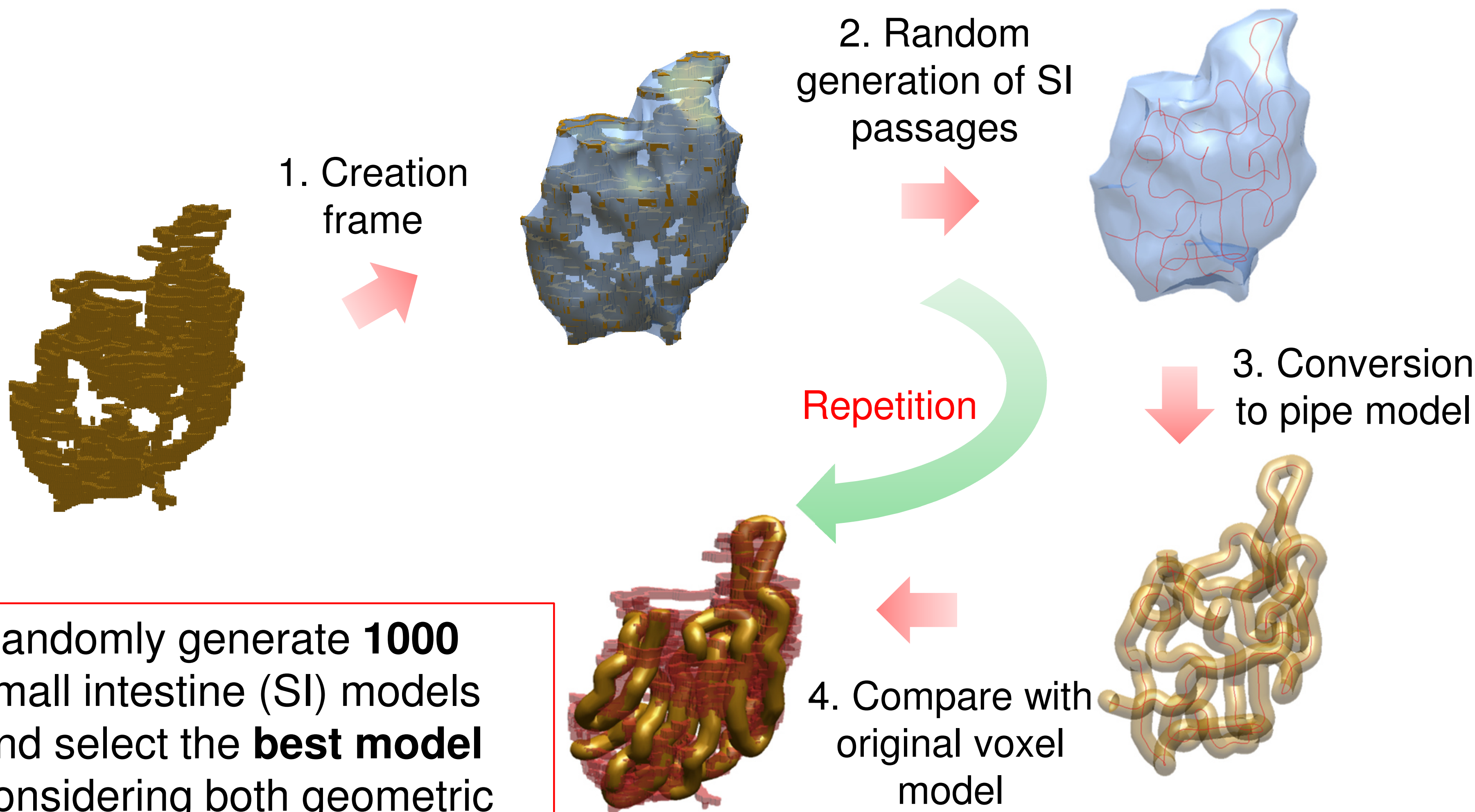


	Reference Mass AM	Reference Mass AF	Reference Number	Reference Range
Extrathoracic	15.0	12.0	55	
Cervical	5.2	4.1	19	
Thoracic	15.0	12.0	55	50-60
Breast (left and right)	10.4	8.3	38	
Mesentery (left and right)	95.5	76.4	350	200-500
Axiliary (left and right)	6.3	5.0	23	8-37
Cubital (left and right)	10.4	8.3	38	
Inguinal (left and right)	10.4	8.3	38	
Popliteal (left and right)	10.4	8.3	38	
Total Mass (g)	178.4	142.7	654	600-700



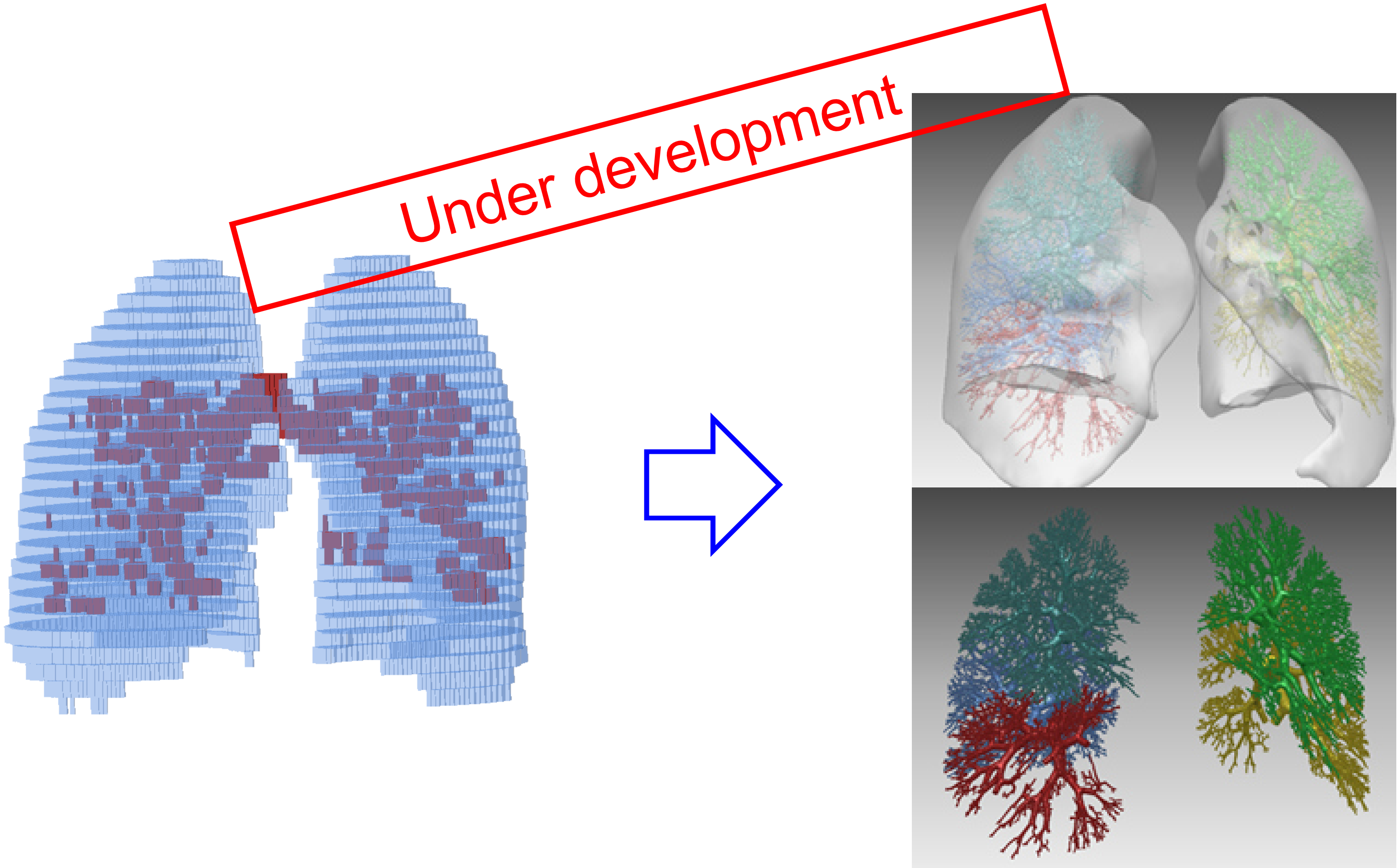
- We have developed a computer program <u>to generate the lymphatic nodes</u> in the polygon-mesh version phantoms, following the procedure which was used to develop the <u>UF/NCI phantoms</u> which have been adopted as ICRP pediatric phantoms.

3-3. Small Intestine

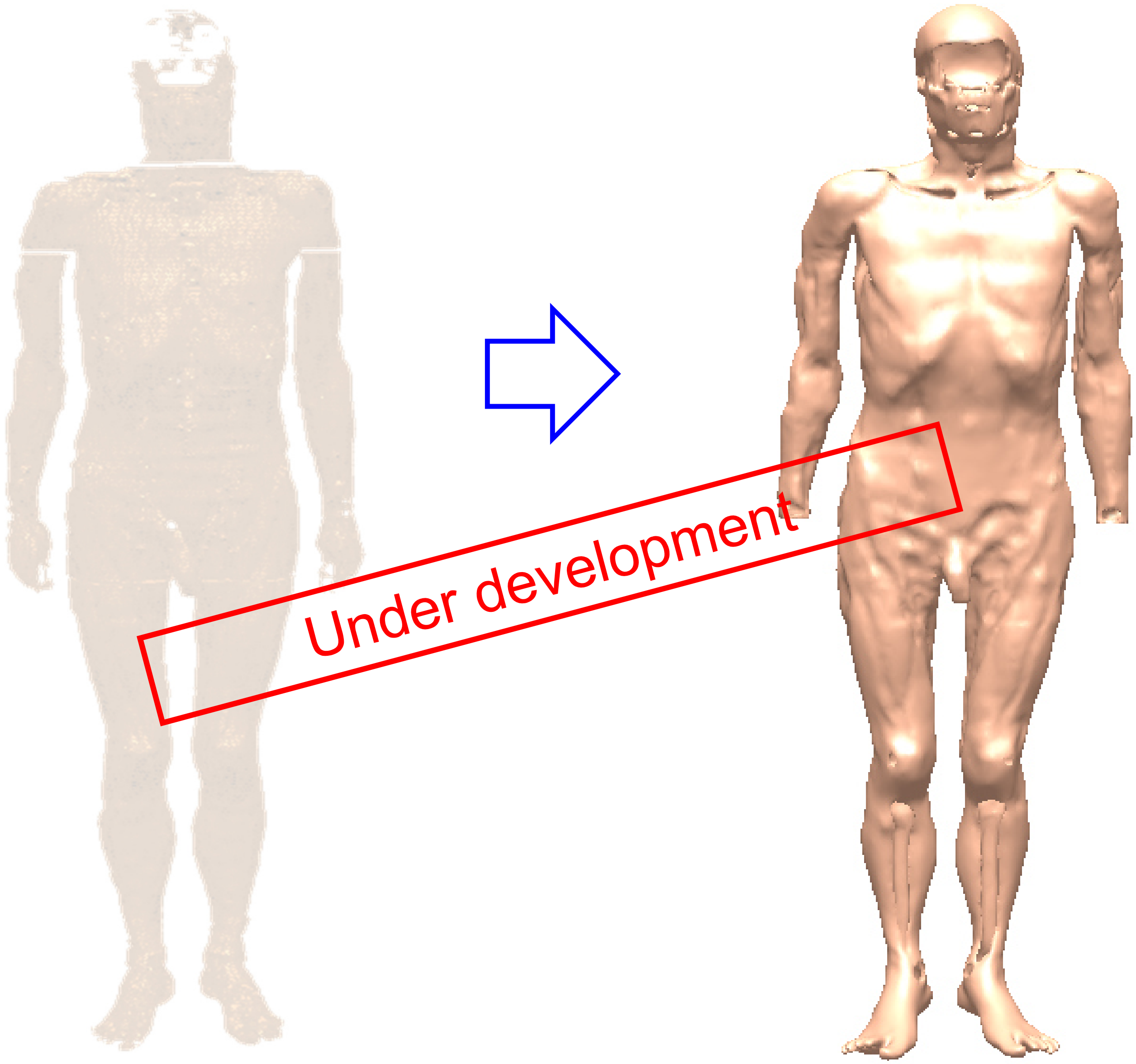


Randomly generate **1000** small intestine (SI) models and select the **best model** considering both geometric and dosimetric similarities with the original voxel model

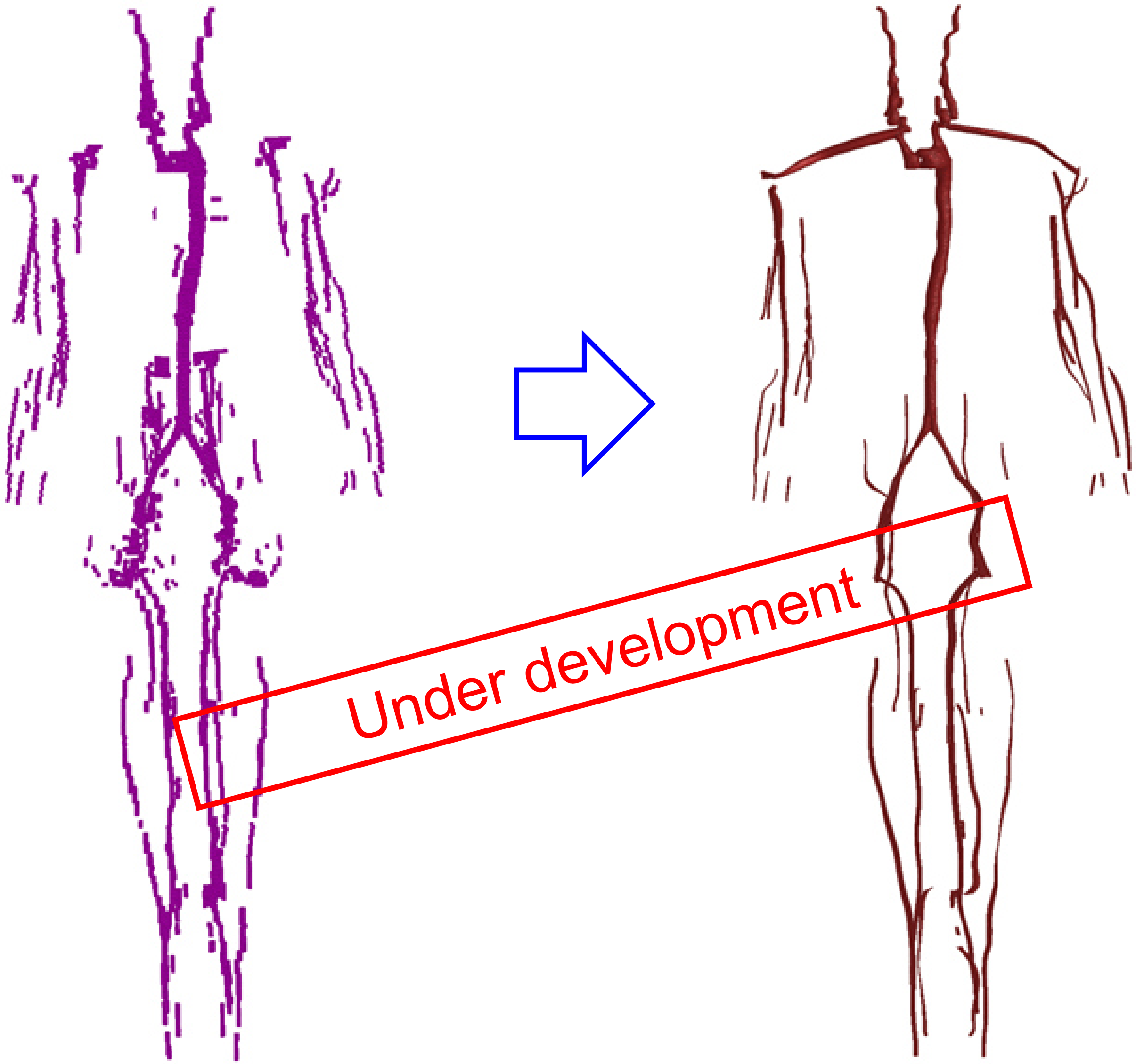
3-4. Lungs (BB ad bb Regions)



3-5. Muscle



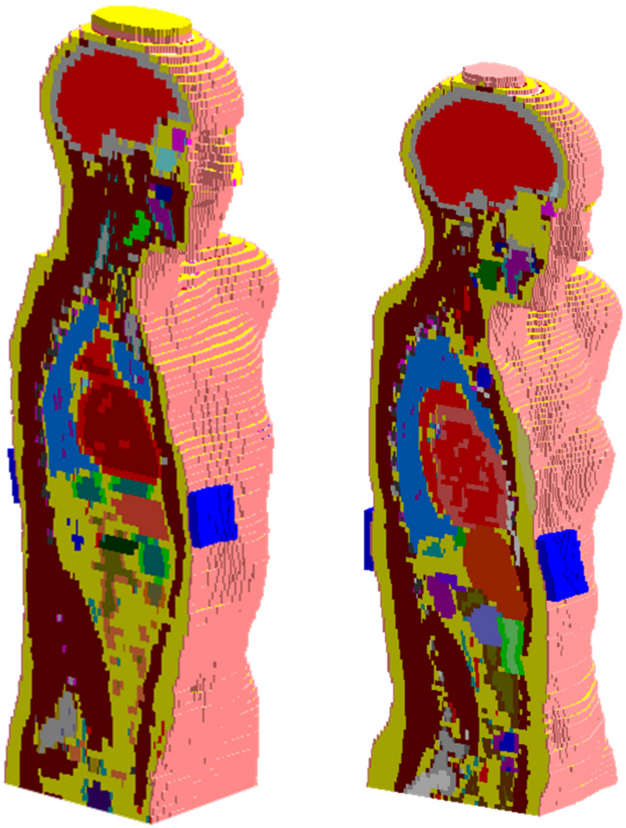
3-6. Blood Vessel



1. Construction of “Simple Organs”
2. Construction of “Skeletal Systems”
3. Construction of “Complex Organs”
4. Preliminary Results

Developed Phantoms (Preliminary)

Male Female



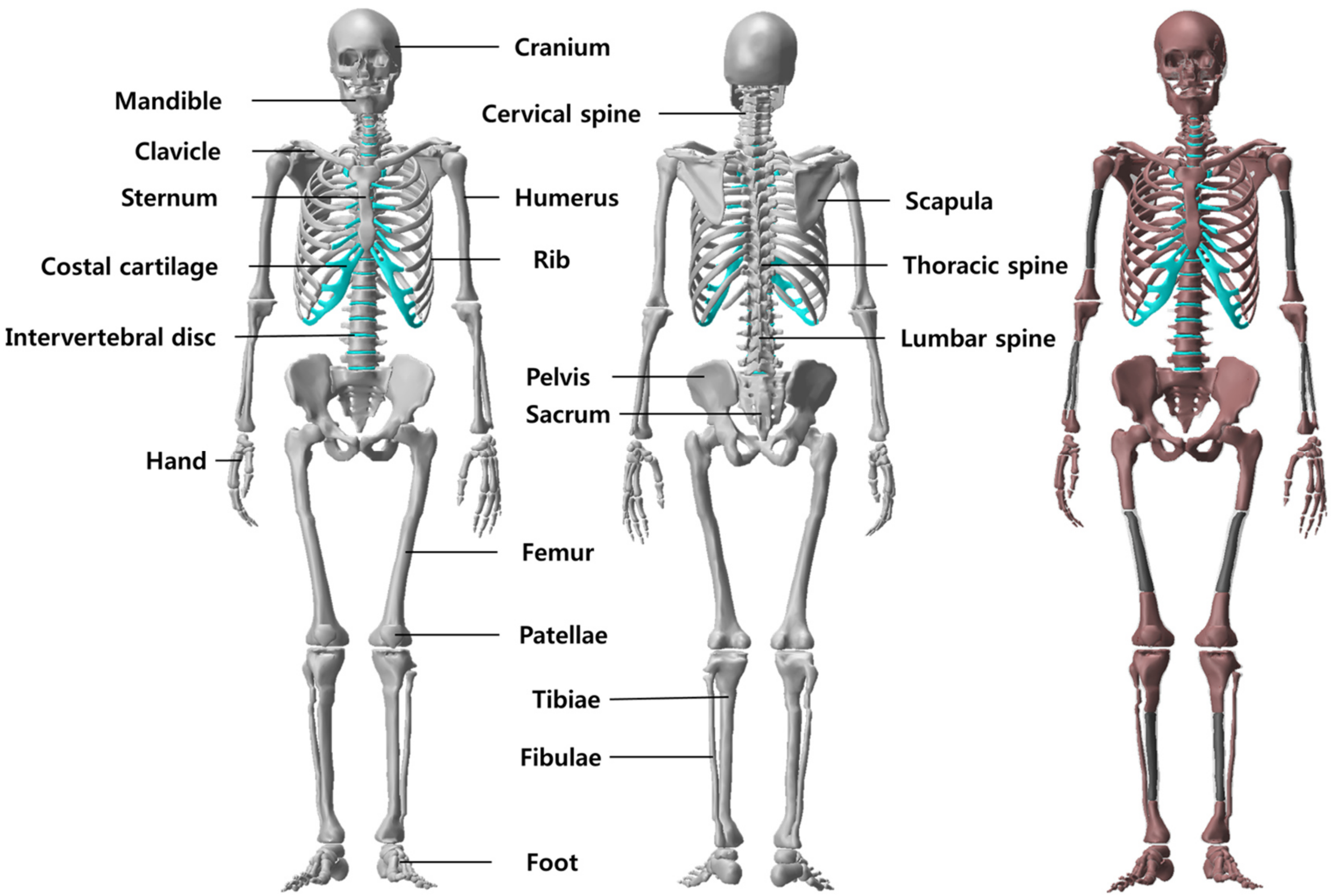
ICRP-110 phantoms
(voxel geometry)

Male Female

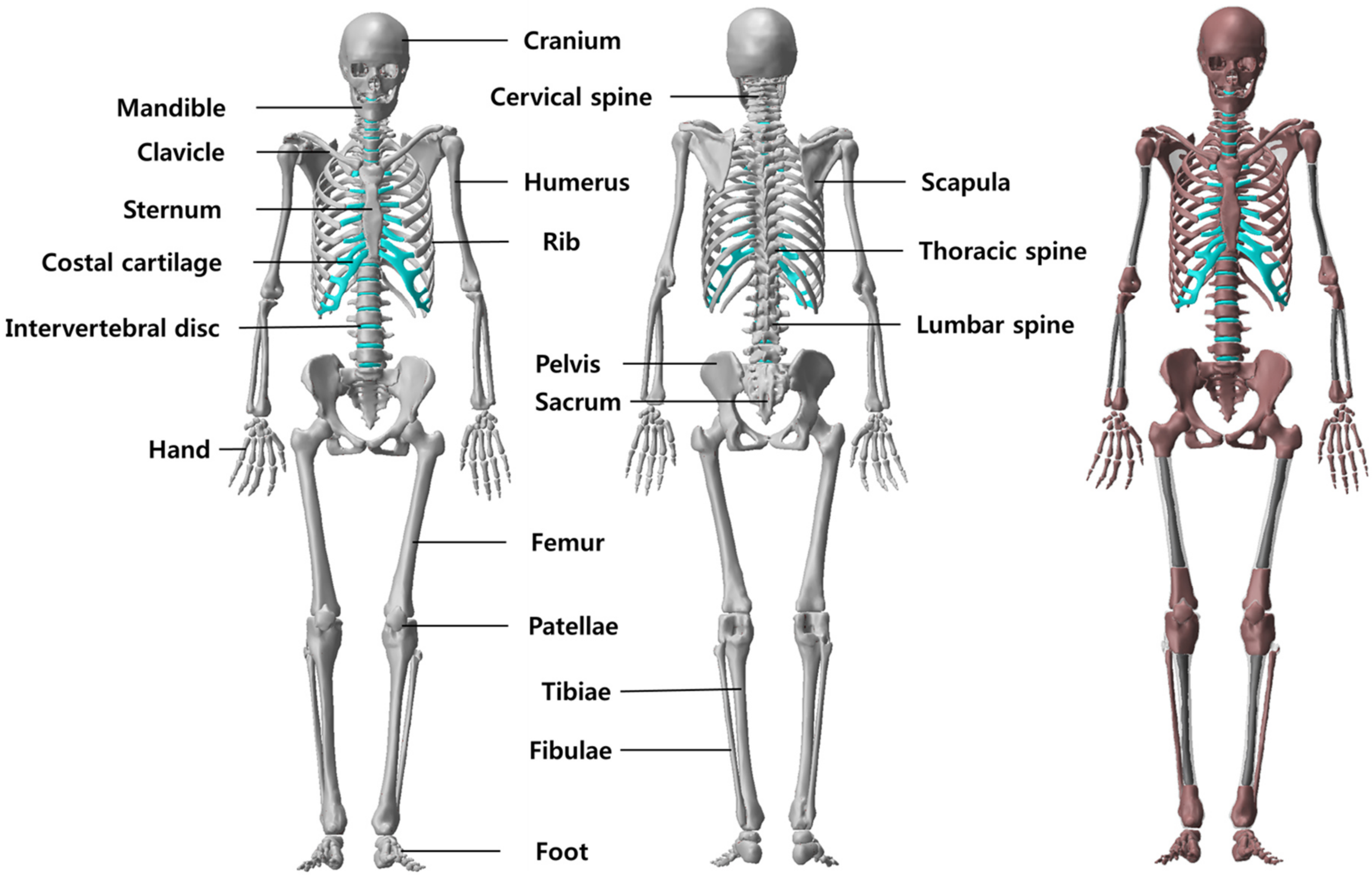
Polygon-mesh version phantoms
(preliminary)

Skeletal System

Male



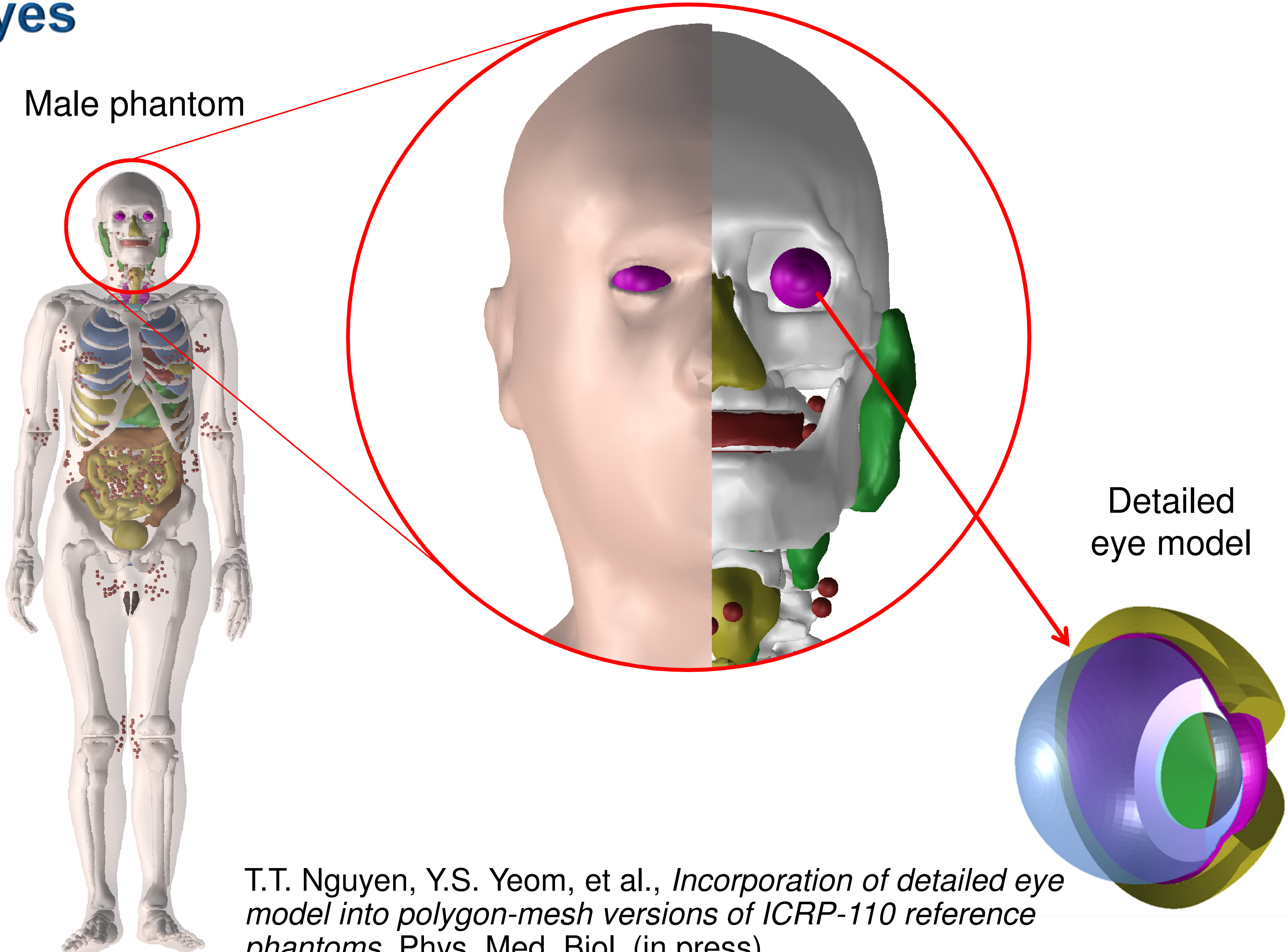
Female


Cranium
Mandible
Cervical spine
Clavicle
Humerus
Scapula
Sternum
Rib
Thoracic spine
Costal cartilage
Intervertebral disc
Lumbar spine
Pelvis
Sacrum
Hand
Femur
Patellae
Tibiae
Fibulae
Foot

Hands & Feet

Male phantom

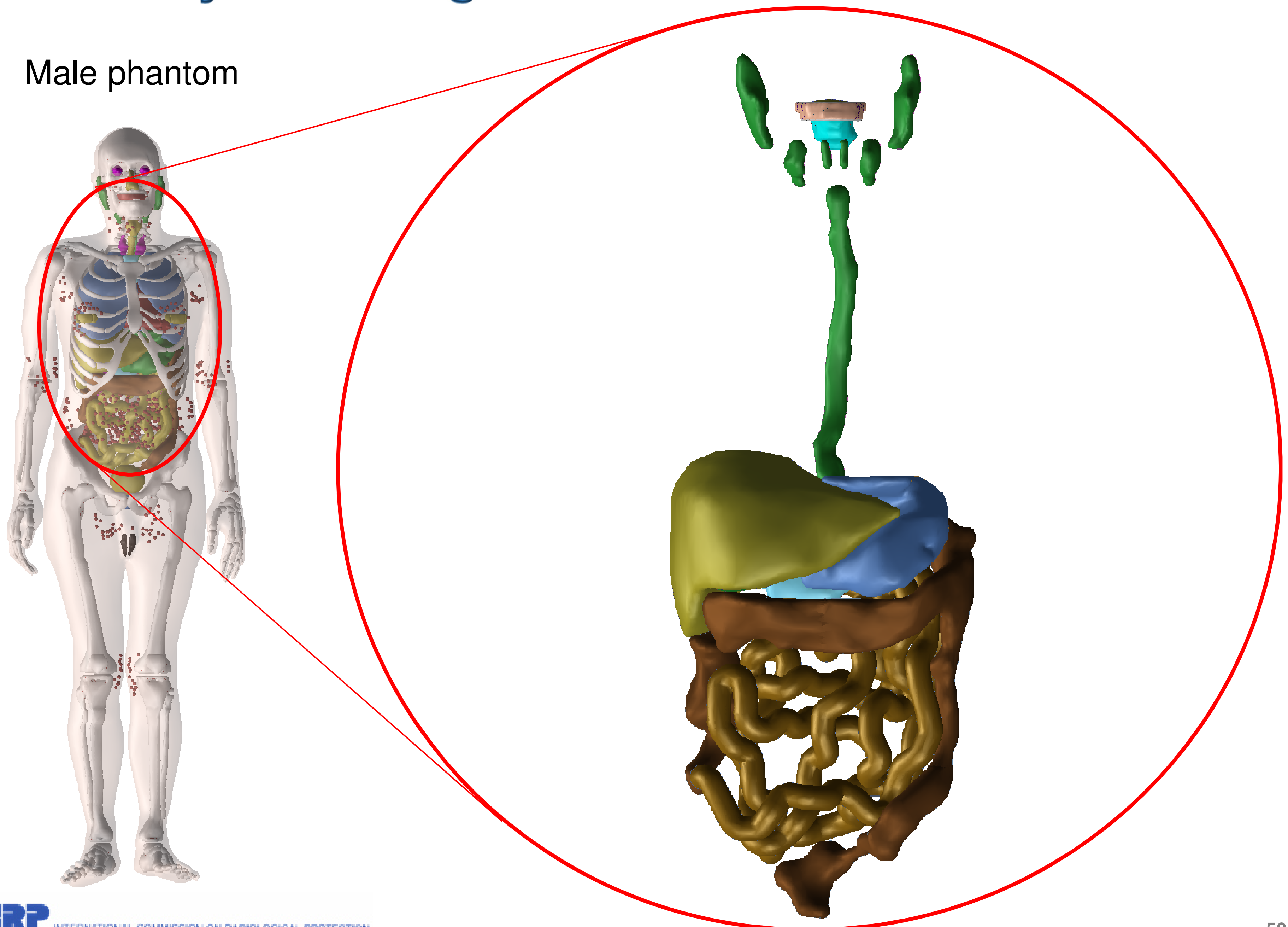
Eyes



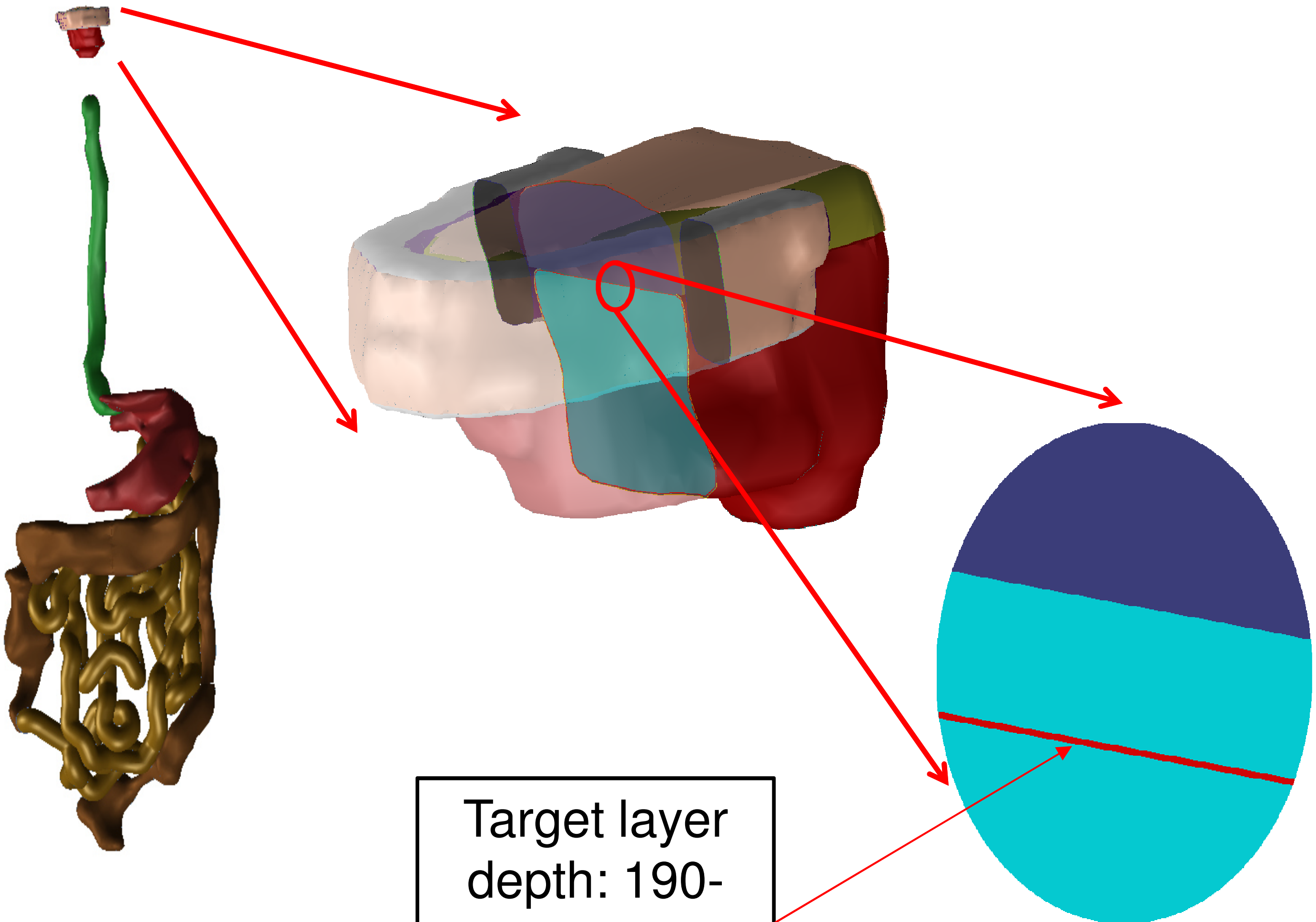
T.T. Nguyen, Y.S. Yeom, et al., *Incorporation of detailed eye model into polygon-mesh versions of ICRP-110 reference phantoms*. Phys. Med. Biol. (in press)

Alimentary Tract Organs

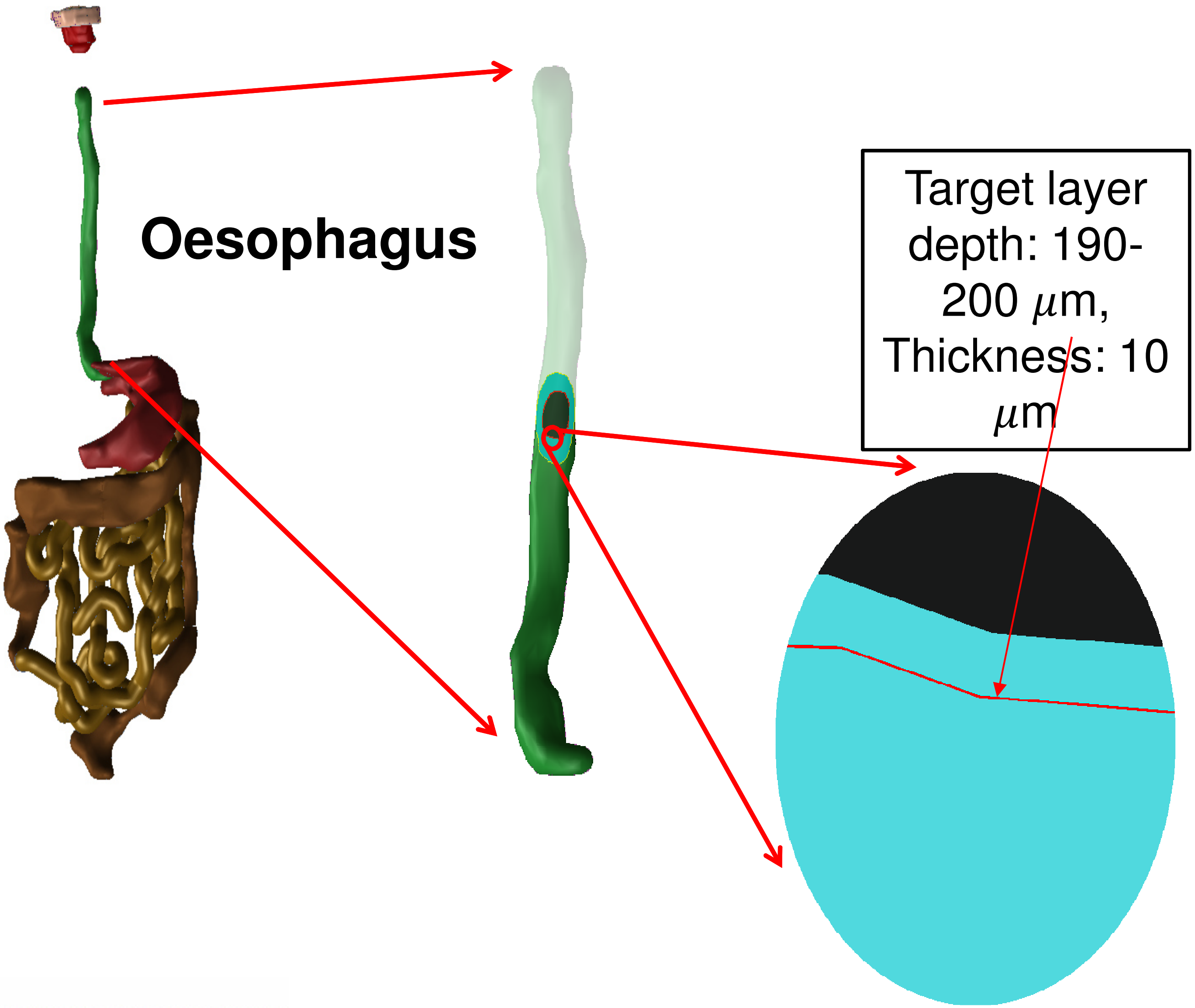
Male phantom

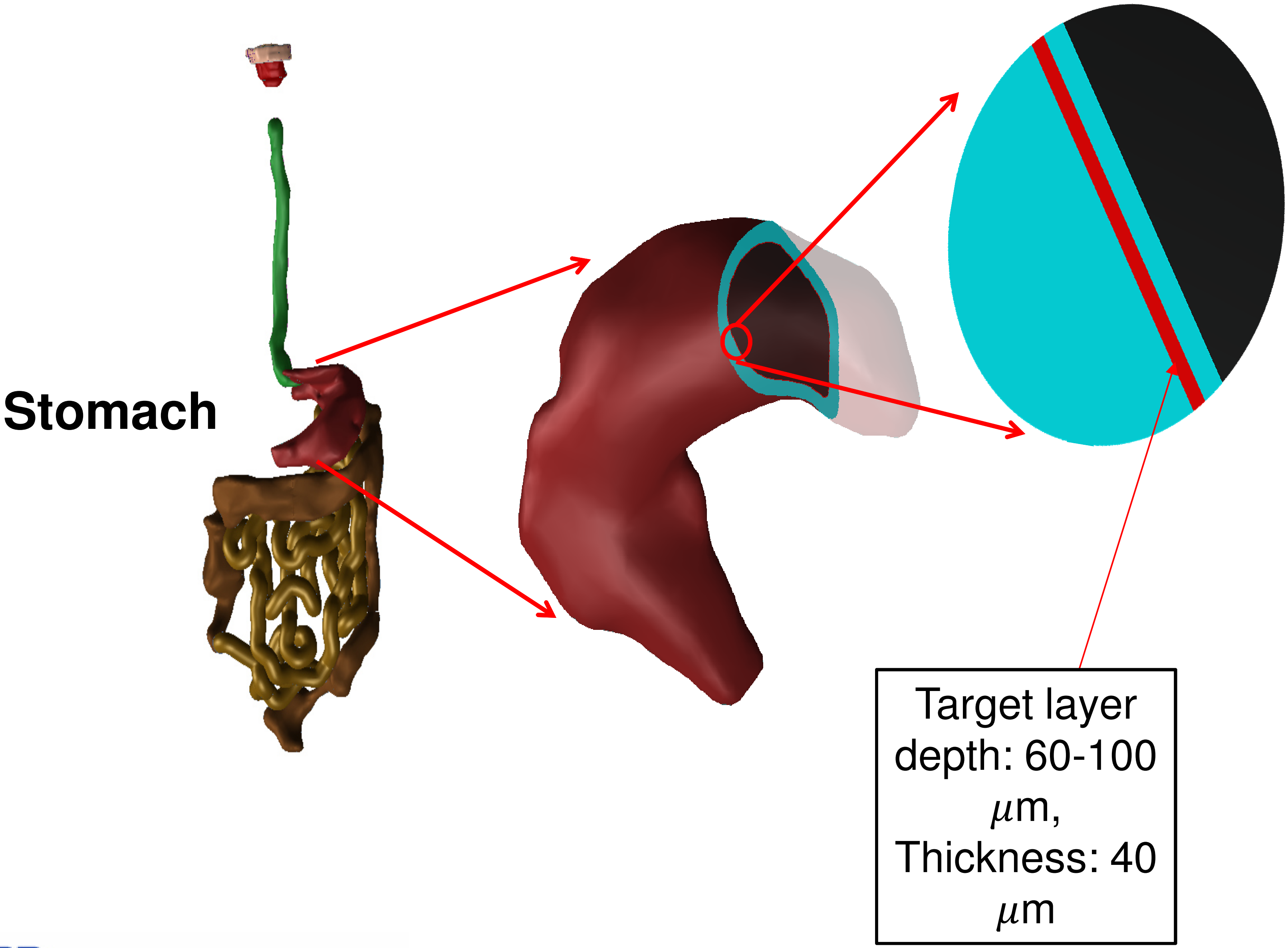


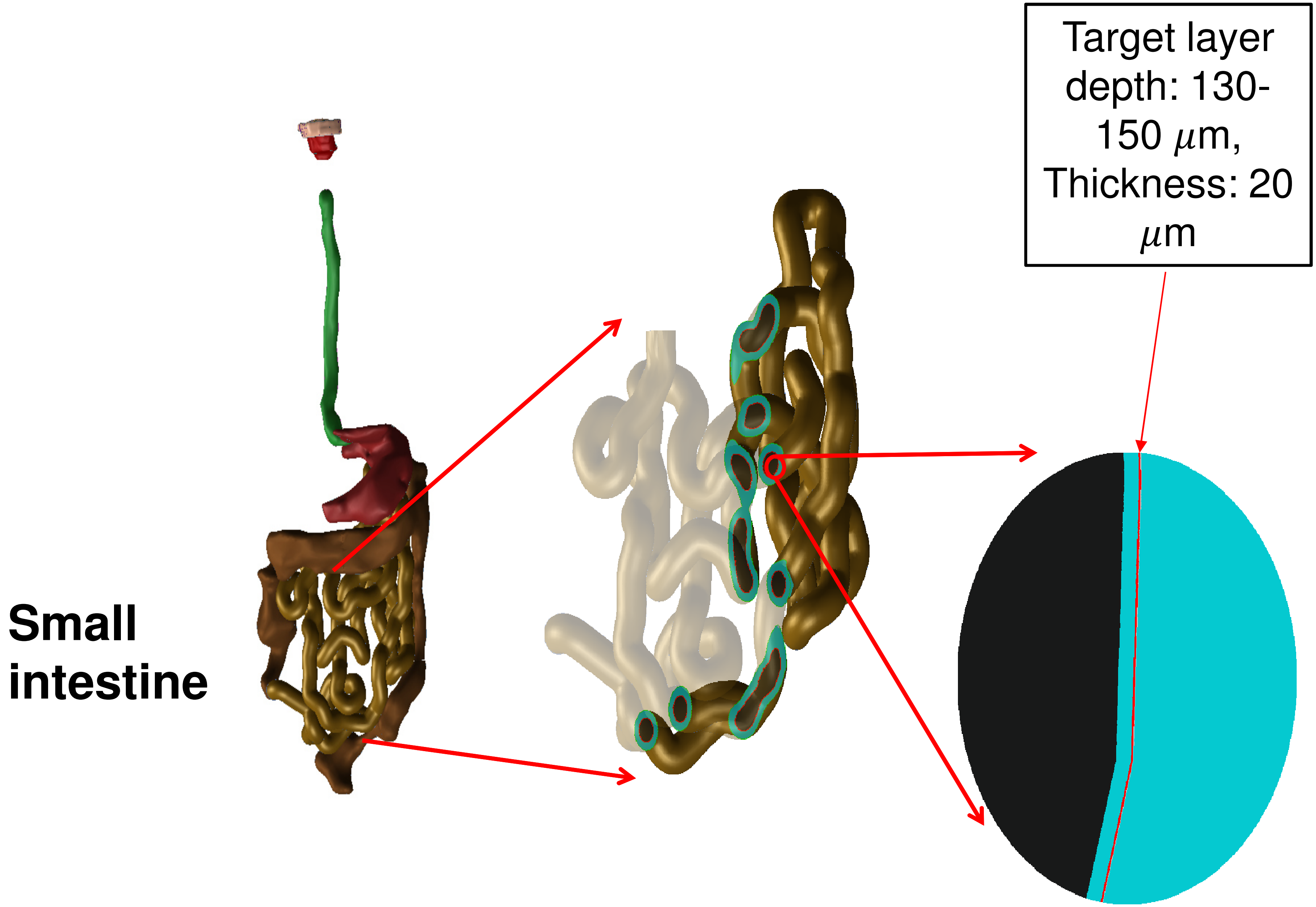
Oral cavity

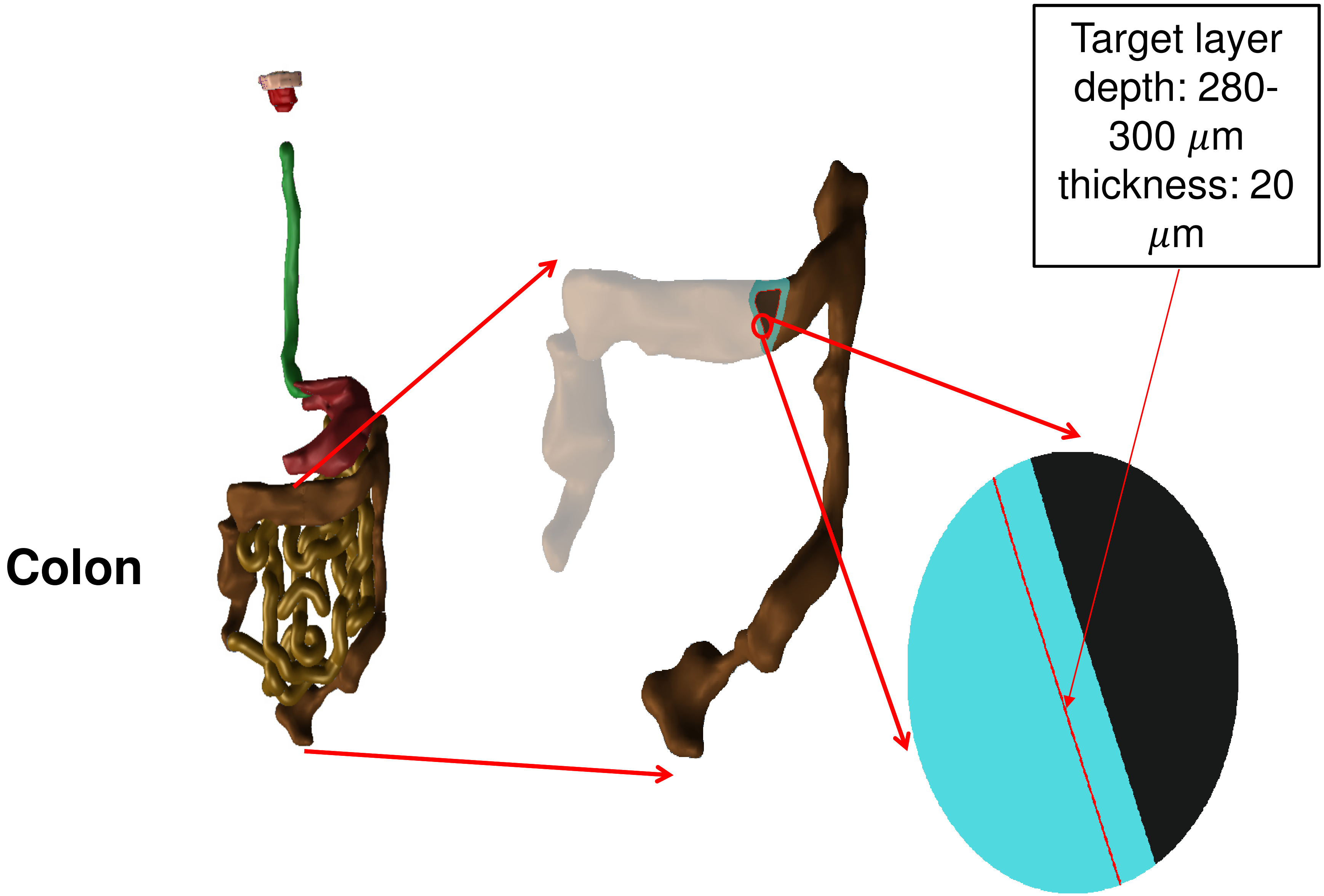


Target layer depth: 190-200 μm, Thickness: 10 μm


Oesophagus
Target layer depth: 190-200 μm, Thickness: 10 μm


Stomach
Target layer depth: 60-100 μm, Thickness: 40 μm

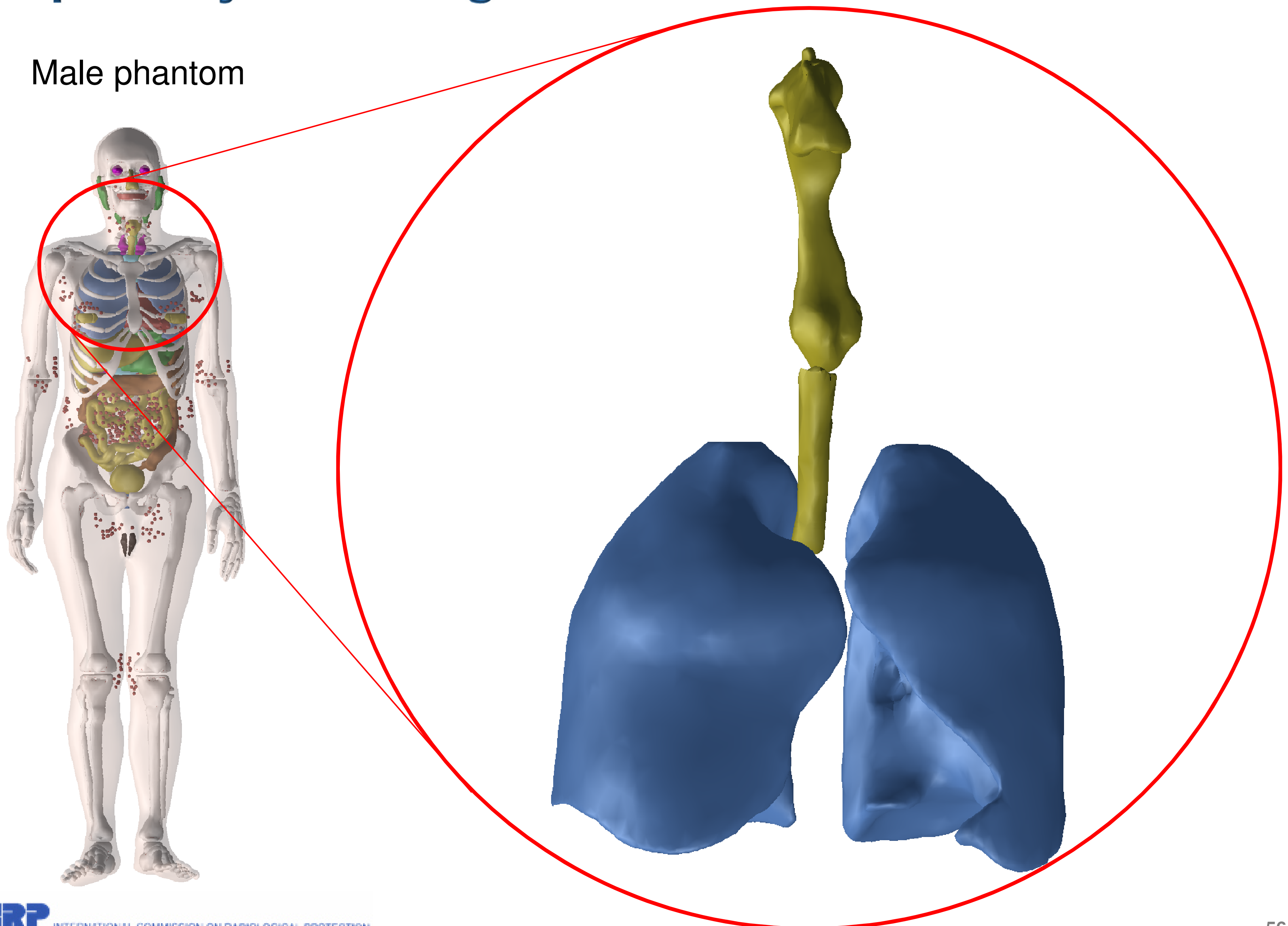

Target layer depth: 130-150 μm, Thickness: 20 μm
Small intestine



Colon
Target layer depth: 280-300 μm thickness: 20 μm

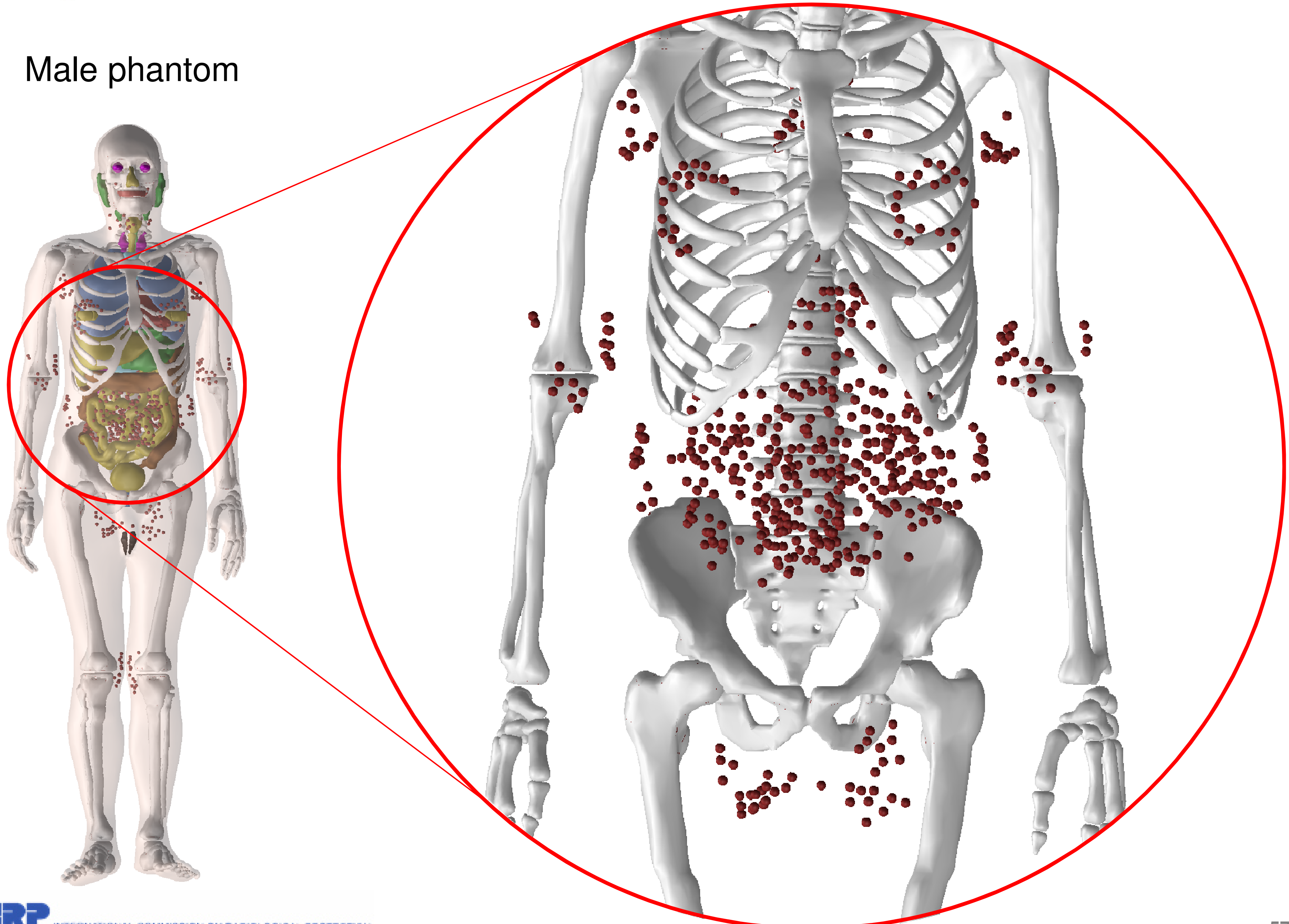
Respiratory Tract Organs

Male phantom



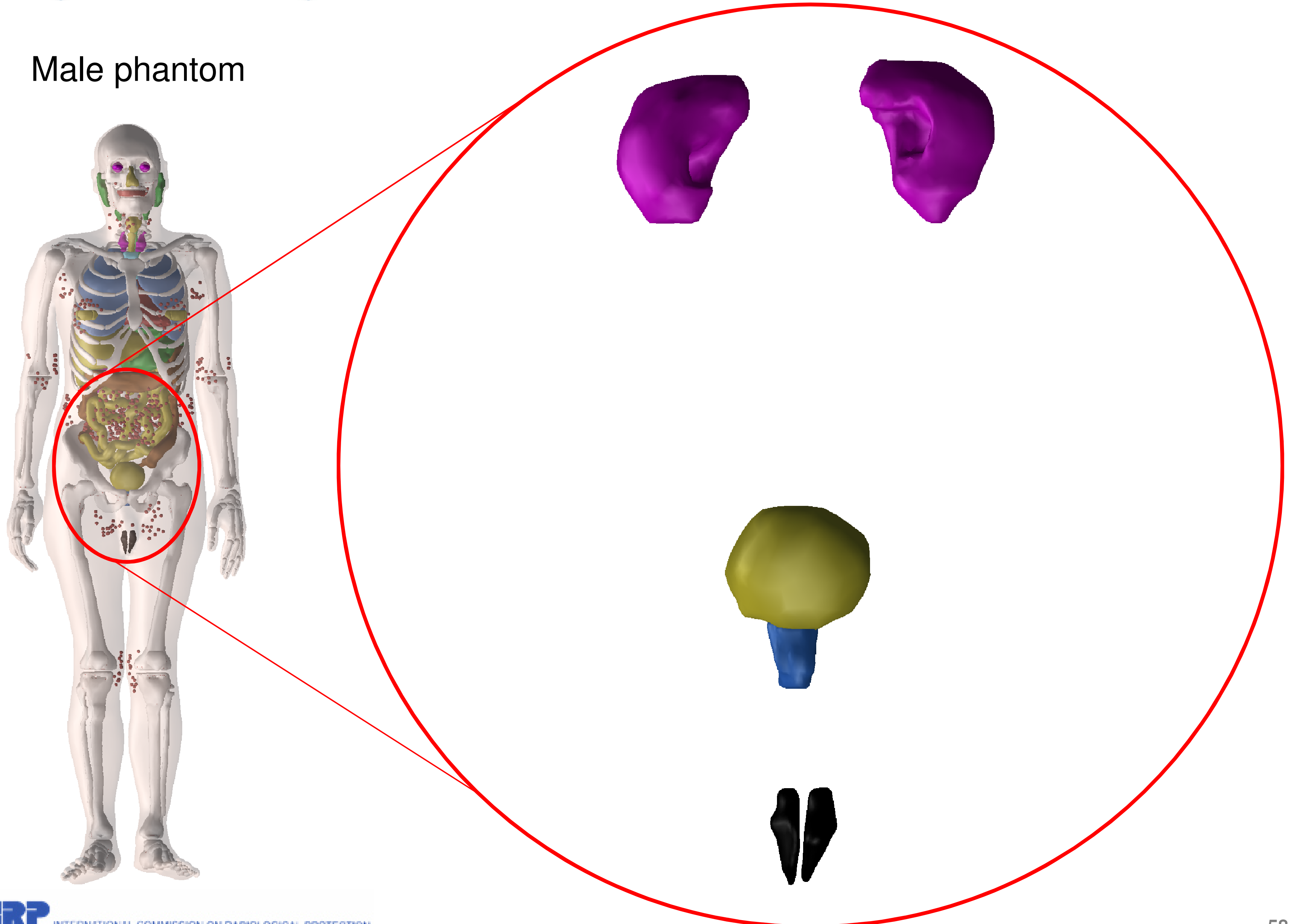
Lymphatic Nodes

Male phantom



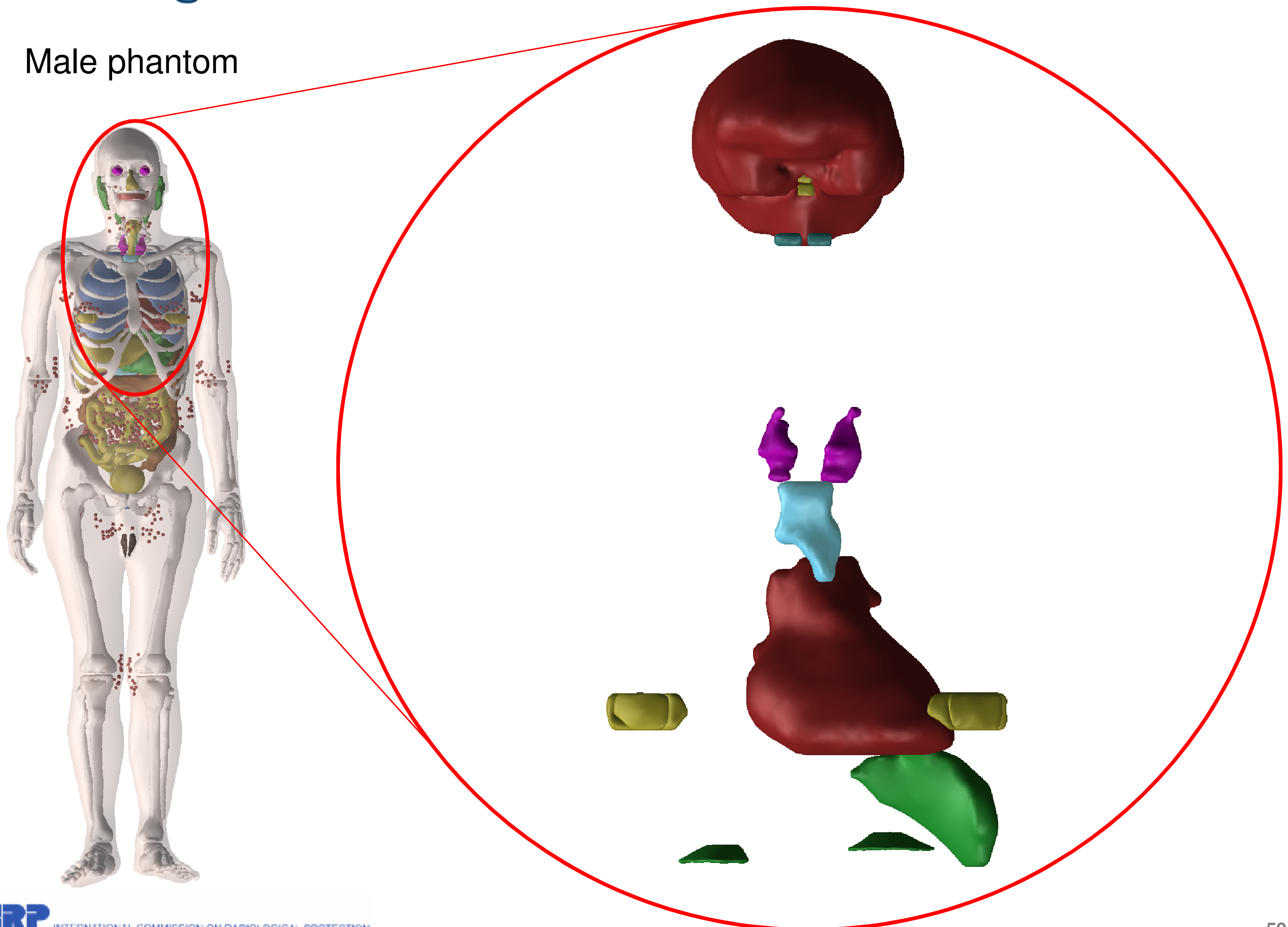
Urogenital Organs

Male phantom

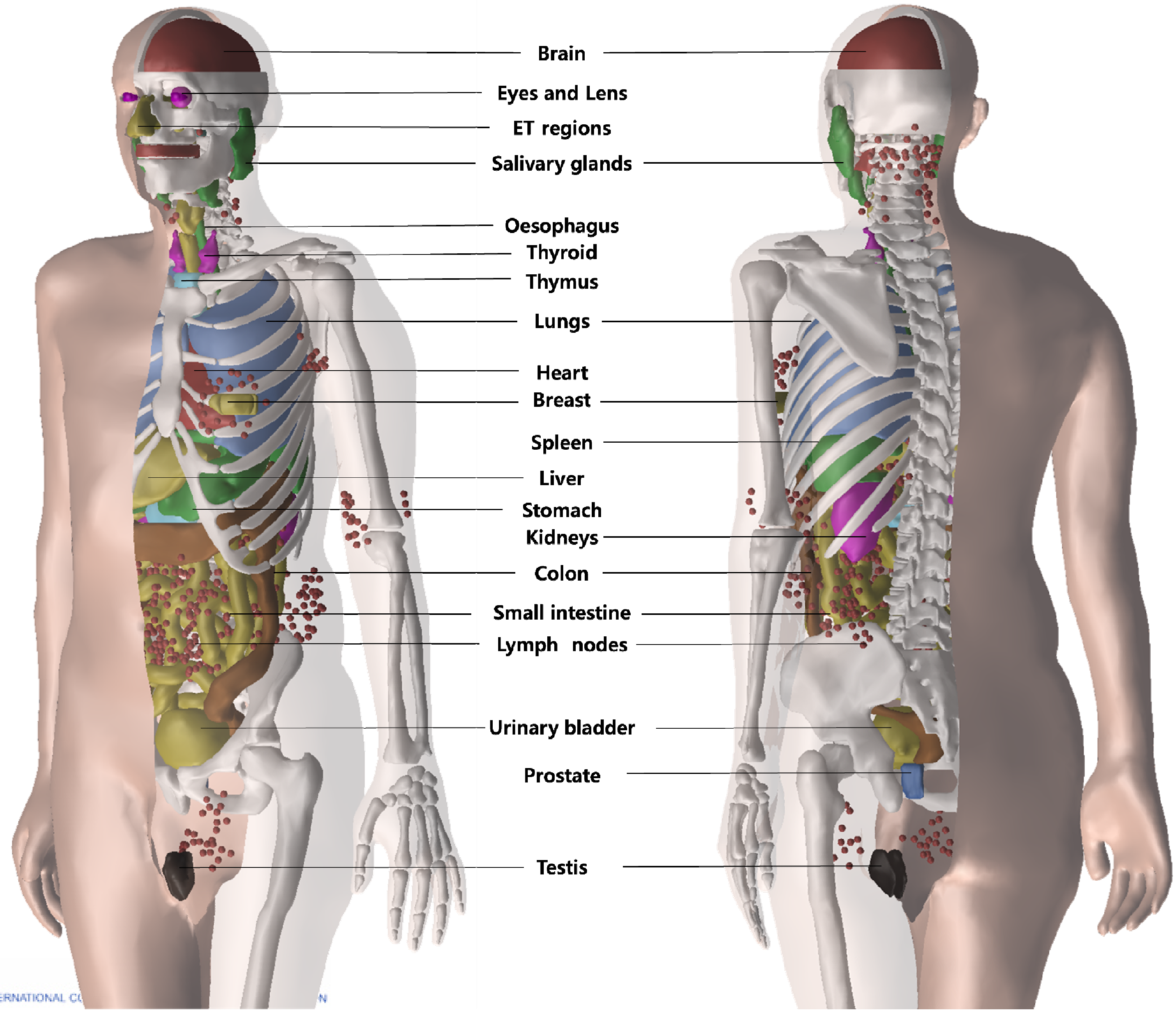


Other Organs / Tissues

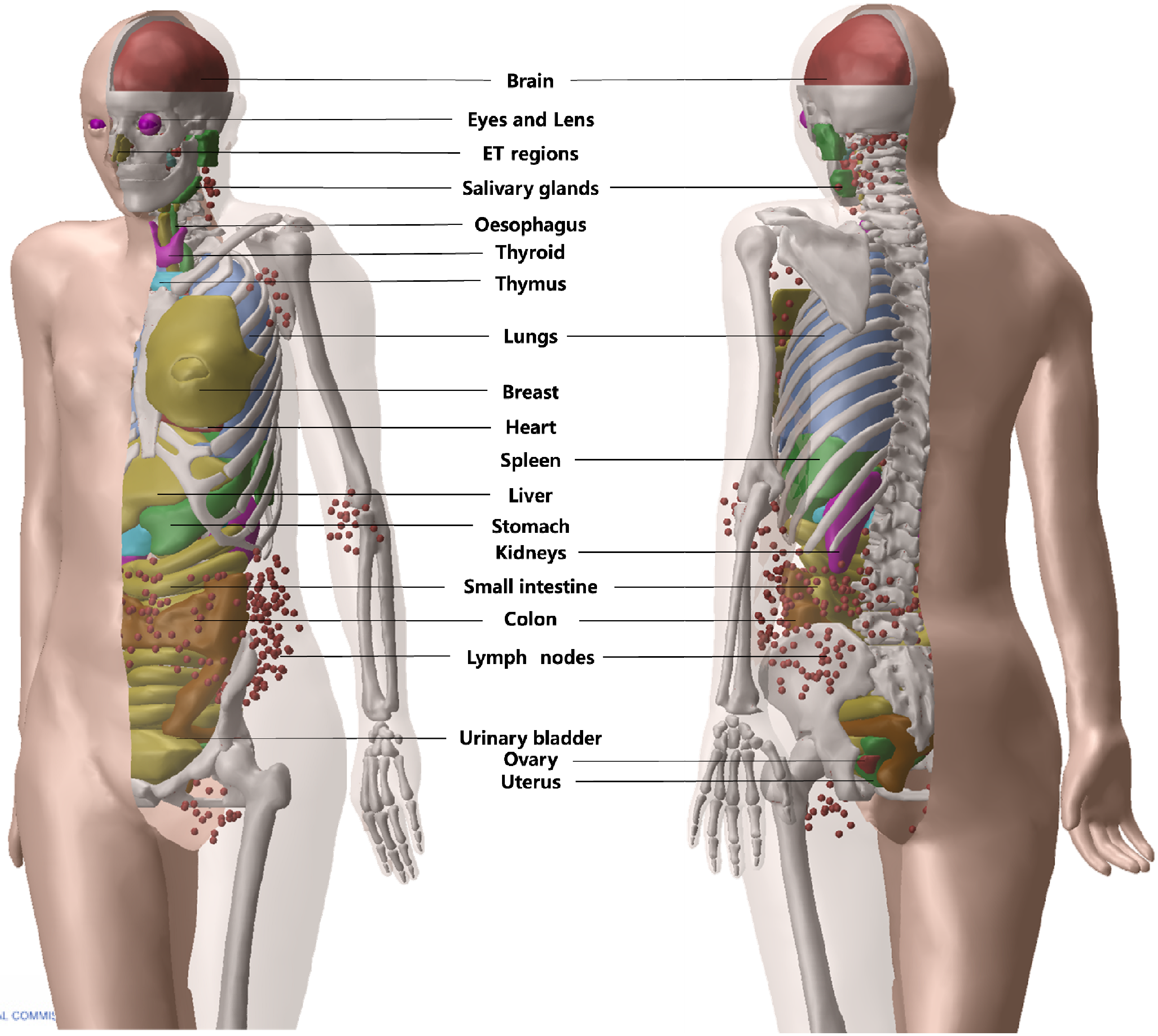
Male phantom



Developed Phantom – Male (Preliminary)

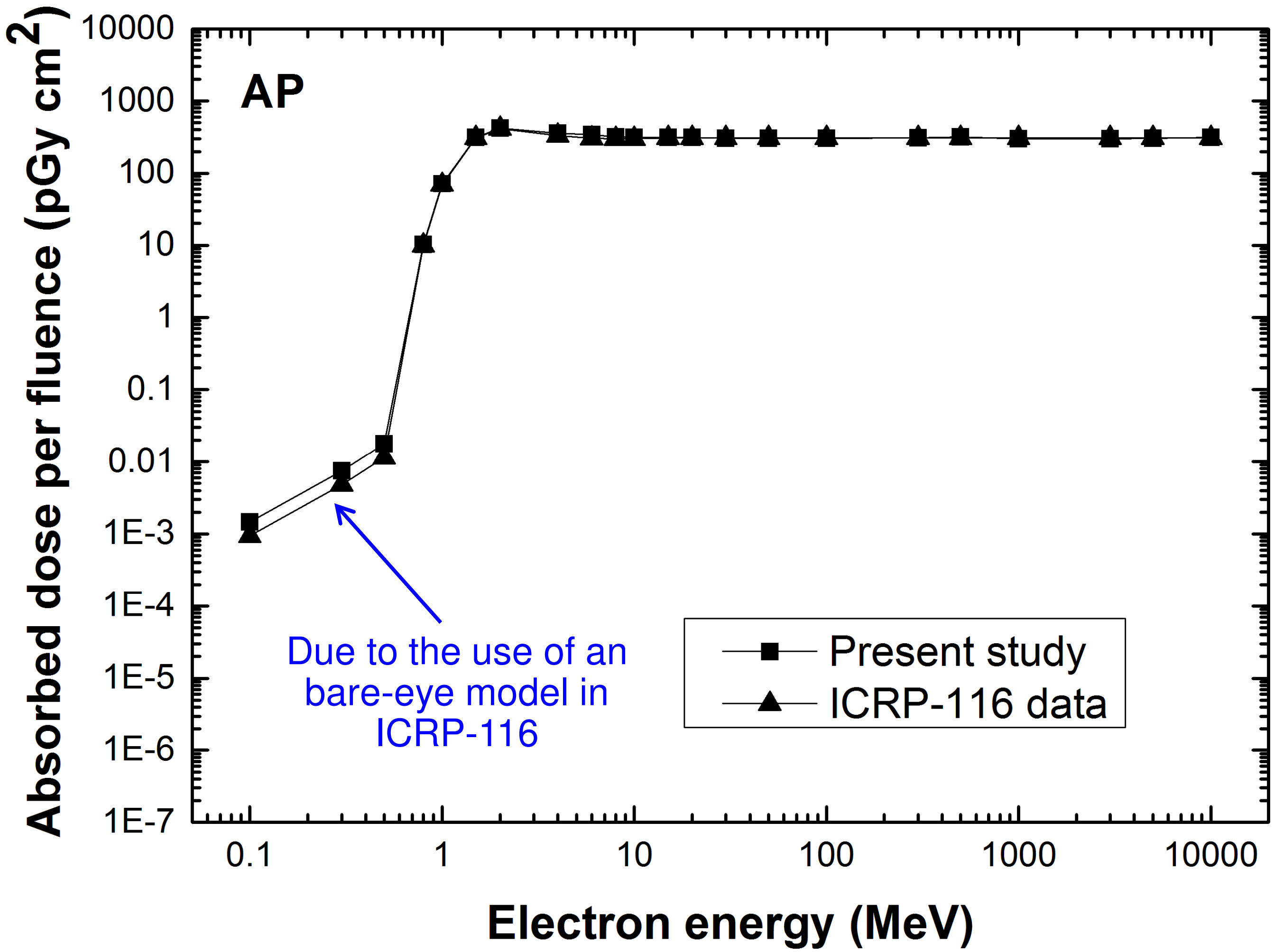


Developed Phantom – Female (Preliminary)



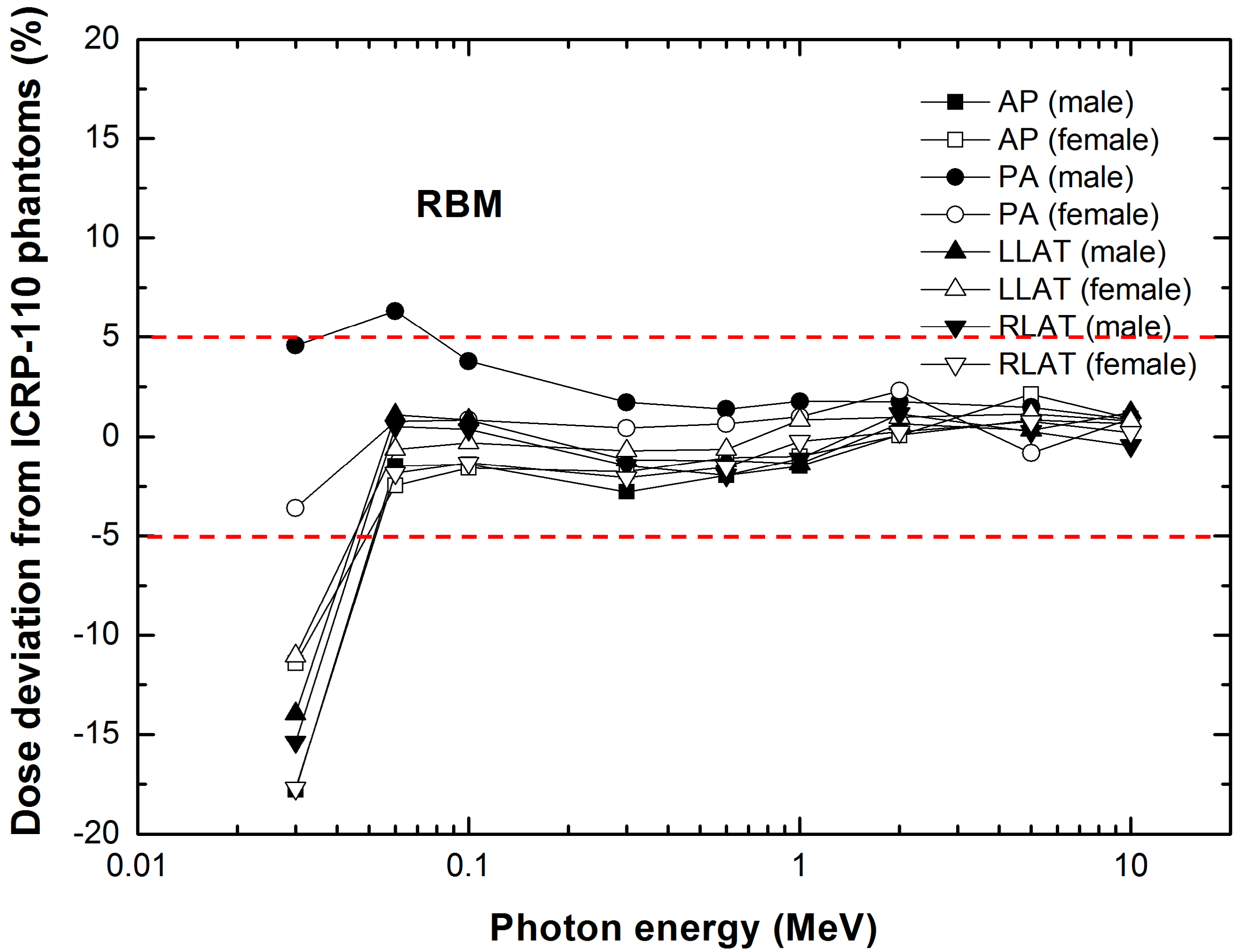
ICRP INTERNATIONAL COMMI

Eye Lens – External Electrons

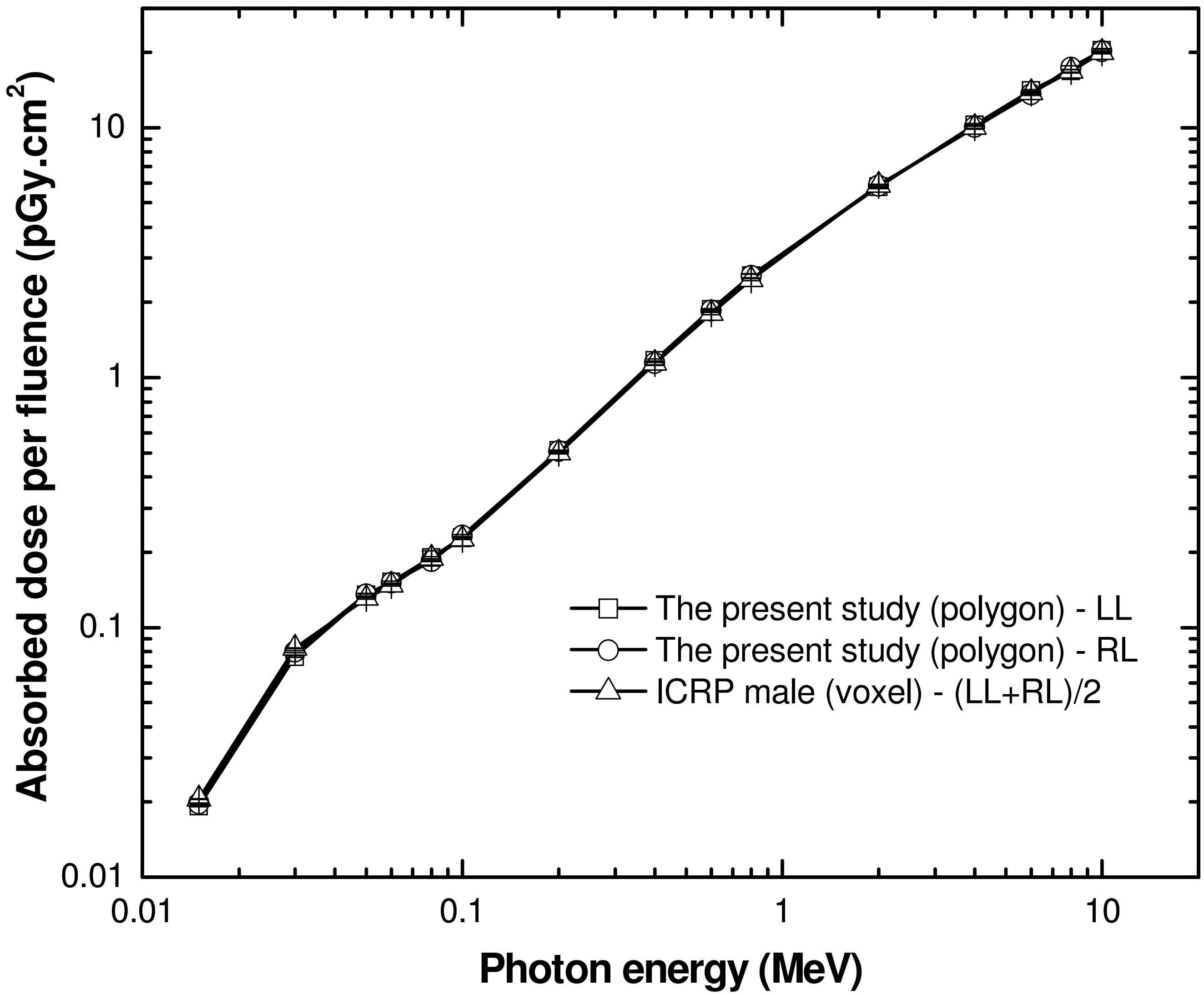


RBM – External Photons

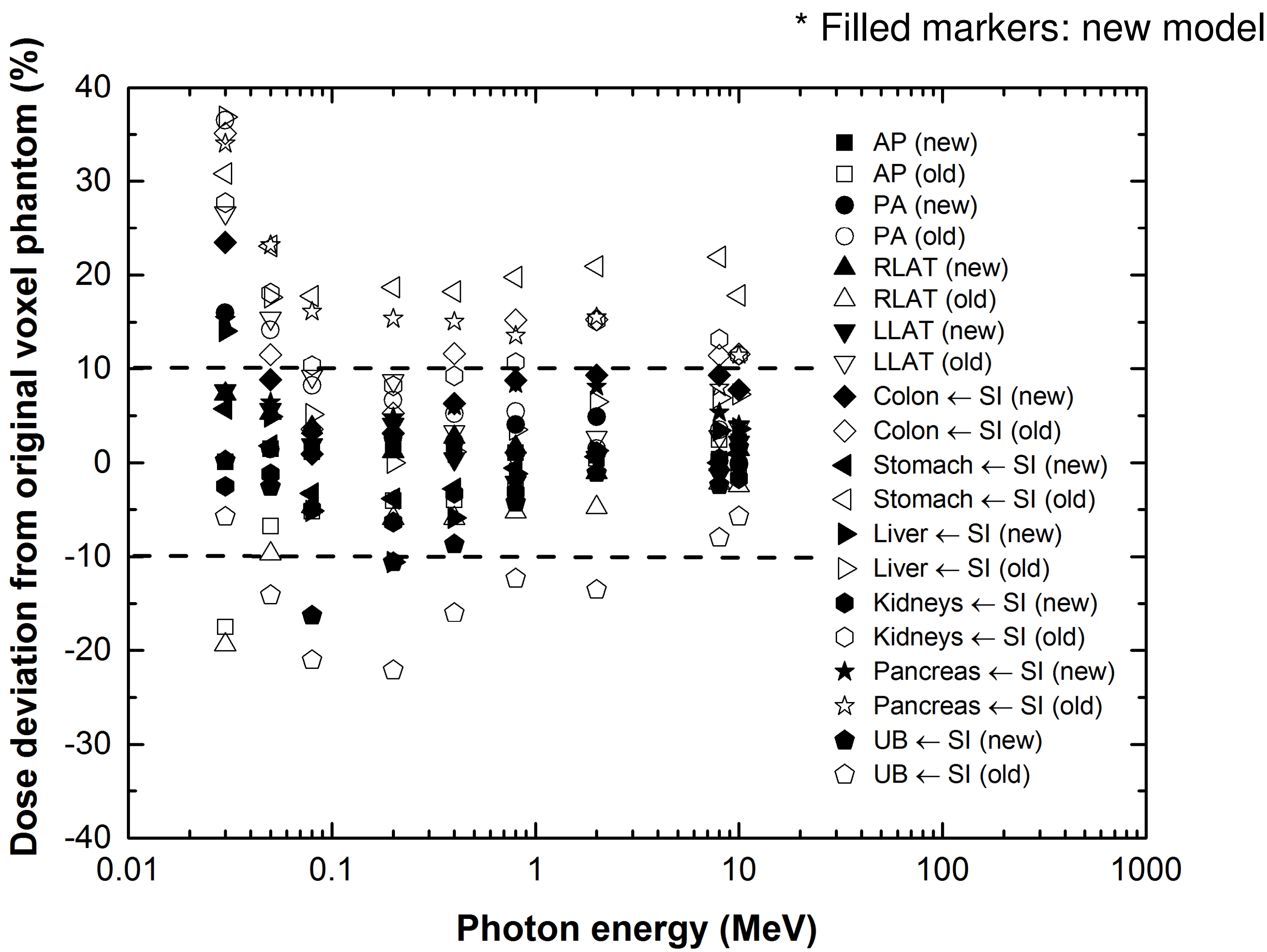
$$\boldsymbol{Deviation}\ (\%) = \frac{\boldsymbol{Dose}\ (\boldsymbol{new}) - \boldsymbol{Dose}\ (\boldsymbol{ICRP-110})}{\boldsymbol{Dose}\ (\boldsymbol{ICRP-110})} \text{ x } 100$$



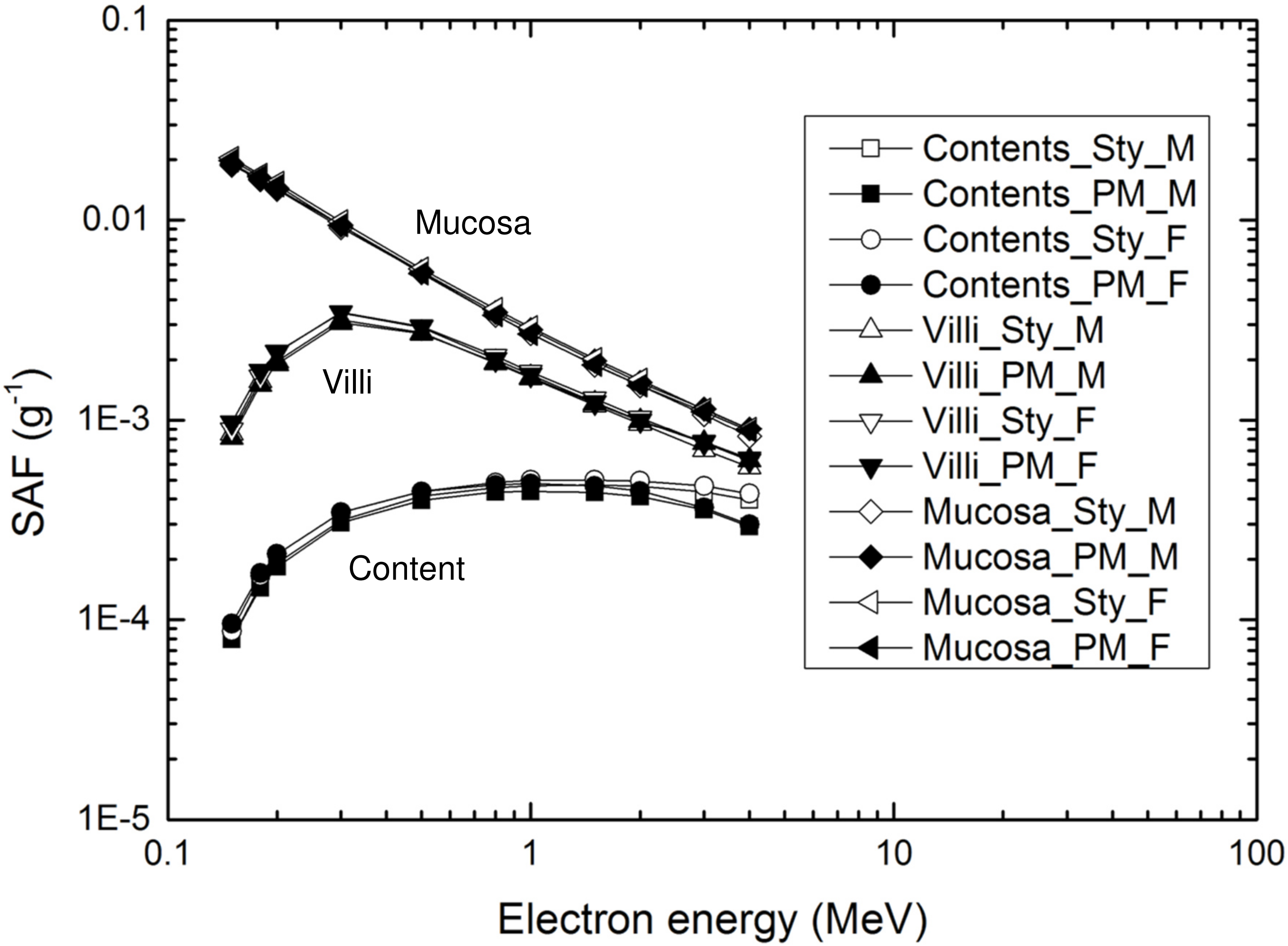
Lymphatic Nodes – External Photons



Small Intestine – External Electrons



Dose Result – Small Intestine – Electron SAF Values



Conclusion

Conclusion

- Currently developing polygon-mesh (PM) versions of the ICRP-110 reference phantoms.

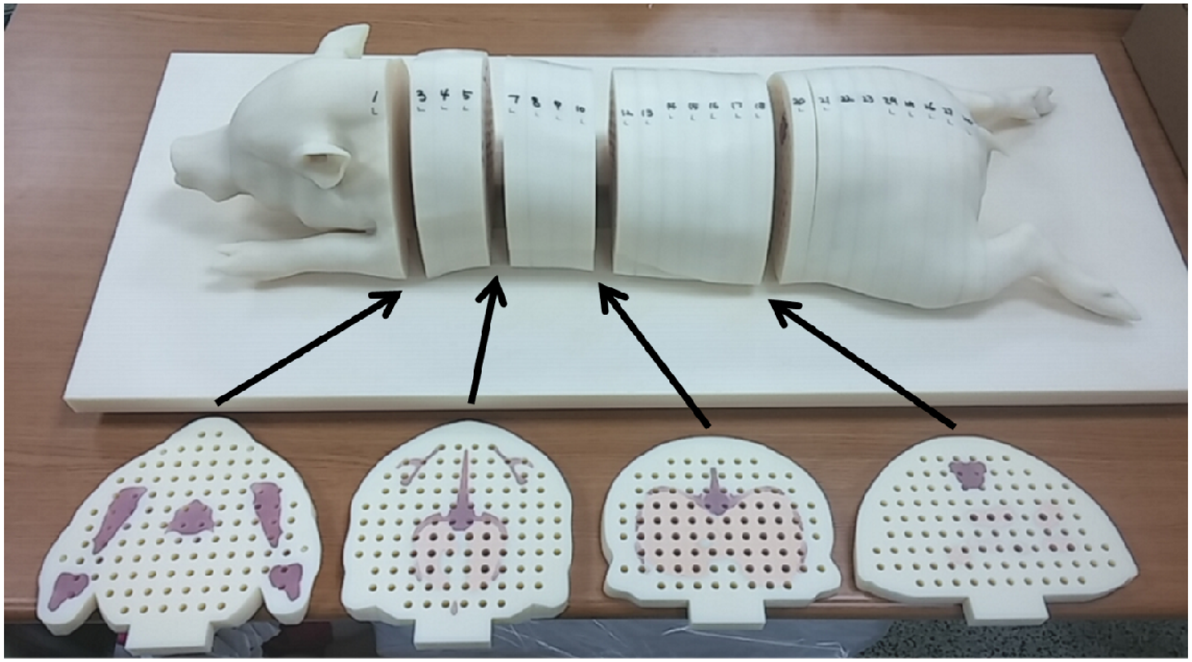
⇩

- The final versions of the developed phantoms will include
  - *continuous and fully-enclosed* surfaces for the skin, stomach, gall bladder, and urinary bladder;
  - *thin target layers (10-300 μm)* in the respiratory and alimentary tract organs; and
  - *detailed and more accurate models* for skeletal system, eye lens, lymphatic nodes, blood vessels, hands, and feet.

- The developed phantoms will provide
  - *”very similar “dose values* with the current ICRP-110 reference phantoms 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 < 0.03 MeV)
- Additionally, the developed phantoms will be *deformable*, *providing different postures* (e.g., walking and sitting postures) to calculate dose coefficients for <u>emergency exposure scenarios</u>, which is planned for the next term of the ICRP Committee 2 (2017-2021).
- We can also make the phantoms move, as necessary in the future, in connection with 3D motion-capture technology.

PM Version of ICRP-110 Male and Female Phantoms

- In conjunction with the project, we are also planning to develop corresponding ICRP ”physical” phantoms.
- KIRAMS (Korea Institute of Radiological and Medical Science).



Mini-pig phantom developed at KIRAMS (2015)

- The project will provide ***"all-in-one,"*** ***deformable, high-quality ICRP phantoms*** to the ICRP and radiation protection community.
- In addition, the developed phantoms could be used
  - as "reference patient phantoms" in radiation therapy and various medical imaging simulations for comparison, optimization, and R&D, and
  - as "platform phantoms" for other applications – e.g., add a detailed ear model for SAR calculation for mobile phones, detailed lung model for X-ray imaging simulation, etc.
- Even ***physical measurement*** will be possible with the ICRP "physical" phantoms in the future.

FAQ - Compatibility with MC Codes

- Polygon-mesh is compatible with most general-purpose Monte Carlo codes including ***Geant4, MCNP6, PHITS (as of August 2015), FLUKA, Penelope, EGS***, and ***MCBEND***.

  ✓ Most MC code developers are interested in polygon-mesh geometry mainly because they want to implement the ***CAD geometry*** in their MC code.

  ✓ Relatively slow in MCNP6, but the problem is expected to be solved soon.

FAQ - Computation Speed

Voxel/Tetrahedral = 0.8-6.8 times

Table 2. Computation times of tetrahedral mesh phantom, PSRK-Man polygonal surface phantom, and voxelized PSRK-Man.

		Computation time (sec)			Ratio	
Particle	Energy (MeV)	Polygonal surface phantom (A)	Tetrahedral mesh phantom (B)	Voxelized phantom (C)	A/B	C/B
Gamma	0.01	214.4 (±68.3)	0.6 (±0.1)	2.4 (±0.1)	375.4 (±124.1)	4 (±0.7)
	1	1491.3 (±487.1)	4.7 (±0.3)	7.4 (±0.3)	314.9 (±104.8)	1.6 (±0.1)
	100	13 017.0 (±3767.5)	27.6 (±2.2)	30.4 (±1.6)	471.9 (±141.5)	1.1 (±0.1)
	10 000	24 917.2 (±6579.6)	43.3 (±4.2)	45.8 (±3.2)	575.3 (±68.3)	1.1 (±0.1)
Neutron	0.01	716.2 (±189.7)	41.7 (±1.7)	87.6 (±2.8)	17.2 (±4.6)	2.1 (±0.1)
	1	737.6 (±73.9)	84.4 (±2.3)	165.0 (±7.1)	8.8 (±0.9)	2.0 (±0.1)
	100	16 493.7 (±3064.5)	91.7 (±8.1)	85.0 (±3.2)	179.9 (±37.0)	0.9 (±0.1)
	10 000	74 457.4 (±16 970.9)	268.8 (±28.3)	246.0 (±14.3)	277.0 (±69.5)	0.9 (±0.1)
Electron	0.01	352.5 (±93.3)	0.7 (±0.1)	3.1 (±0.1)	532.5 (±163.9)	4.4 (±0.6)
	1	46 10.4 (±1055.2)	5.5 (±0.4)	7.5 (±0.1)	831.6 (±198.0)	1.4 (±0.1)
	100	82 624.0 (±14 317.1)	136.8 (±7.6)	141.3 (±3.1)	603.8 (±109.8)	1.0 (±0.1)
	10 000	103 518.9 (±17 826.2)	174.0 (±9.5)	174.9 (±6.2)	595.1 (±107.5)	1.0 (±0.1)
Proton	0.01	68.3 (±16.0)	0.5 (±0.1)	3.4 (±0.1)	149.4 (±38.3)	6.8 (±1.4)
	1	2492.7 (±746.7)	3.9 (±0.1)	5.9 (±0.1)	645.3 (±193.6)	1.5 (±0.0)
	100	197 032.4 (±15 929.1)	1025.1 (±34.4)	863.1 (±10.1)	192.2 (±16.8)	0.8 (±0.0)
	10 000	154 536.0 (±31 712.8)	460.9 (±19.8)	403.4 (±15.0)	335.3 (±70.3)	0.9 (±0.0)

Y. S. Yeom, J. H. Jeong, M. C. Han, C. H. Kim, "Tetrahedral-mesh-based computational human phantom for fast Monte Carlo dose calculations," ***Phys. Med. Biol.*, 59:3173-3185 (2014)**

* Note: Voxel resolution (C) : 1.301 x 1.301 x 1.301 mm^3 (= 29,602,950 voxels)
Average polygon size (B): 0.51 cm^2 (= 120,850 polygons)

Thank you!