Polygon Mesh Conversion of ICRP Reference Phantoms

Tokyo, February 18, 2016

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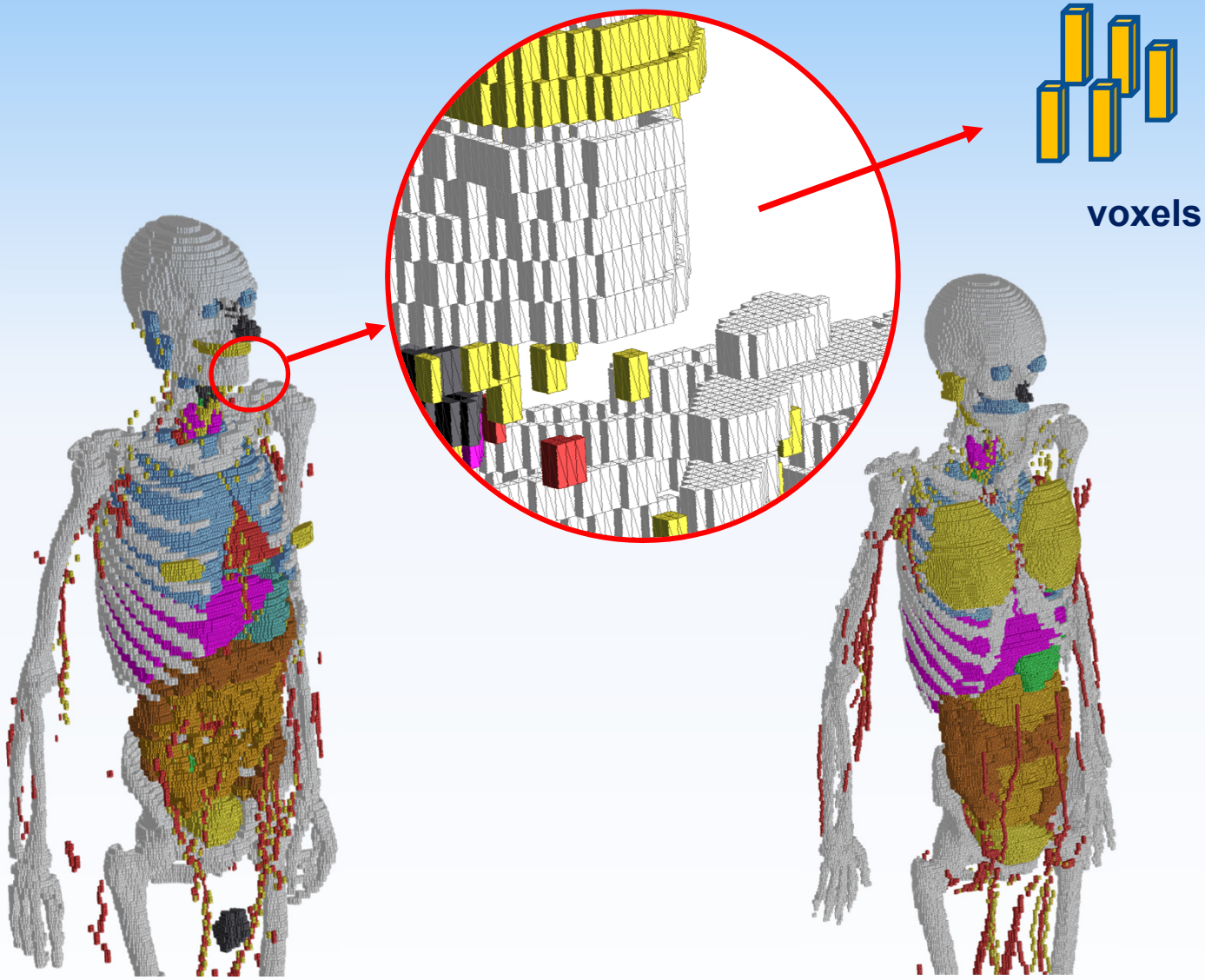
ICRP Committee 2 / Hanyang University

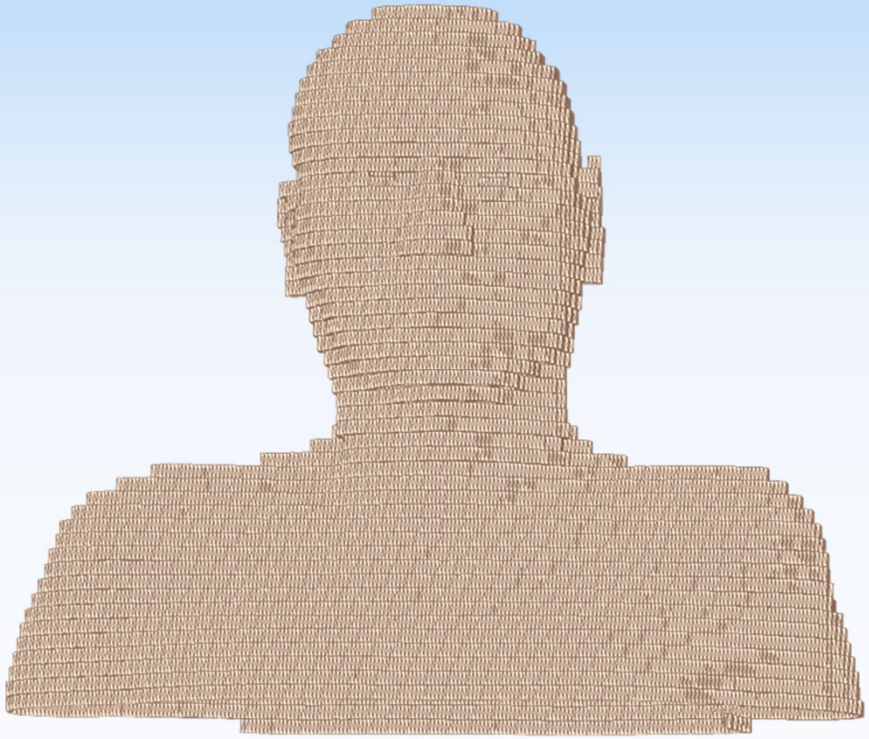
ICRP-110 Reference Phantoms



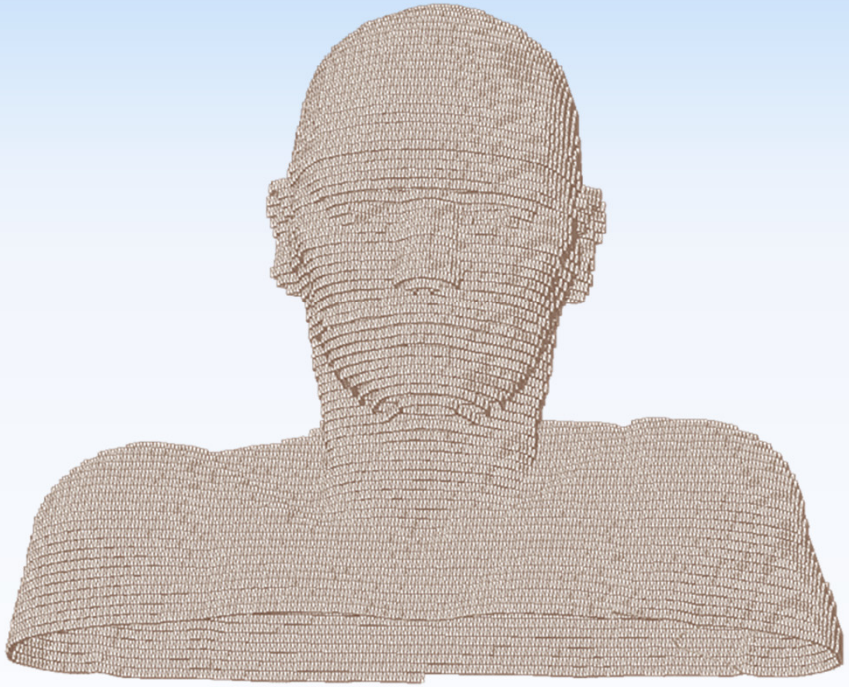
Male phantom
(Voxel size: 2.137×2.137×8 mm^3)

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

Problem #1 (Skin)

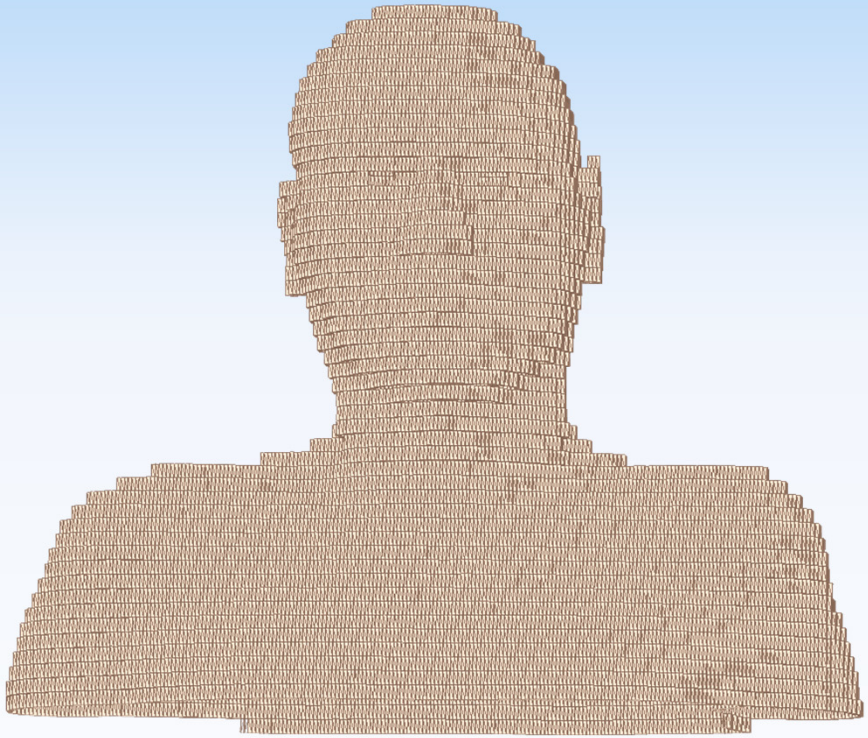


ICRP reference male phantom
(2.137 × 2.137 × 8 mm^3)

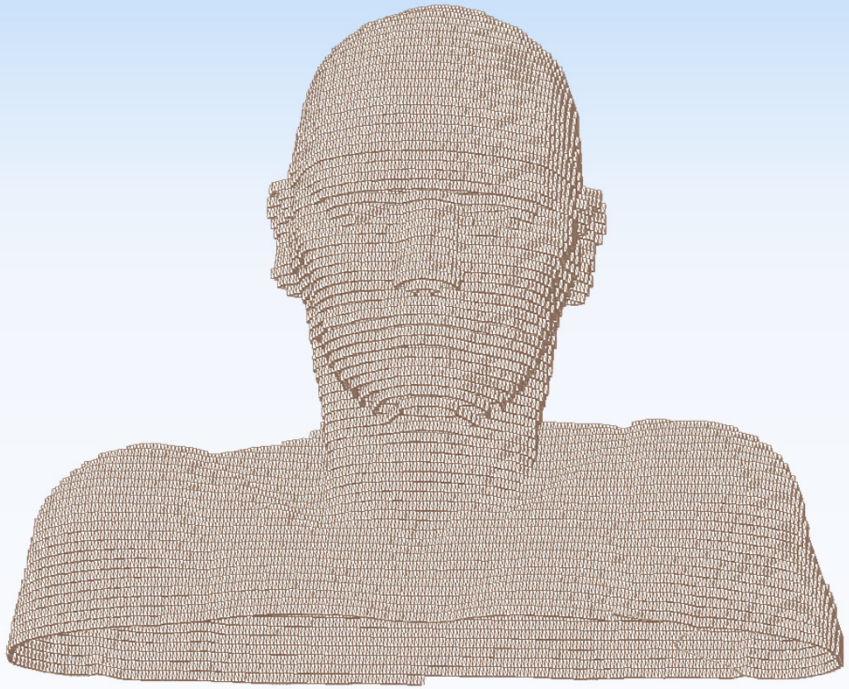


ICRP reference female phantom
(1.775 × 1.775 × 4.8 mm^3)

Problem #1 (Skin)



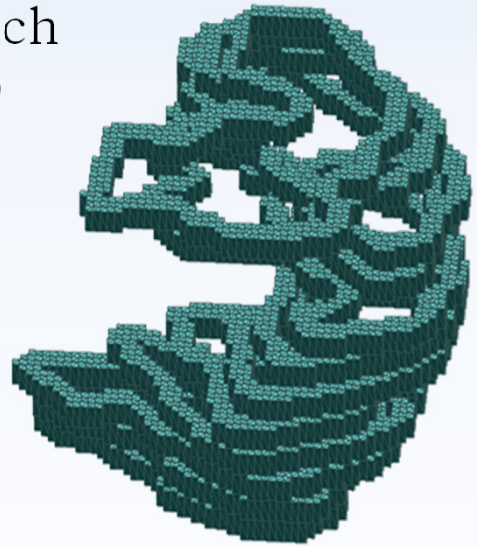
ICRP reference male phantom
(2.137 × 2.137 × 8 mm^3)

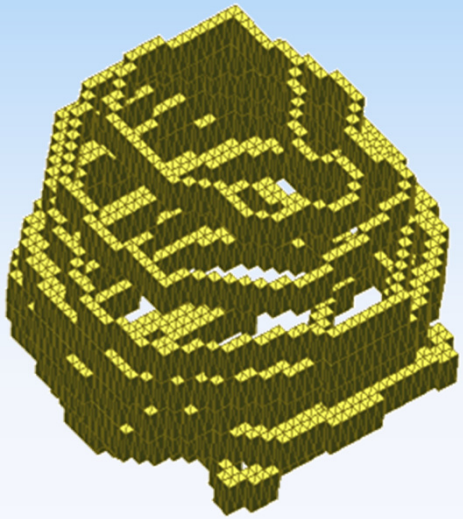


ICRP reference female phantom
(1.775 × 1.775 × 4.8 mm^3)

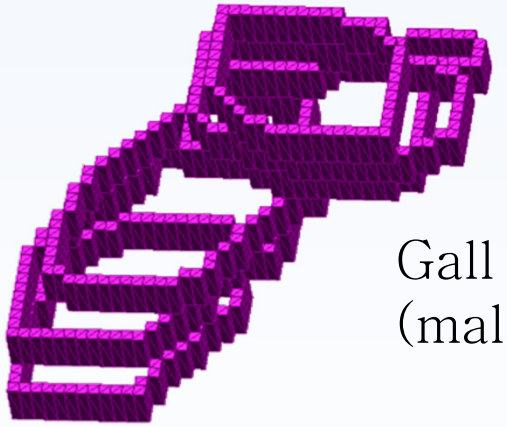
Problem #2 (Hollow Organs)

Stomach
(male)



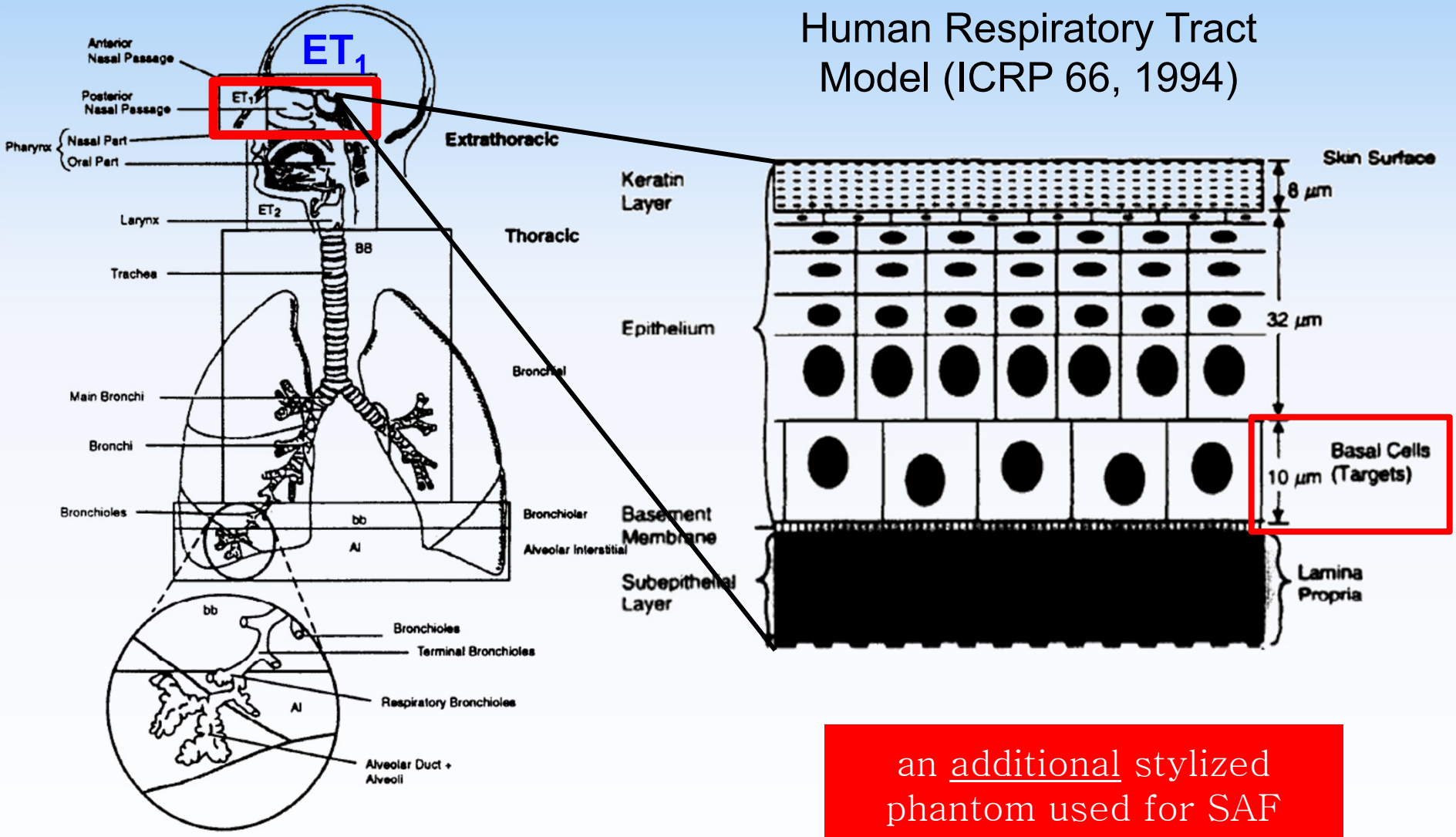


Urinary bladder
(male)



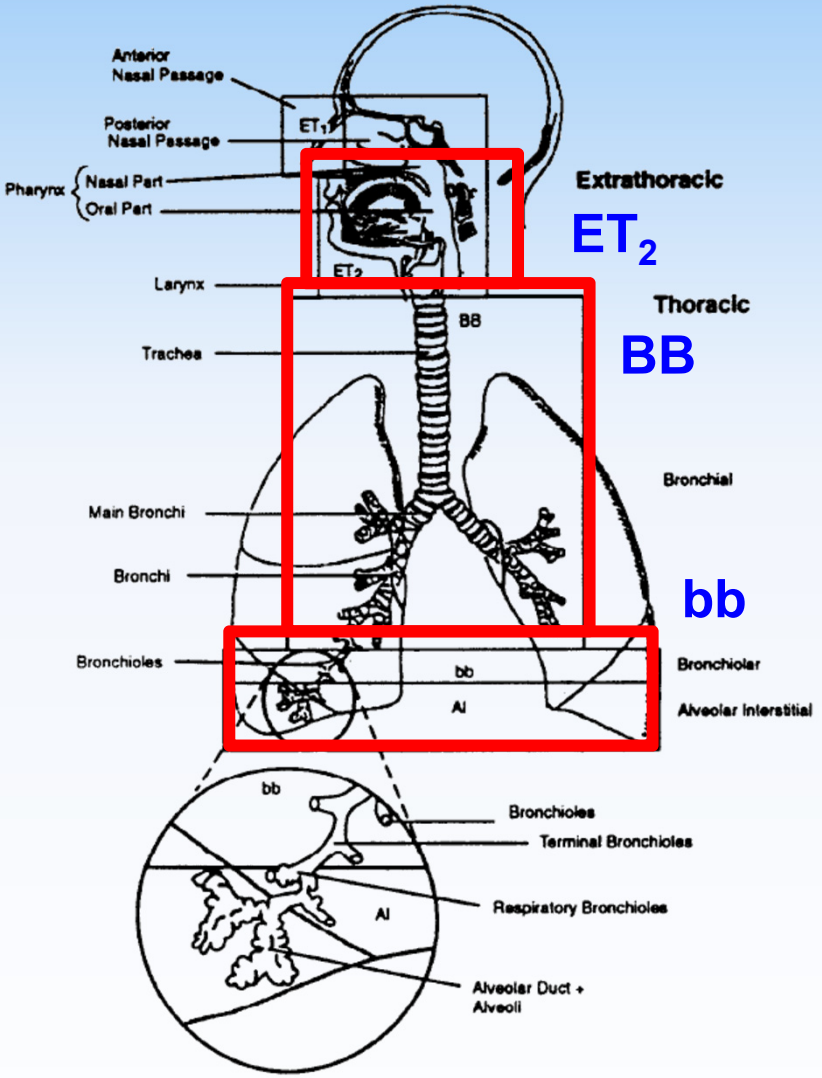
Gall bladder
(male)

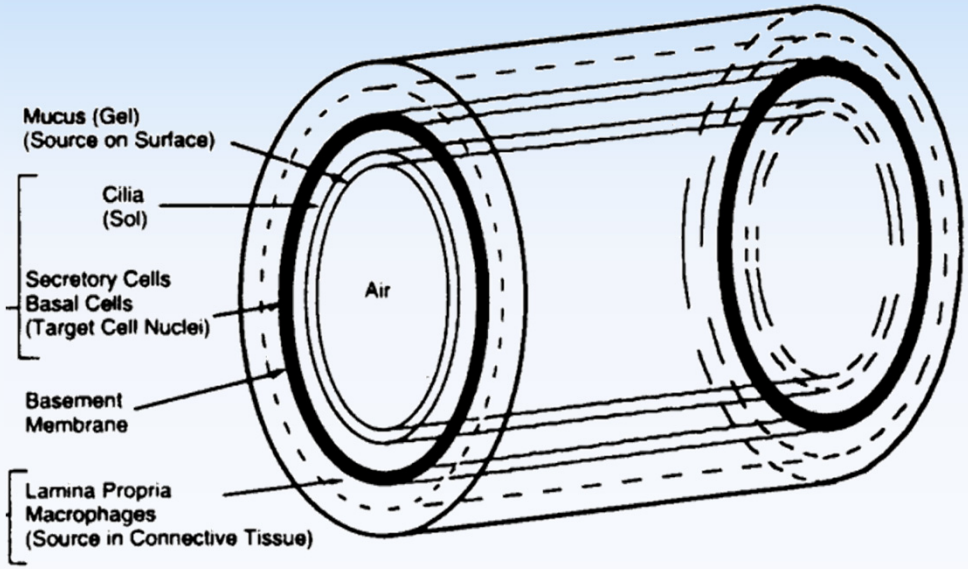
Problem #3 (Respiratory Tract Organs)



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

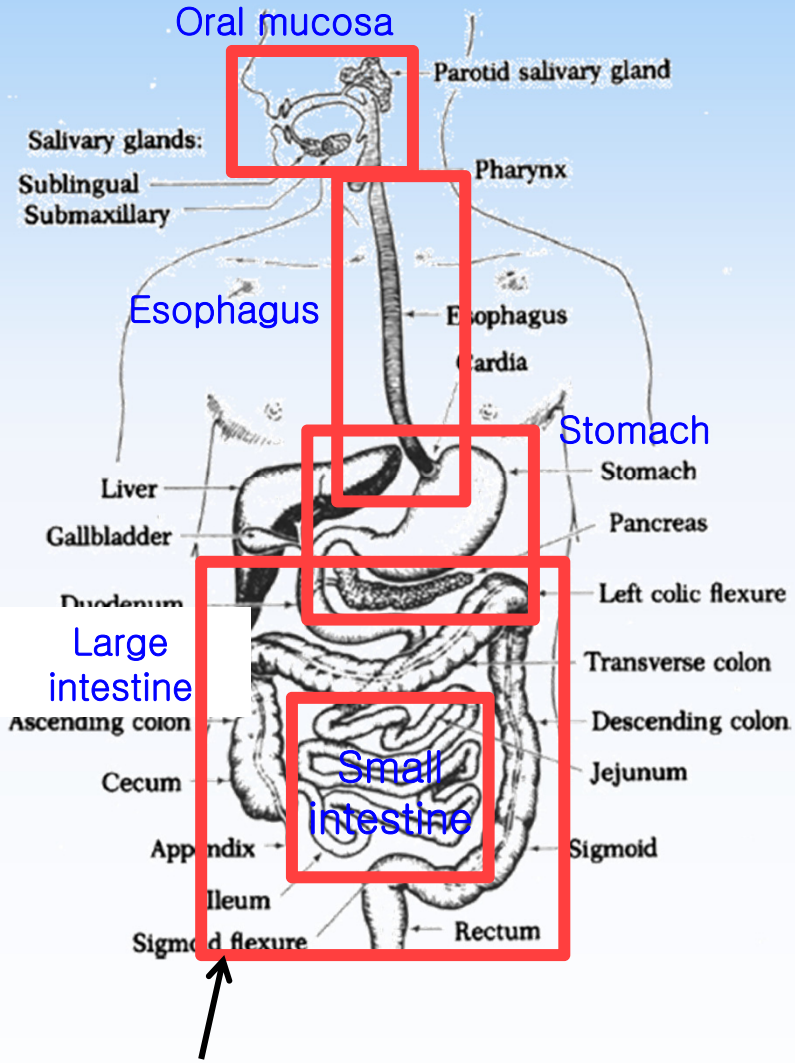
ICRP 66, 1994



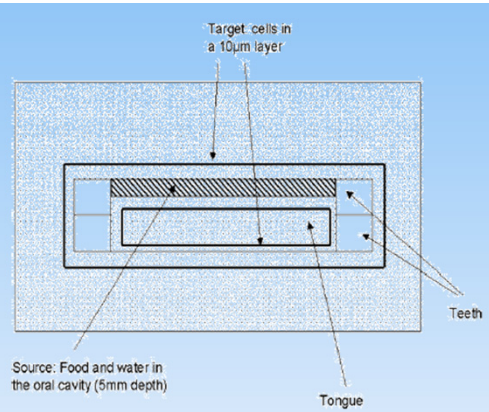


3 additional stylized phantoms used for SAF calculations

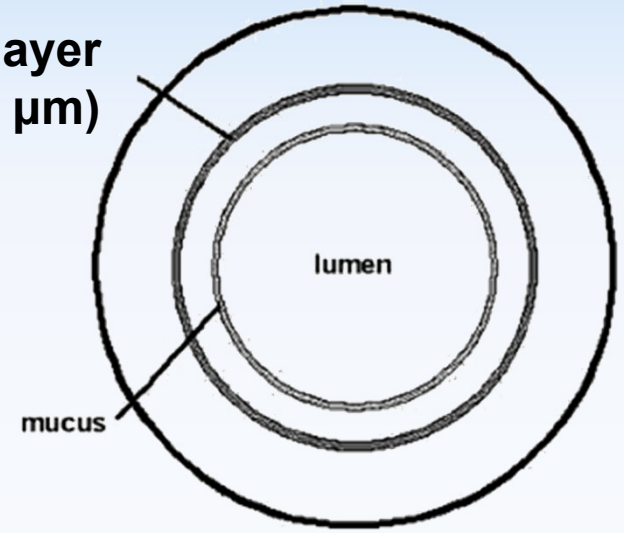
Problem #4 (Alimentary Tract Organs)



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



Target layer (60-100 μm)

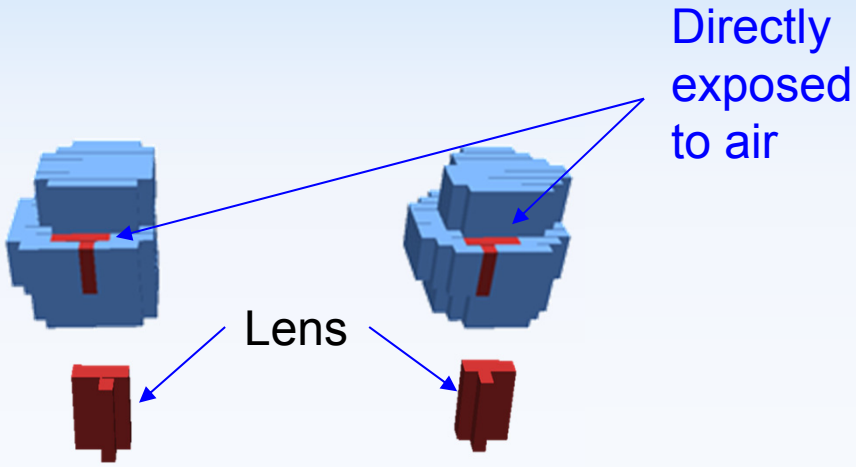


Human Alimentary Tract Model (ICRP 100, 2006)

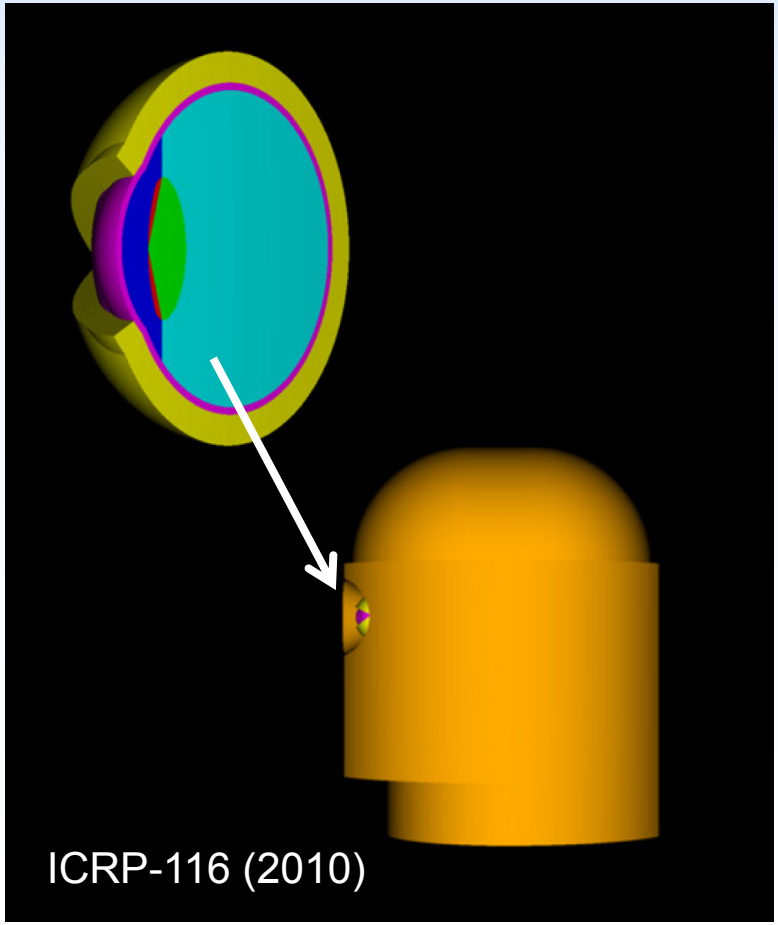
7 additional stylized phantoms used for SAF calculations

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 phantoms do not include ***the 50-μm-thick radiosensitive target layer of the skin***, and an additional stylized phantom is used for assessing the equivalent dose specified for localized skin exposure.
- 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]

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 (8-50 μm) in the alimentary and respiratory tract organs, and skin; and
  3. detailed and more accurate models for skeletal system, eyes, lymphatic nodes, blood vessels, hands, feet, etc.

Current Status 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”

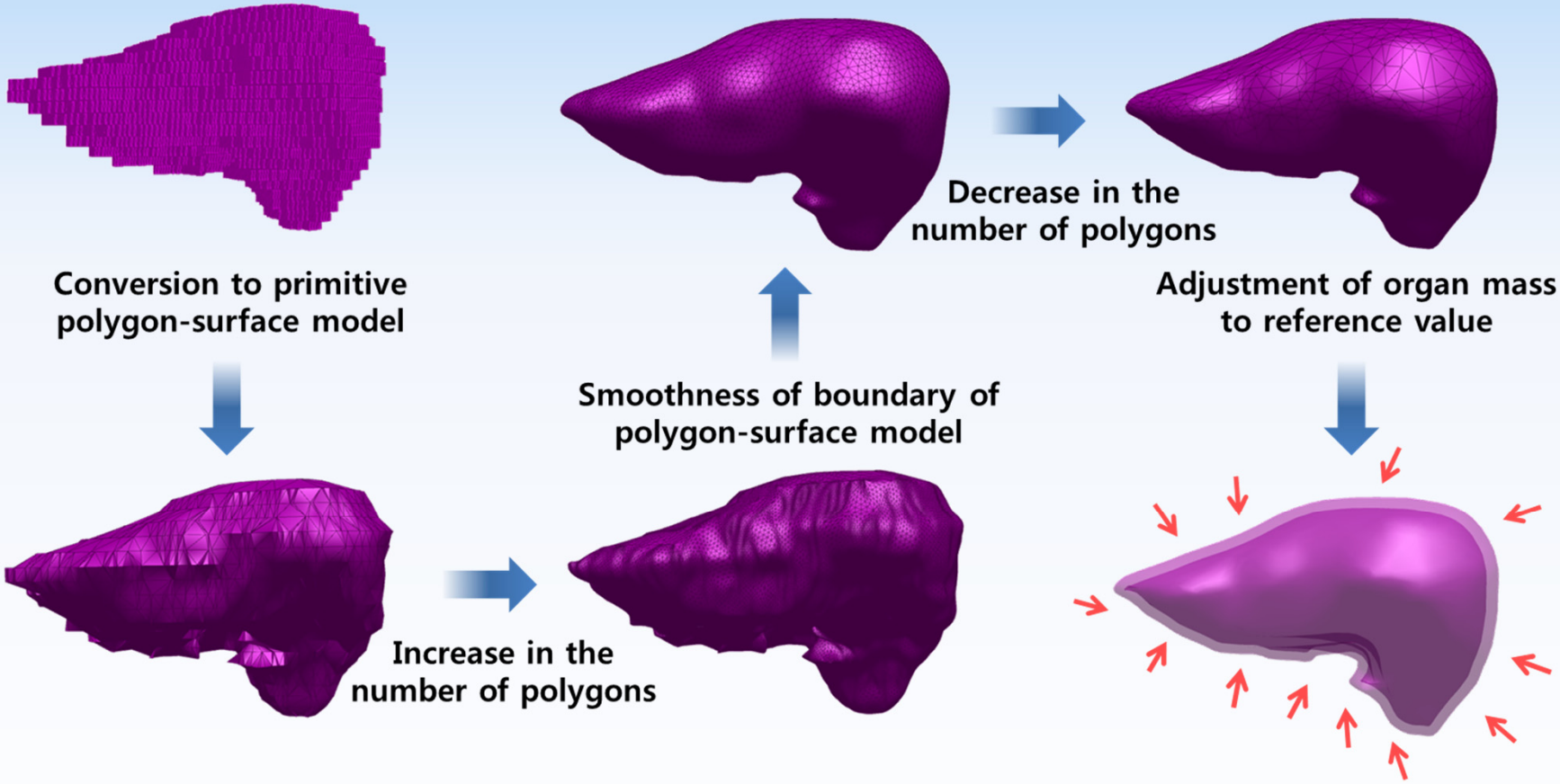
2. Construction of “Skeletal Systems”

3. Construction of “Complex Organs”

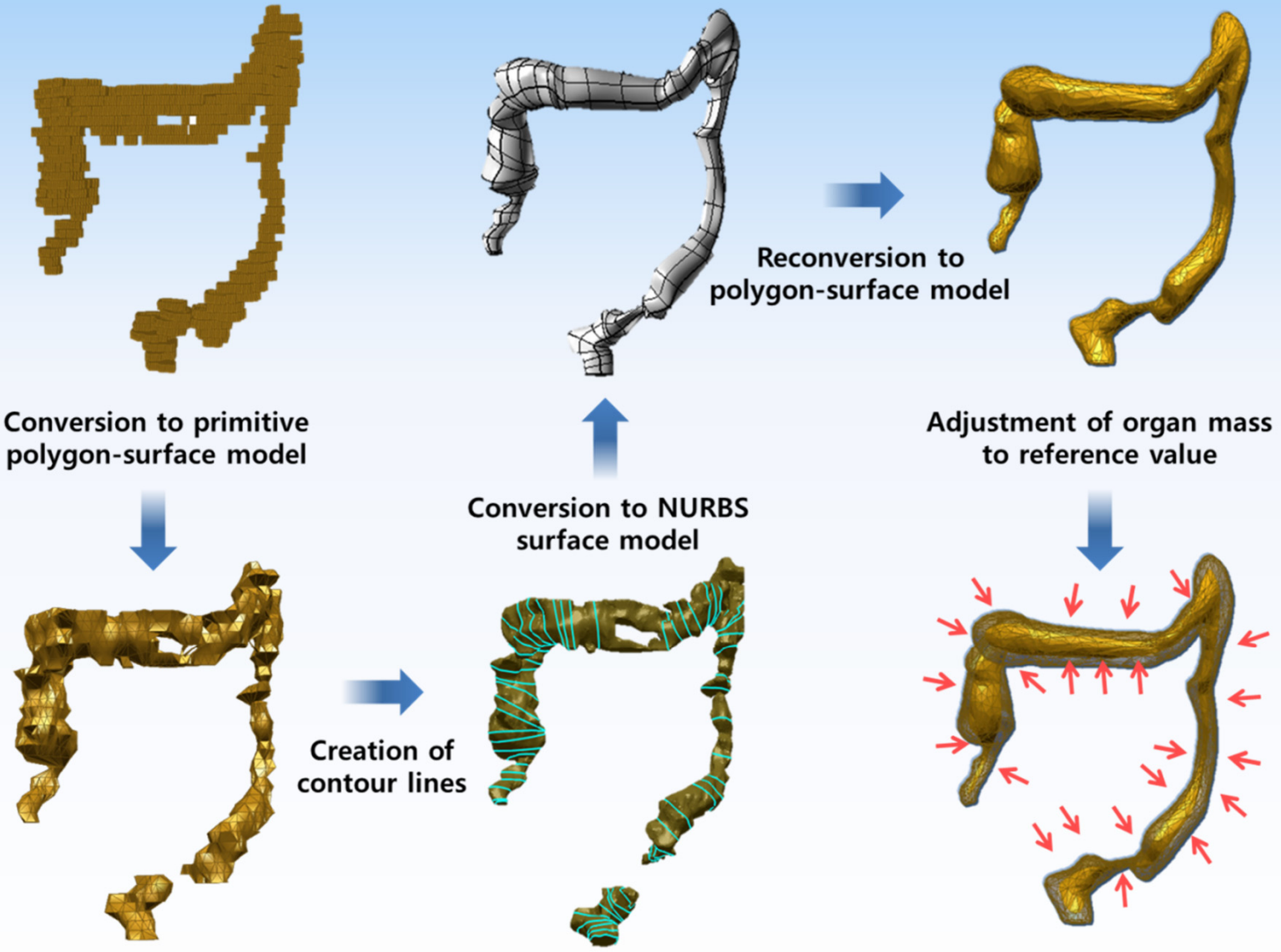
4. Preliminary Results

Conversion Methods

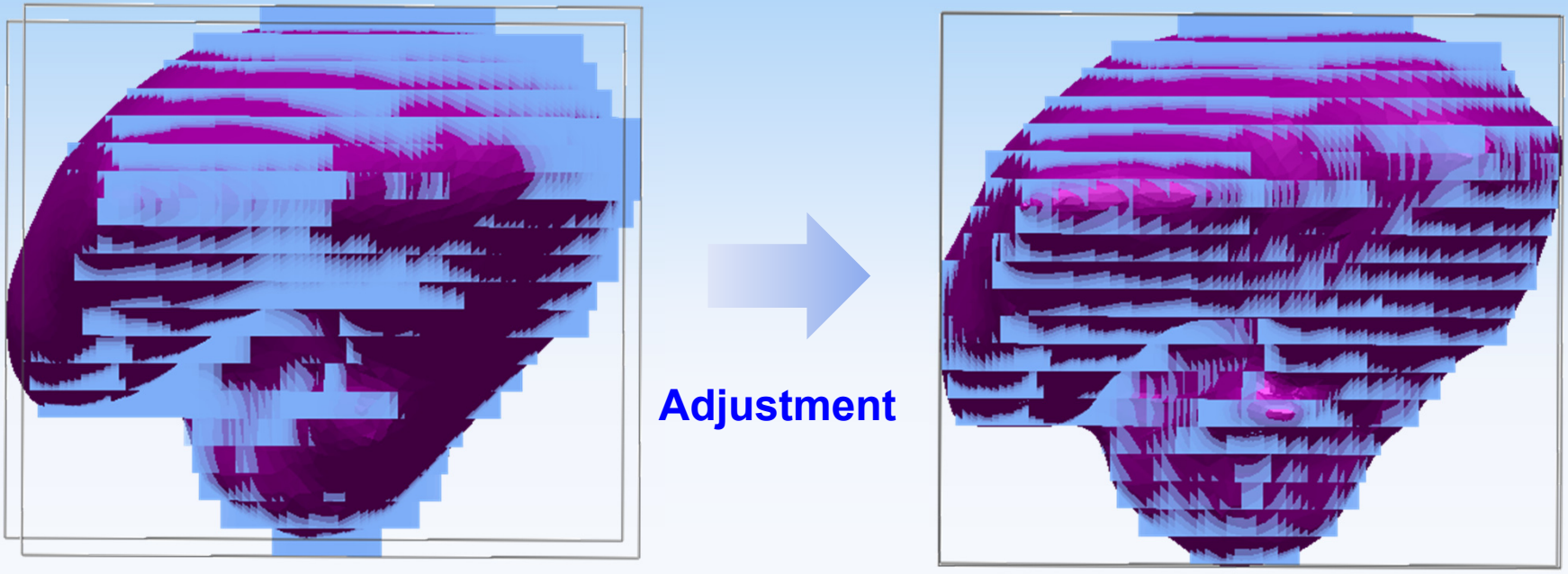
Method #1



Method #2


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

Adjustment and Monitoring Methods

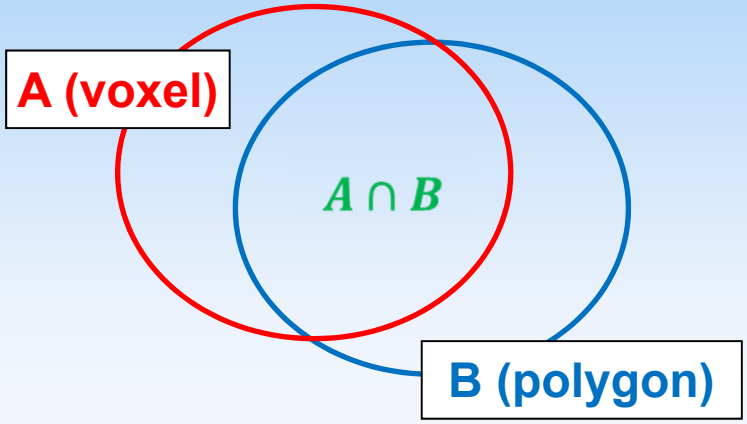


Before **After**

- 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

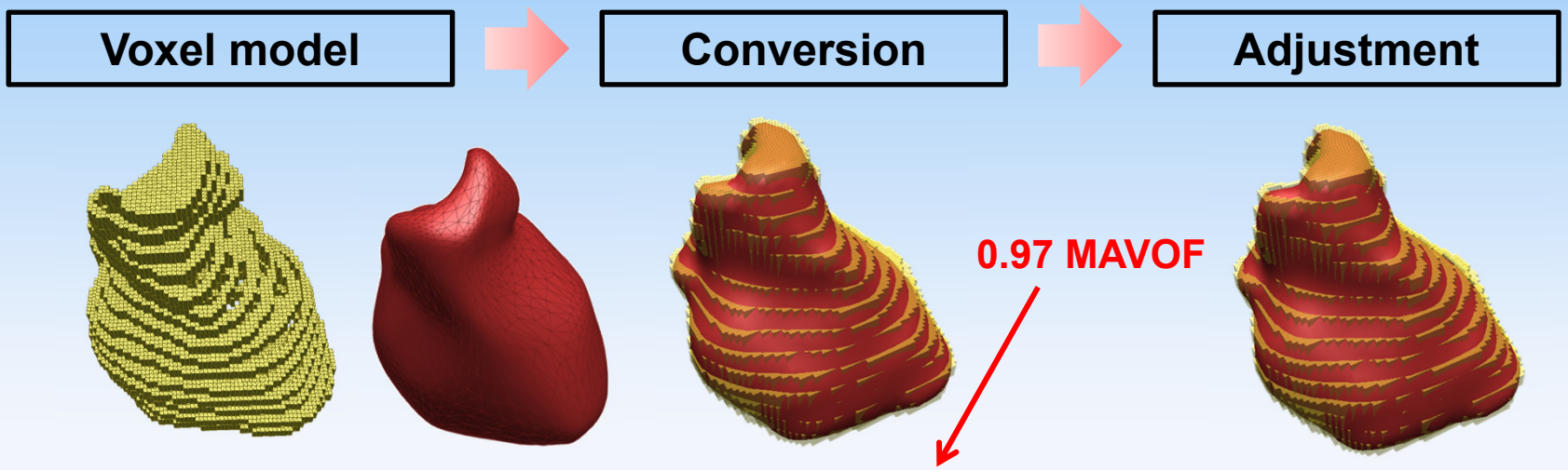
- **Dice index (DI)**
  - ✓ "Volume overlap fraction"
  - ✓ DI > 97% of maximally achievable volume overlap fraction (MAVOF)



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

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

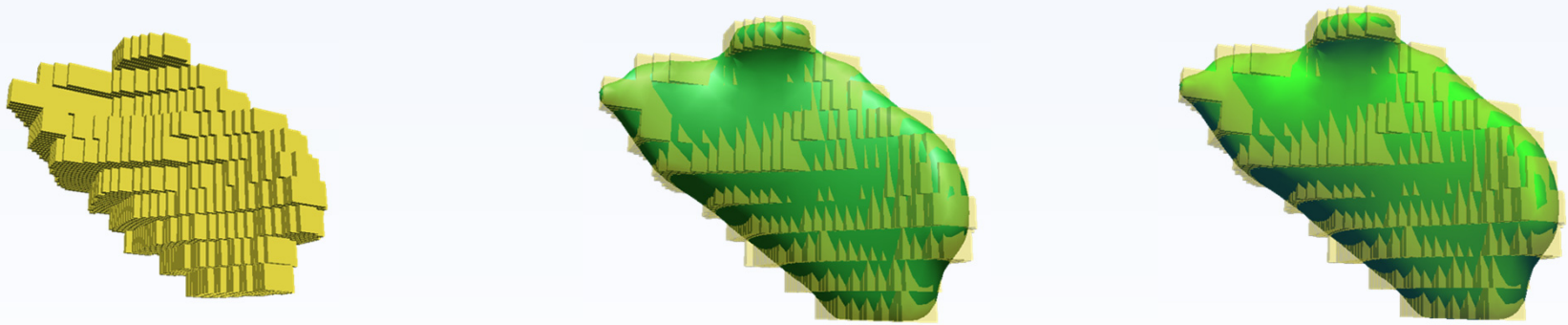
Examples



Heart
(male)

DI: 0.96 (ADI: 0.94)
CD: 0.59 mm

DI: 0.96 (ADI: 0.94)
CD: 0.47 mm

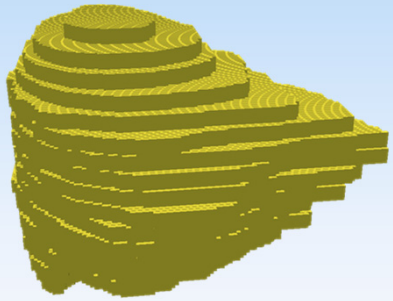


Spleen
(male)

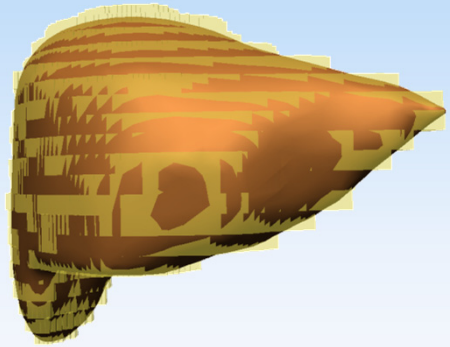
DI: 0.91 (ADI: 0.92)
CD: 0.76 mm

DI: 0.94 (ADI: 0.92)
CD: 0.26 mm

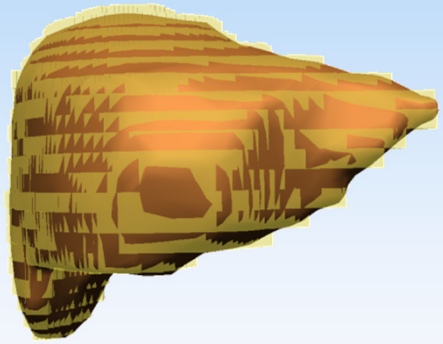
Voxel model	Conversion	Adjustment



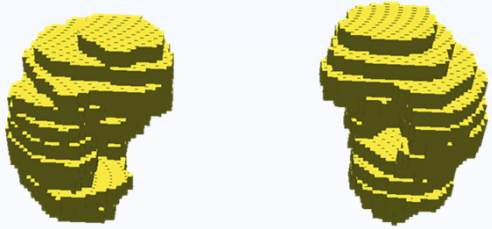
Liver
(male)



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



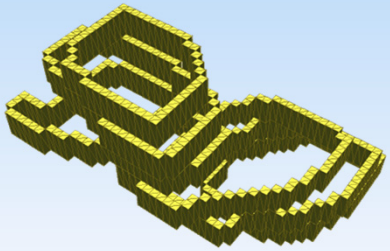
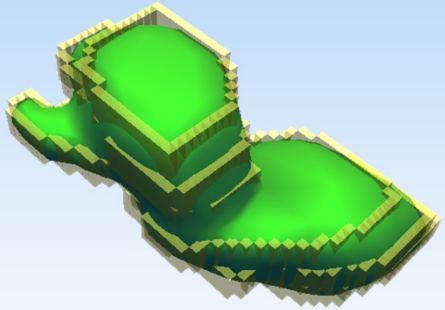
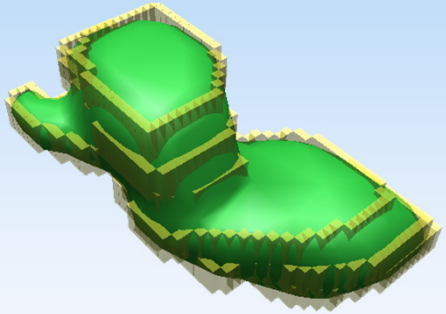
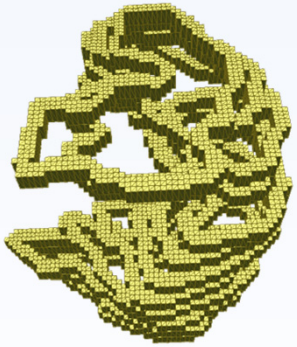
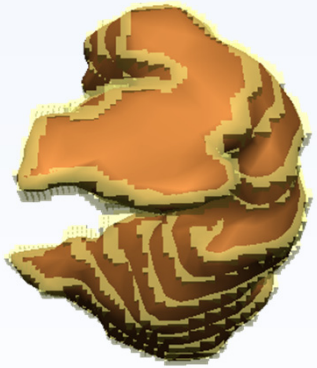
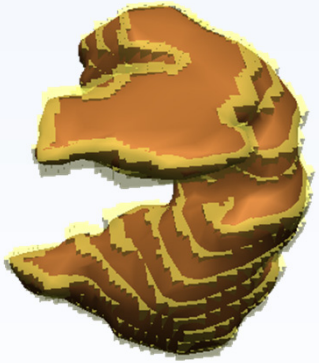
DI: 0.97 (ADI: 0.94)
CD: 0.33 mm

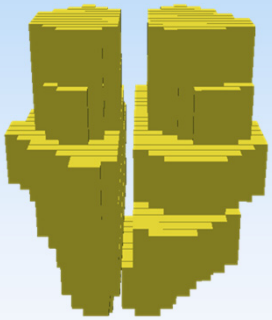
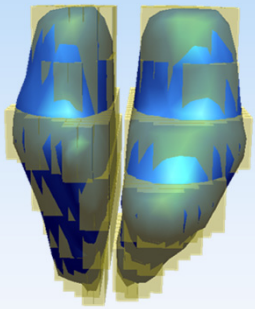
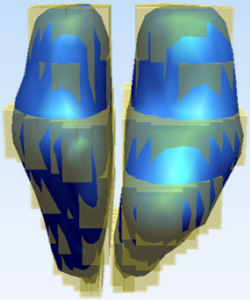
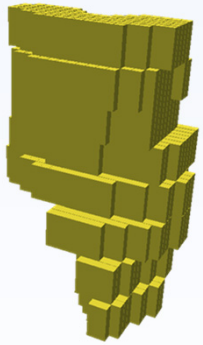


Kidneys
(male)

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”

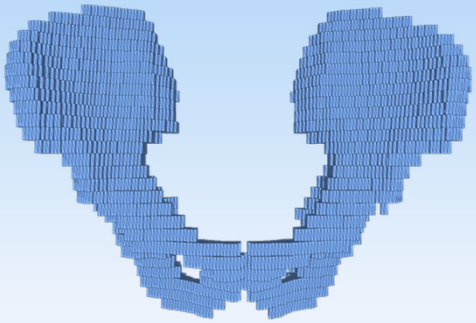
2. Construction of “Skeletal Systems”

3. Construction of “Complex Organs”

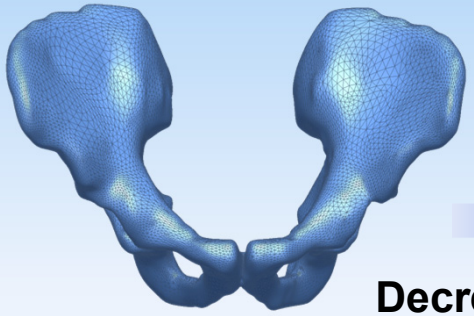
4. Preliminary Results

Construction of Simple Skeletons - Conversion

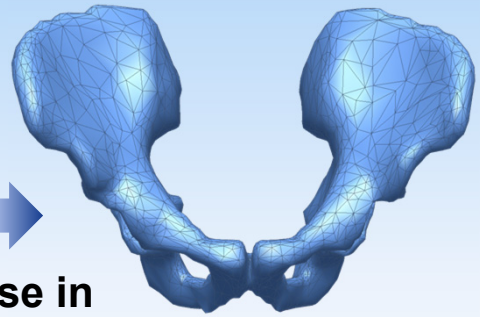
- Humeri
- Ulnae
- Clavicles
- Femora
- Tibiae
- Mandible
- Pelvis
- Scapulae
- Sacrum
- Sternum
- Cranium
- Ribs
- Spines
- Feet
- Hands



Conversion to PM model

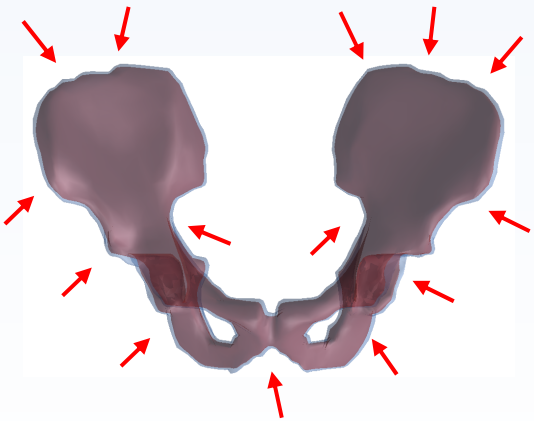


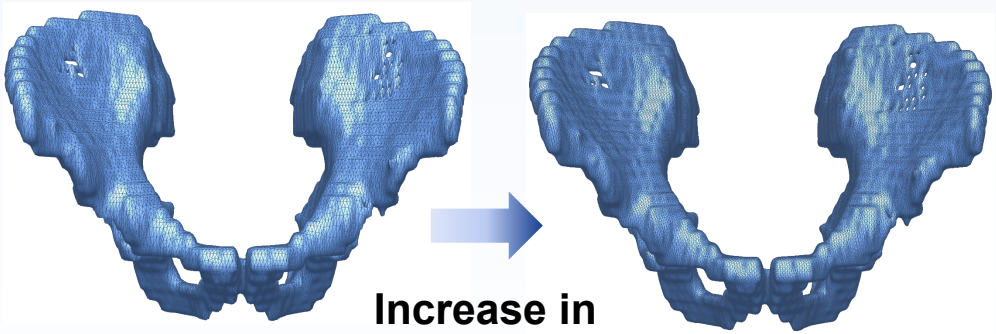
Refinement and smoothness



Decrease in number of facets

Construction of inner structure and mass adjustment

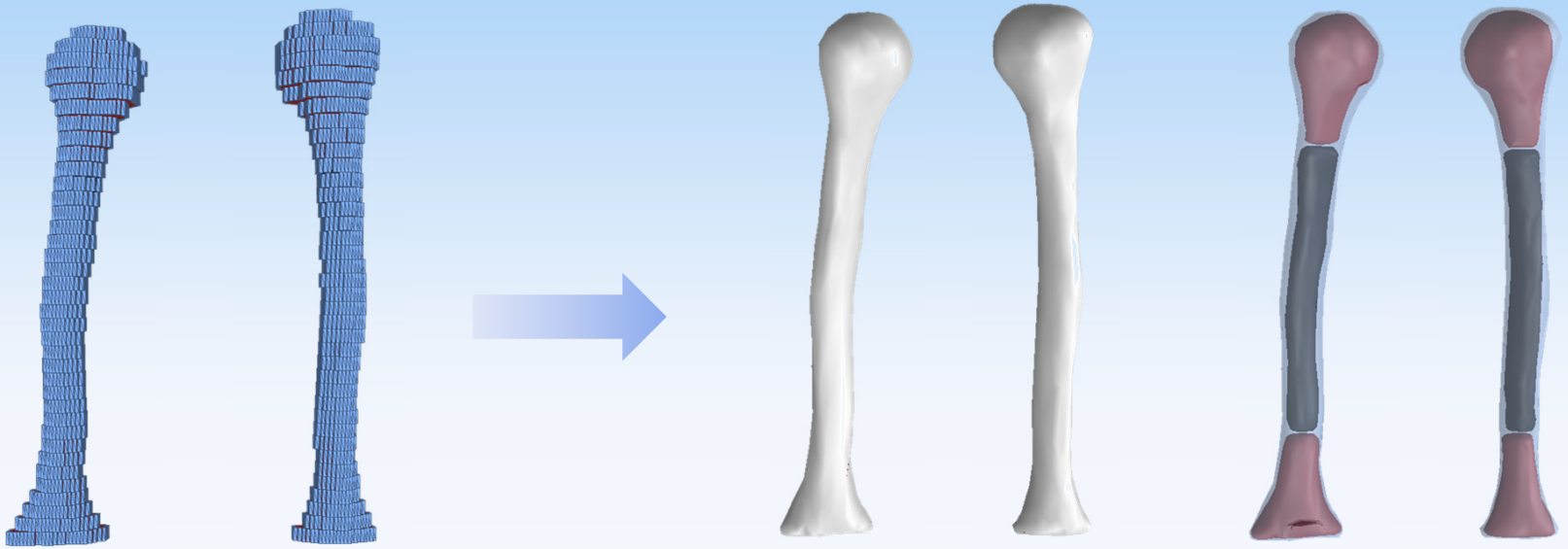




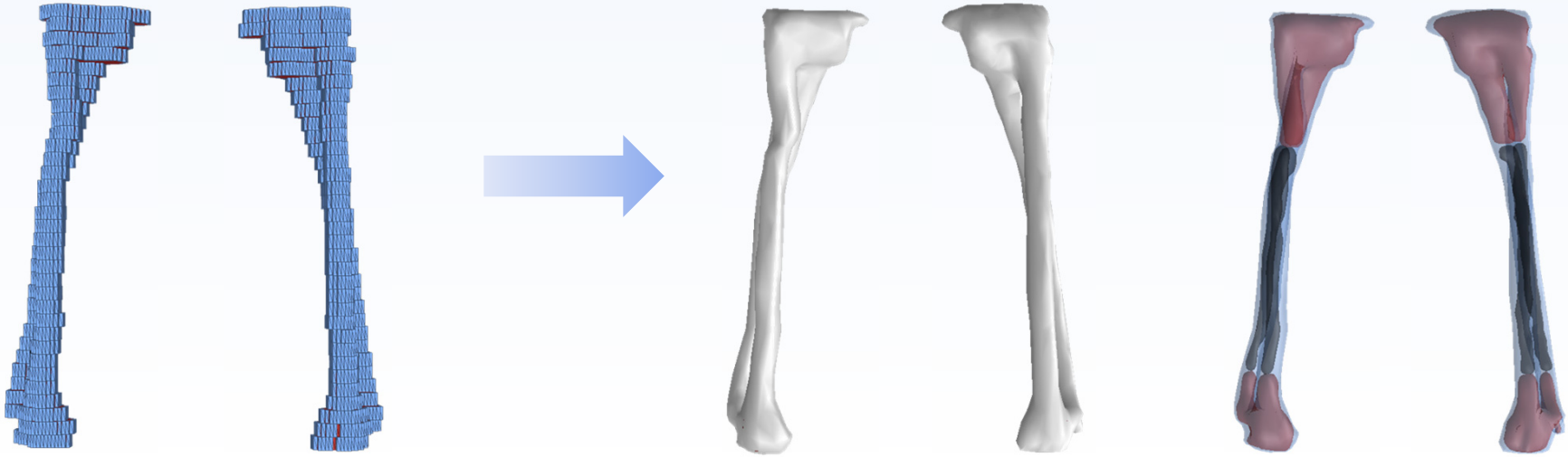
Increase in number of facets

Examples

Humeri

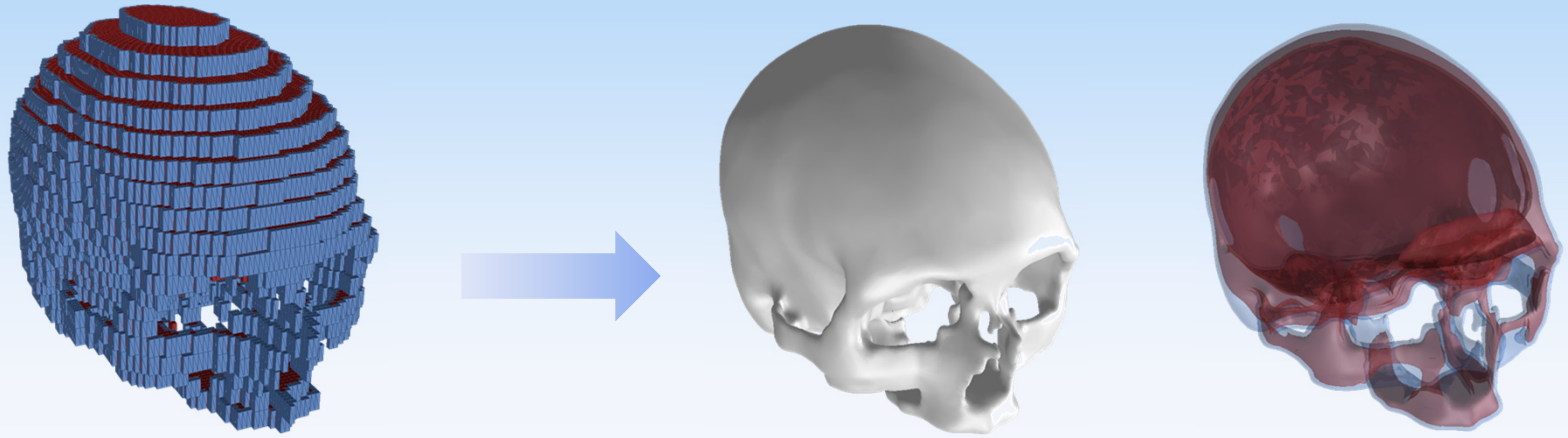


Ulnae and radii

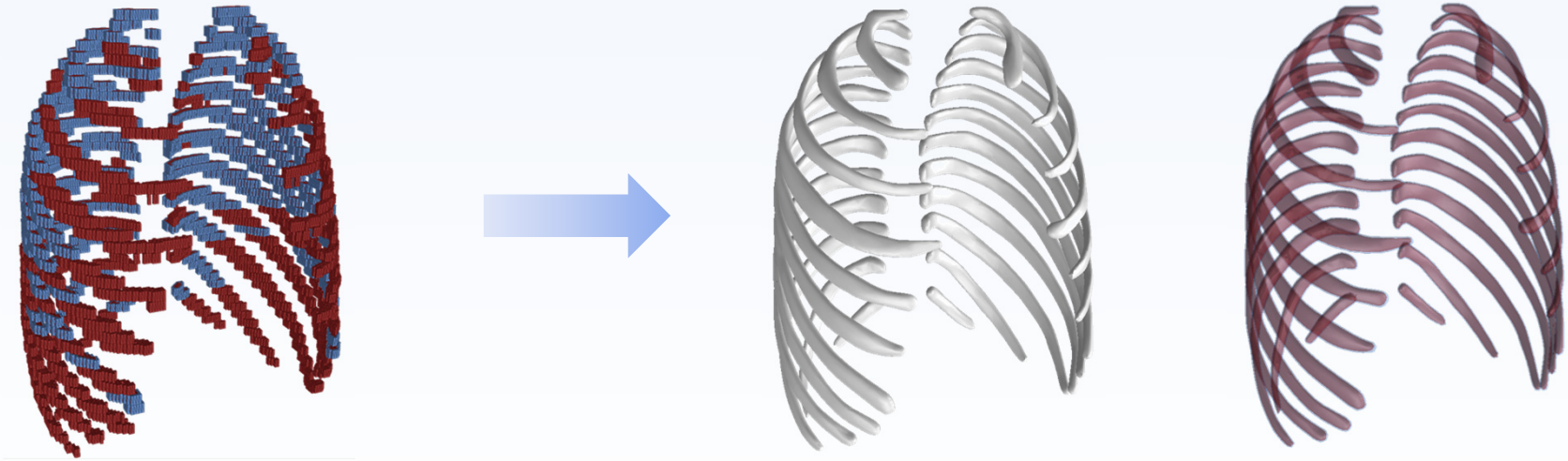


Examples

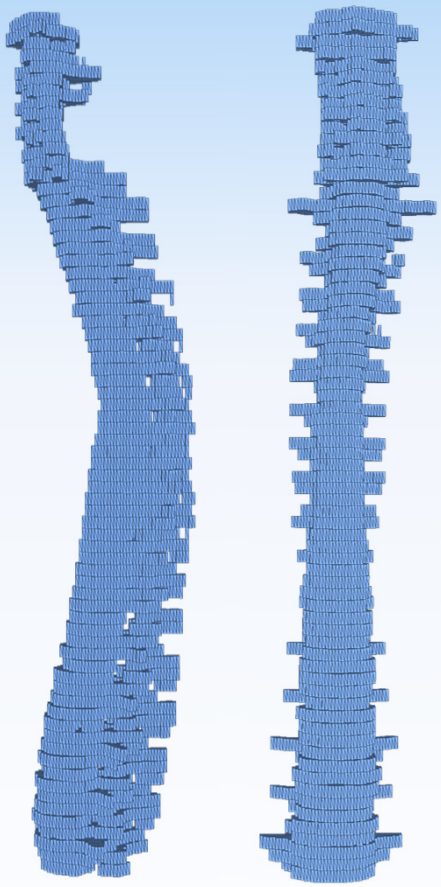
Cranium



Ribs



Construction of Spines

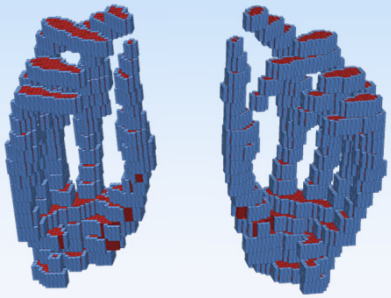


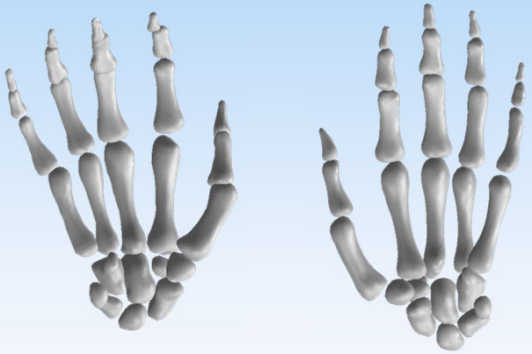
Adjustment

Voxel model

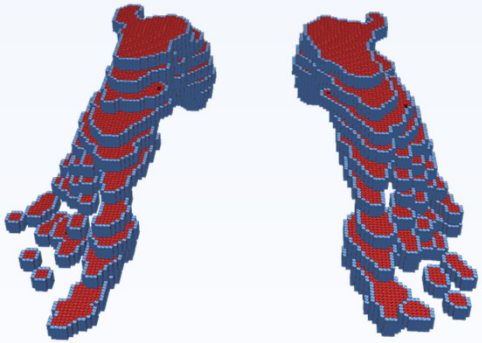
High-quality polygon-mesh model

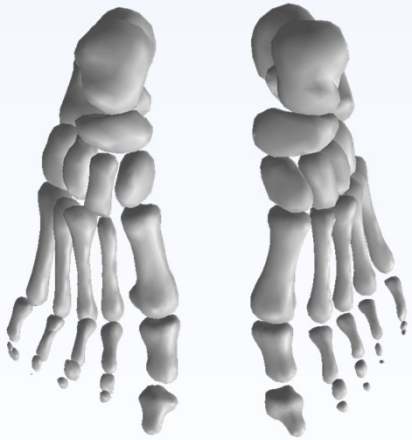
Construction of Hands and Feet





Adjustment

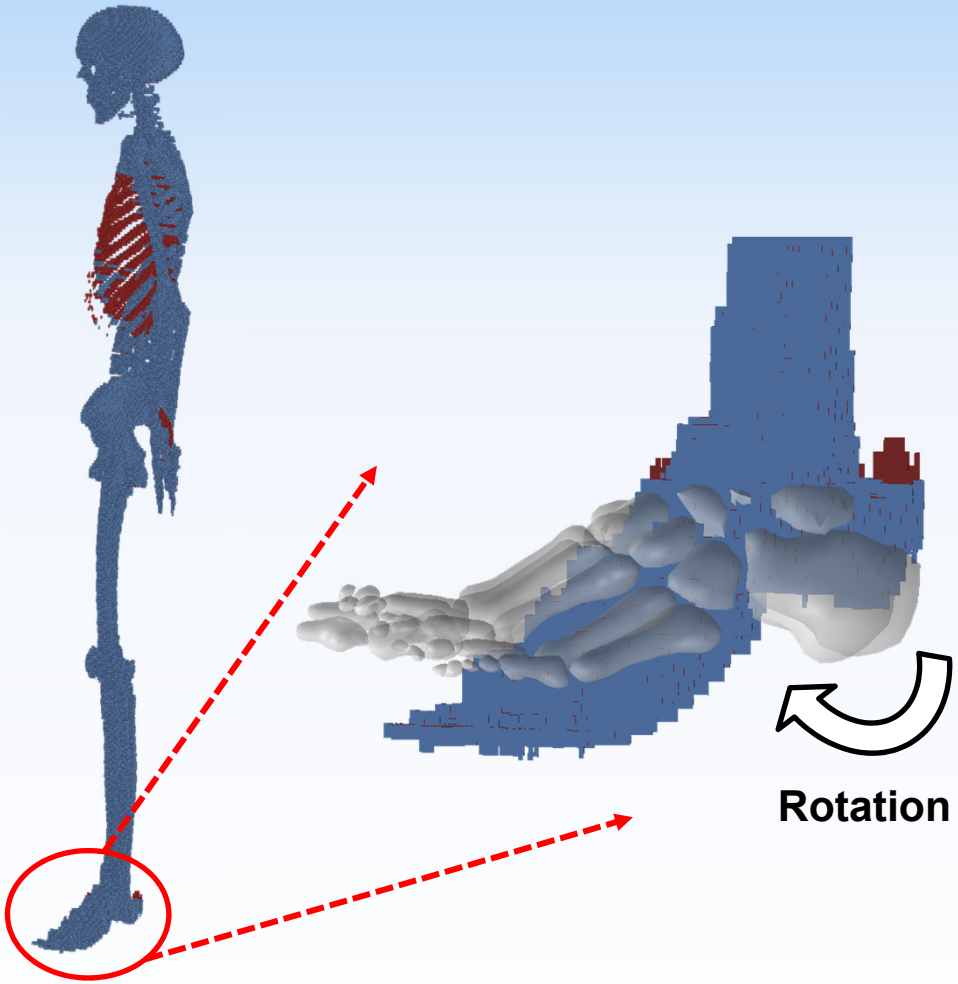




Voxel models

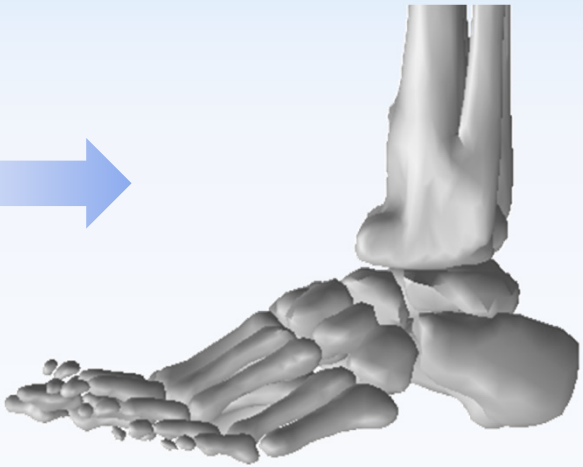
High-quality polygon model

Correction of Toe-standing Feet



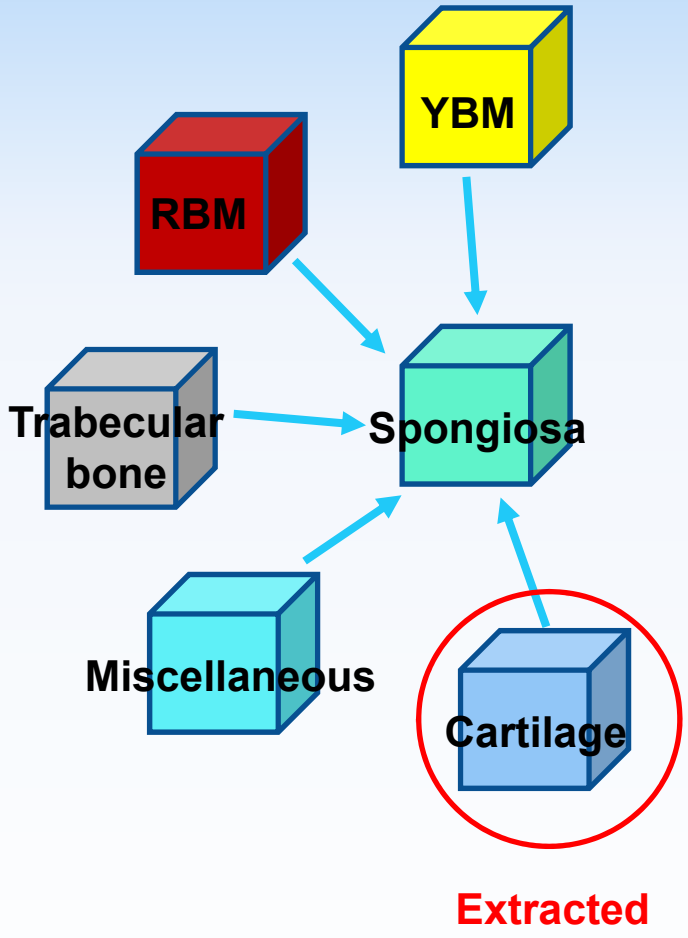
Toe-standing feet (female)

Rotation

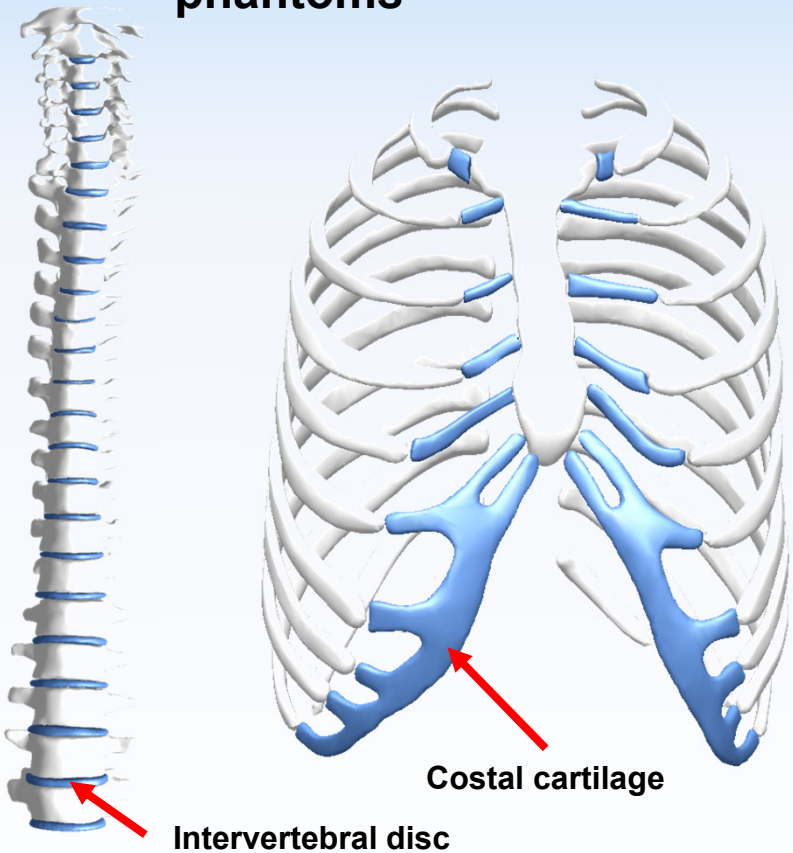


Normal standing feet

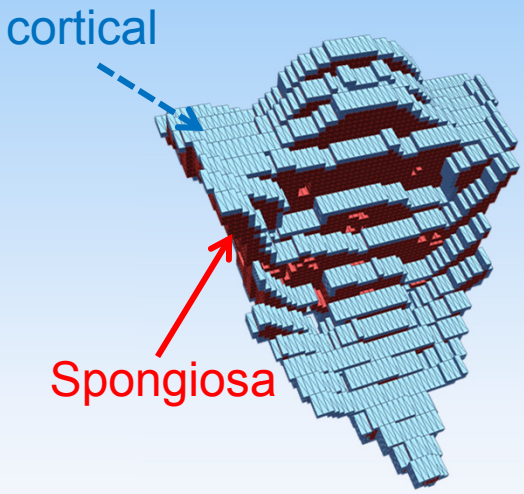
Extraction of Cartilage / Cartilage Modeling



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

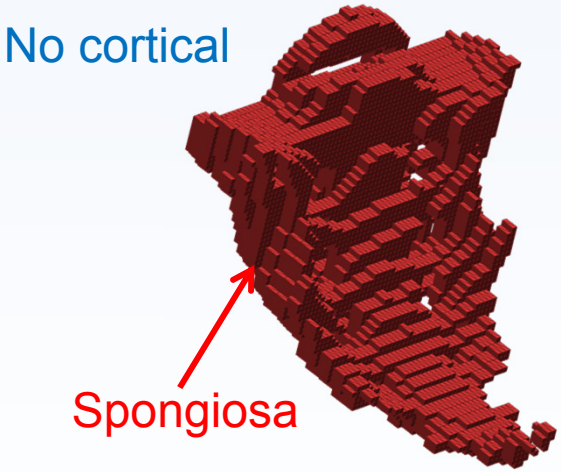


Correction of Female Sacrum

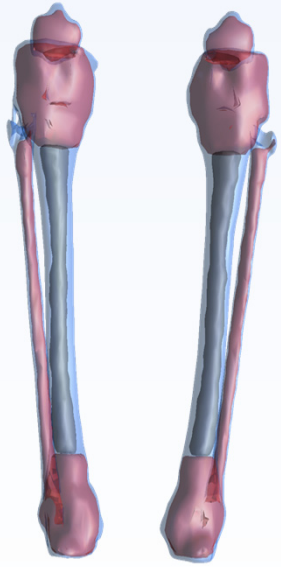


Male sacrum

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%

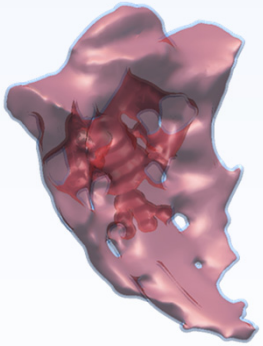


Female sacrum



Lower leg bones

Borrow cortical bone



Sacrum

1. Construction of “Simple Organs”

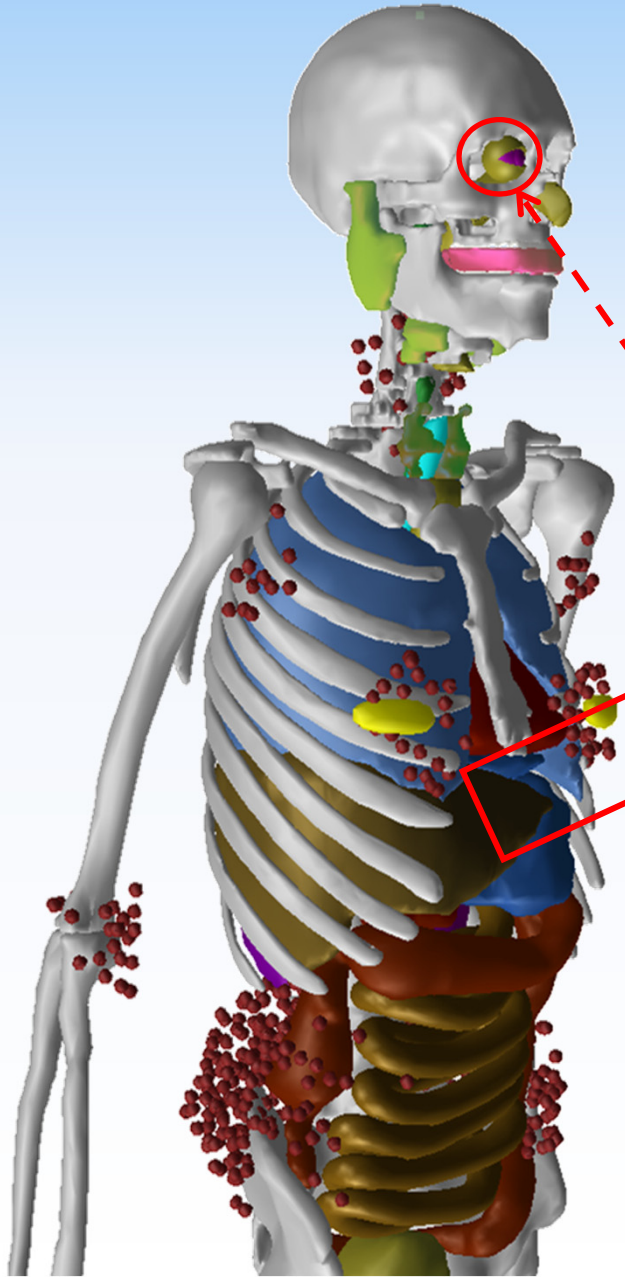
2. Construction of “Skeletal Systems”

3. Construction of “Complex Organs”

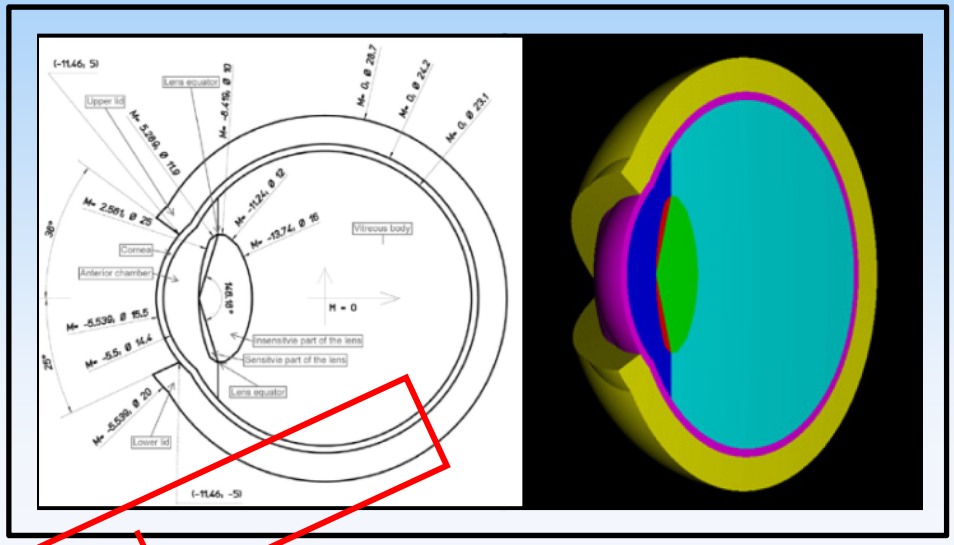
~80% completed

4. Preliminary Results

3-1. Eyes

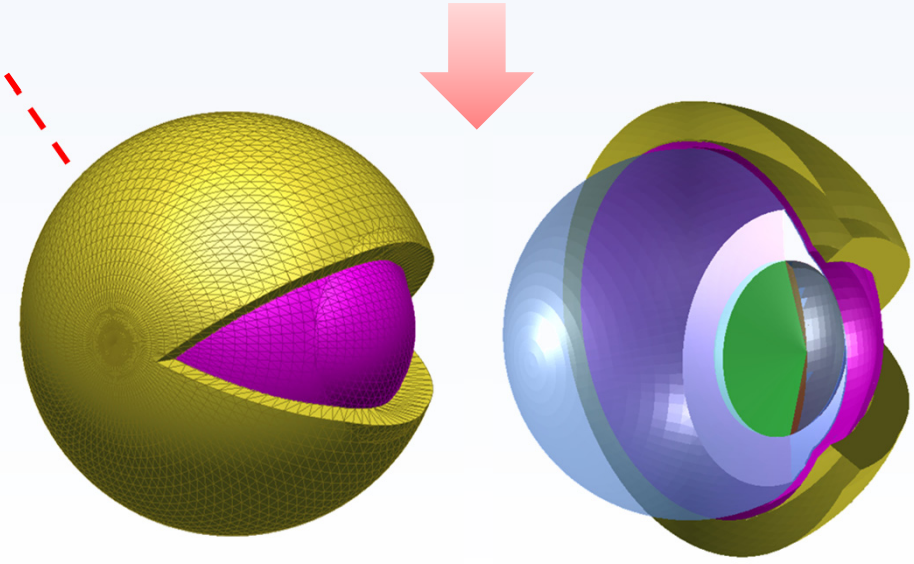


ICRP stylized eye model (ICRP-116)

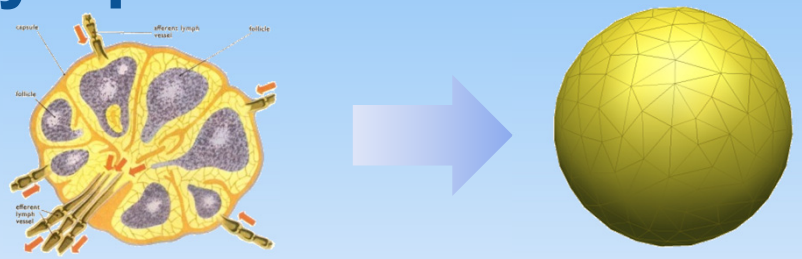


Completed

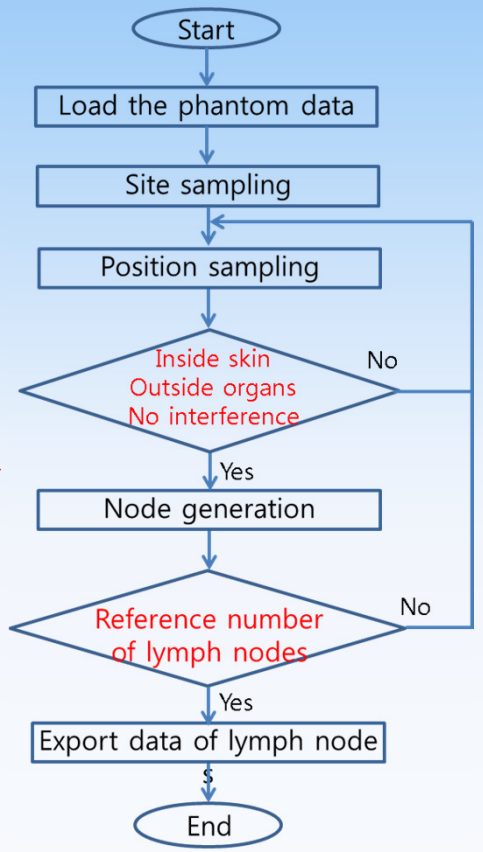
Conversion to polygonal model



3-2. Lymphatic Nodes



	Reference Mass		Reference Number	Reference Range
	AM	AF		
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

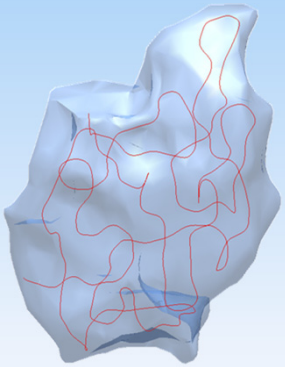


- We have developed a computer program to generate the lymphatic nodes in the polygon-mesh version phantoms, following the procedure which was used to develop the UF/NCI phantoms which have been adopted as ICRP pediatric phantoms.

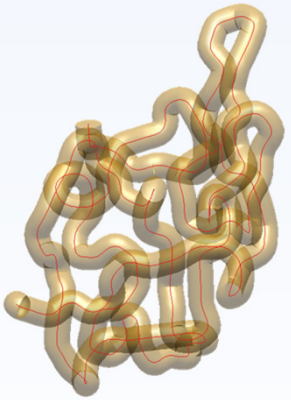
3-3. Small Intestine

1. Creation frame

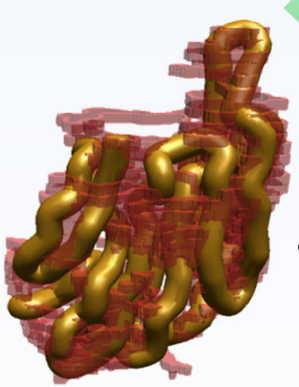
2. Random generation of SI passages



3. Conversion to pipe model



4. Compare with original voxel model

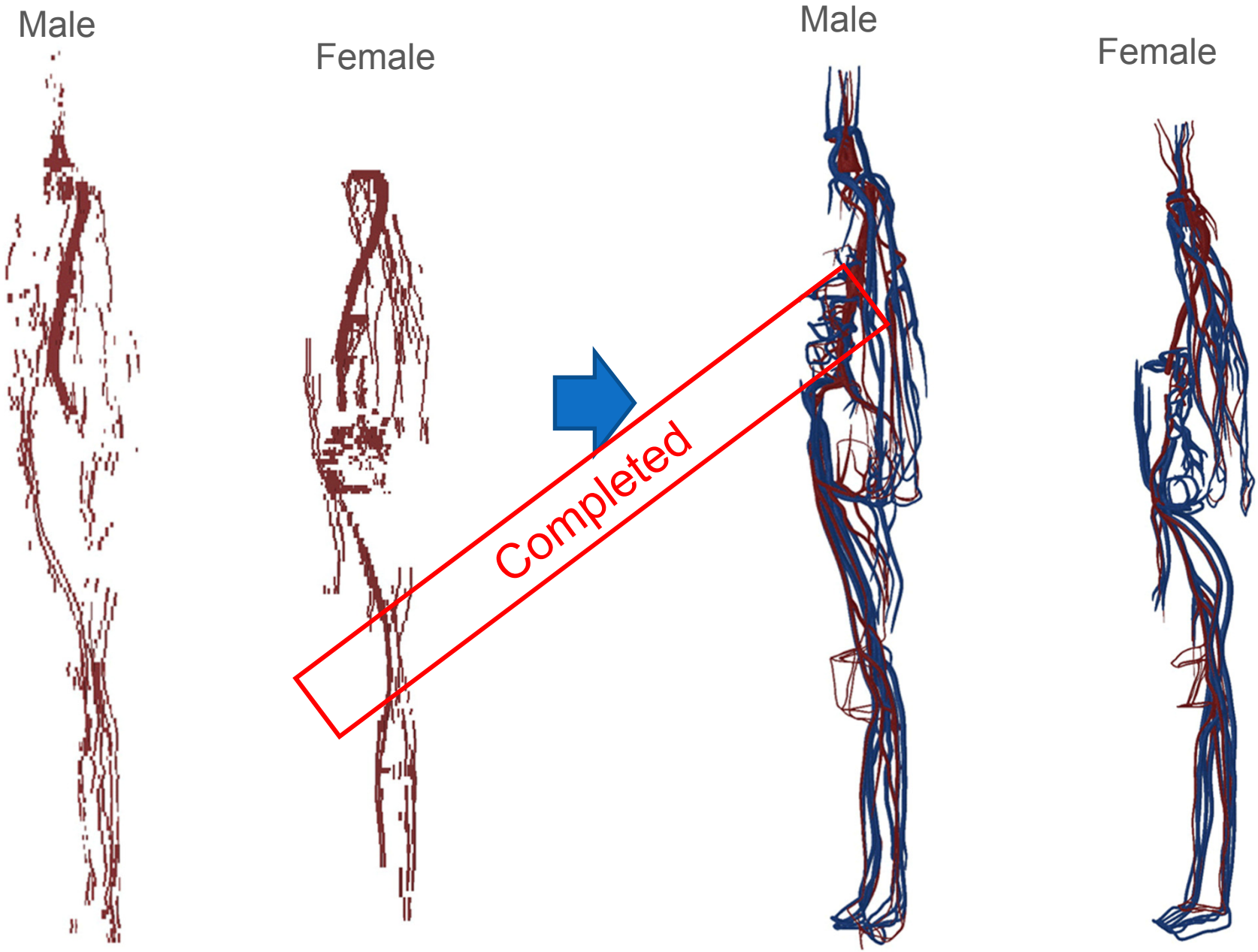


Repetition

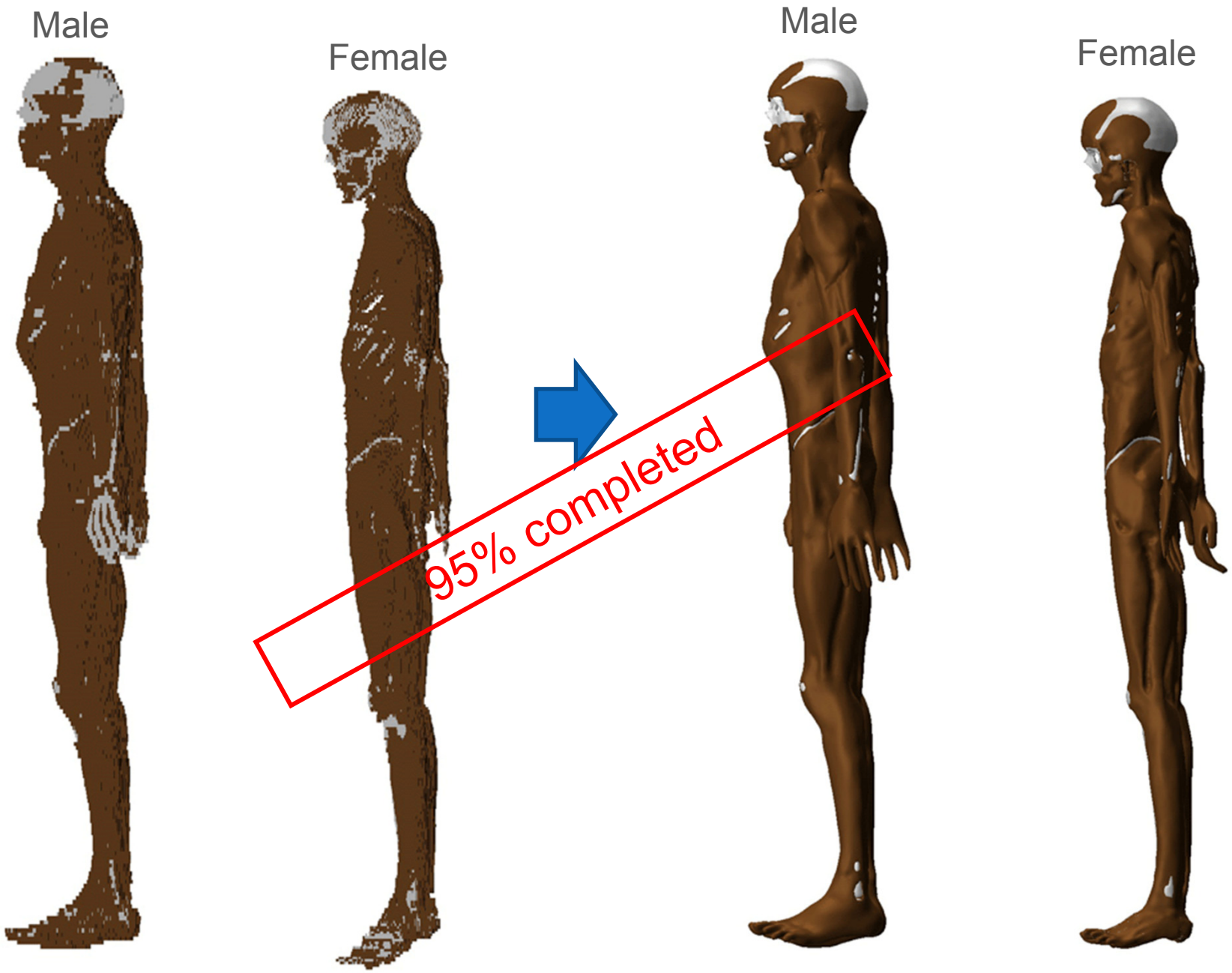
Ready for use (for female)

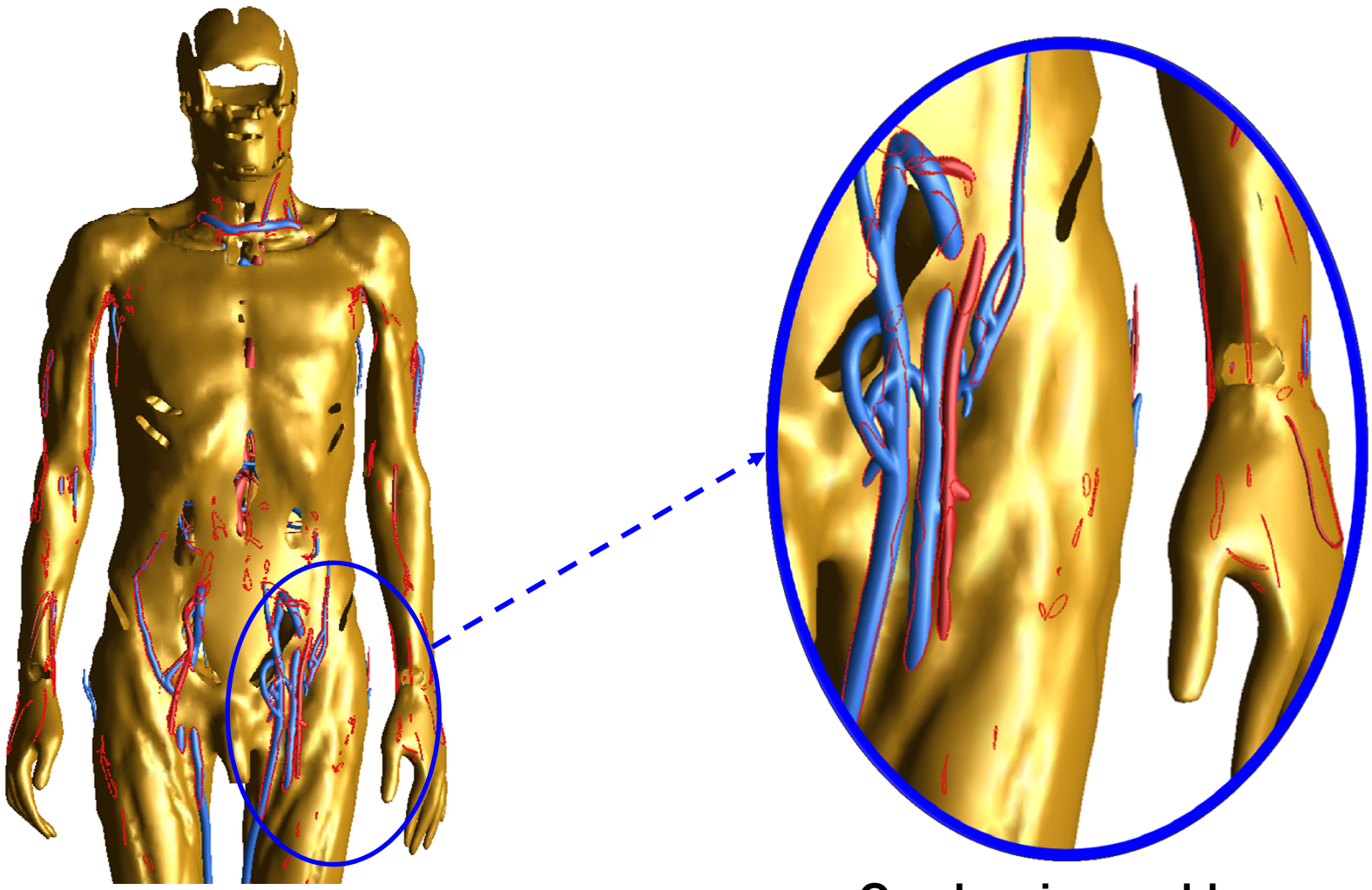
Randomly generate **1000** small intestine (SI) models and select the **best model** considering both geometric and dosimetric similarities with the original voxel model

3-4. Blood Vessel



3-5. Muscle



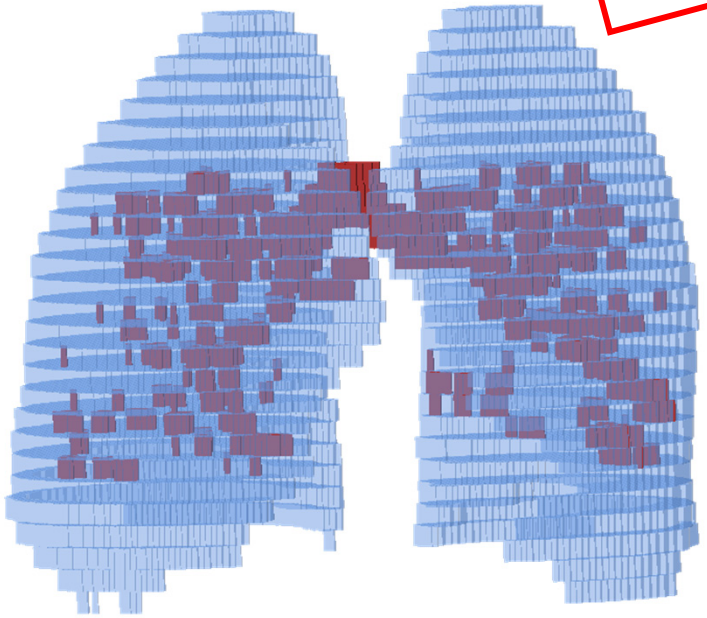


Overlapping problems

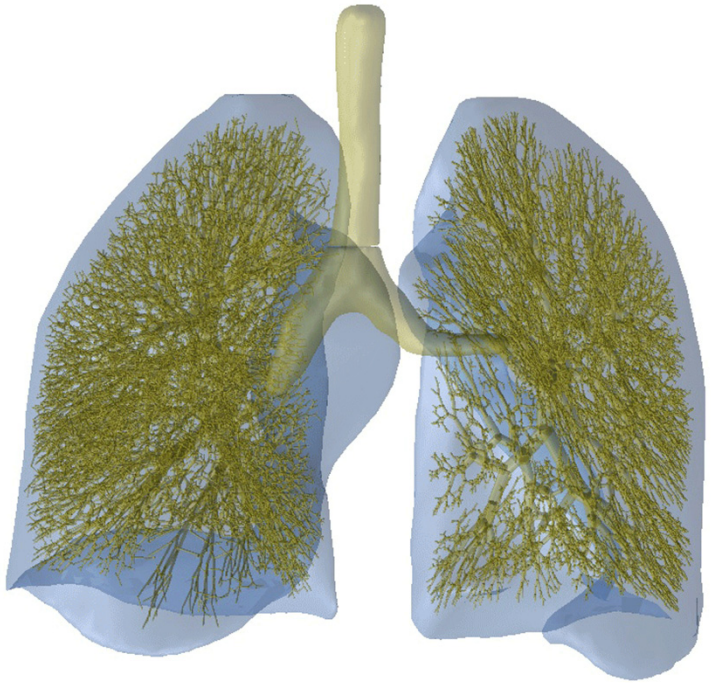
- Currently, we are doing final adjustment to remove the overlaps with the blood vessels

3-6. Lungs (BB ad bb Regions)

Airways under development

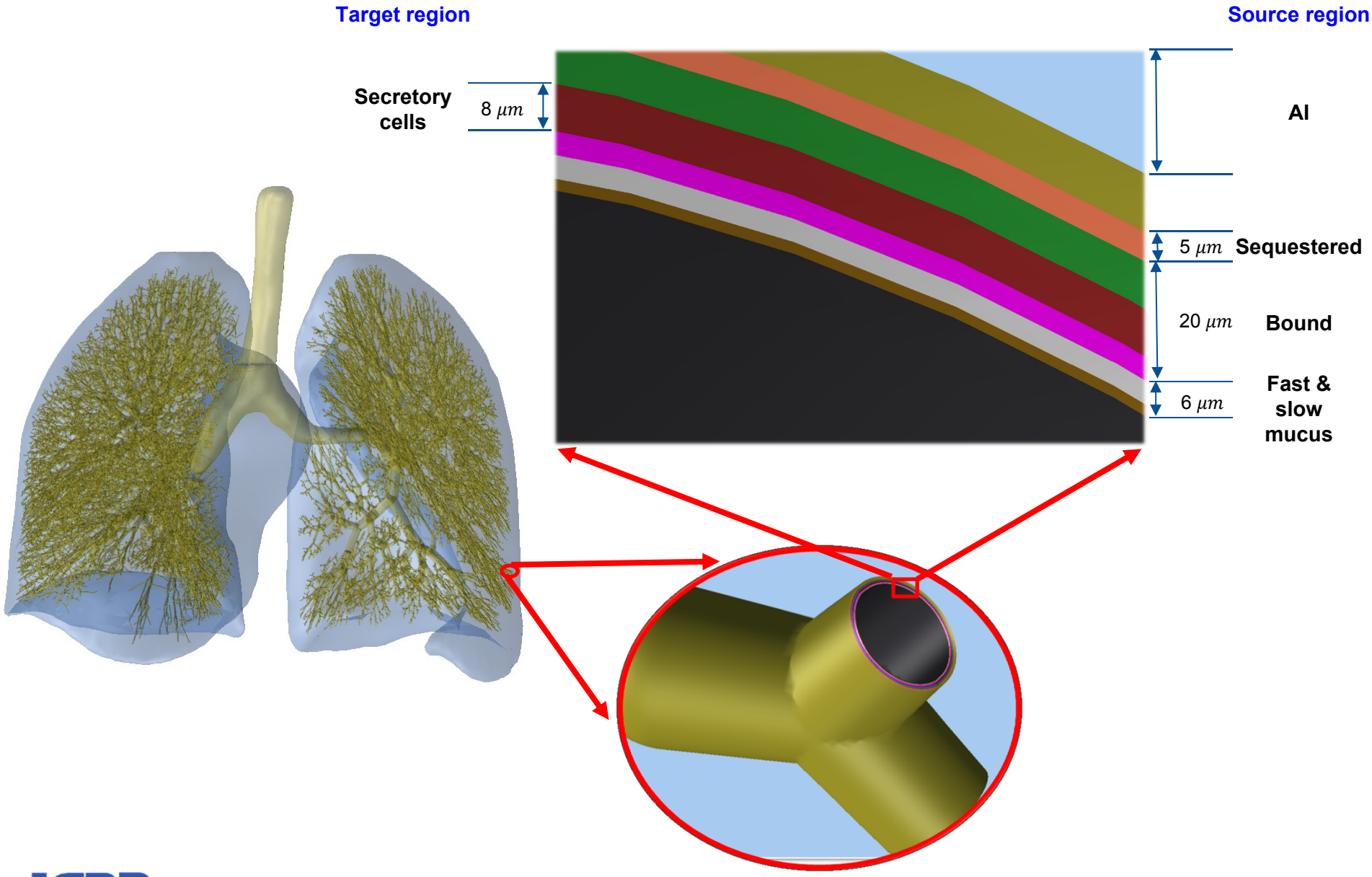


Male's lungs



Male's lungs

Lung Model


Target region
Source region
Secretory cells
8 μm
Al
5 μm
Sequestered
20 μm
Bound
6 μm
Fast & slow mucus
Bronchiolar (bb)

1. Construction of “Simple Organs”

2. Construction of “Skeletal Systems”

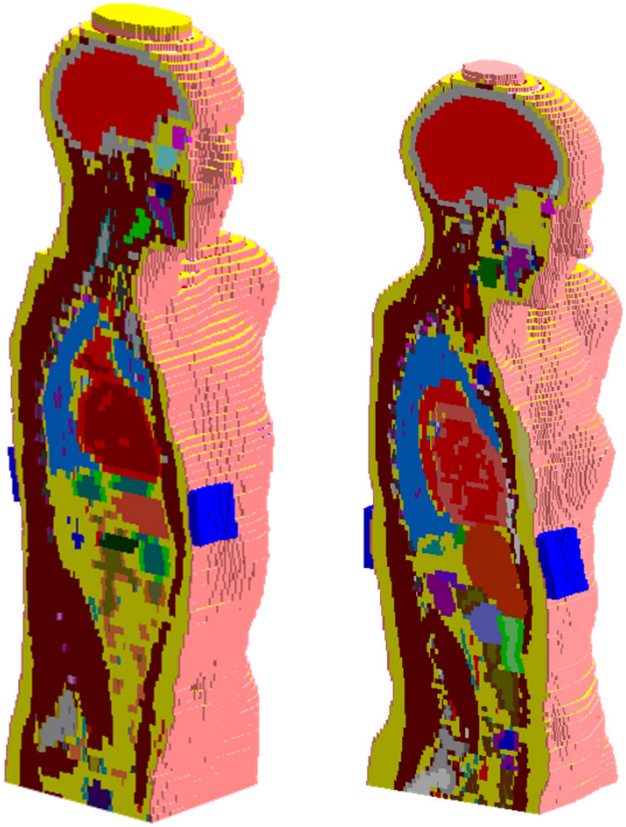
3. Construction of “Complex Organs”

4. Preliminary Results

Developed Phantoms (Preliminary)

Male

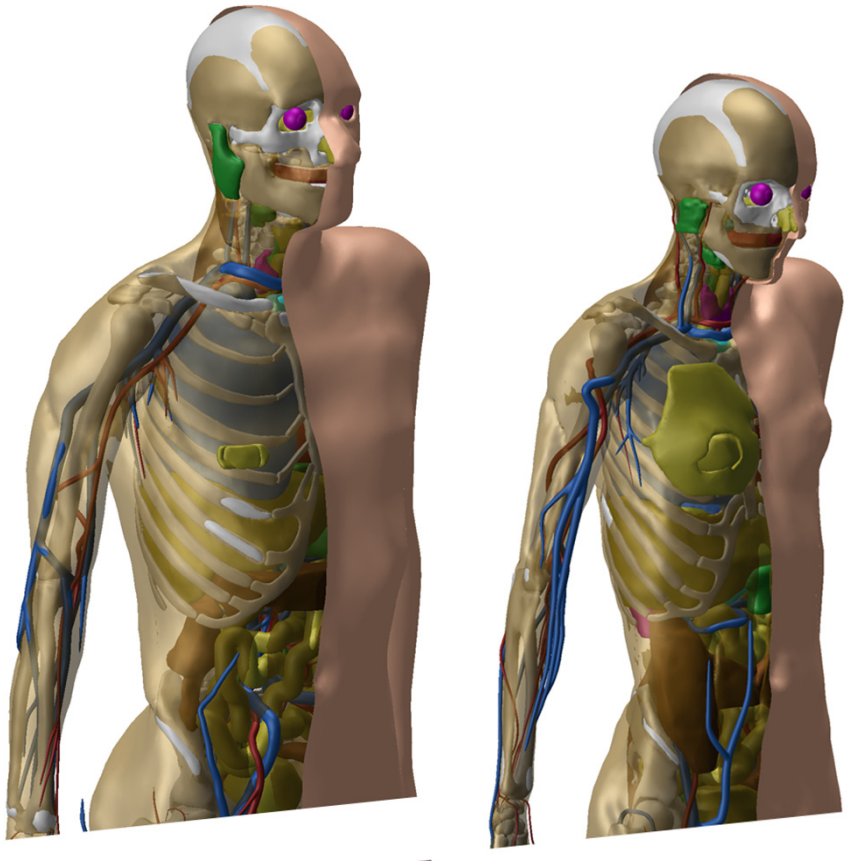
Female



ICRP-110 phantoms
(voxel geometry)

Male

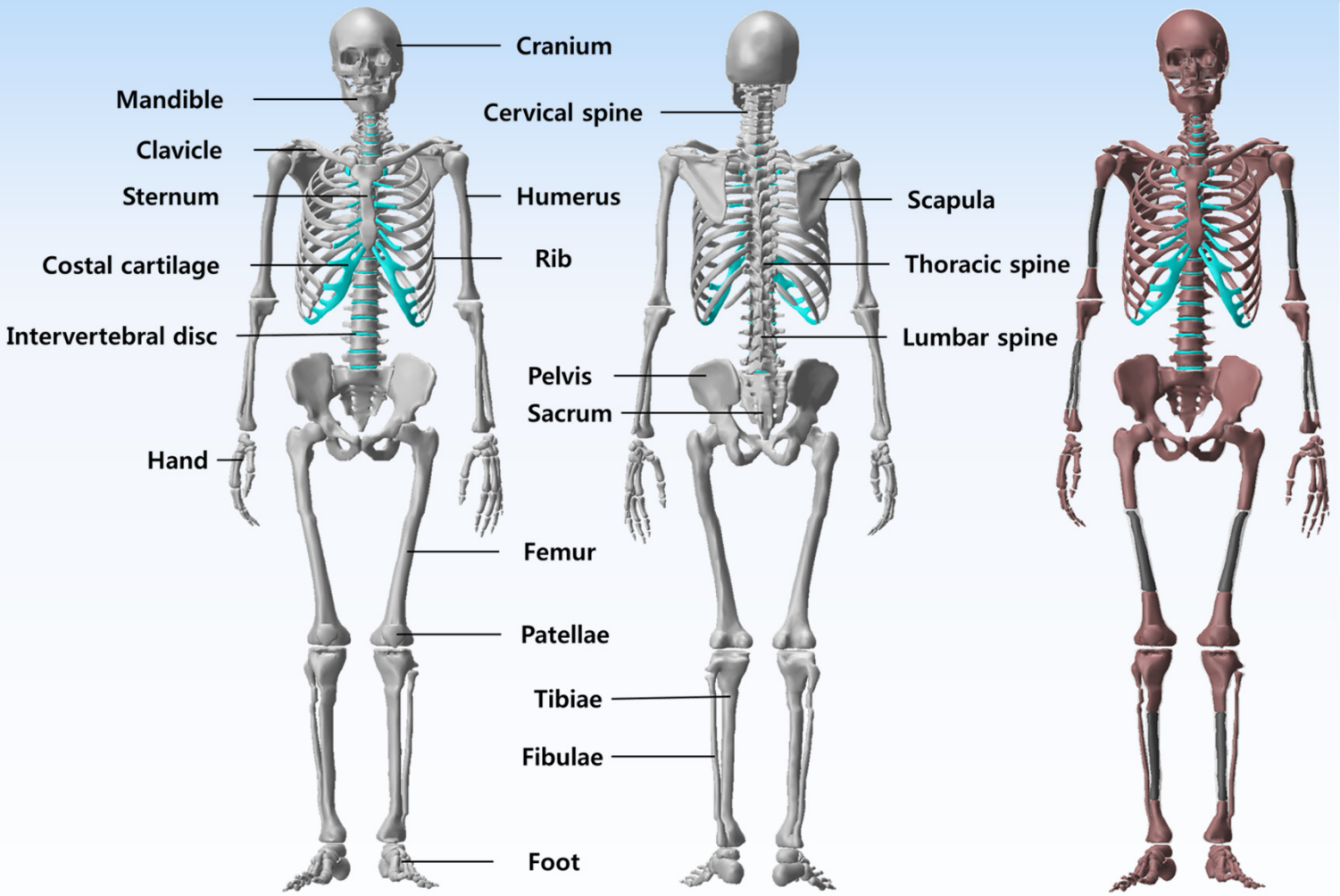
Female



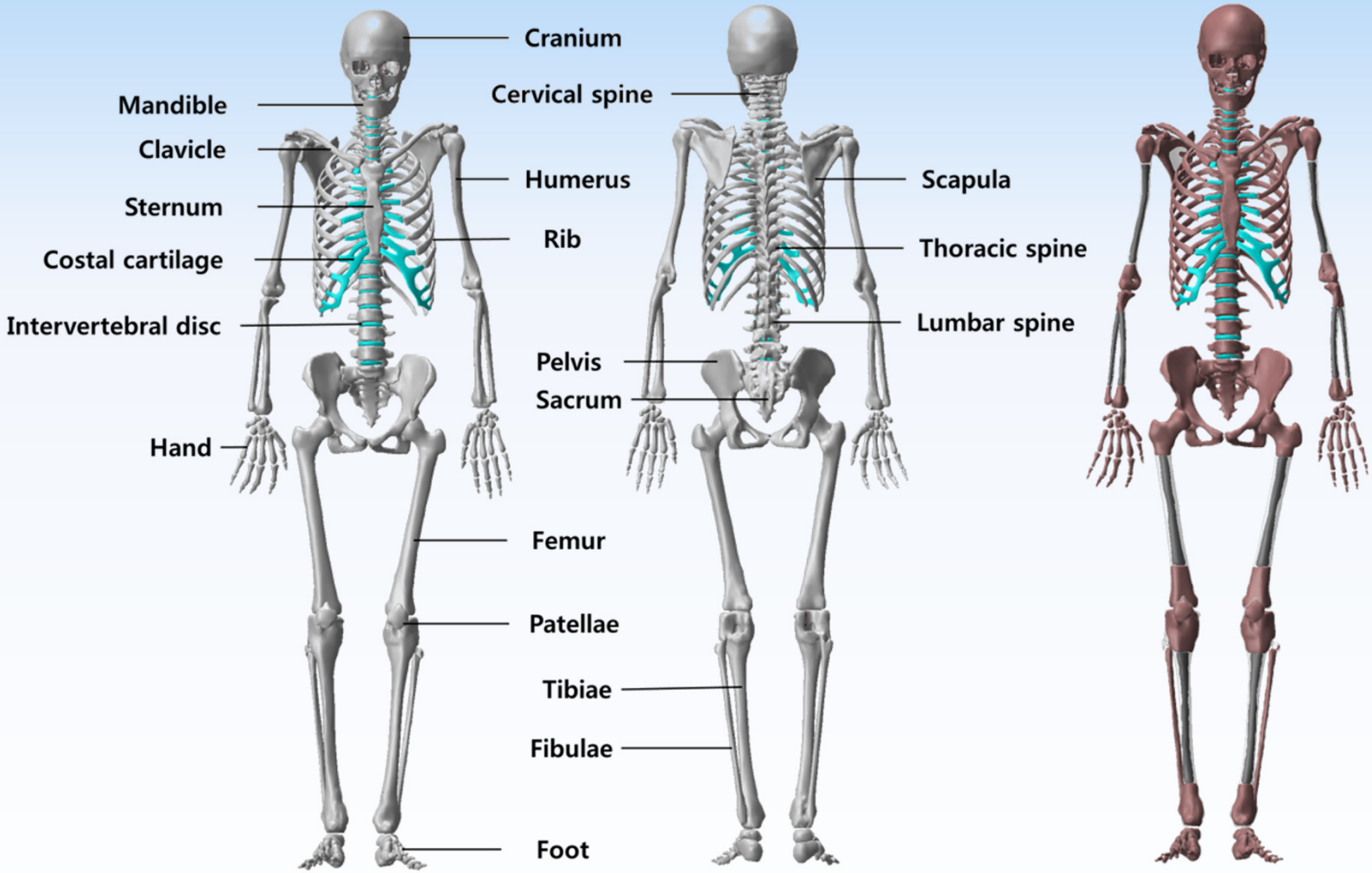
Polygon-mesh version phantoms
(preliminary)

Skeletal System

Male

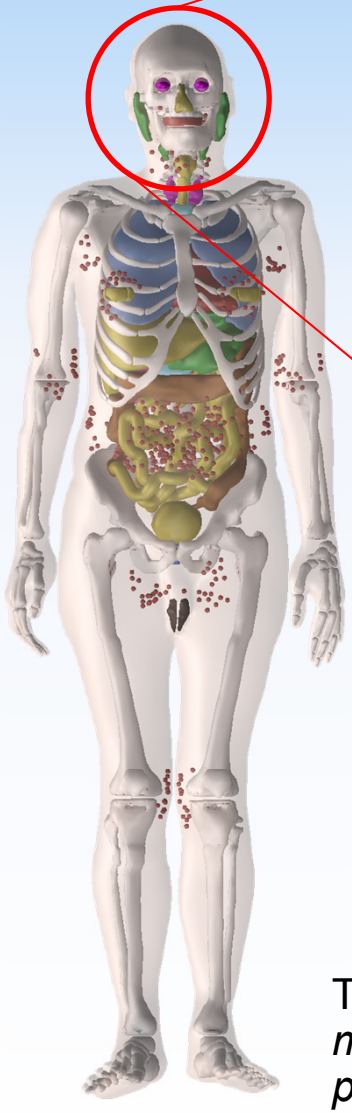


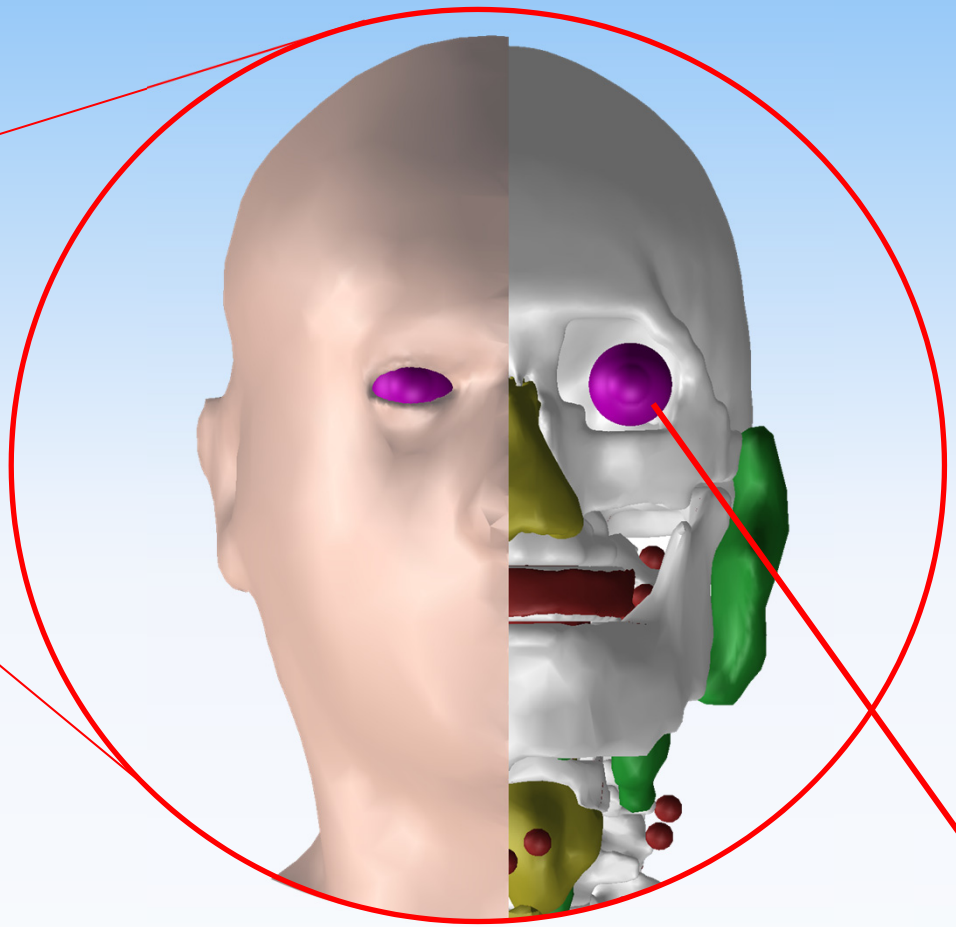
Female


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

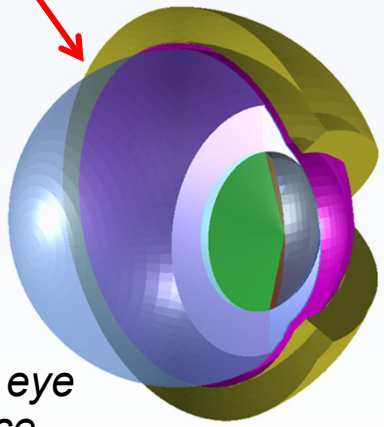
Eyes

Male phantom





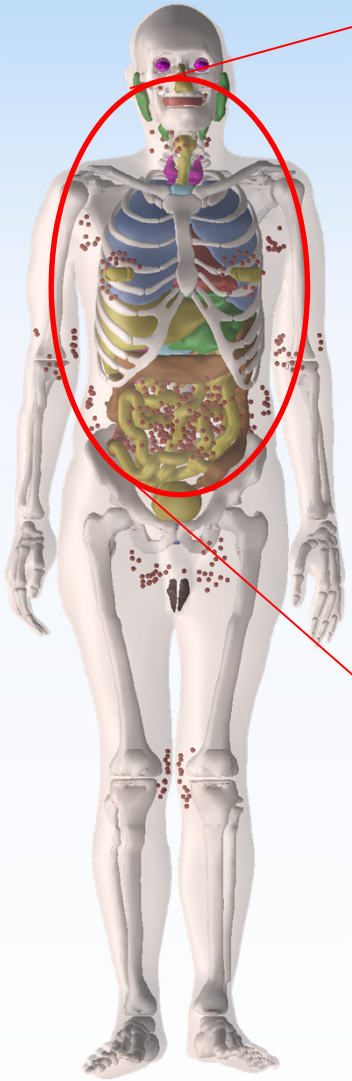
Detailed eye model

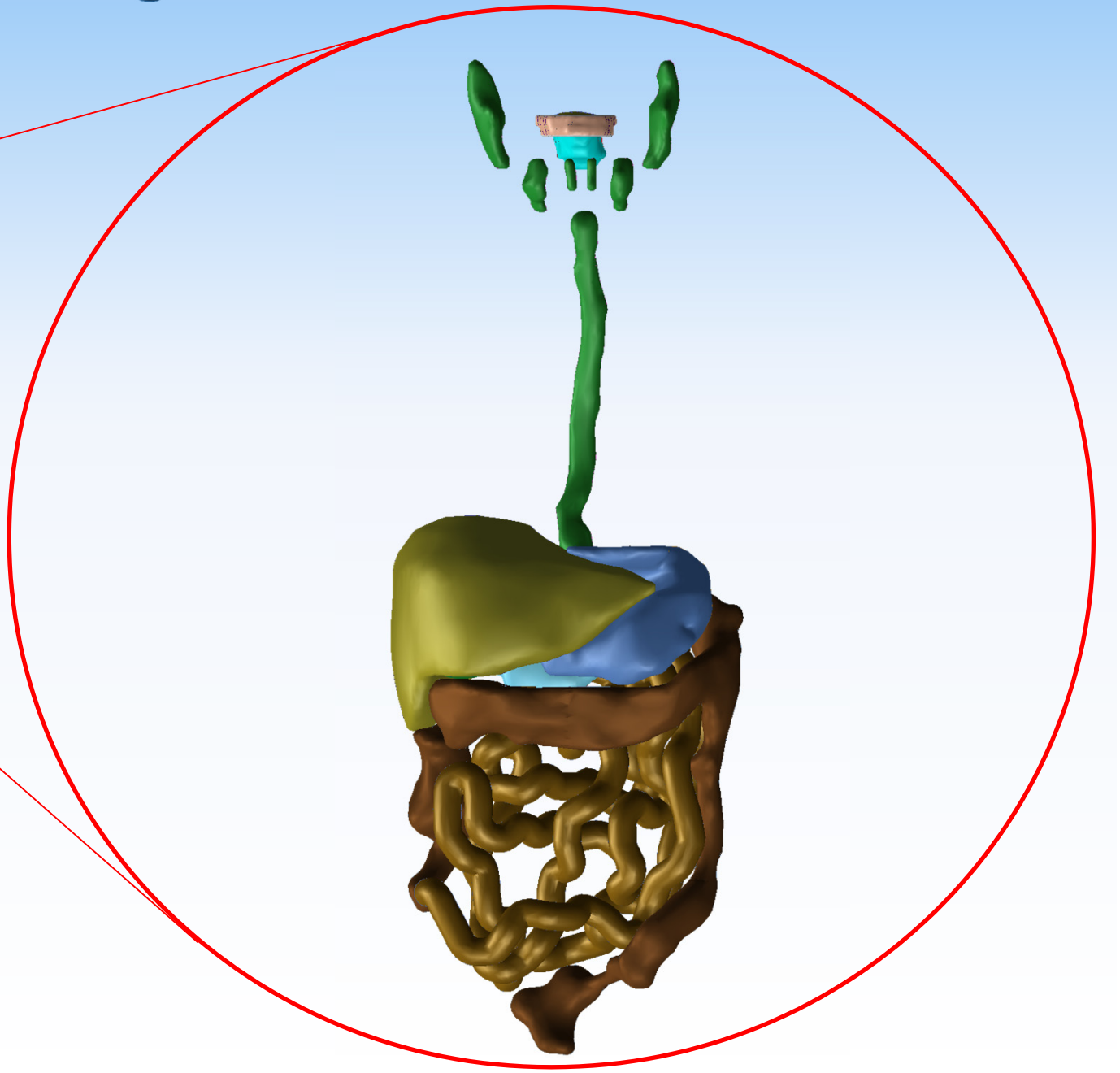


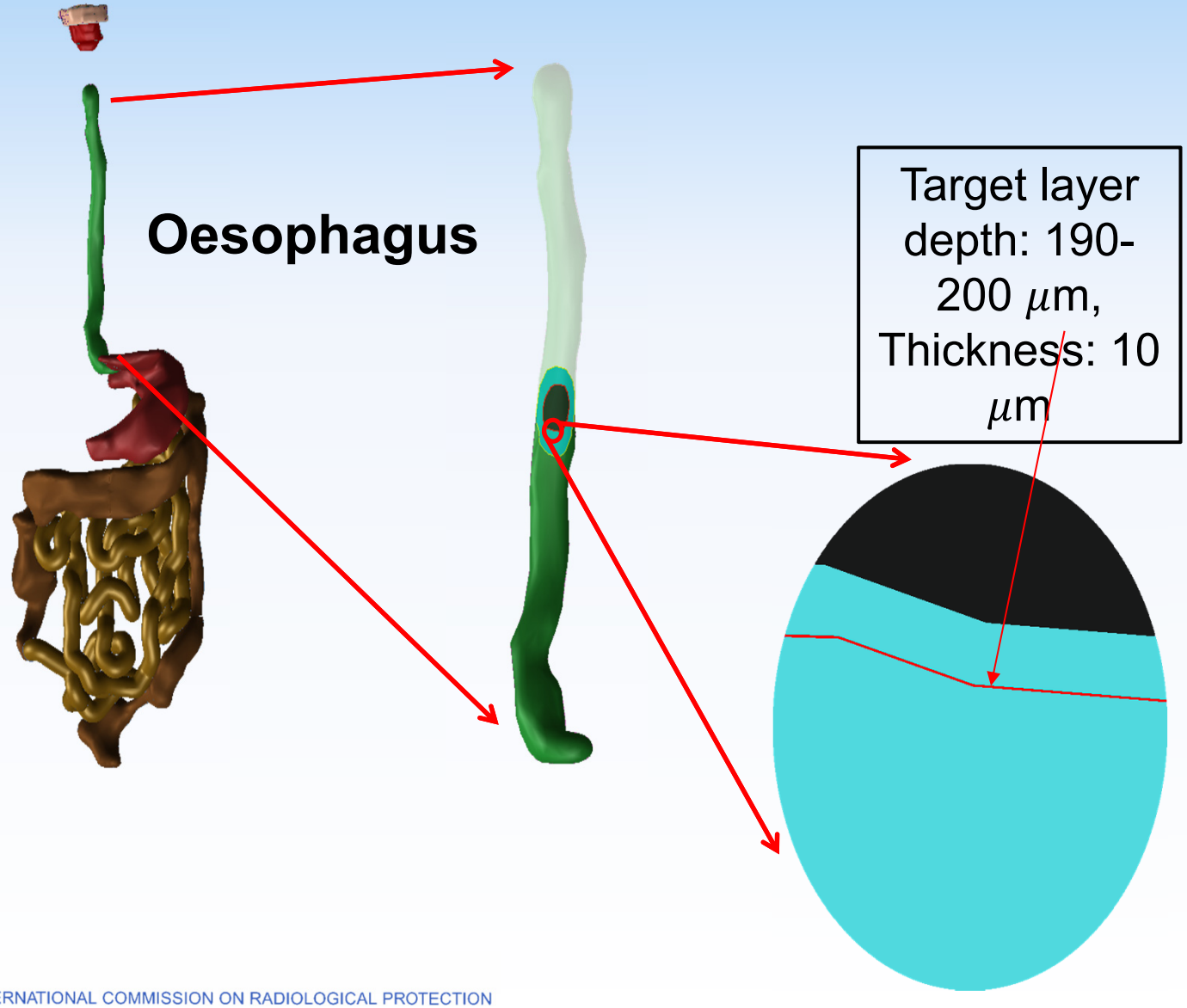
T.T. Nguyen, Y.S. Yeom, et al., *Incorporation of detailed eye model into polygon-mesh versions of ICRP-110 reference phantoms*. Phys. Med. Biol. (2015)

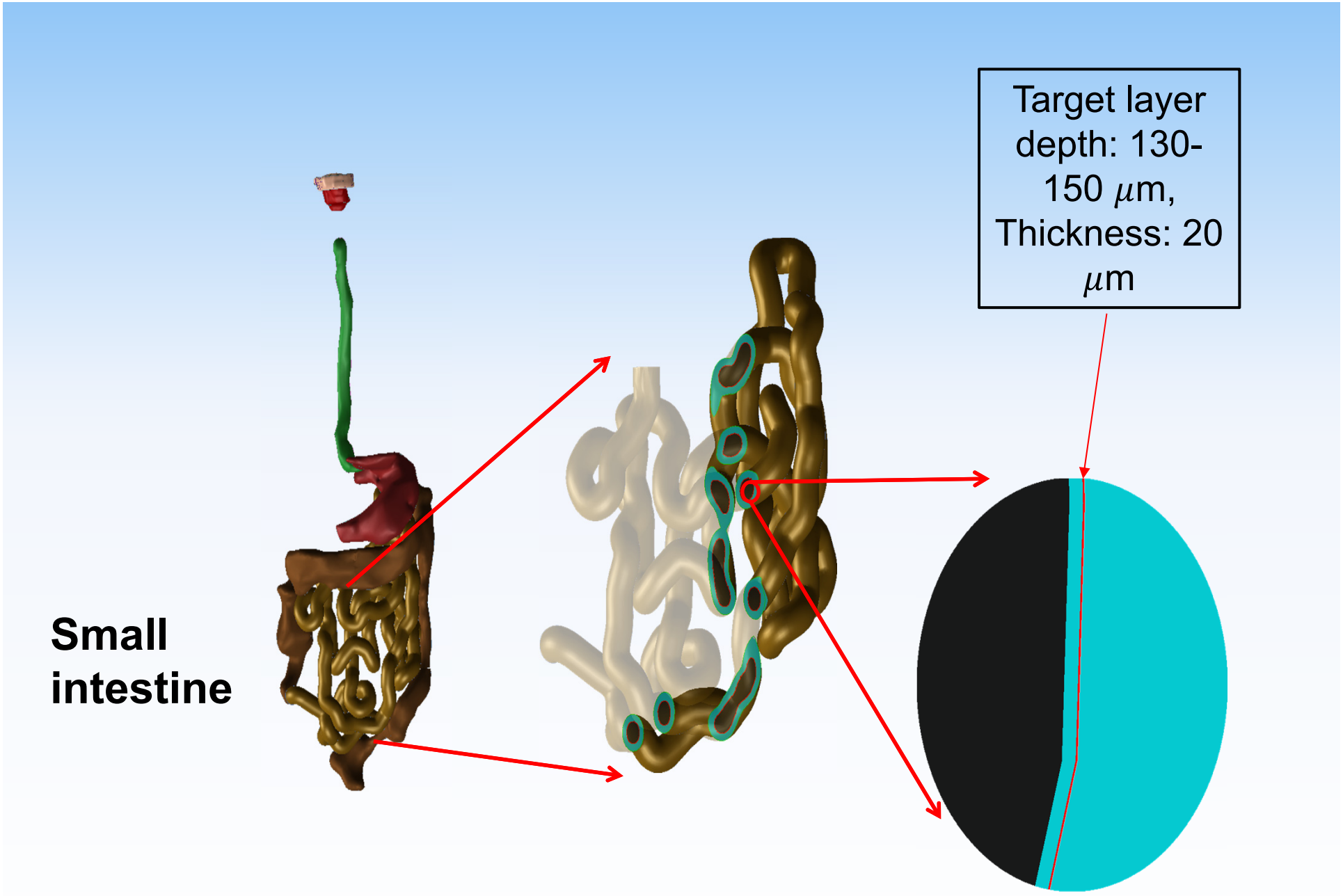
Alimentary Tract Organs

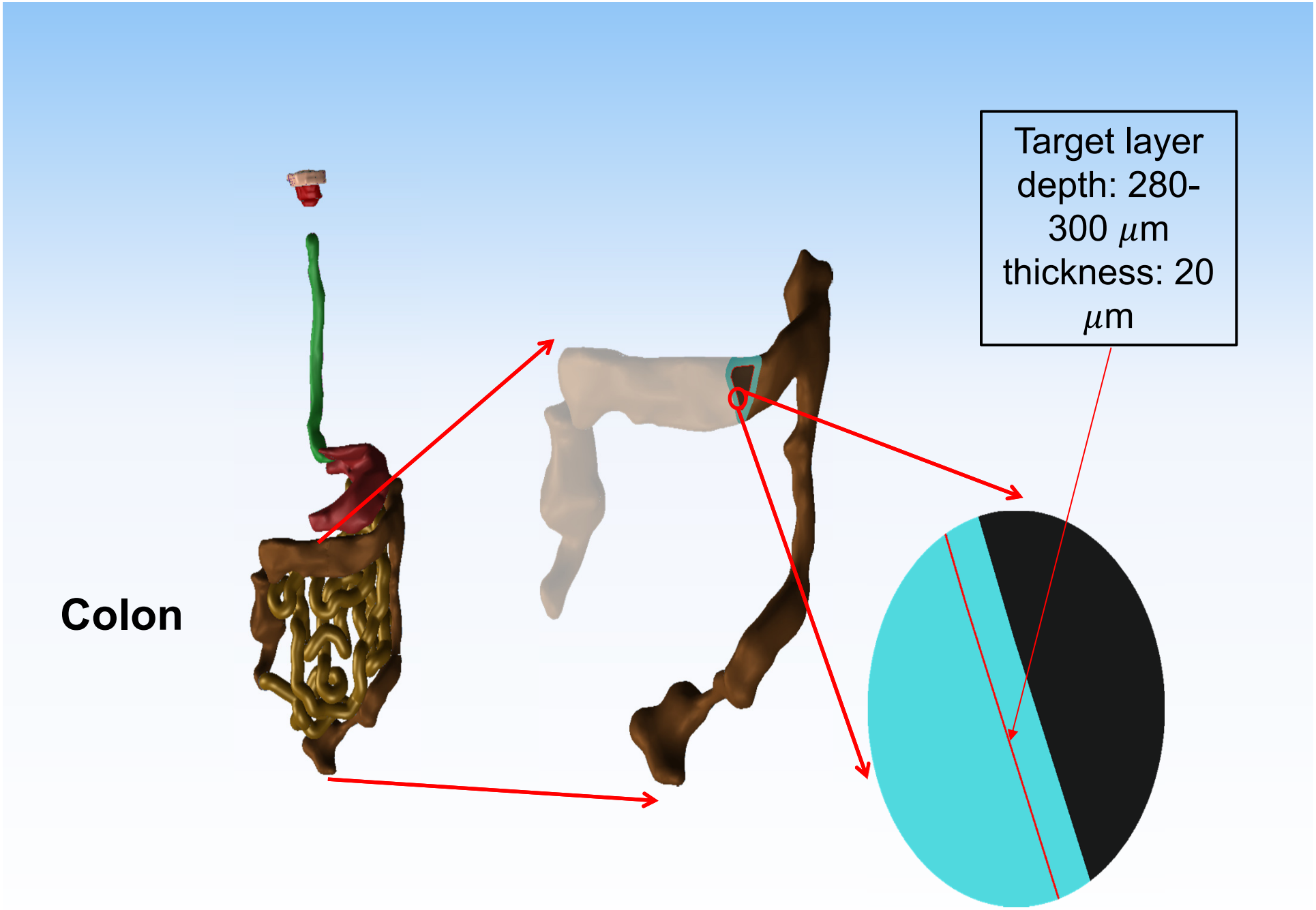
Male phantom





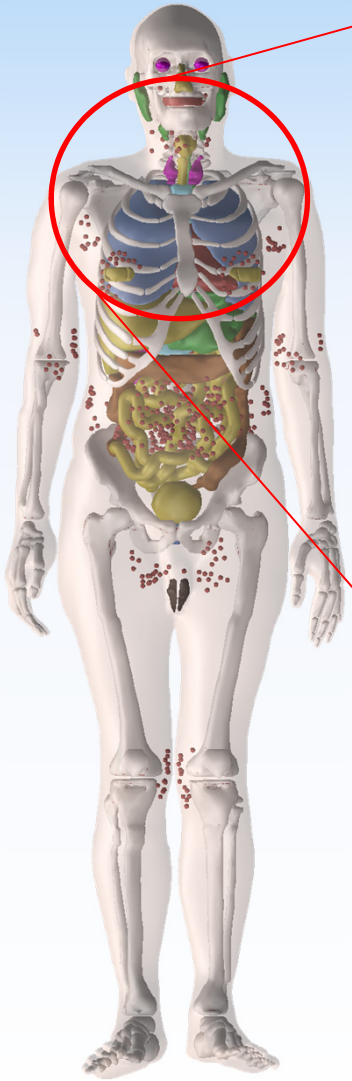

Oesophagus
Target layer depth: 190-200 μm, Thickness: 10 μm

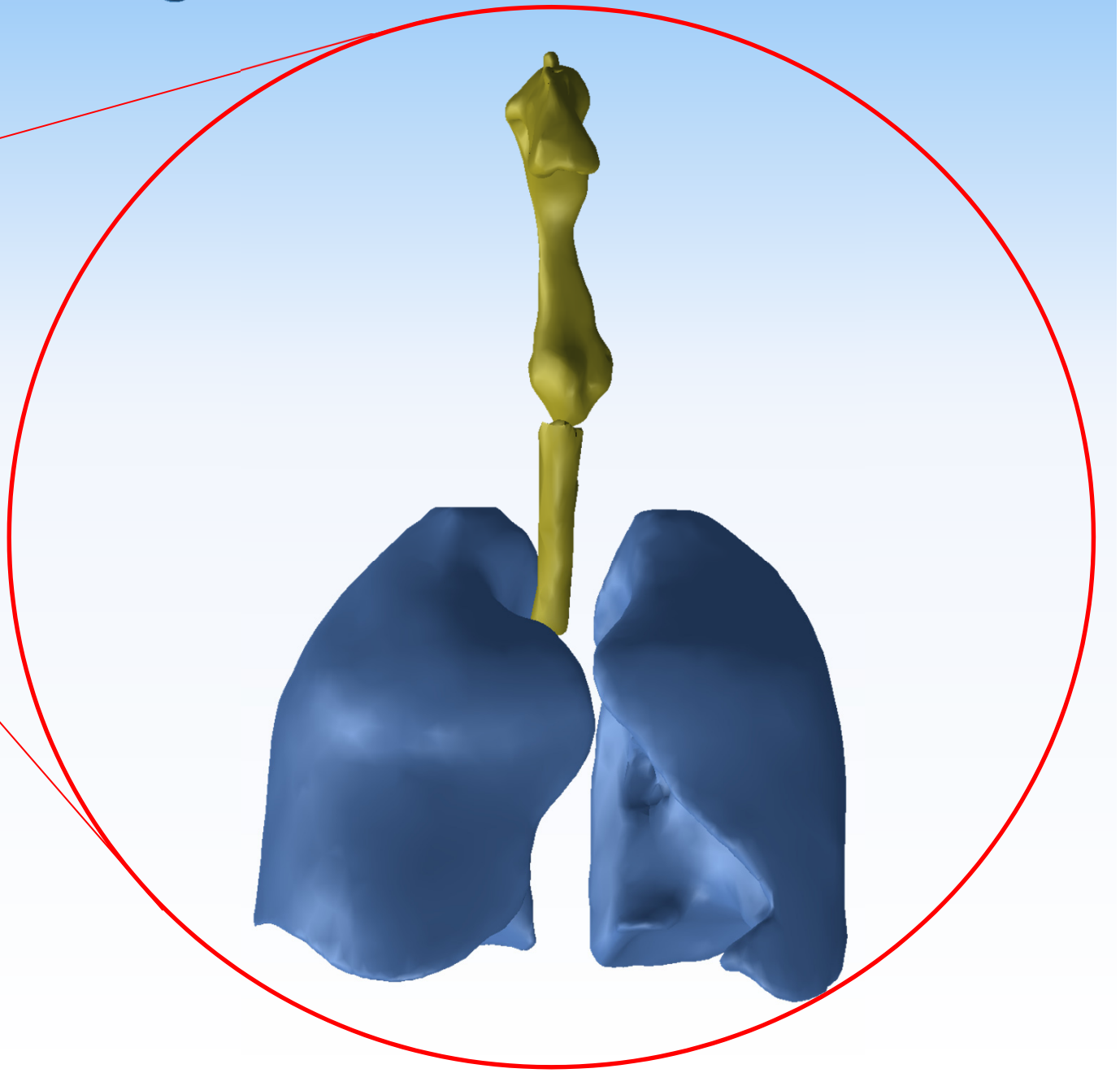

Target layer depth: 130-150 μm, Thickness: 20 μm
Small intestine


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

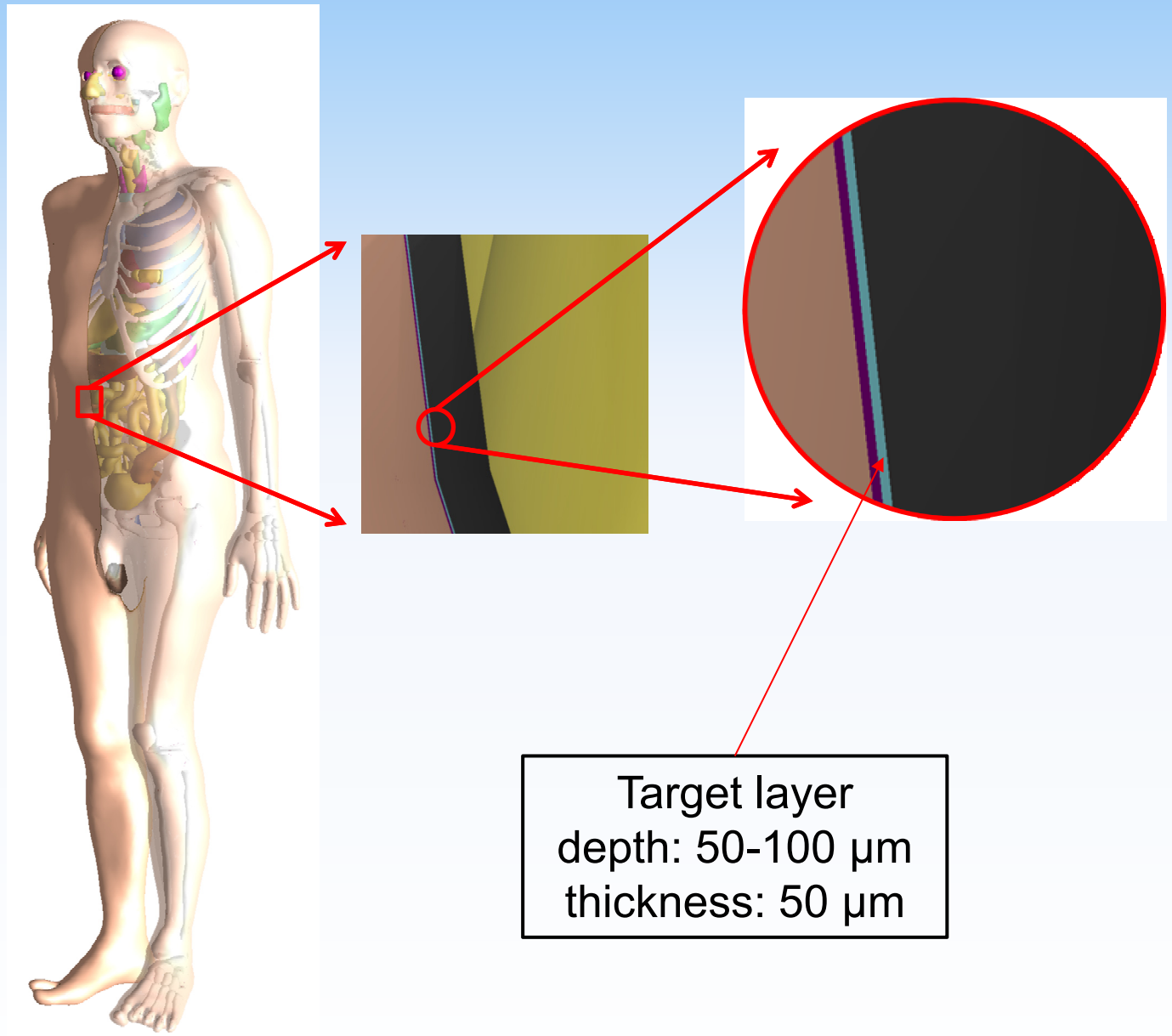
Respiratory Tract Organs

Male phantom





Skin – Target Layer

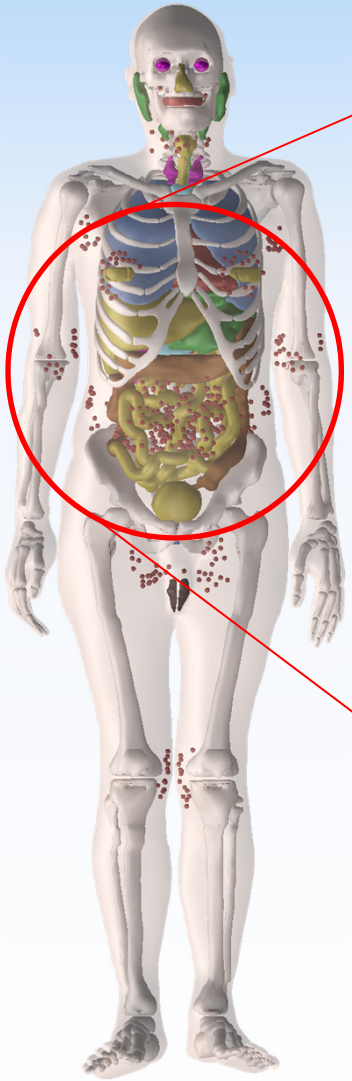


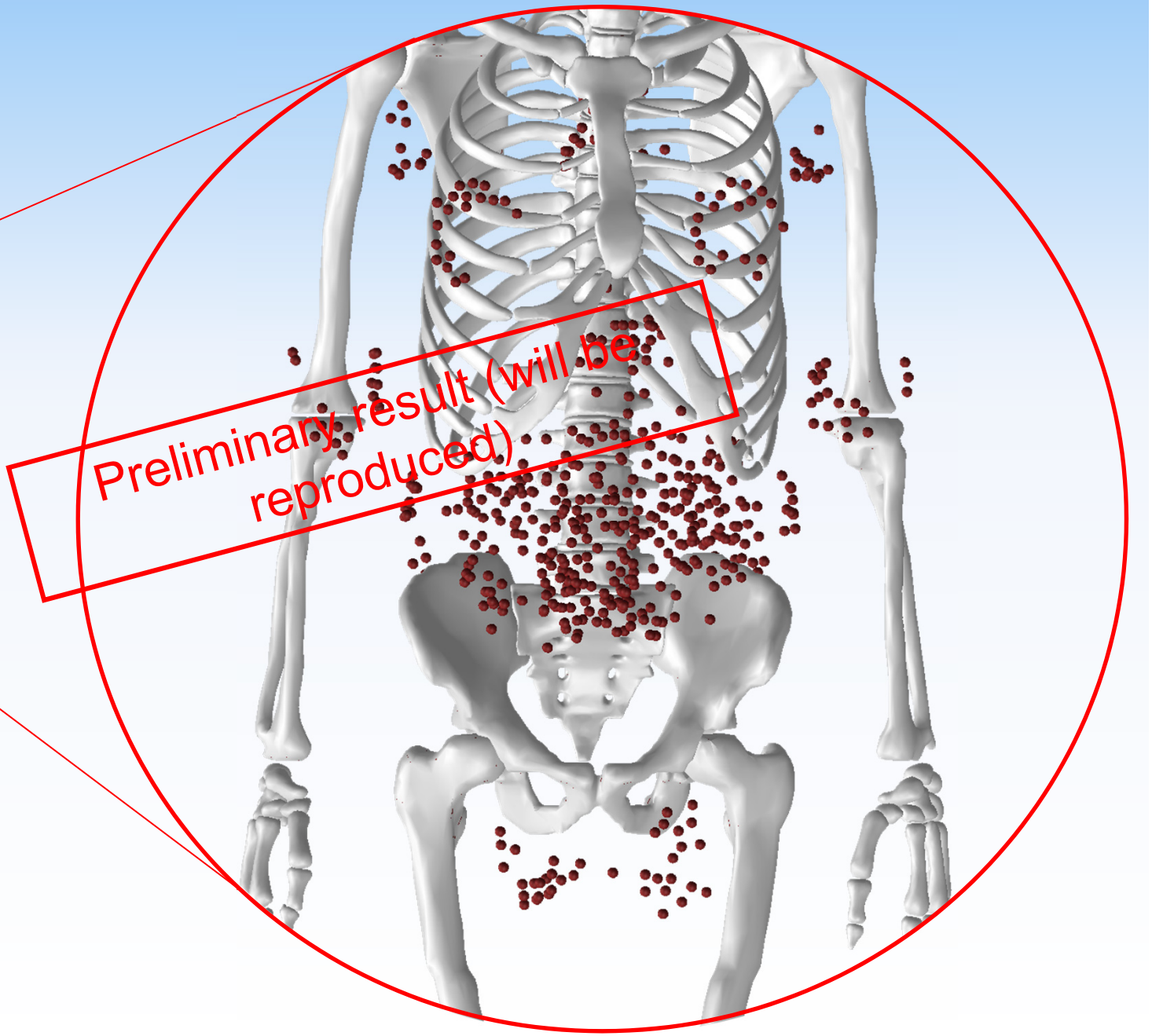
Male phantom

Target layer
depth: 50-100 µm
thickness: 50 µm

Lymphatic Nodes

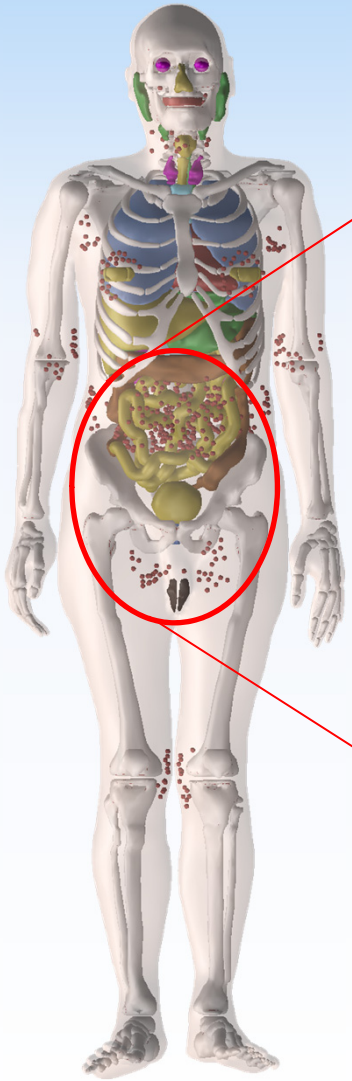
Male phantom

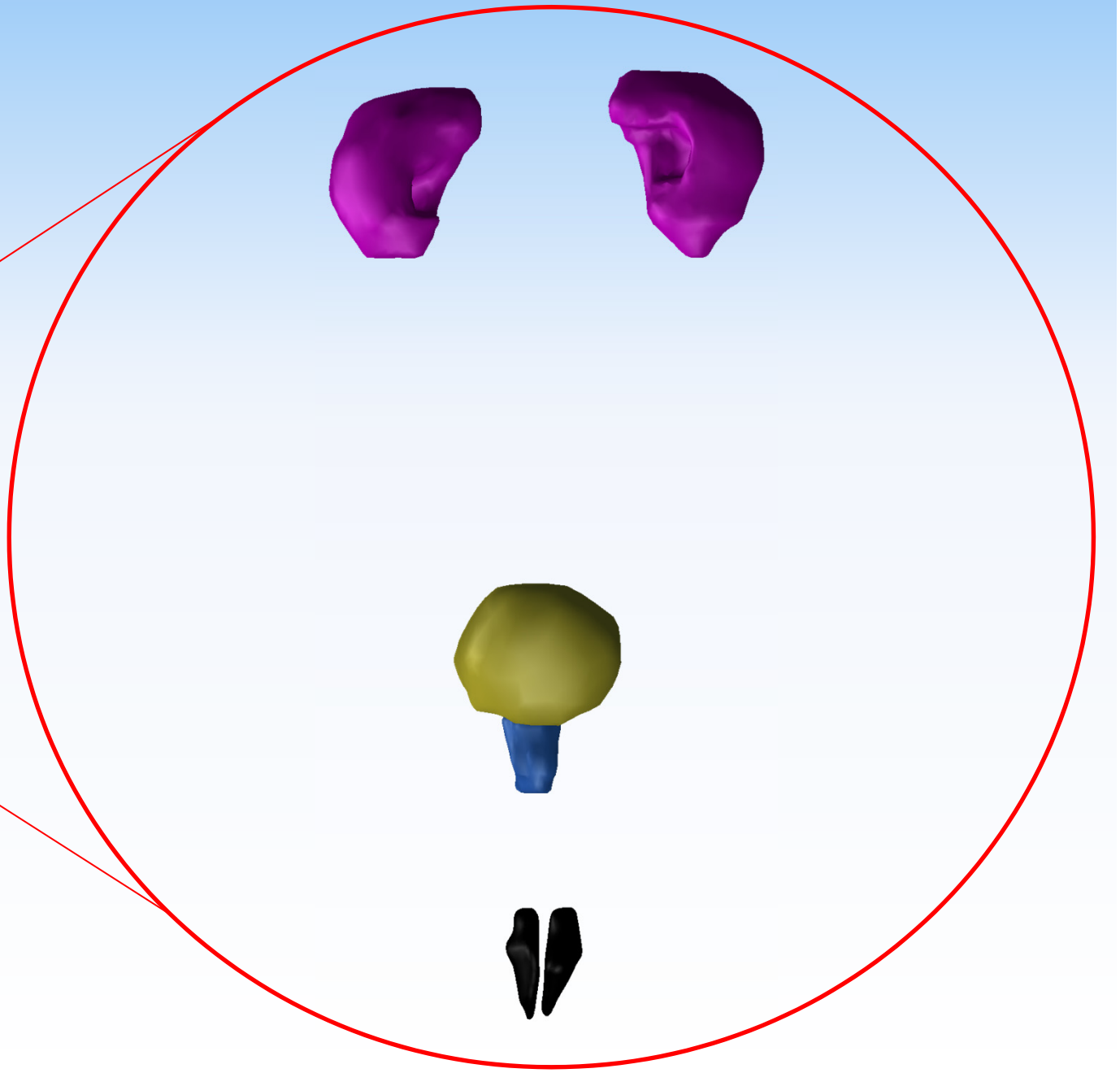




Urogenital Organs

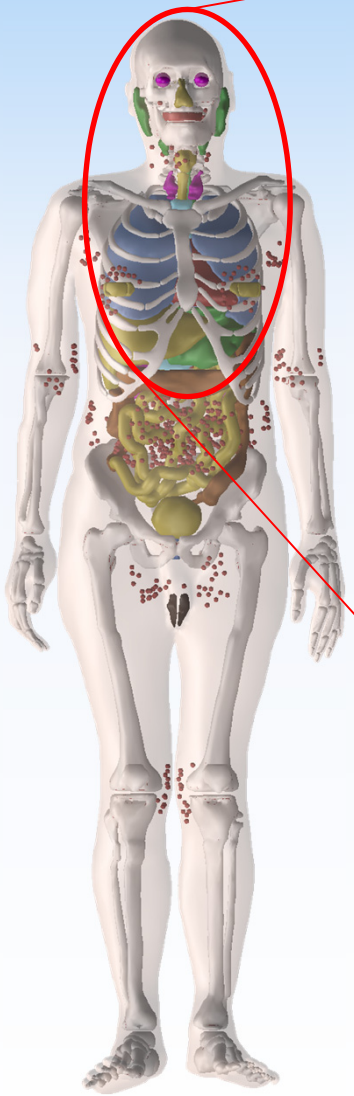
Male phantom

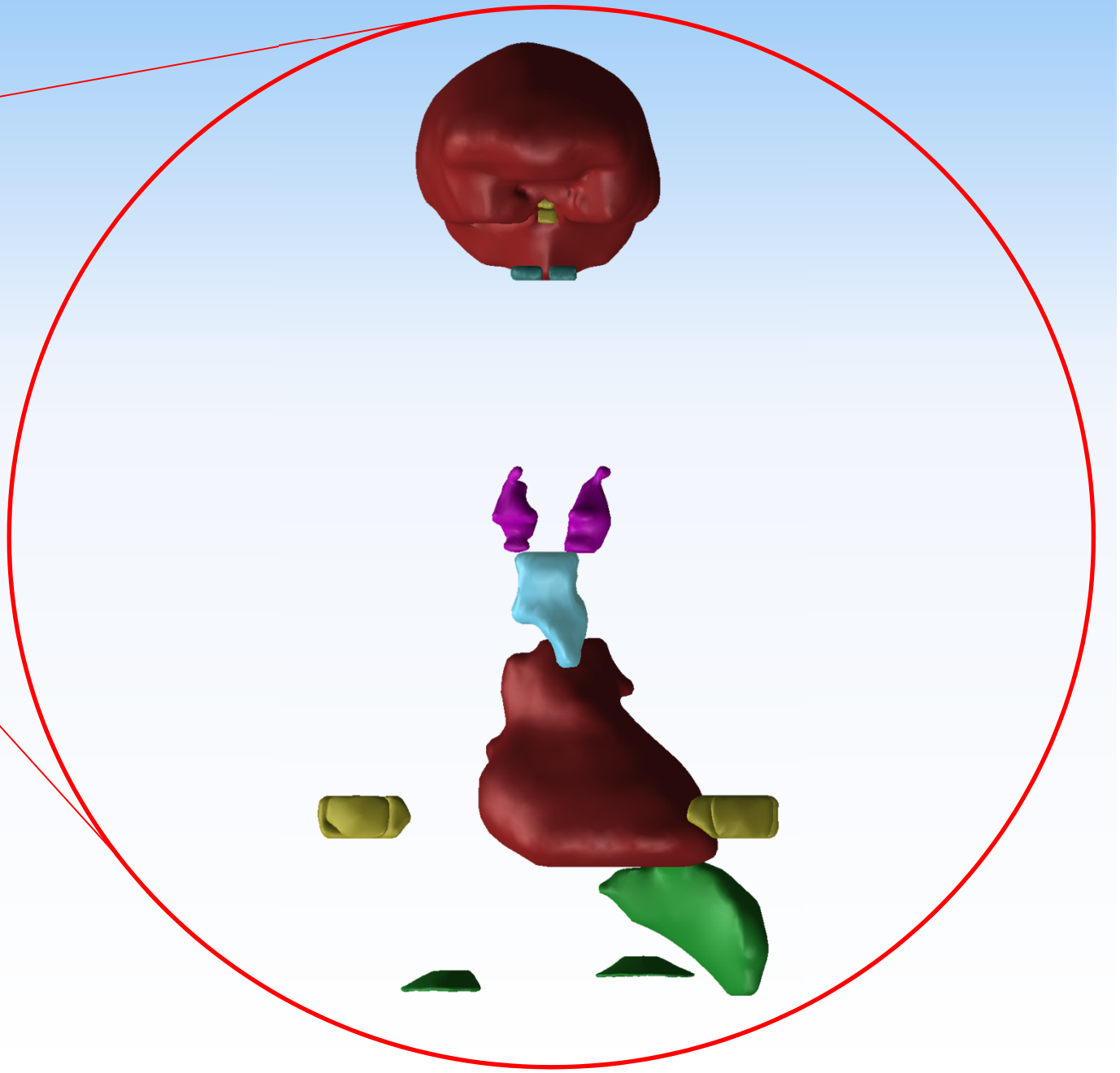




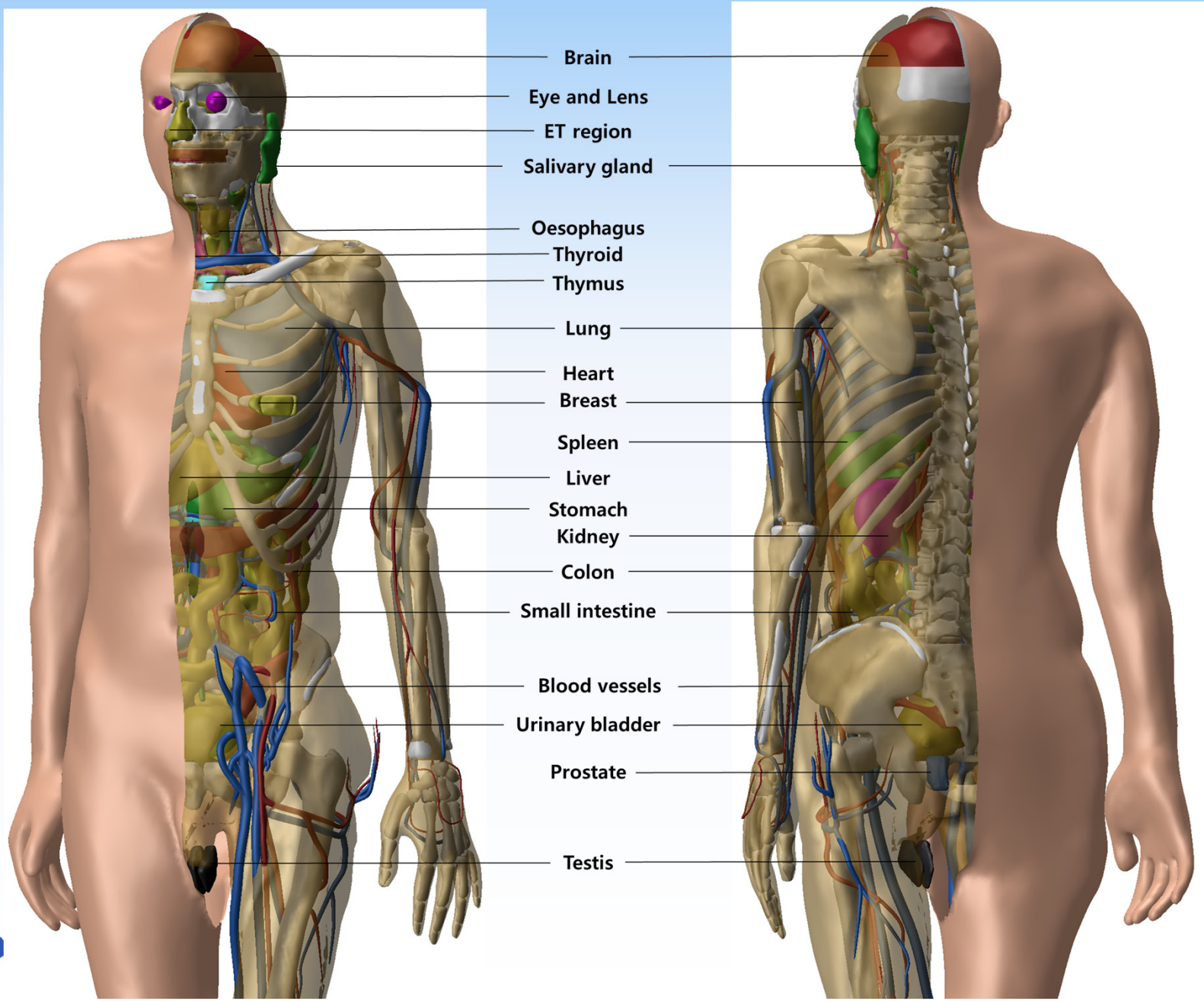
Other Organs / Tissues

Male phantom

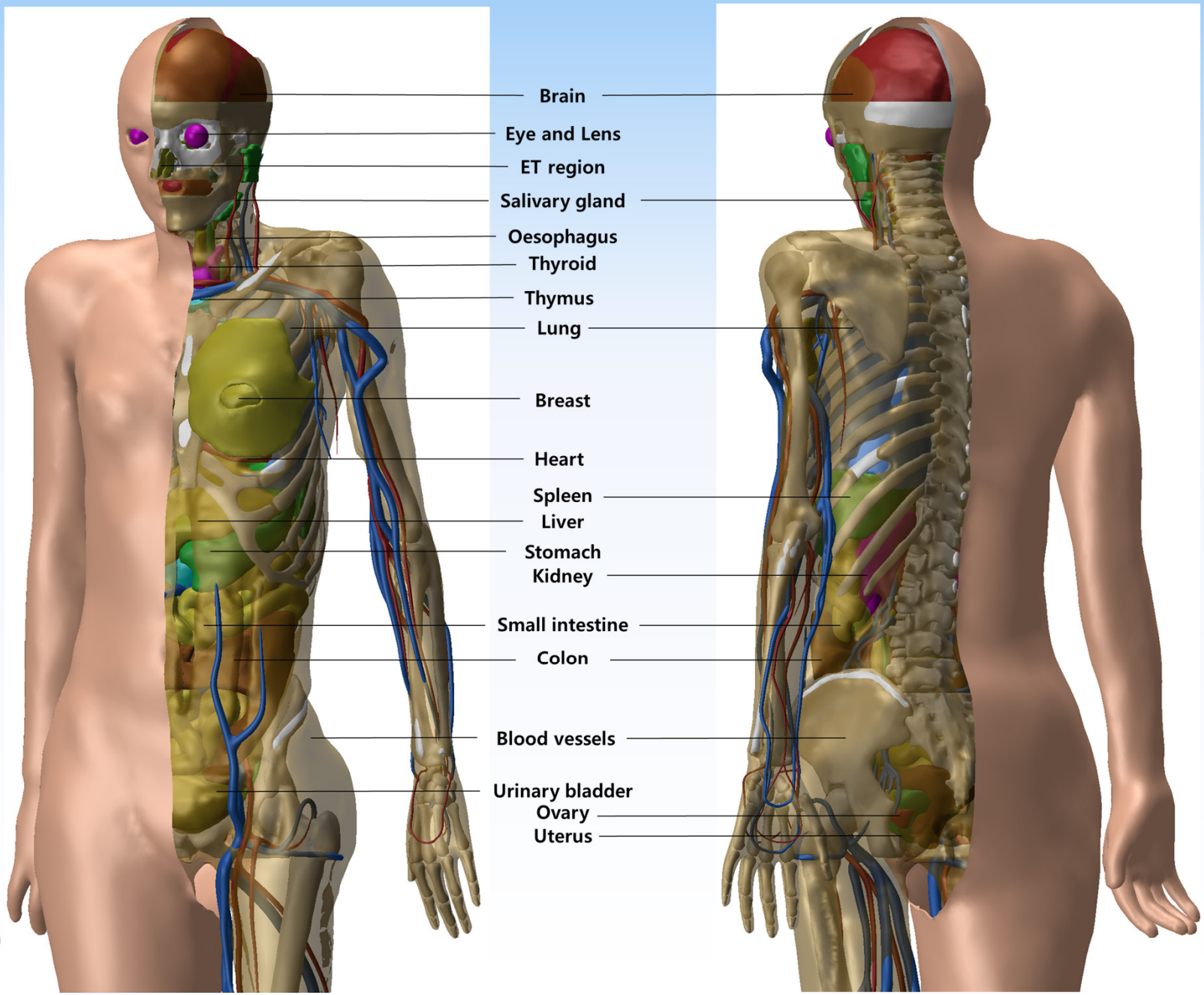




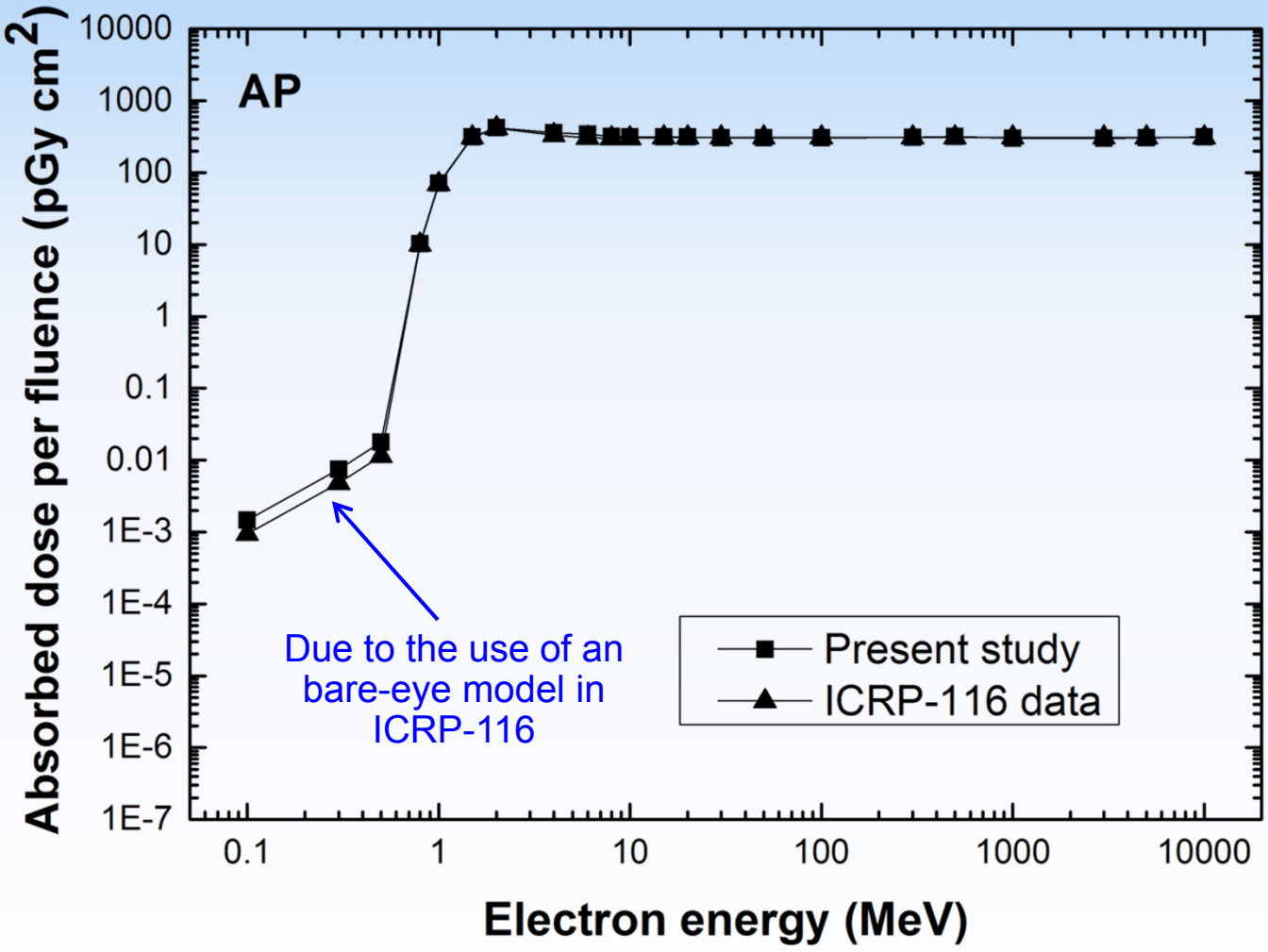
Developed Phantom – Male (Preliminary)



Developed Phantom – Female (Preliminary)

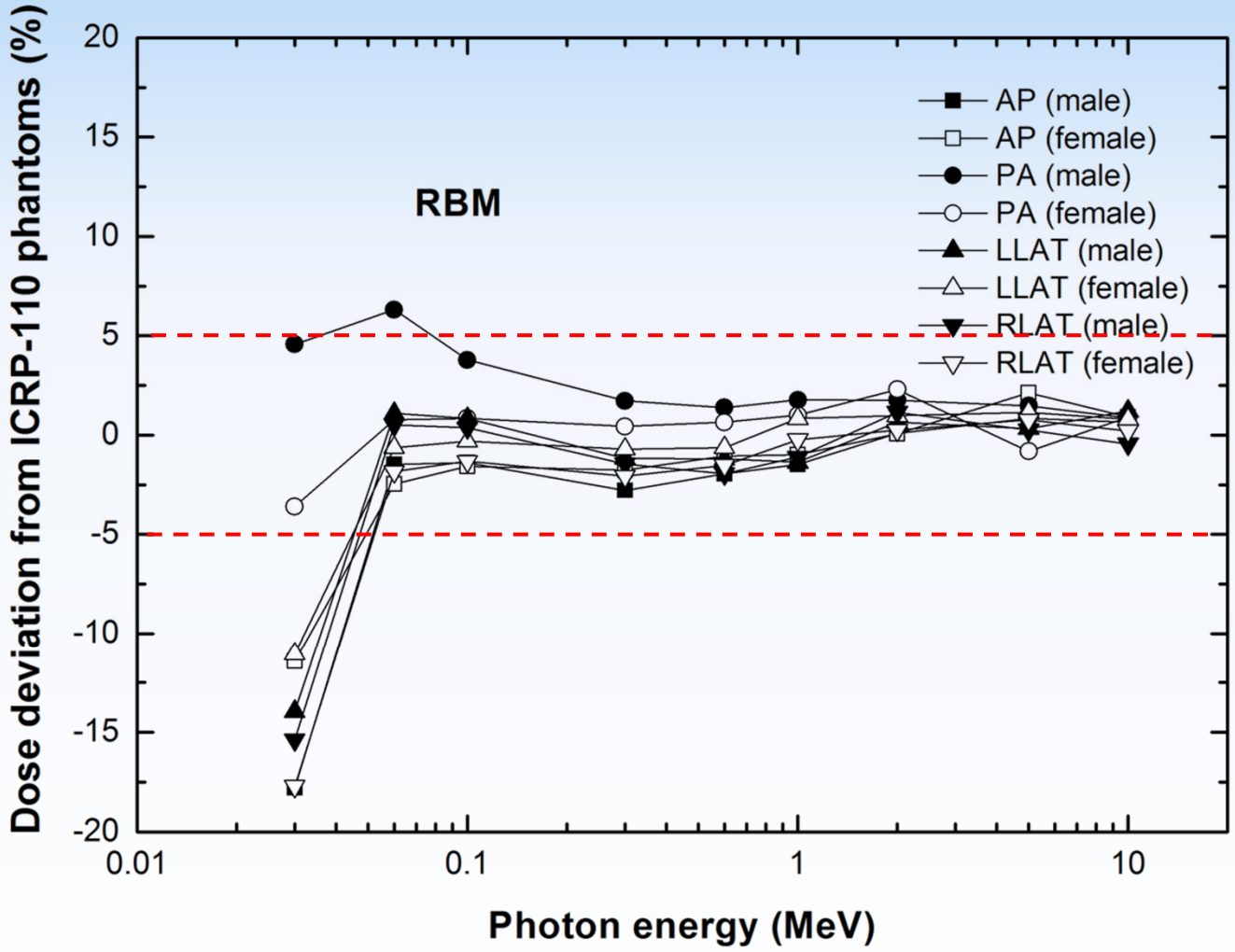


Eye Lens – External Electrons

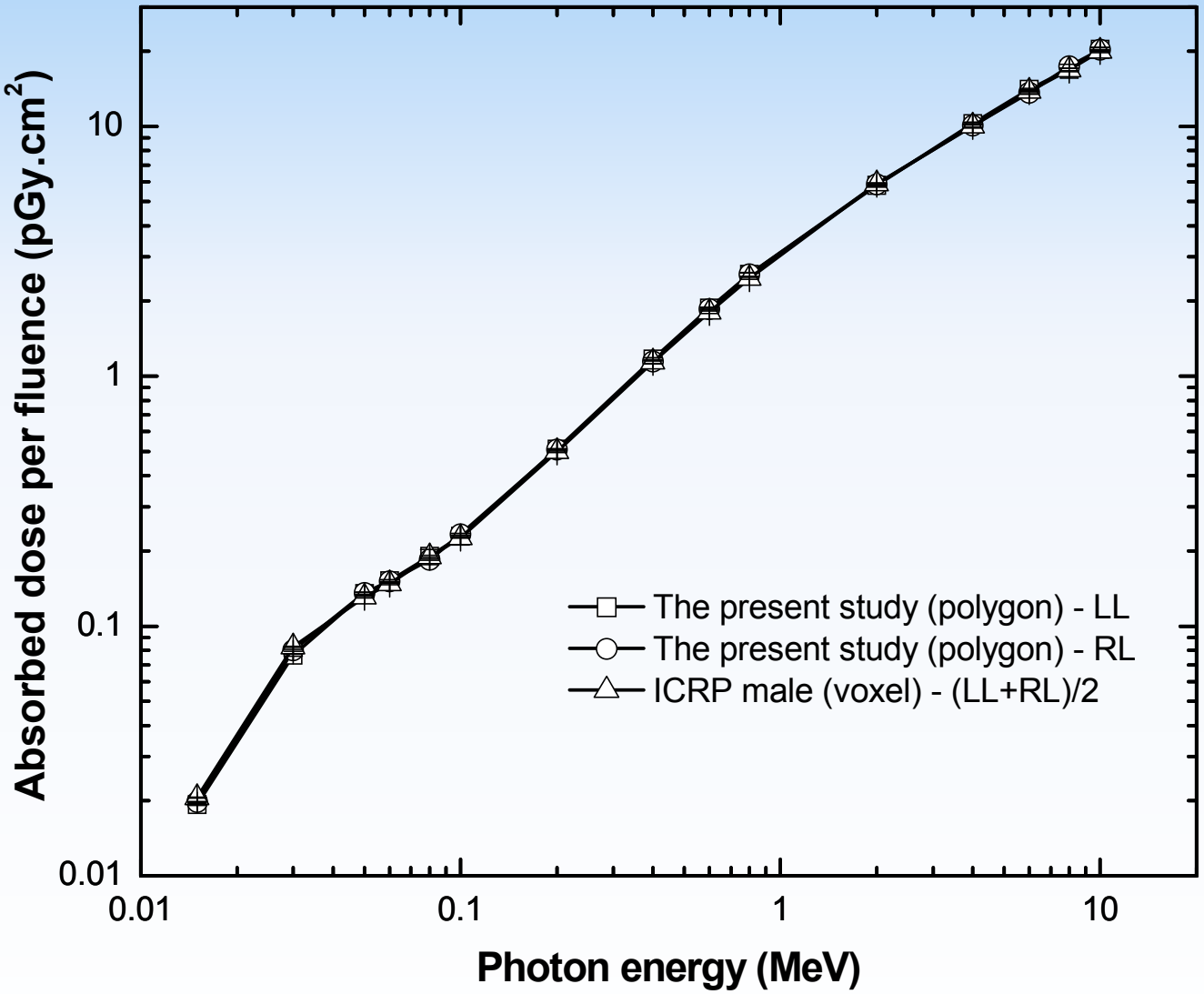


RBM – External Photons

$$\textbf{\textit{Deviation}}\ (\%) = \frac{\textit{Dose (new)} - \textit{Dose (ICRP-110)}}{\textit{Dose (ICRP-110)}} \times 100$$

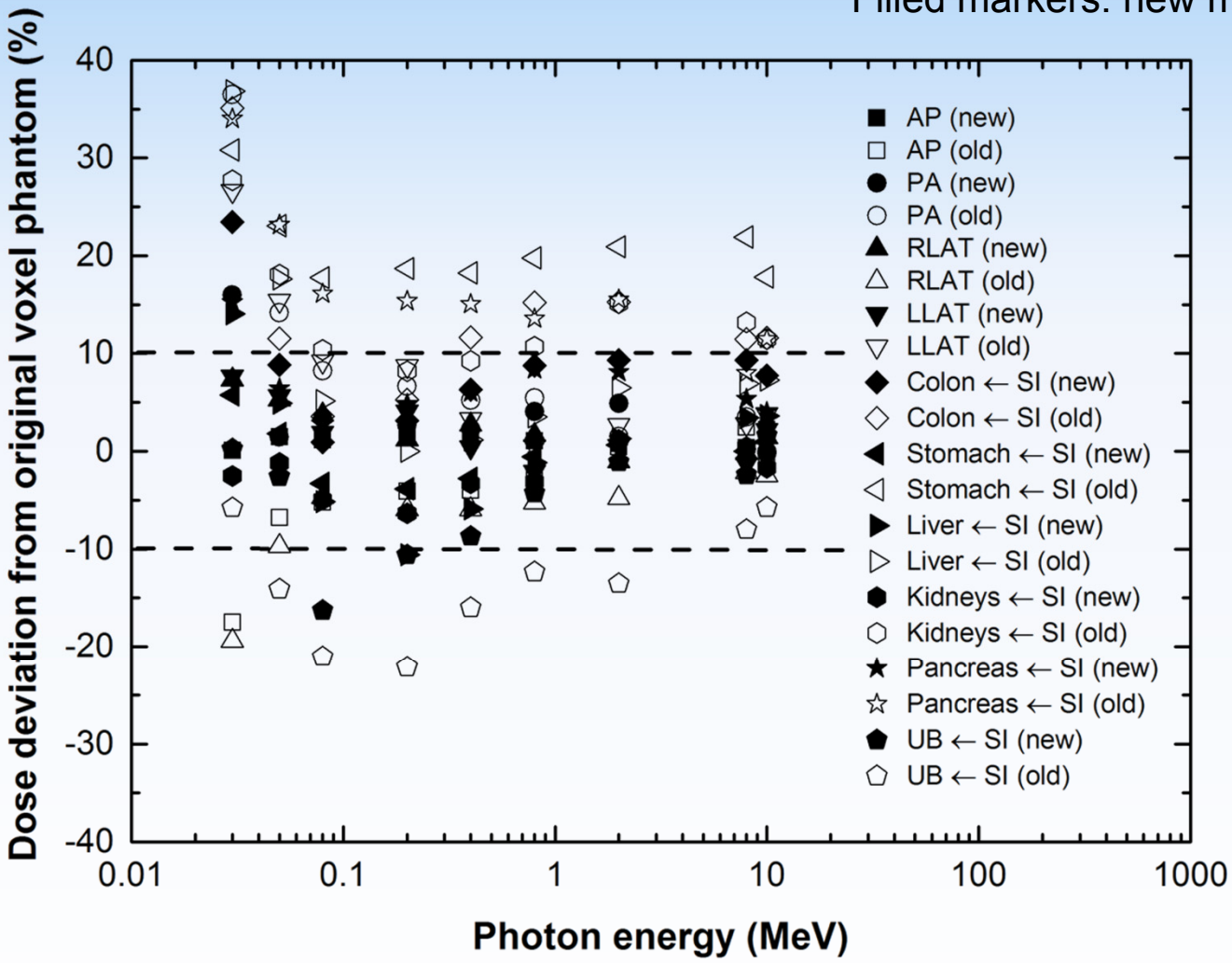


Lymphatic Nodes – External Photons

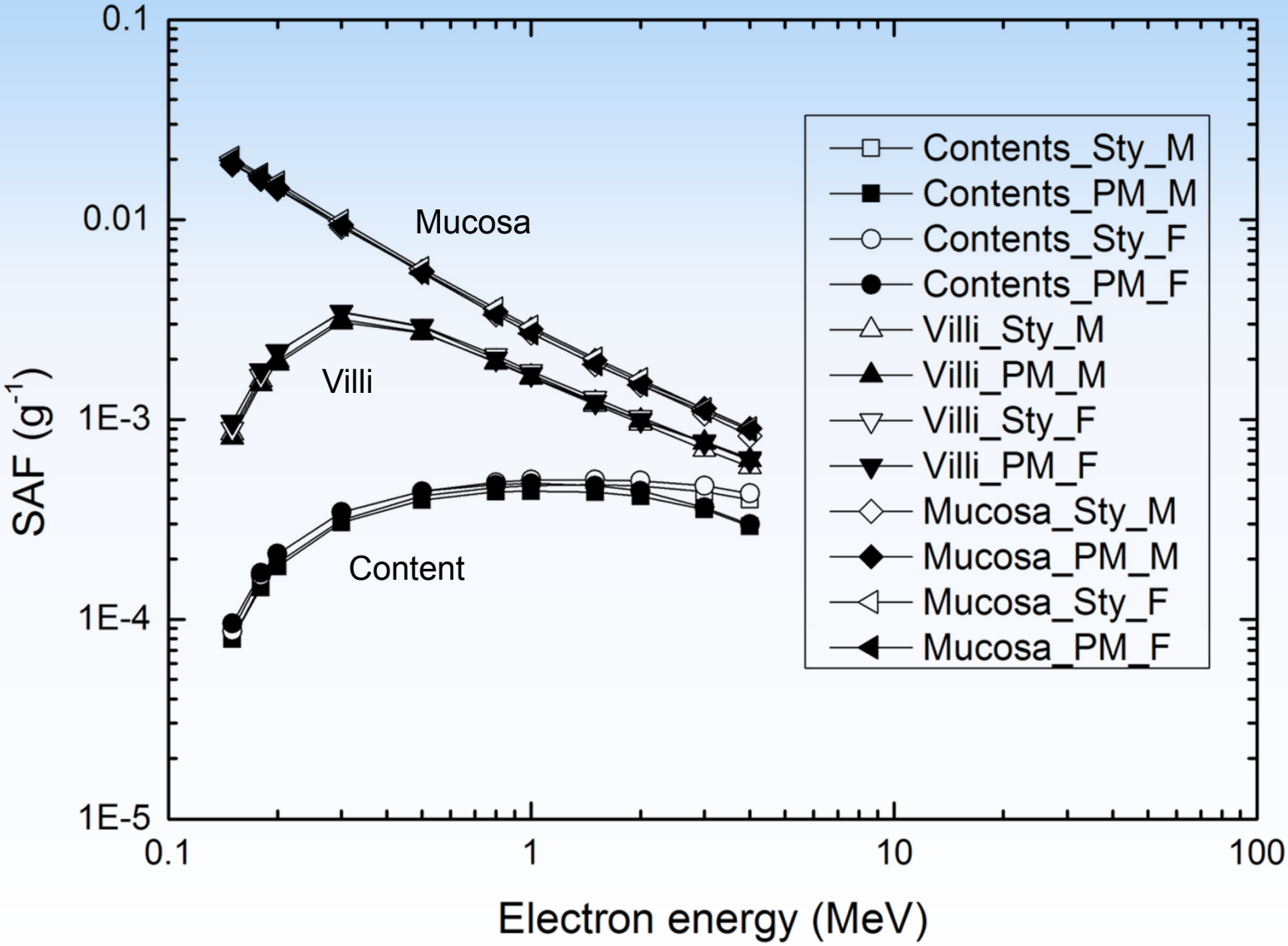


Small Intestine – External Electrons

* Filled markers: new model



Dose Result – Small Intestine – Electron SAF Values



Conclusion

Conclusion

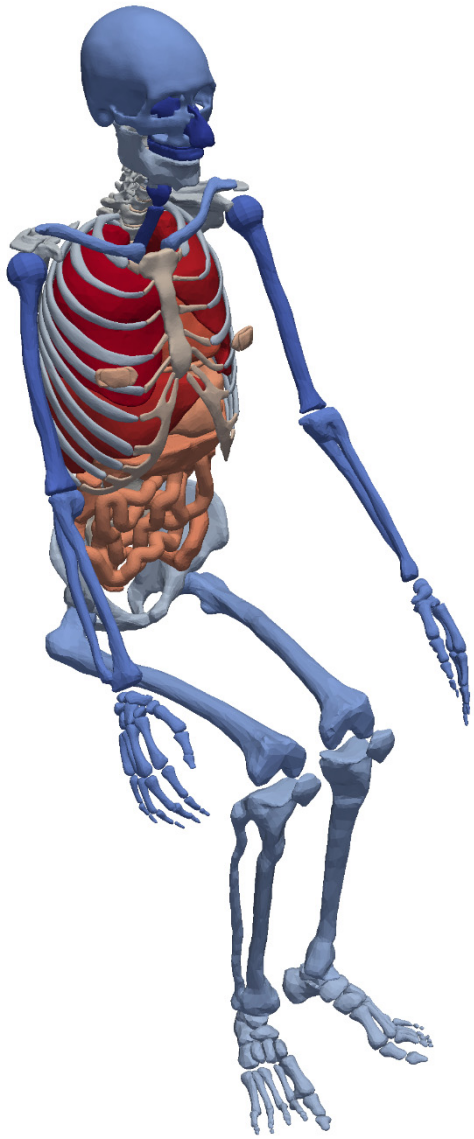
- Currently developing polygon-mesh (PM) versions of the ICRP-110 reference phantoms.

- 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 (8-50 μm)* in the respiratory and alimentary tract organs, and skin; and
  - *detailed and more accurate models* for skeletal system, eye lens, lymphatic nodes, blood vessels, hands, and feet.

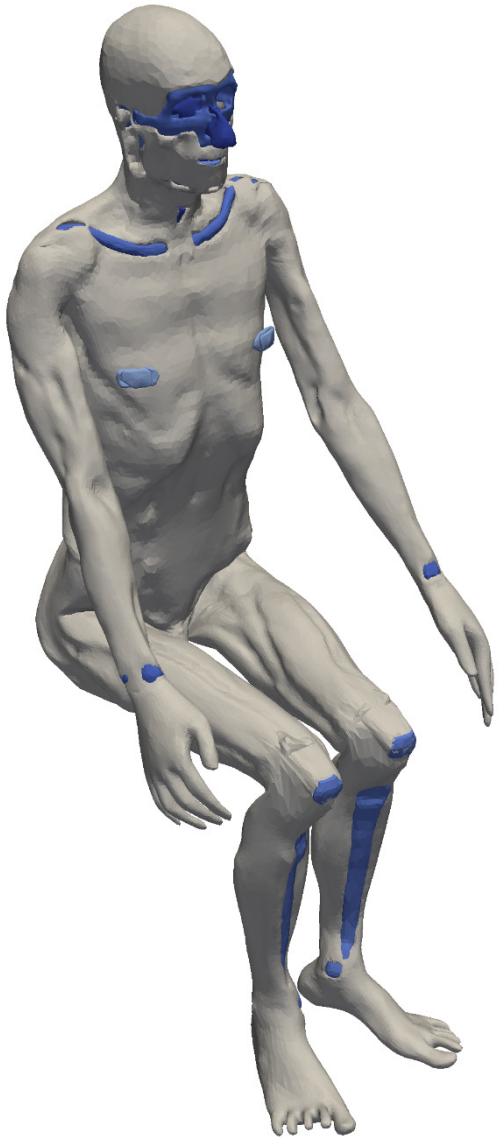
- The developed phantoms will provide
  - ***"very similar "dose values*** with the current ICRP-110 reference phantoms for highly-penetrating radiations (photons ≥ 0.03 MeV, neutrons), and
  - ***"more accurate" or "correct "dose values*** for weakly-penetrating radiations (electrons, ions, low energy photons < 0.03 MeV)
- The project will provide ***"all-in-one," deformable, high-quality ICRP phantoms*** to the ICRP and radiation protection community.
- Additionally, the developed phantoms will be ***deformable***, ***providing different postures*** (e.g., walking and sitting postures) to calculate dose coefficients for emergency exposure scenarios, which is planned for the next term of the ICRP (2017-2021).

Sitting Posture

Internal



Muscle

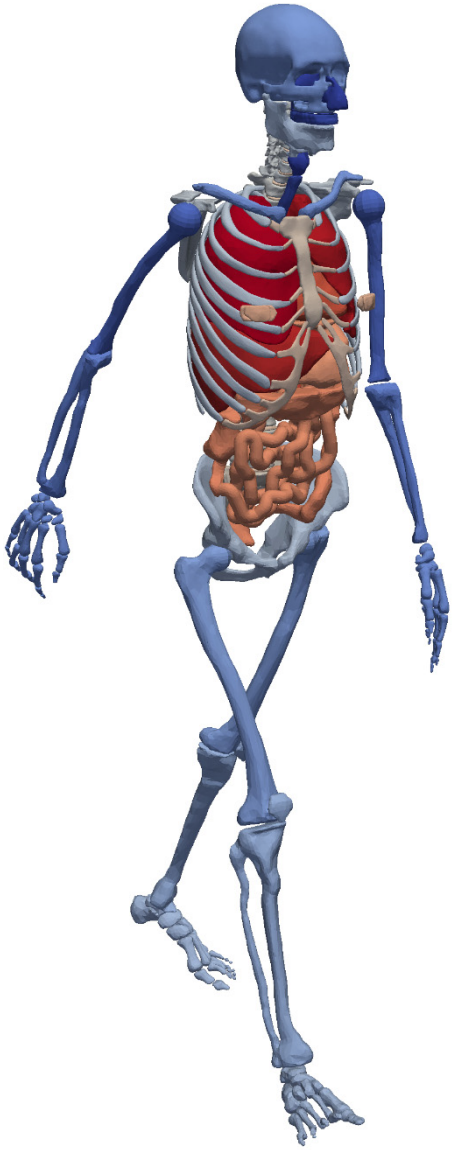


Skin

Polygon-mesh version of ICRP-110 male phantom

Walking Posture

Internal



Muscle

Skin

Thank you!

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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)

Estimation of required computation time

Calculation conditions:

1. Phantom
   - Polygon-mesh version of ICRP-110 male and female phantoms
   - Including muscle, but not including blood vessels

2. Monte Carlo code and computer
   - Geant4 10.01.p02 (latest version)
   - Physics model: FTFP_BERT_HP_LIV package
   - Cut value: 0.7 mm (photons and electron), 0 mm (neutron and proton)
   - CPU: Intel(R) Xeon(R) CPU E5-2697 v2 @ 2.70GHz (a single core)

3. Particle geometry and energy
   - Photon, electron, and neutron
   - AP geometry
   - 3 energies (0.01 MeV, 10 MeV, 10 GeV) for photon and electron
   - 10^{-9} MeV added for neutron

4. Target uncertainty in DC: 2% (as per ICRP-116 Paragraphs 121-123)

Required computation time – photon

Target tissue		Number of particles required			Computation time required (min)		
		0.01 MeV	10 MeV	10 GeV	0.01 MeV	10 MeV	10 GeV
RBM	M	4.50×10^{8}	3.15×10^{5}	2.47×10^{5}	520 (±20)	4.6 (±0.03)	7.0 (±0.04)
	F	1.46×10^{9}	4.93×10^{5}	4.07×10^{5}	1584 (±100)	6.3 (±0.1)	11 (±0.4)
Colon	M	1.86×10^{11}	5.04×10^{6}	6.59×10^{5}	2.15 (±0.08) $\times 10^{5}$	73 (±0.5)	19 (±0.1)
	F	7.24×10^{9}	4.74×10^{6}	1.36×10^{6}	7.8 (±0.499) $\times 10^{3}$	60 (±0.7)	38 (±1)
Lung	M	1.47×10^{10}	9.86×10^{5}	1.12×10^{6}	1.70 (±0.07) $\times 10^{4}$	14 (±0.1)	32 (±0.2)
	F	5.08×10^{10}	4.76×10^{5}	7.96×10^{5}	5.52 (±0.35) $\times 10^{4}$	6.1 (±0.1)	22 (±1)
Stomach	M	7.71×10^{11}	1.69×10^{6}	2.53×10^{6}	8.92 (±0.34) $\times 10^{5}$	24 (±0.2)	71 (±0.4)
	F	3.69×10^{10}	5.08×10^{6}	2.18×10^{6}	4.01 (±0.25) $\times 10^{4}$	65 (±0.8)	60 (±2)
Breast	M	3.12×10^{6}	4.70×10^{7}	3.70×10^{7}	3.6 (±0.1)	679 (±4)	1048 (±7)
	F	3.23×10^{5}	2.58×10^{6}	3.81×10^{6}	0.4 (±0.02)	33 (±0.4)	105 (±4)
Remainder tissues	M	1.47×10^{8}	2.25×10^{6}	9.10×10^{5}	169 (±7)	33 (±0.2)	26 (±0.2)
	F	2.41×10^{8}	1.57×10^{6}	1.04×10^{6}	262 (±17)	20 (±0.2)	29 (±1)
Gonads	M	3.63×10^{7}	2.94×10^{7}	1.44×10^{7}	42 (±2)	425 (±3)	409 (±3)
	F	-	5.78×10^{7}	1.41×10^{7}	-	738 (±9)	389 (±14)
Bladder	M	-	4.01×10^{6}	5.85×10^{6}	-	58 (±0.4)	166 (±1)
	F	3.98×10^{8}	1.23×10^{7}	1.21×10^{7}	433 (±27)	157 (±2)	334 (±12)
Oesophagus	M	3.84×10^{10}	6.22×10^{6}	5.25×10^{6}	4.44 (±0.17) $\times 10^{4}$	90 (±0.6)	149 (±1)
	F	3.93×10^{11}	9.94×10^{6}	1.96×10^{6}	4.27 (±0.27) $\times 10^{5}$	127 (±2)	54 (±1)
Liver	M	3.63×10^{10}	5.83×10^{5}	1.21×10^{6}	4.20 (±0.16) $\times 10^{4}$	8.4 (±0.1)	34 (±0.2)
	F	1.79×10^{10}	9.52×10^{5}	5.90×10^{5}	1.94 (±0.12) $\times 10^{4}$	12 (±0.1)	16 (±1)
Thyroid	M	1.06×10^{9}	2.96×10^{7}	1.55×10^{7}	1224 (±47)	428 (±3)	438 (±3)
	F	1.66×10^{9}	3.15×10^{7}	3.47×10^{7}	1804 (±114)	402 (±5)	958 (±35)
Endosteum	M	3.47×10^{8}	2.48×10^{5}	1.42×10^{5}	401 (±15)	3.6 (±0.02)	4.0 (±0.03)
	F	1.01×10^{9}	2.34×10^{5}	2.00×10^{5}	1096 (±70)	3.0 (±0.04)	5.5 (±0.2)
Brain	M	-	6.29×10^{5}	9.78×10^{5}	-	9.1 (±0.1)	28 (±0.2)
	F	-	6.85×10^{5}	4.51×10^{5}	-	8.7 (±0.1)	12 (±0.5)
Salivary glands	M	3.80×10^{8}	6.41×10^{6}	1.19×10^{7}	440 (±17)	93 (±0.6)	337 (±2)
	F	6.18×10^{10}	8.12×10^{6}	6.00×10^{6}	6.71 (±0.43) $\times 10^{4}$	104 (±1)	166 (±6)
Skin	M	4.75×10^{3}	1.31×10^{5}	5.95×10^{4}	5.49 (±0.21) $\times 10^{-3}$	1.9 (±0.01)	1.7 (±0.01)
	F	3.42×10^{3}	7.64×10^{4}	4.66×10^{4}	3.72 (±0.24) $\times 10^{-3}$	0.97 (±0.01)	1.3 (±0.05)
Effective dose		7.93×10^{5}	6.02×10^{5}	2.56×10^{5}	**0.91 (±0.03)**	**8.12 (±0.06)**	**7.12 (±0.17)**

Required computation time – electron

Target tissue		Number of particles required			Computation time required (min)		
		0.01 MeV	10 MeV	10 GeV	0.01 MeV	10 MeV	10 GeV
RBM	M	-	1.18×10^5	6.24×10^4	-	3.9 (±0.02)	12 (±0.3)
	F	-	7.68×10^4	4.83×10^4	-	2.6 (±0.01)	9.5 (±0.2)
Colon	M	-	1.50×10^6	4.8×10^5	-	50 (±0.3)	93 (±2)
	F	-	2.97×10^5	2.13×10^5	-	10 (±0.03)	42 (±1)
Lung	M	-	1.65×10^5	2.04×10^5	-	5.5 (±0.03)	40 (±1)
	F	-	1.92×10^5	4.09×10^4	-	6.5 (±0.02)	8.0 (±0.2)
Stomach	M	-	9.81×10^5	2.33×10^6	-	33 (±0.2)	452 (±11)
	F	-	8.00×10^5	3.18×10^5	-	27 (±0.1)	62 (±2)
Breast	M	-	8.76×10^5	1.04×10^6	-	29 (±0.2)	201 (±5)
	F	5.29×10^{11}	1.47×10^5	1.06×10^5	$9.12\ (\pm 0.38) \times 10^5$	5.0 (±0.02)	21 (±0.5)
Remainder tissues	M	-	4.14×10^5	3.29×10^4	-	14 (±0.1)	260 (±6)
	F	-	7.19×10^5	1.33×10^5	-	24 (±0.1)	26 (±0.7)
Gonads	M	-	1.54×10^6	5.81×10^6	-	52 (±0.3)	1124 (±27)
	F	-	1.04×10^8	7.85×10^6	-	3520 (±12)	1539 (±39)
Bladder	M	-	1.09×10^6	3.32×10^5	-	37 (±0.2)	64 (±2)
	F	-	8.86×10^5	7.63×10^5	-	30 (±0.1)	150 (±4)
Oesophagus	M	-	2.49×10^6	1.44×10^6	-	83 (±0.5)	279 (±7)
	F	-	4.13×10^6	9.03×10^5	-	140 (±0.5)	177 (±4)
Liver	M	-	9.02×10^4	2.95×10^5	-	3.0 (±0.02)	57 (±1)
	F	-	2.63×10^5	9.46×10^4	-	8.9 (±0.03)	19 (±0.5)
Thyroid	M	-	2.28×10^6	4.23×10^6	-	76 (±0.4)	820 (±20)
	F	-	2.90×10^6	2.76×10^6	-	98 (±0.3)	541 (±14)
Endosteum	M	-	3.82×10^4	3.29×10^4	-	1.3 (±0.01)	6.4 (±0.2)
	F	-	3.81×10^4	3.67×10^4	-	1.3 (±0.004)	7.2 (±02)
Brain	M	-	3.44×10^5	1.41×10^5	-	12 (±0.1)	27 (±0.7)
	F	-	9.48×10^5	4.48×10^5	-	32 (±0.1)	88 (±2)
Salivary glands	M	-	2.41×10^6	1.52×10^6	-	81 (±0.5)	294 (±7)
	F	-	6.86×10^6	1.11×10^6	-	232 (±0.8)	217 (±5)
Skin	M	2.93×10^3	1.70×10^4	5.0×10^3	$5.40\ (\pm 1.28) \times 10^{-3}$	0.57 (±0.003)	0.97 (±0.02)
	F	2.30×10^3	8.79×10^3	9.87×10^3	$3.96\ (\pm 0.16) \times 10^{-3}$	0.3 (±0.001)	1.9(±0.05)
Effective dose		2.34×10^3	1.33×10^5	1.03×10^5	**$4.68\ (\pm 0.65) \times 10^{-3}$**	**4.45 (±0.02)**	**20 (±0.5)**

Required computation time – neutron

170 days (single core) – multi-core, VRT (implicit capture)

Target tissue		Number of particles required				Computation time required (min)			
		1x 10^{-9} MeV	0.01 MeV	10 MeV	10 GeV	1x 10^{-9} MeV	0.01 MeV	10 MeV	10 GeV
RBM	M	2.16 x 10^6	1.42 x 10^6	1.75 x 10^5	1.89 x 10^5	144 (±1)	139 (±2)	11 (±0.1)	12 (±0.7)
	F	2.52 x 10^6	1.05 x 10^6	2.98 x 10^5	2.71 x 10^5	178 (±2)	105 (±1)	17 (±0.1)	15 (±0.5)
Colon	M	8.42 x 10^6	6.64 x 10^6	2.16 x 10^6	7.02 x 10^6	562 (±6)	650 (±12)	136 (±2)	458 (±26)
	F	3.06 x 10^7	1.12 x 10^7	4.36 x 10^6	1.90 x 10^6	2160 (±23)	1119 (±14)	253 (±2)	105 (±3)
Lung	M	5.15 x 10^6	3.88 x 10^6	1.90 x 10^5	8.07 x 10^5	344 (±4)	380 (±7)	12 (±0.2)	53 (±3)
	F	4.70 x 10^6	4.38 x 10^6	3.40 x 10^5	1.21 x 10^6	332 (±4)	436 (±5)	20 (±0.2)	67 (±2)
Stomach	M	8.55 x 10^6	5.75 x 10^6	3.13 x 10^6	2.96 x 10^6	571 (±6)	562 (±10)	197 (±3)	193 (±11)
	F	2.81 x 10^7	1.41 x 10^7	3.18 x 10^6	2.12 x 10^6	1980 (±21)	1409 (±17)	184 (±2)	118 (±4)
Breast	M	1.90 x 10^8	4.26 x 10^7	1.85 x 10^7	4.3 x 10^7	1.27 (±0.01) x10^4	4167 (±74)	1159 (±15)	2802 (±159)
	F	5.74 x 10^6	3.93 x 10^6	8.09 x 10^5	2.53 x 10^6	405 (±4)	392(±5)	47 (±0.4)	140 (±4)
Remainder tissues	M	1.42 x 10^7	4.43 x 10^6	1.73 x 10^7	8.27 x 10^5	951 (±10)	434 (±8)	1086 (±14)	54 (±3)
	F	1.00 x 10^7	8.67 x 10^6	1.44 x 10^7	9.80 x 10^5	709 (±7)	865 (±10)	838 (±7)	54 (±2)
Gonads	M	4.23 x 10^7	3.34 x 10^7	1.24 x 10^7	3.56 x 10^7	2825 (±29)	3271 (±58)	778 (±10)	2322 (±132)
	F	1.88 x 10^8	2.52 x 10^8	3.63 x 10^7	1.69 x 10^7	1.33 (±0.01) x10^4	**2.51 (±0.03) x10^4**	1947 (±16)	935 (±30)
Bladder	M	3.16 x 10^7	1.71 x 10^7	8.93 x 10^6	2.47 x 10^6	2111 (±22)	1677 (±30)	561 (±7)	161 (±9)
	F	2.38 x 10^7	1.72 x 10^7	1.09 x 10^7	2.51 x 10^6	1681 (±18)	1718 (±21)	630 (±5)	139 (±4)
Oesophagus	M	1.27 x 10^8	2.59 x 10^7	4.40 x 10^6	2.94 x 10^6	8484 (±87)	2539 (±45)	276 (±4)	192 (±11)
	F	9.16 x 10^7	6.76 x 10^7	2.84 x 10^6	6.58 x 10^6	6463 (±68)	6739 (±81)	165 (±1)	365 (±12)
Liver	M	1.78 x 10^6	3.63 x 10^6	6.25 x 10^5	6.94 x 10^5	119 (±1)	356 (±6)	39 (±0.5)	45 (±3)
	F	4.85 x 10^6	1.70 x 10^6	3.59 x 10^5	6.60 x 10^5	342 (±4)	170 (±2)	21 (±0.2)	37 (±1)
Thyroid	M	2.54 x 10^8	5.9 x 10^7	1.82 x 10^7	1.79 x 10^7	1.7 (±0.02) x10^4	5769 (±102)	1145 (±15)	1165 (±66)
	F	1.36 x 10^8	1.60 x 10^8	3.38 x 10^7	3.65 x 10^7	9589 (±101)	10159 (±200)	1958 (±16)	2023 (±64)
Endosteum	M	1.30 x 10^6	7.80 x 10^5	1.30 x 10^5	2.6 x 10^5	87 (±1)	76 (±1)	8.2 (±0.1)	17 (±1)
	F	1.63 x 10^6	7.88 x 10^5	1.41 x 10^5	1.88 x 10^5	115 (±1)	79 (±1)	8.2 (±0.07)	10 (±0.3)
Brain	M	3.58 x 10^6	5.17 x 10^6	3.52 x 10^5	9.4 x 10^5	239 (±2)	506 (±9)	22 (±0.3)	61 (±3)
	F	1.77 x 10^7	1.42 x 10^7	6.71 x 10^5	6.43 x 10^5	1252 (±13)	1413 (±17)	39 (±0.3)	36 (±1)
Salivary glands	M	7.33 x 10^7	4.61 x 10^7	3.44 x 10^6	1.87 x 10^7	4893 (±50)	4508(±80)	216 (±3)	1222 (±69)
	F	6.26 x 10^7	5.98 x 10^7	3.59 x 10^6	1.06 x 10^7	4420 (±47)	5961 (±72)	209 (±2)	590 (±19)
Skin	M	1.20 x 10^6	3.94 x 10^5	1.69 x 10^5	7.43 x 10^4	80 (±1)	39 (±0.7)	11 (±0.1)	4.8 (±0.3)
	F	1.14 x 10^6	3.17 x 10^5	1.30 x 10^5	1.11 x 10^5	81 (±1)	32 (±0.4)	7.5 (±0.06)	6.2 (±0.2)
Effective dose		4.16 x 10^6	2.00 x 10^6	7.51 x 10^5	4.84 x 10^5	283 (±2)	**198 (±2)**	**45.7 (±0.4)**	**29.8 (±1.2)**

Required time - alimentary tract / electron SAFs

Target organ	Source region		Number of particles required			Computation time required (min)		
			0.01 MeV	2 MeV	4 MeV	0.01 MeV	2 MeV	4 MeV
Oral cavity	Food	M	2.25×10^9	2.69×10^4	1.65×10^4	16,219	2.4	2.7
		F	3.23×10^9	4.24×10^4	2.03×10^4	23,886	3.3	3.0
Oesophagus	Lumen (fast)	M	1.28×10^9	1.39×10^4	1.47×10^4	11,360	1.3	2.0
		F	7.67×10^8	2.07×10^4	8.62×10^3	6,442	1.7	1.3
Stomach	Lumen	M	2.85×10^8	5.42×10^4	2.81×10^4	39	3.9	3.4
		F	2.22×10^8	1.63×10^4	3.63×10^3	29	1.0	0.4
Small intestine	Lumen	M	2.22×10^8	1.24×10^4	1.00×10^4	3,307	1.2	1.8
		F	1.41×10^8	1.22×10^4	8.99×10^3	1,695	1.1	1.4
Right colon	Lumen	M	1.28×10^9	6.38×10^4	1.54×10^4	10,461	4.5	1.9
		F	1.20×10^9	1.30×10^4	1.18×10^4	8,901	0.8	1.4
Left colon	Lumen	M	8.41×10^8	1.76×10^4	1.05×10^4	7,668	1.3	1.5
		F	9.10×10^8	5.84×10^4	9.02×10^3	7,173	3.9	1.1
Rectosigmoid	Lumen	M	2.25×10^9	1.29×10^4	1.65×10^4	10,838	0.9	2.1
		F	1.49×10^9	3.29×10^4	4.58×10^3	11,334	2.2	0.5

Physics model: Livermore
Cut value: 1 um (photon and electron)
CPU: AMD Opteron™6176 (@ 2.3 GHz, single core)