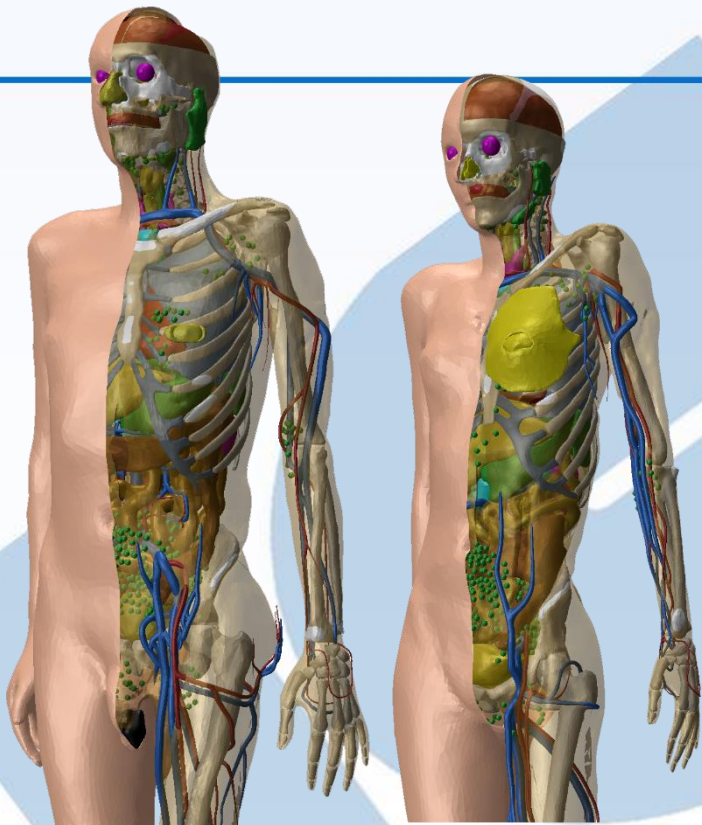


Development of Adult Mesh-type Reference Computational Phantoms



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Member, ICRP Task Group 103**

ICRP Webinar, 17 January 2023

Development Procedure

1. Phantom conversion to mesh format
 - Simple organs and tissues
 - Complex organs and tissues
 - ✓ Skeletal system
 - ✓ Small intestine
 - ✓ Lymphatic nodes
 - ✓ Eyes
 - ✓ Blood in large vessels
 - ✓ Muscle
2. Inclusion of blood in organs and tissues
3. Inclusion of thin target and source regions
 - Skin
 - Alimentary tract system
 - Respiratory tract system
 - Urinary bladder

Development Procedure – Part 1

1. Phantom conversion to mesh format

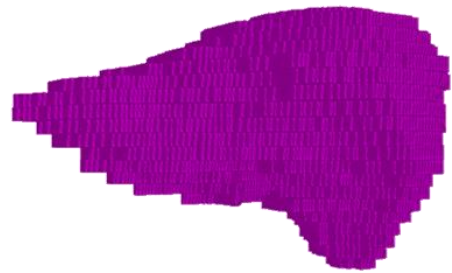
- Simple organs and tissues
- Complex organs and tissues
 - ✓ Skeletal system
 - ✓ Small intestine
 - ✓ Lymphatic nodes
 - ✓ Eyes
 - ✓ Blood in large vessels
 - ✓ Muscle

2. Inclusion of blood in organs and tissues

3. Inclusion of thin target and source regions

- Skin
- Alimentary tract system
- Respiratory tract system
- Urinary bladder

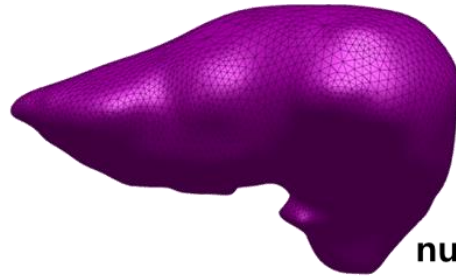
Simple Organs/Tissues



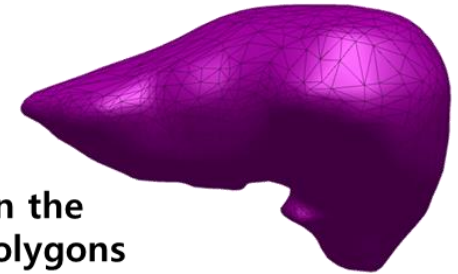
Conversion to primitive polygon-surface model



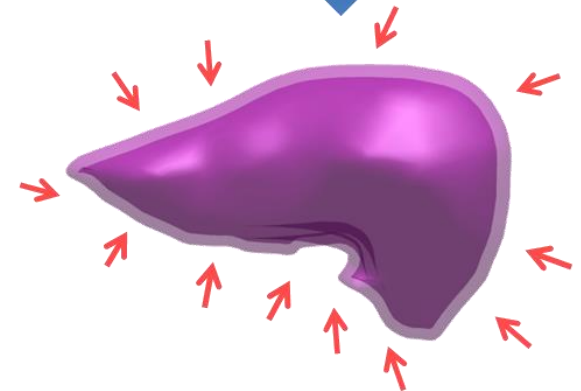
Increase in the number of polygons



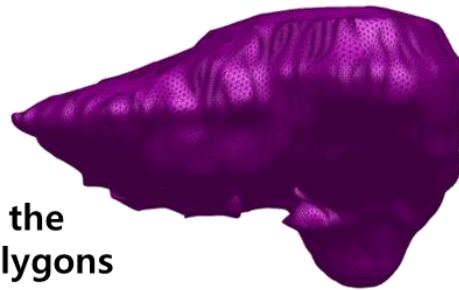
Decrease in the number of polygons



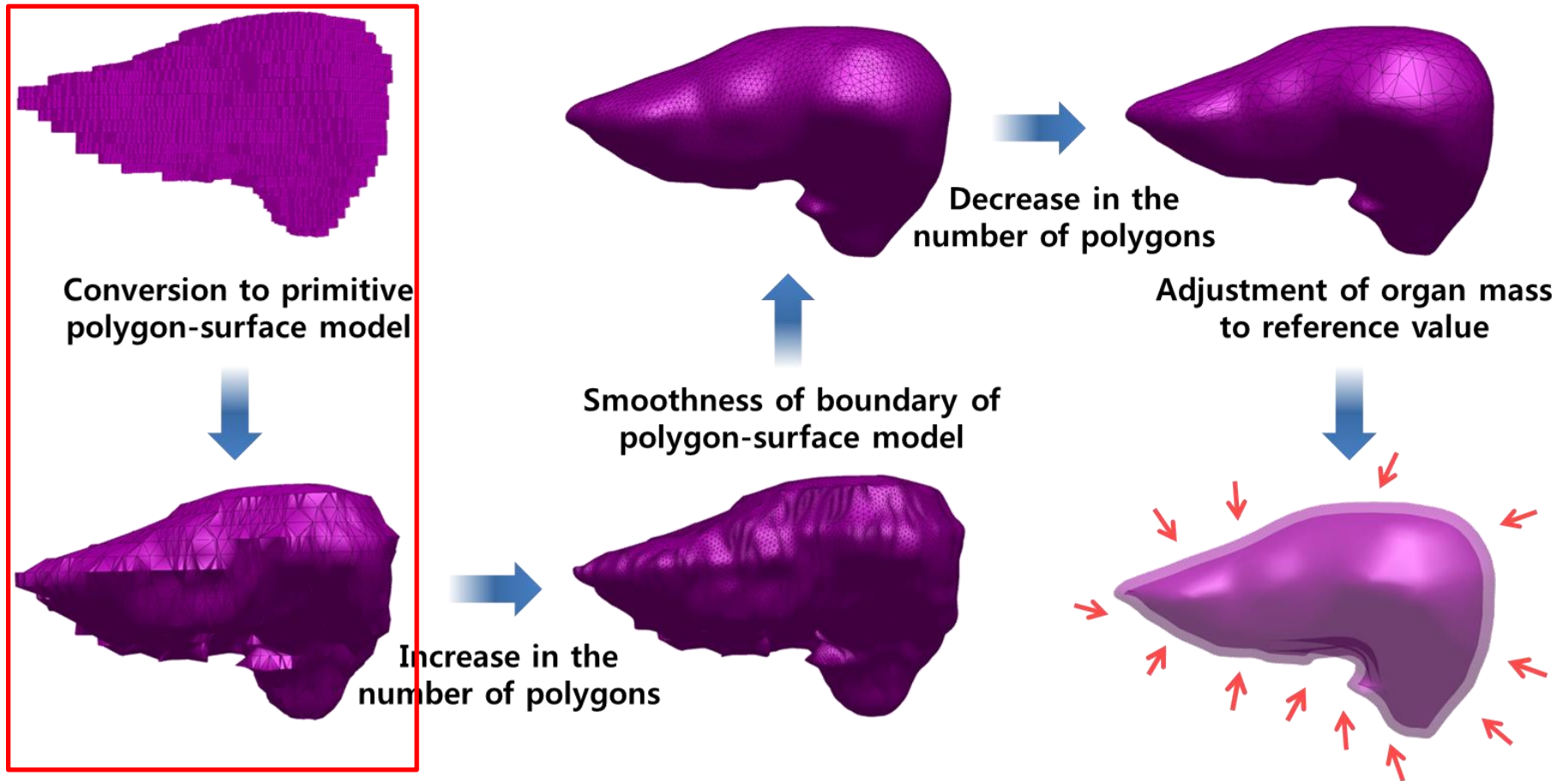
Adjustment of organ mass to reference value



Smoothness of boundary of polygon-surface model

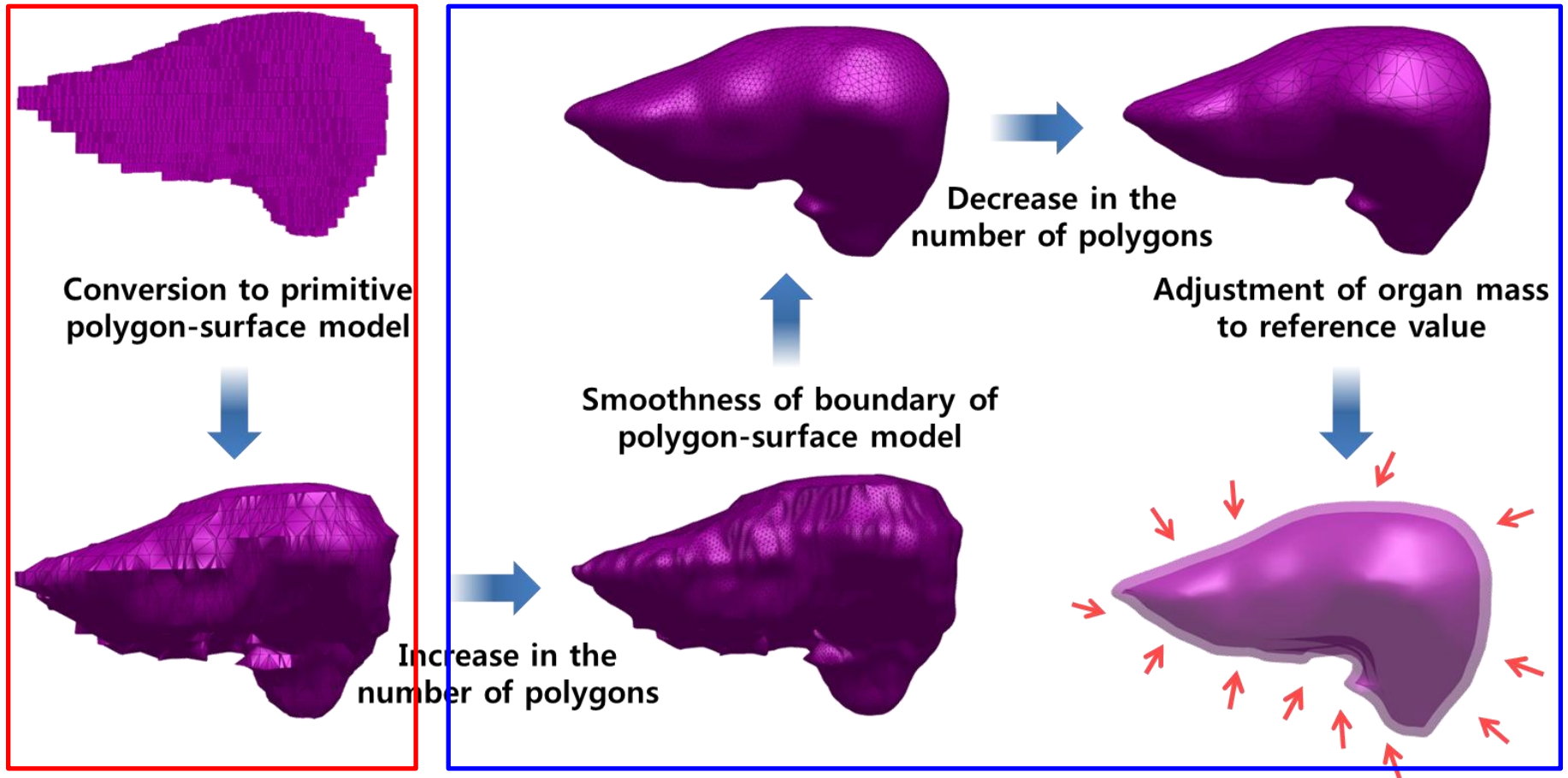


Simple Organs/Tissues



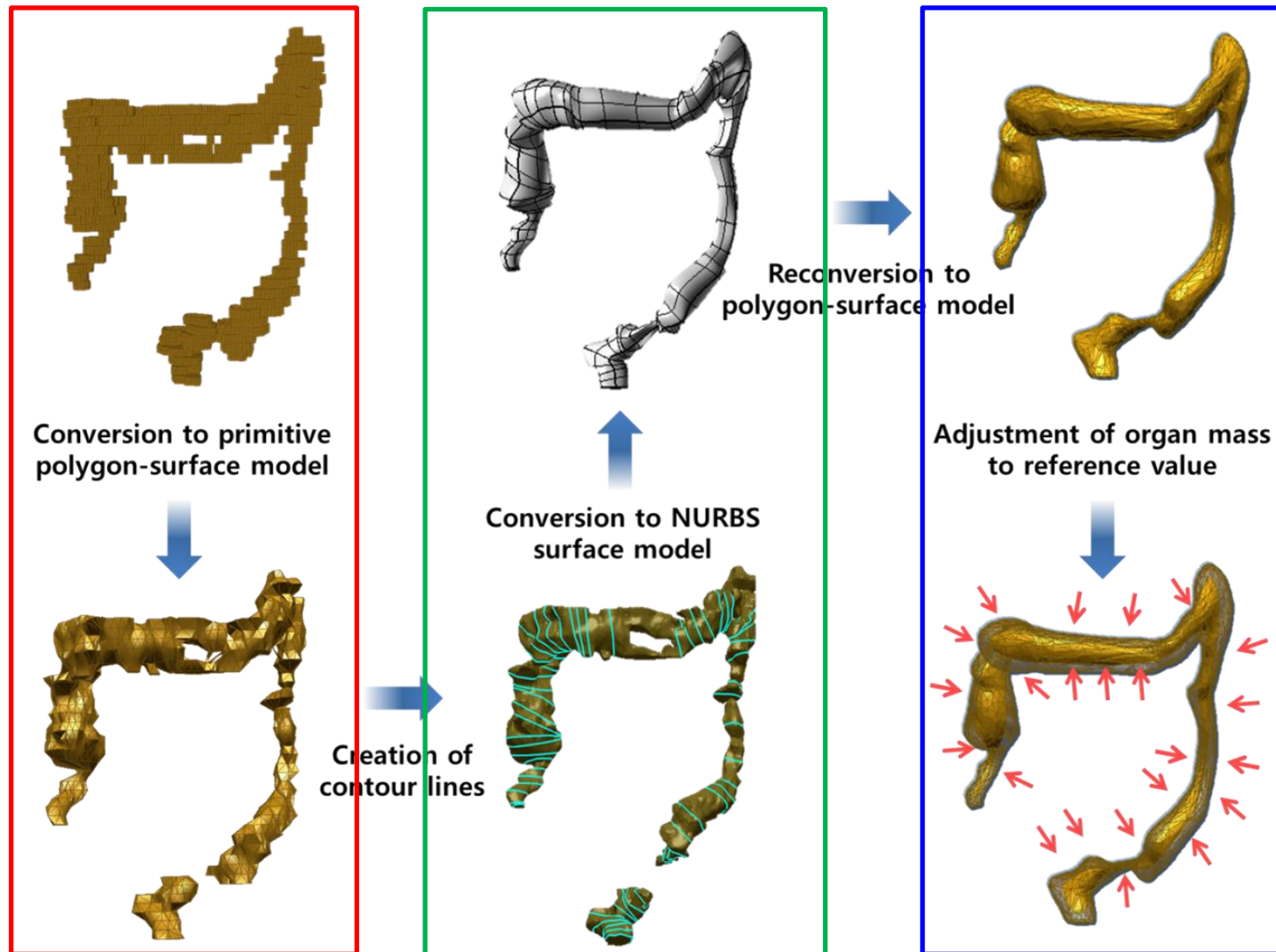
- 3D-DOCTOR (Able Software Corp., USA)

Simple Organs/Tissues



- 3D-DOCTOR (Able Software Corp., USA)
- Rapidform (INUS Technology, Korea)

Simple Organs/Tissues – Large Intestine



- 3D-DOCTOR (Able Software Corp., USA)
- Rapidform (INUS Technology, Korea)
- Rhinoceros (Robert McNeel & Associates, USA)

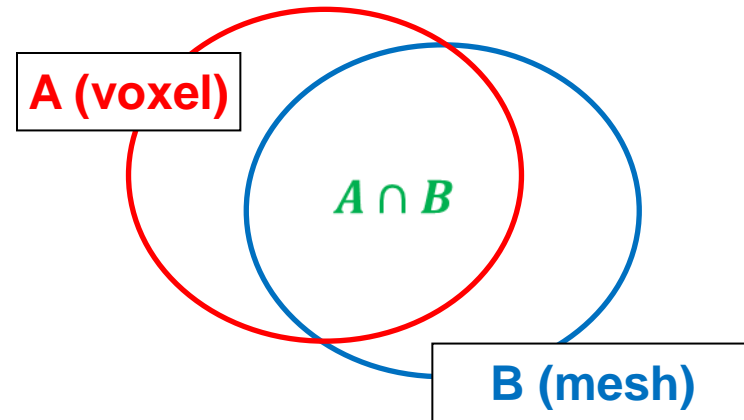
Simple Organs/Tissues – Conversion Criteria

■ Dice index (DI)

- ✓ “Volume overlap fraction”
- ✓ $DI > 95\%$ of maximum achievable Dice index (MADI)

■ Centroid distance (CD)

- ✓ Distance between the centroids of two objects in comparison
- ✓ $CD \leq 0.5$ mm

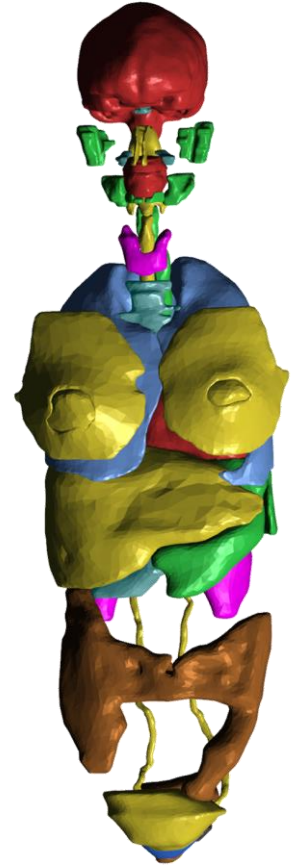
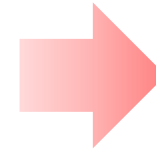
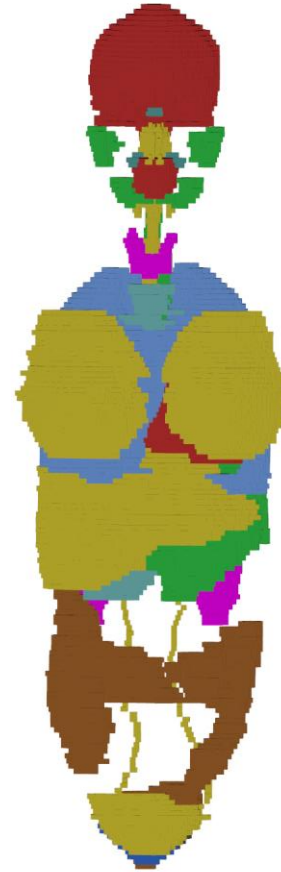
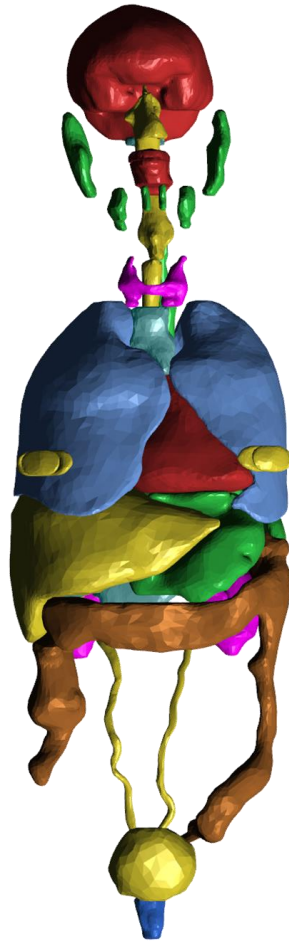
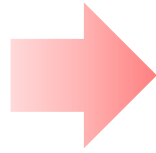
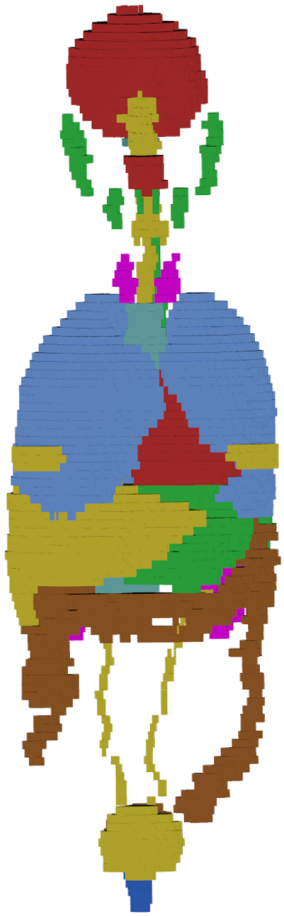


$$DI = \frac{A \cap B}{(A + B)/2}$$

Simple Organs/Tissues – Internal Organs/Tissues

Male

Female



Voxel

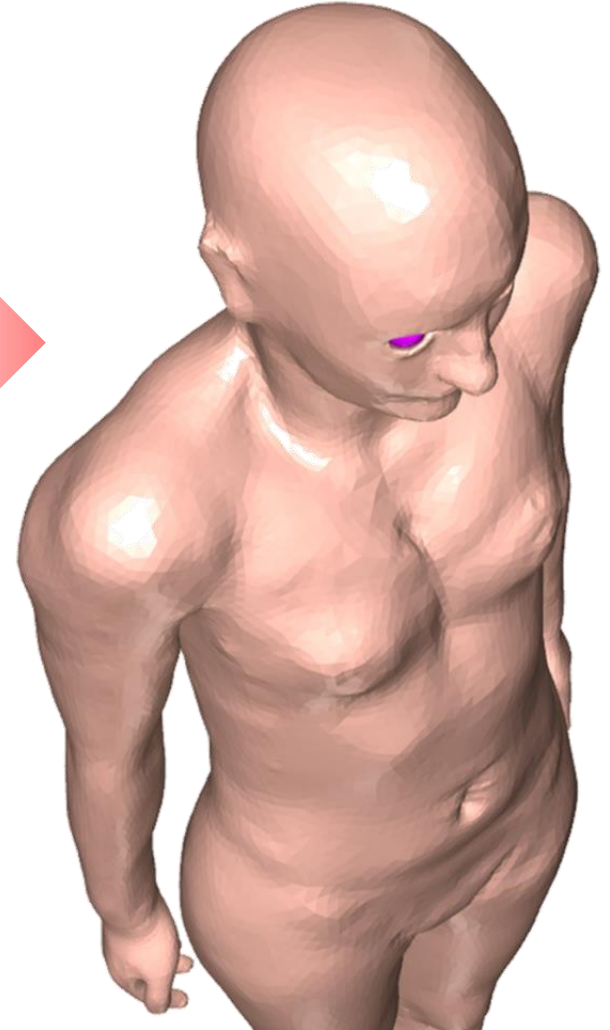
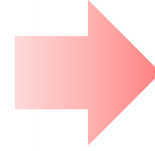
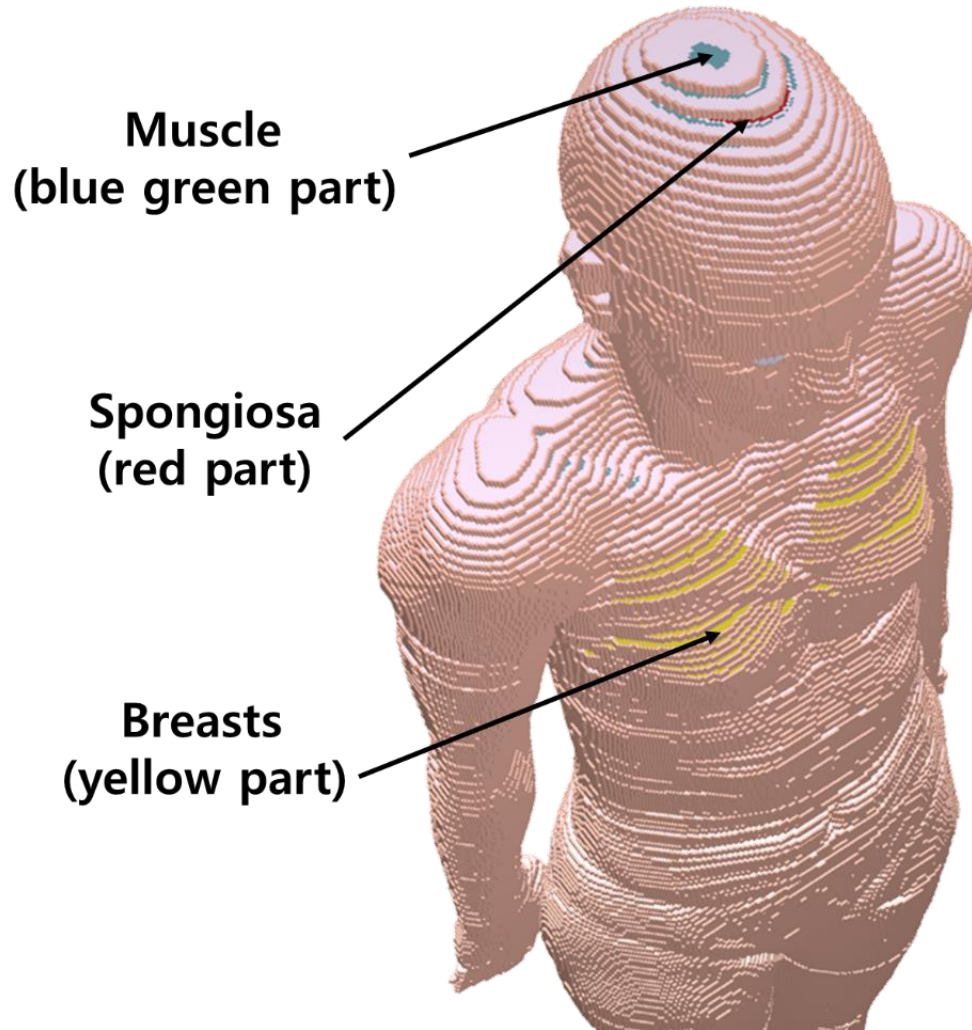
Mesh

Voxel

Mesh

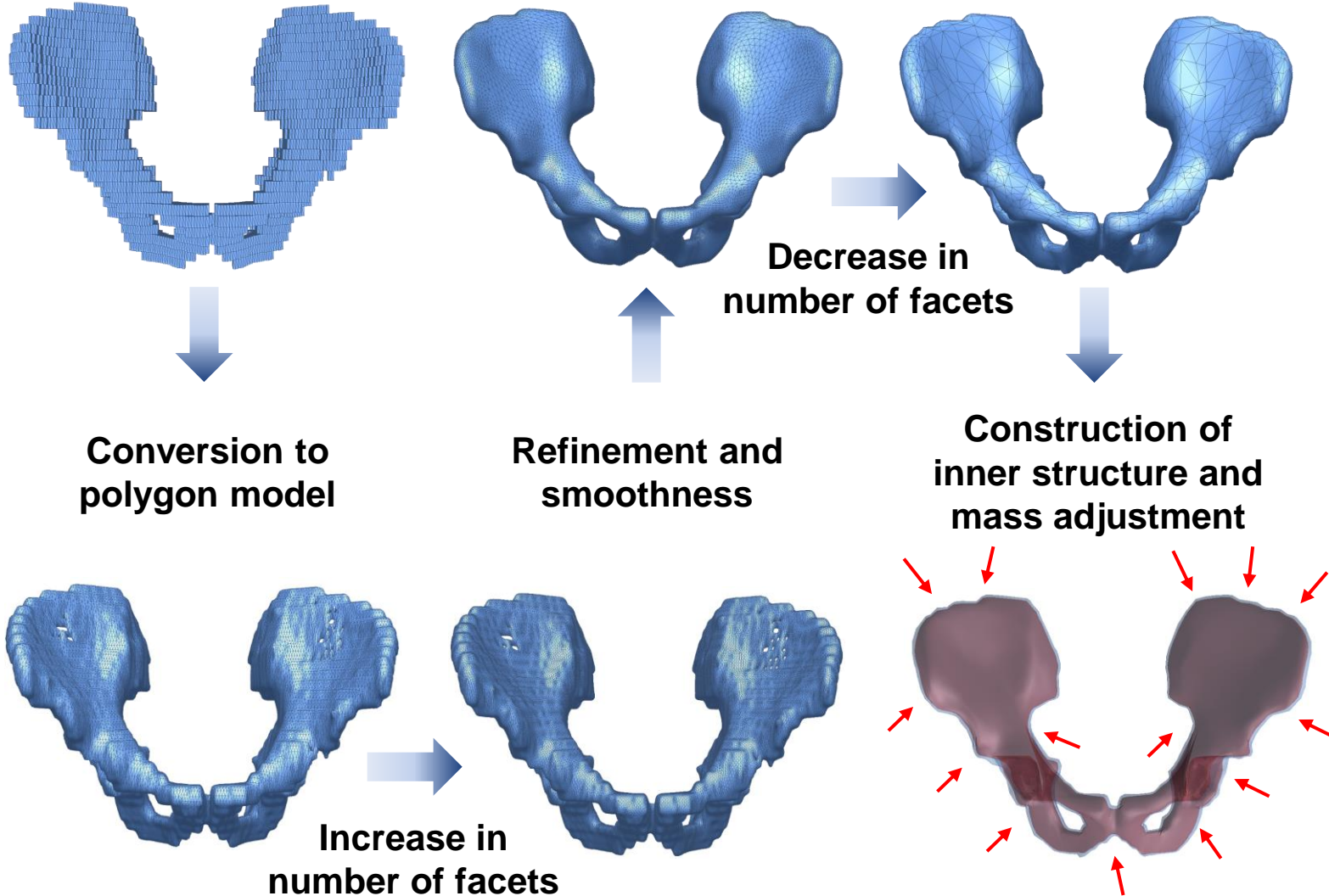
Simple Organs/Tissues - Skin

Female



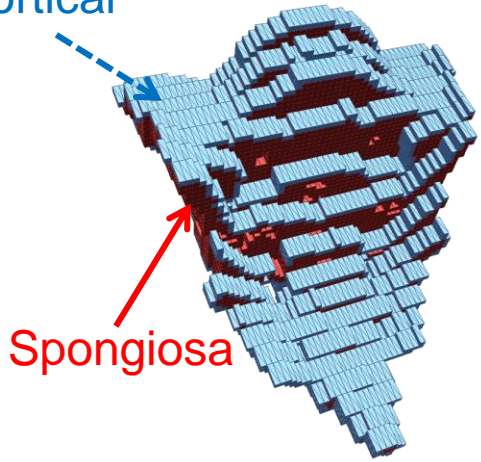
Skeletal System – Simple Bones

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



Correction – Sacrum (Female)

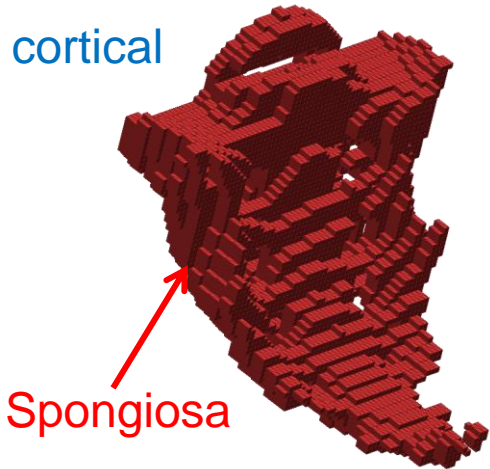
cortical



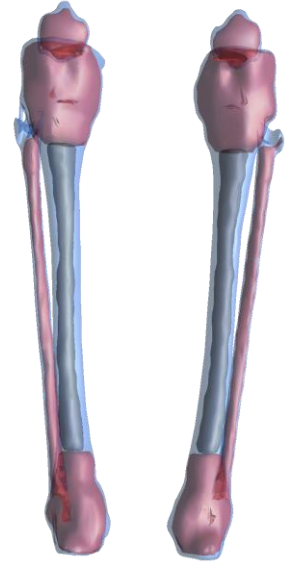
Male sacrum

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%

No cortical

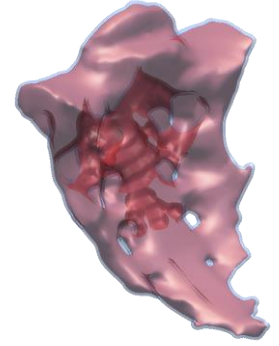


Female sacrum



Lower leg bones

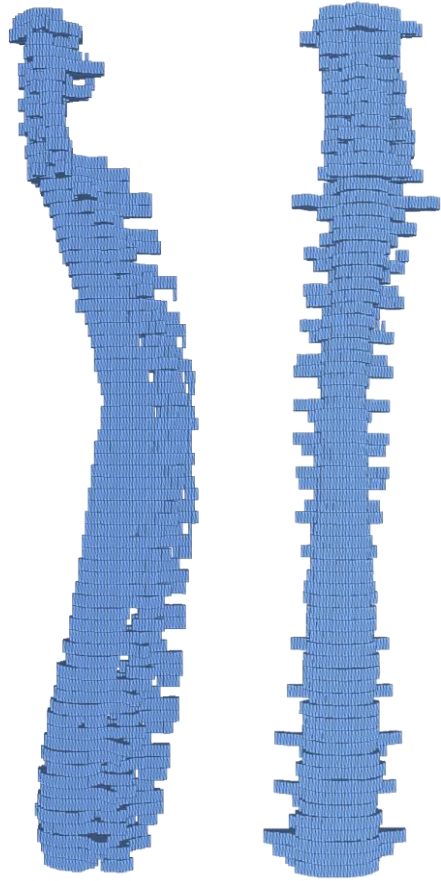
Borrow cortical bone



Sacrum

Skeletal System – Spines

Male



Voxel model

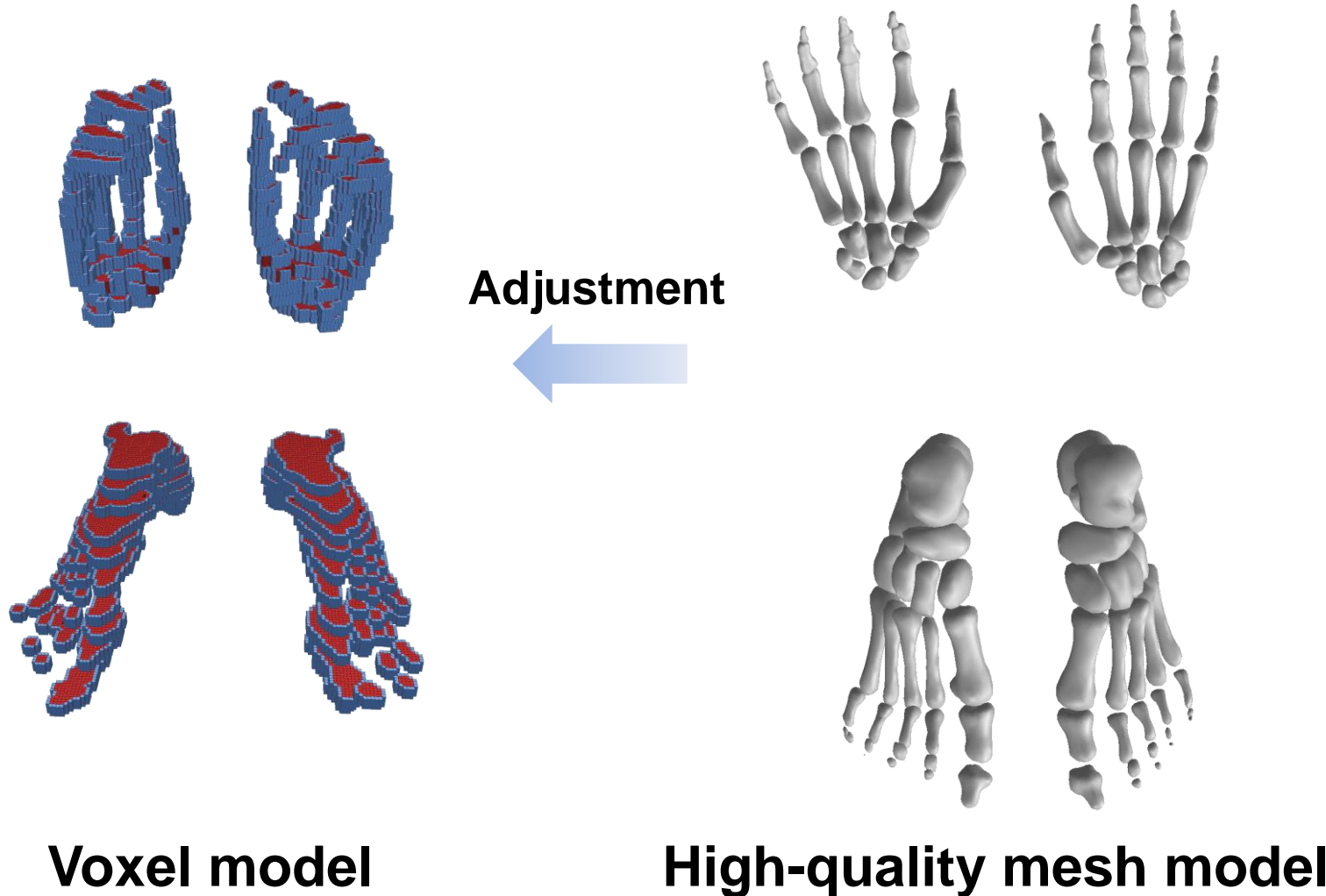
Adjustment



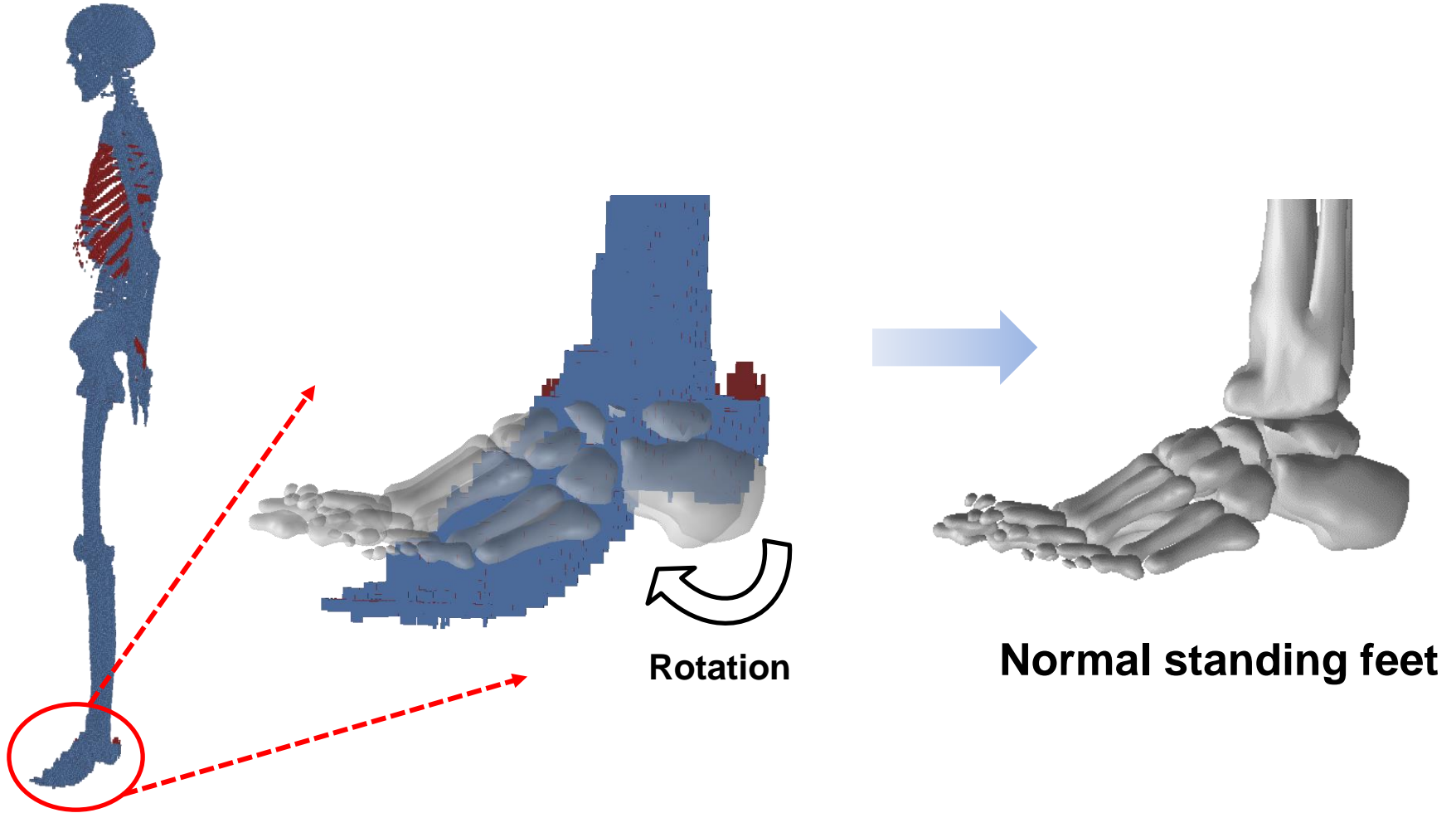
High-quality mesh model

Skeletal System – Hands and Feet

Male



Correction - Toe-standing Feet (Female)

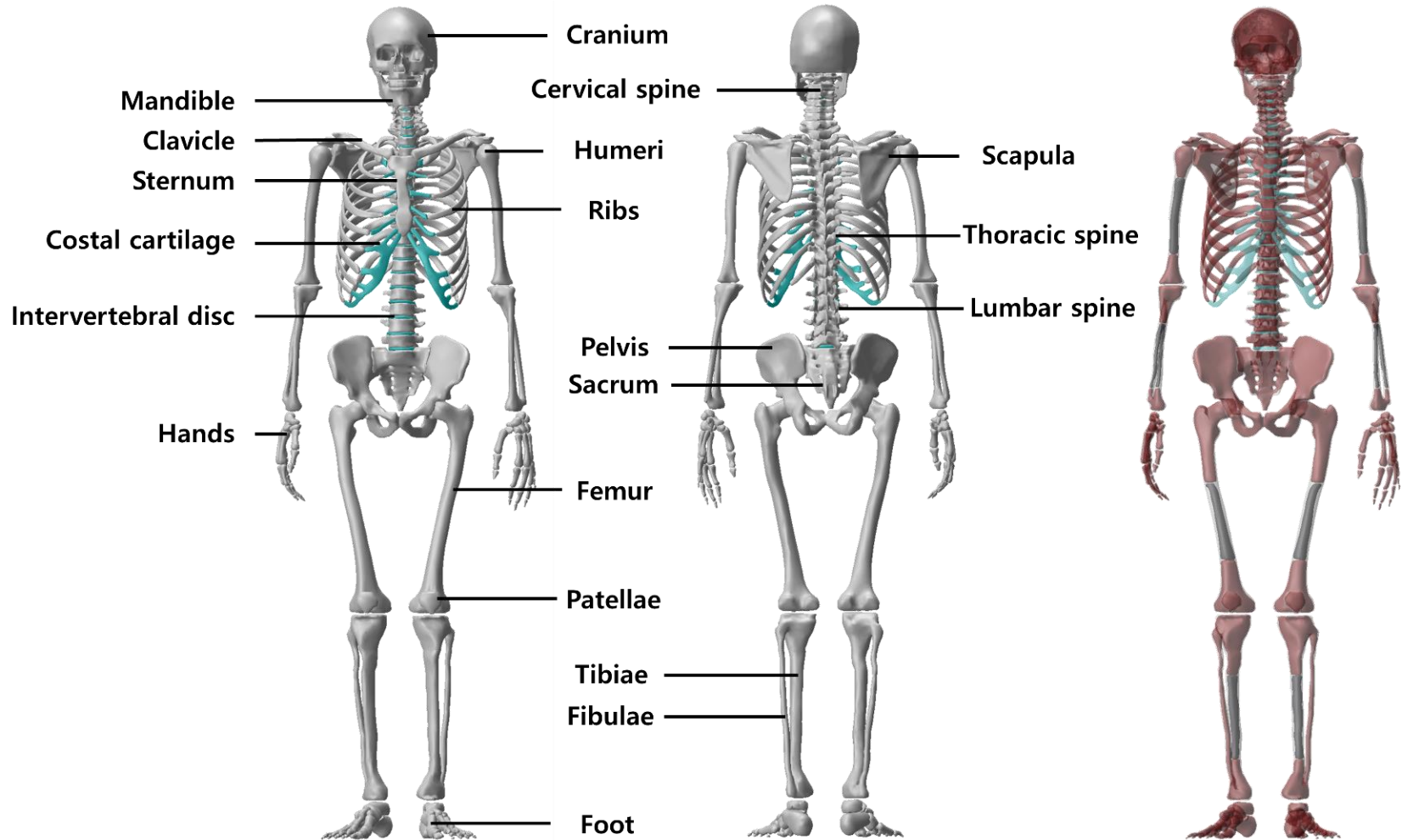


Toe-standing feet (female)

Normal standing feet

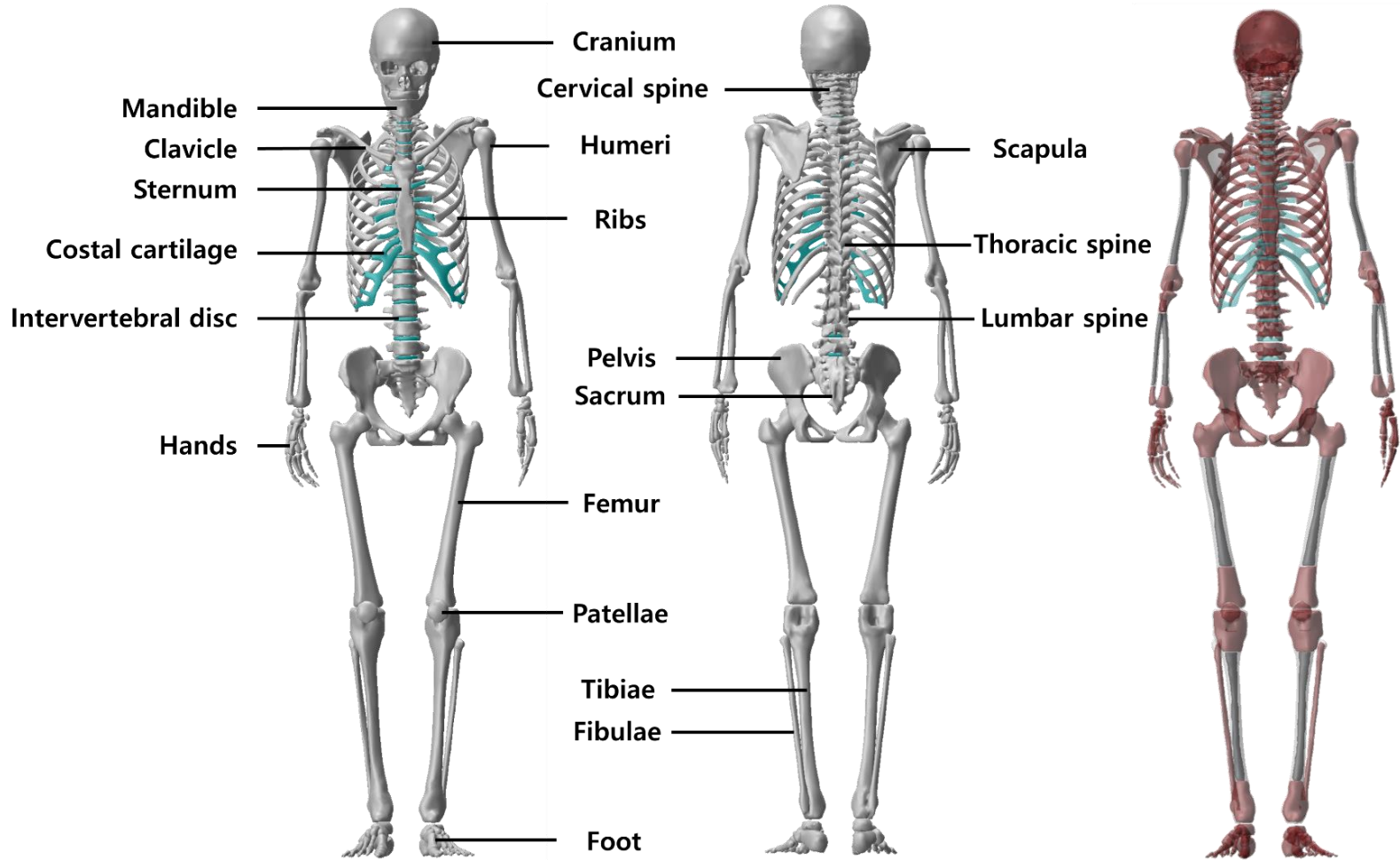
Skeletal System – Male

Male



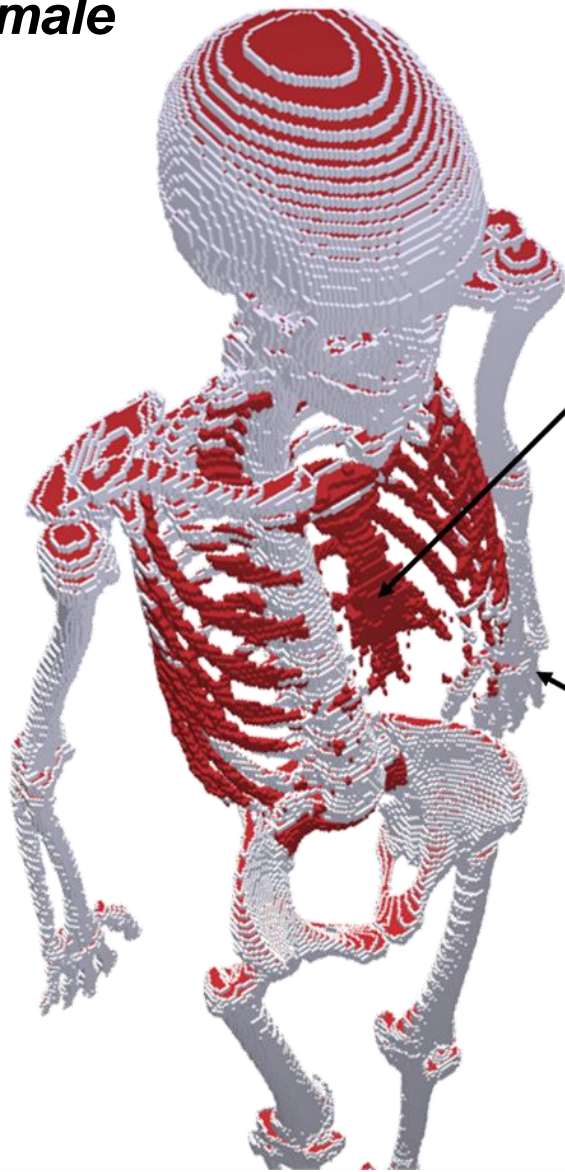
Skeletal System – Female

Female



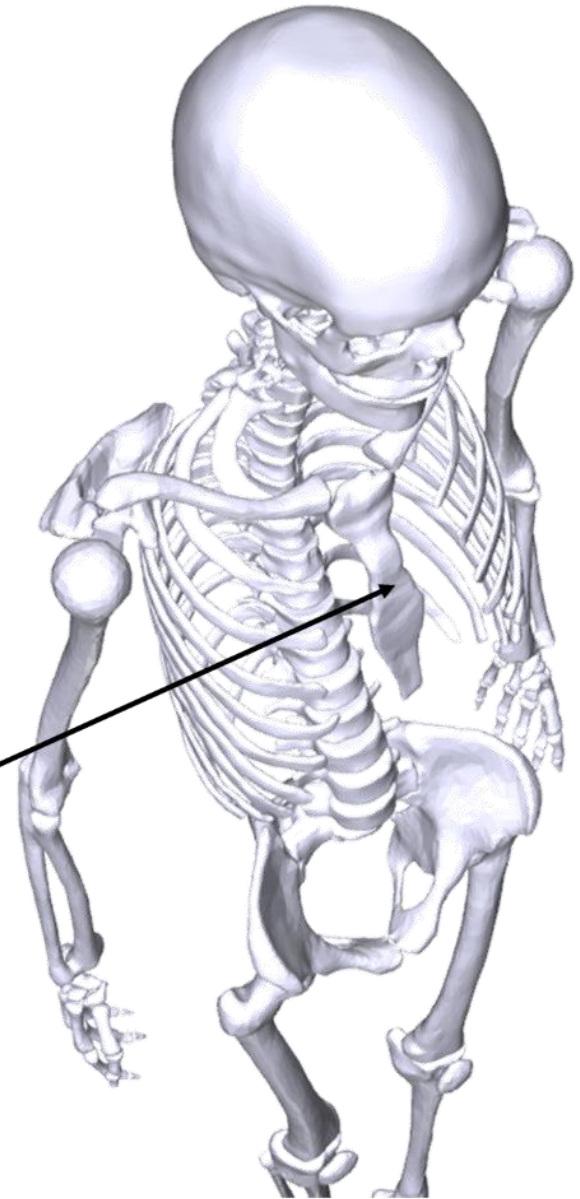
Skeletal System (Voxel vs Mesh)

Female



Spongiosa
(red part)

Cortical bone
(gray part)



Small Intestine



Voxel (male)

How?



Viewed in Complete Anatomy

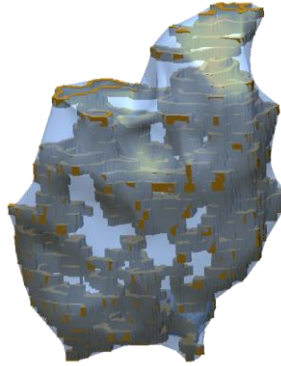


Small Intestine



Voxel (male)

1. Creation
frame

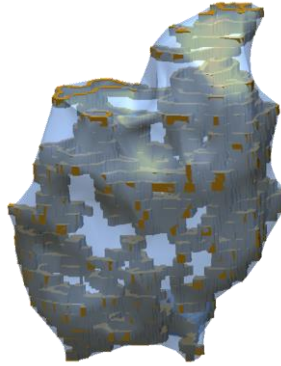


Small Intestine

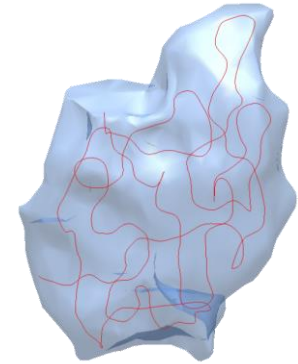


Voxel (male)

1. Creation
frame



2. Random
generation of SI
passages

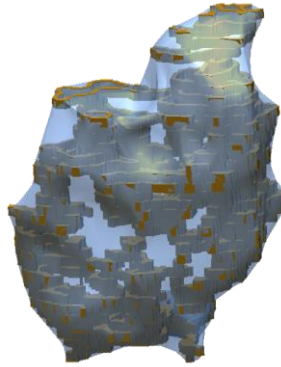


Small Intestine

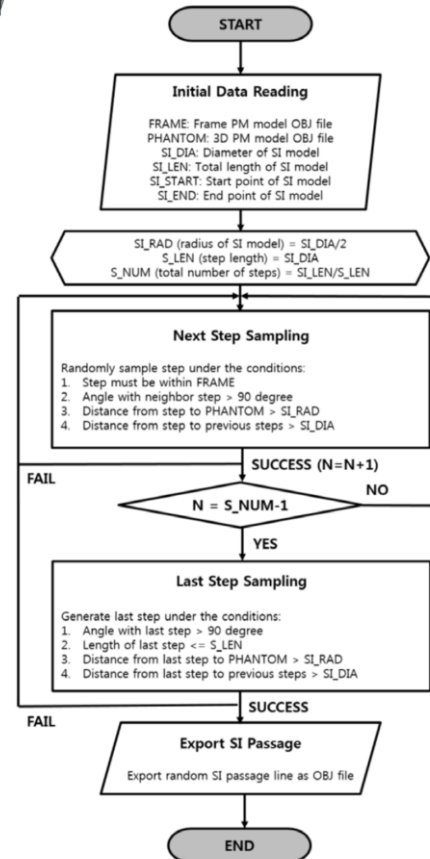
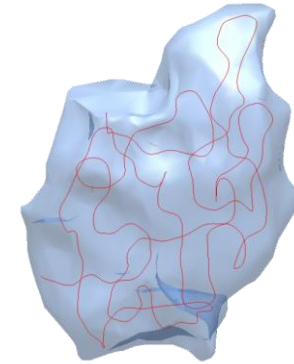


Voxel (male)

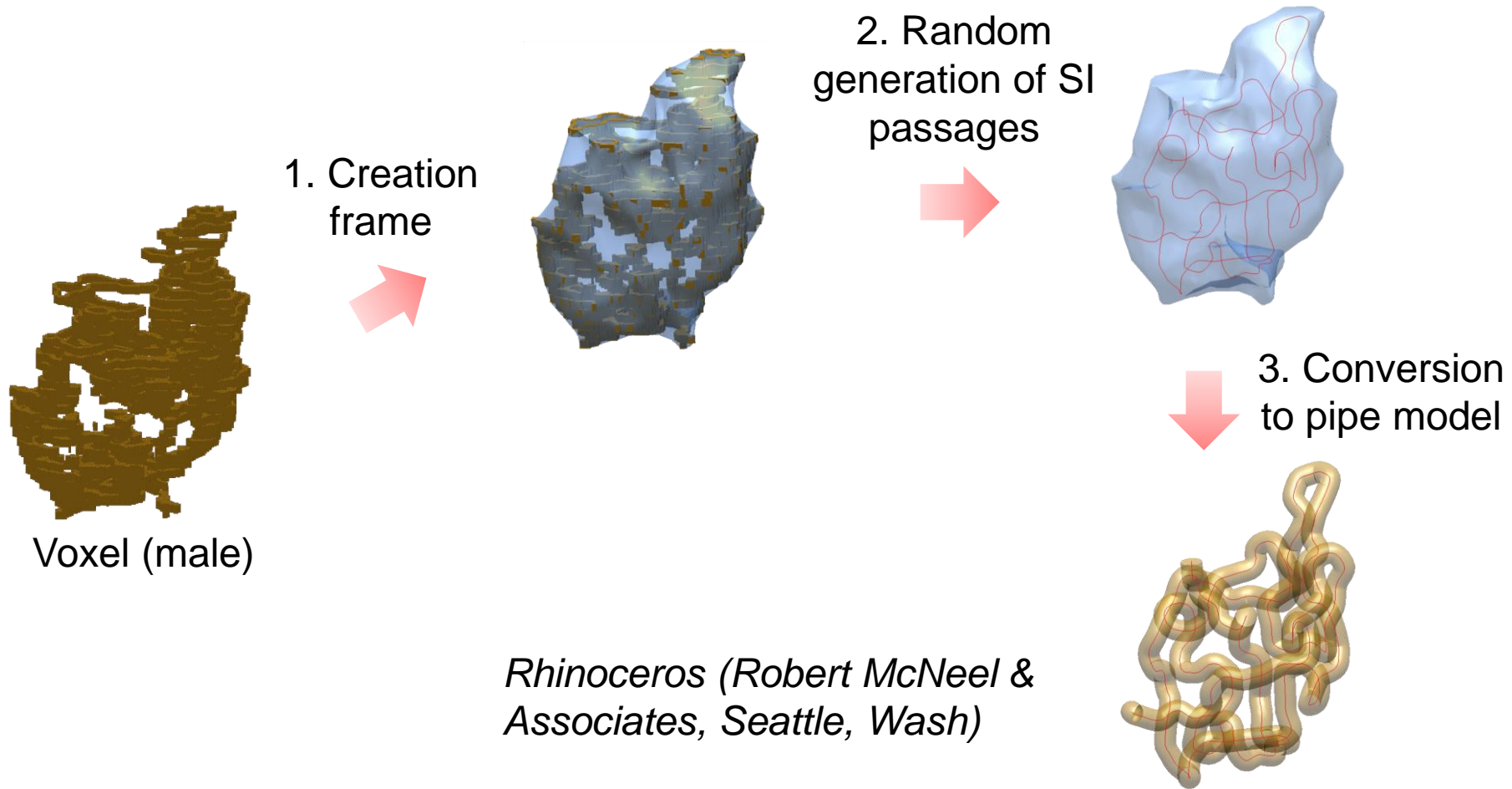
1. Creation frame



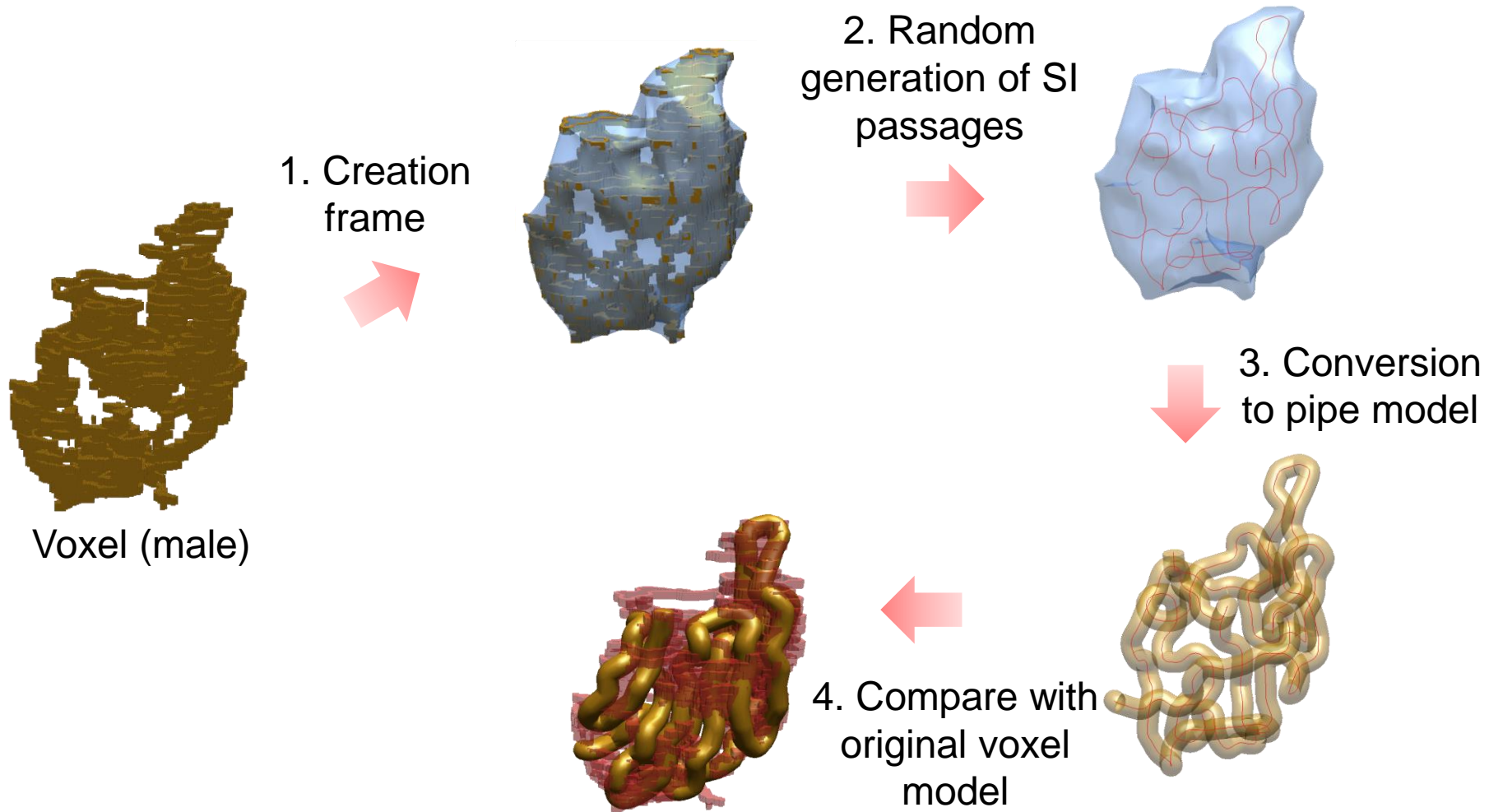
2. Random generation of SI passages



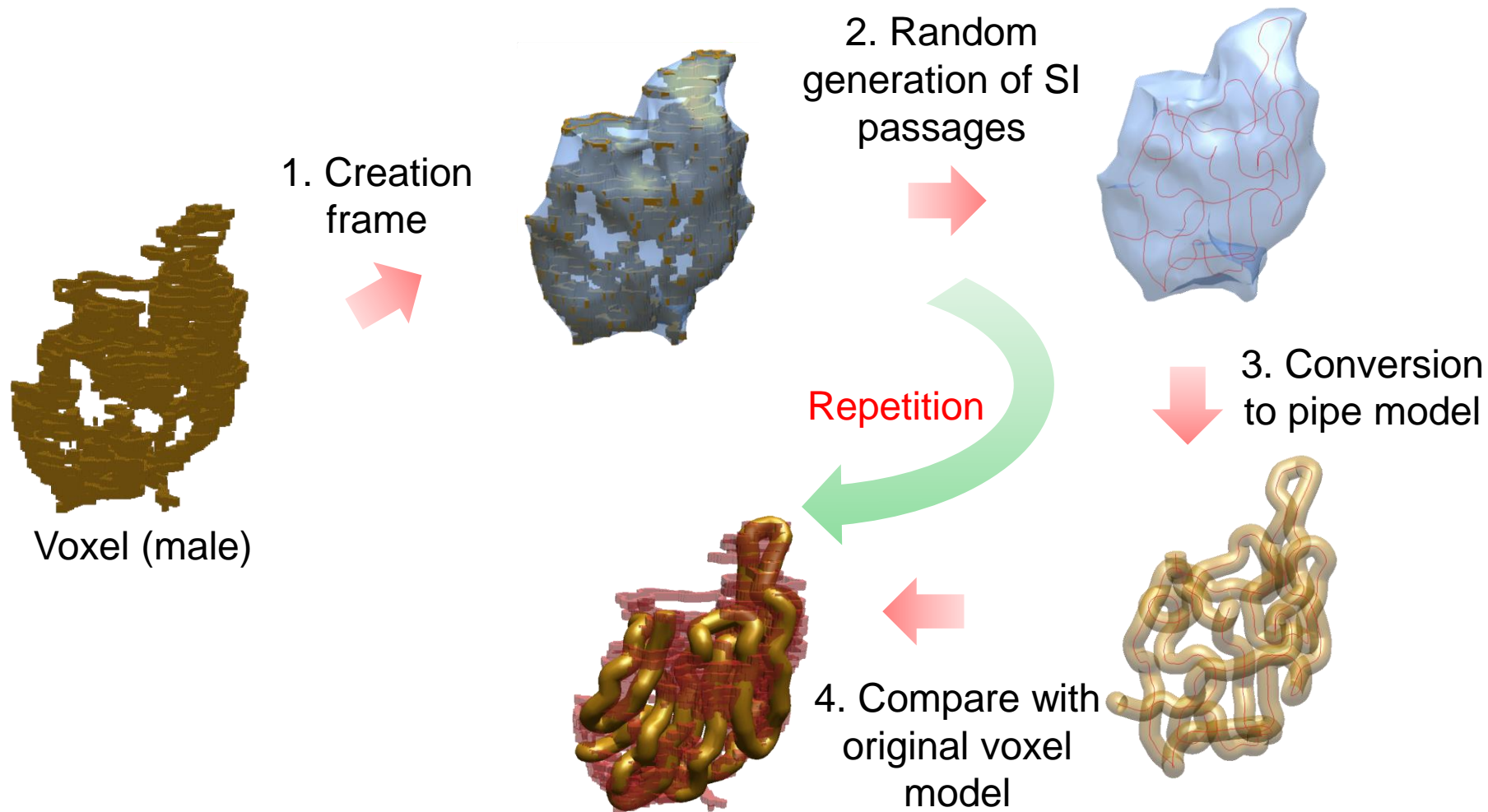
Small Intestine



Small Intestine



Small Intestine



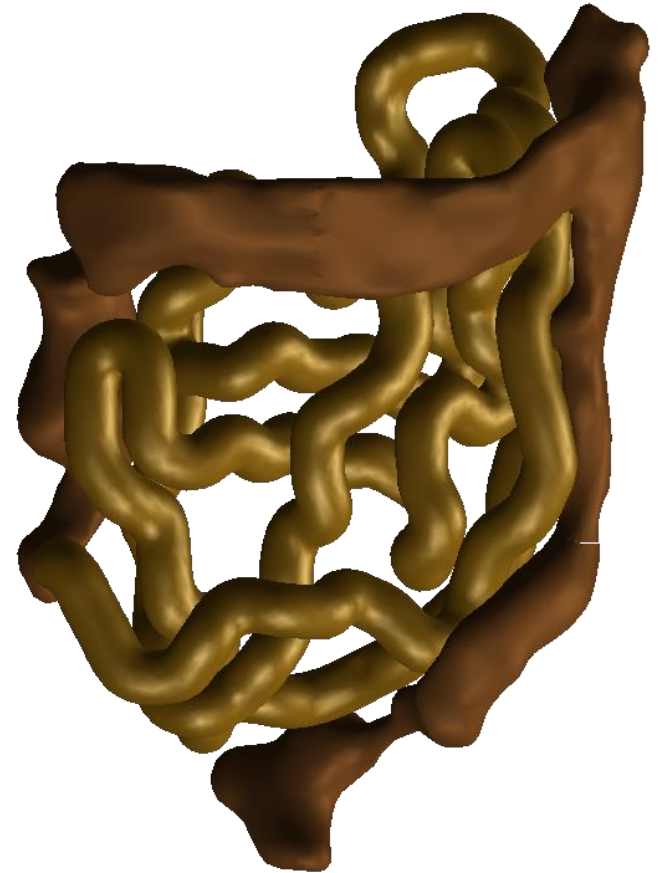
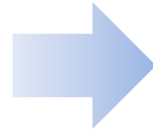
Generated **1000** small intestine (SI) models and selected the **best model** considering both geometric and dosimetric similarities with the original voxel model.

Small Intestine - Male

Male



Voxel



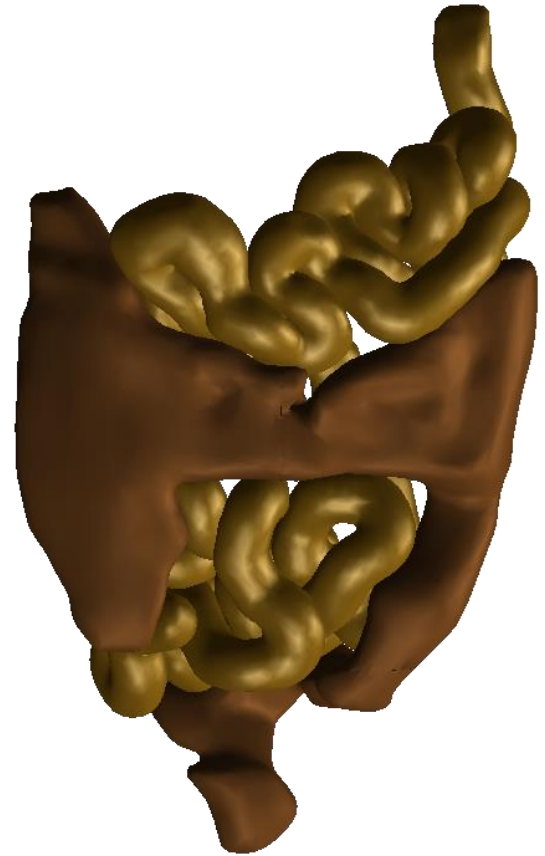
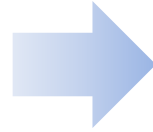
Mesh

Small Intestine - Female

Female



Voxel



Mesh

Lymphatic Nodes



Male



Female

Lymphatic Nodes

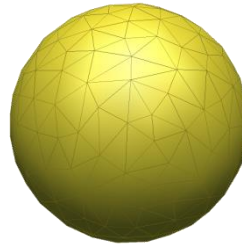
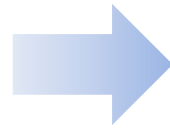
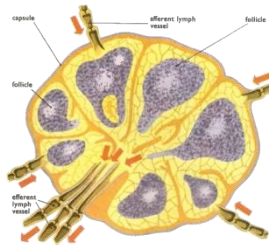
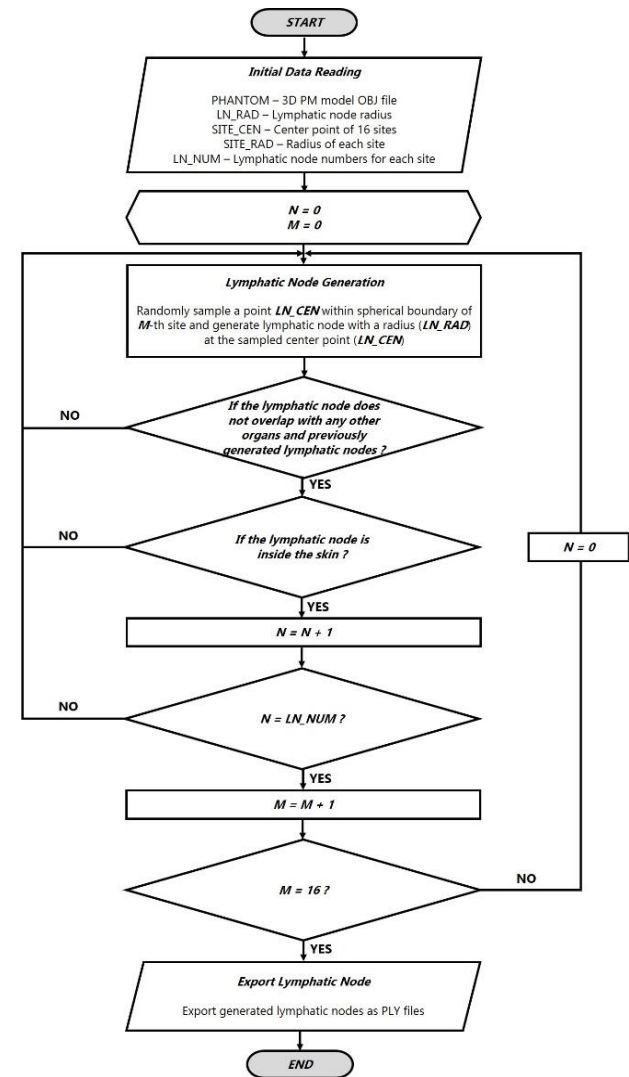


Table 3.1. Lymphatic node numbers and masses for Reference Adult Male and Reference Adult Female derived from the data of *Publications 23, 66, and 89* (ICRP, 1975, 1994a, 2002), along with reference node numbers given in *Publication 89* (ICRP, 2002).

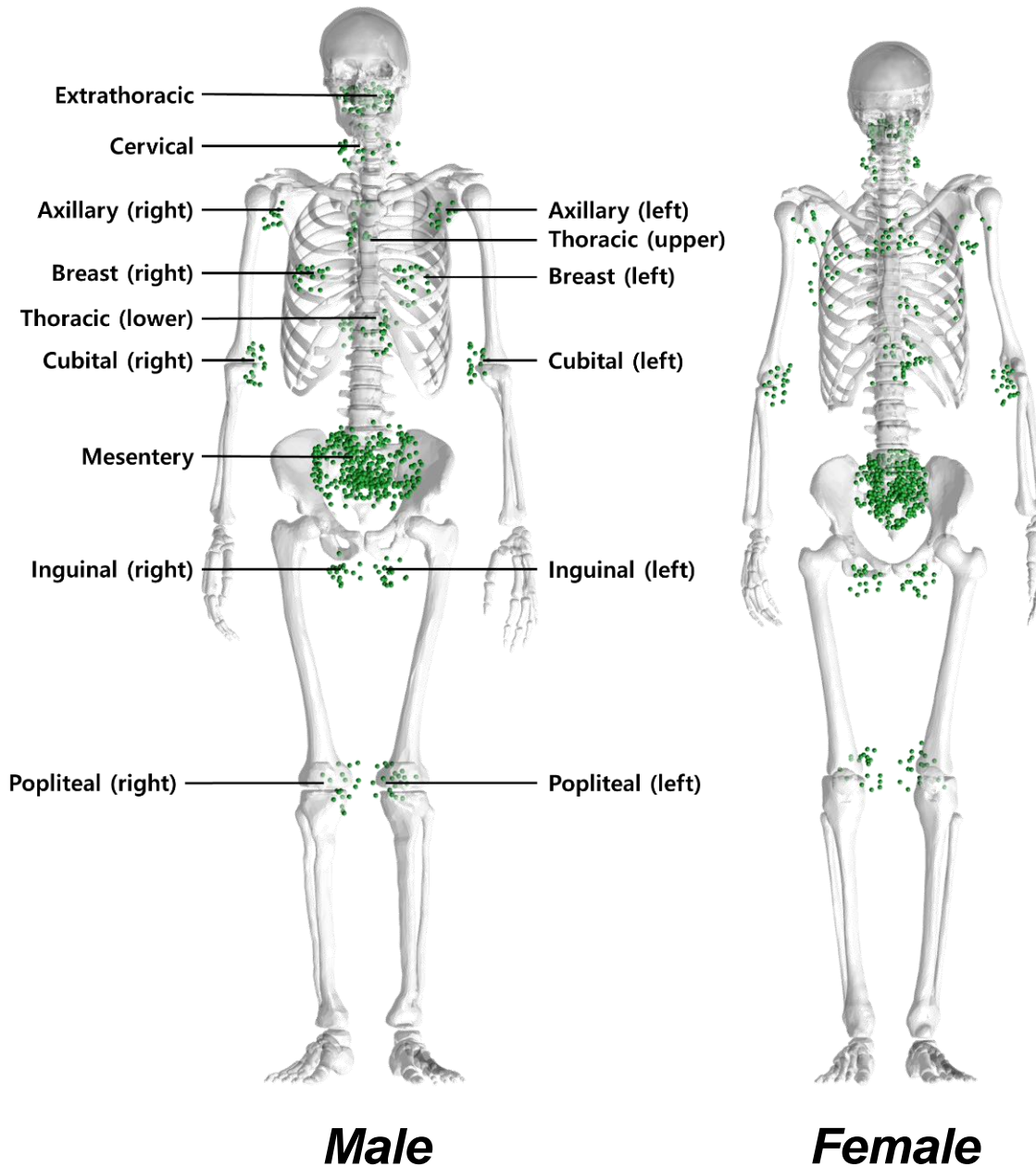
Lymphatic node site	Reference node numbers in <i>Publication 89</i>	Derived node numbers	Mass (g)	
			Male	Female
Extrathoracic		55	15.0	12.0
Cervical		19	5.2	4.1
Thoracic	50–60	55	15.0	12.0
Breast (left and right)		38	10.4	8.3
Mesentery (left and right)	200–500	350	95.5	76.4
Axillary (left and right)	8–37	23	6.3	5.0
Cubital (left and right)		38	10.4	8.3
Inguinal (left and right)		38	10.4	8.3
Popliteal (left and right)		38	10.4	8.3
Total	600–700	654	178.4	142.7

The reference masses of the lymph nodes adopted in ICRP Publication 133

- The lymphatic nodes were randomly generated in the mesh phantoms, following the procedure that was used for the construction of the ICRP pediatric voxel phantoms.

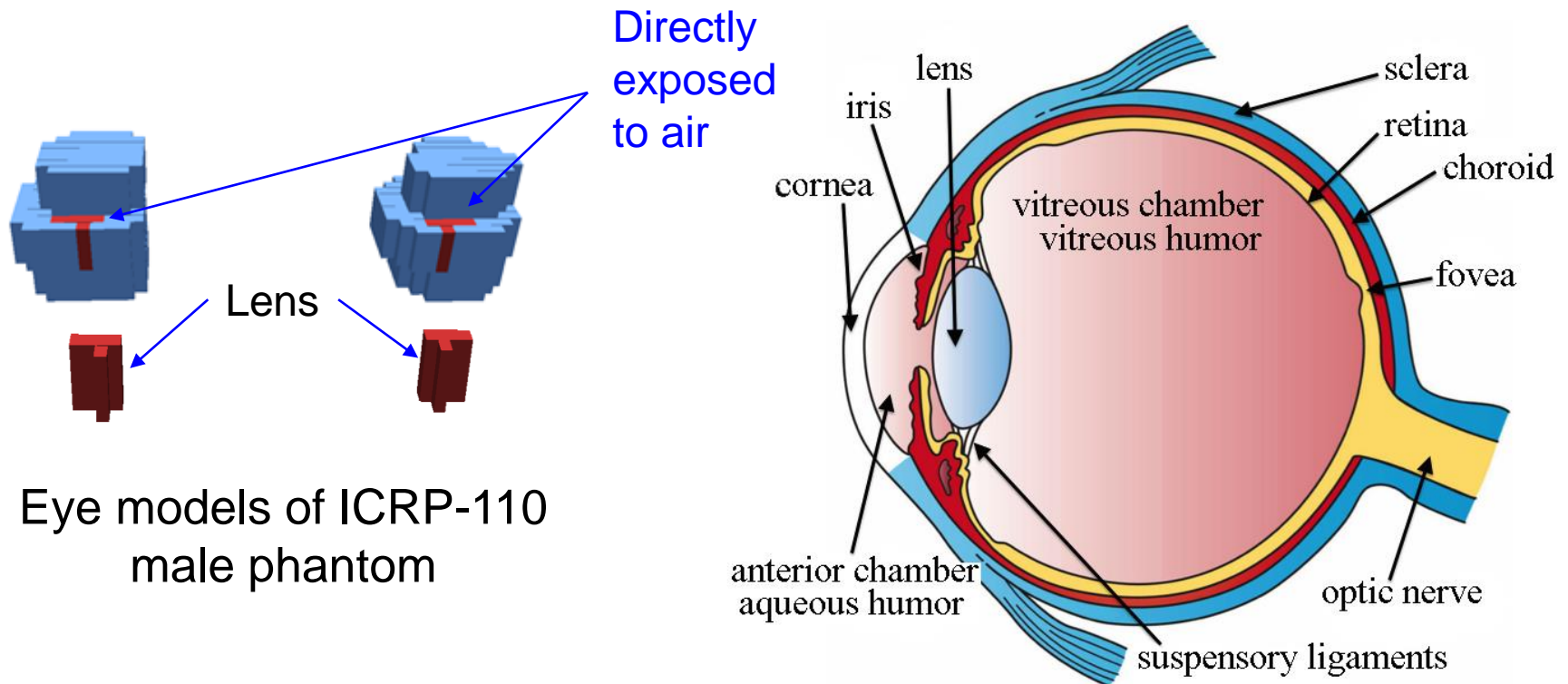


Lymphatic Nodes – Male & Female

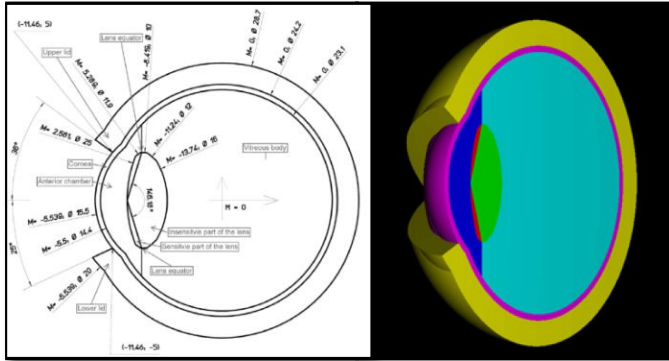


Eyes

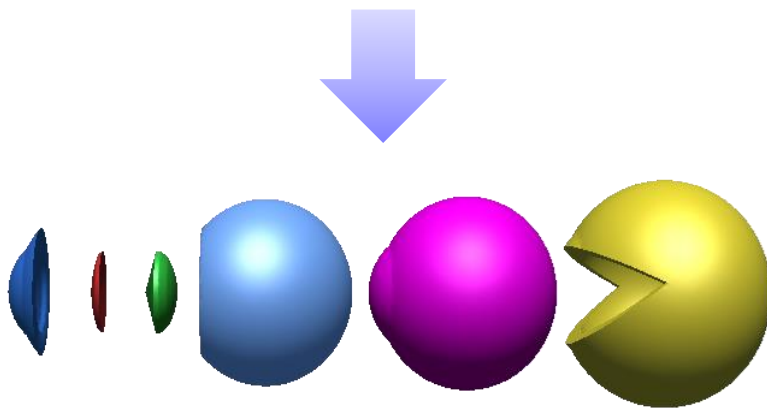
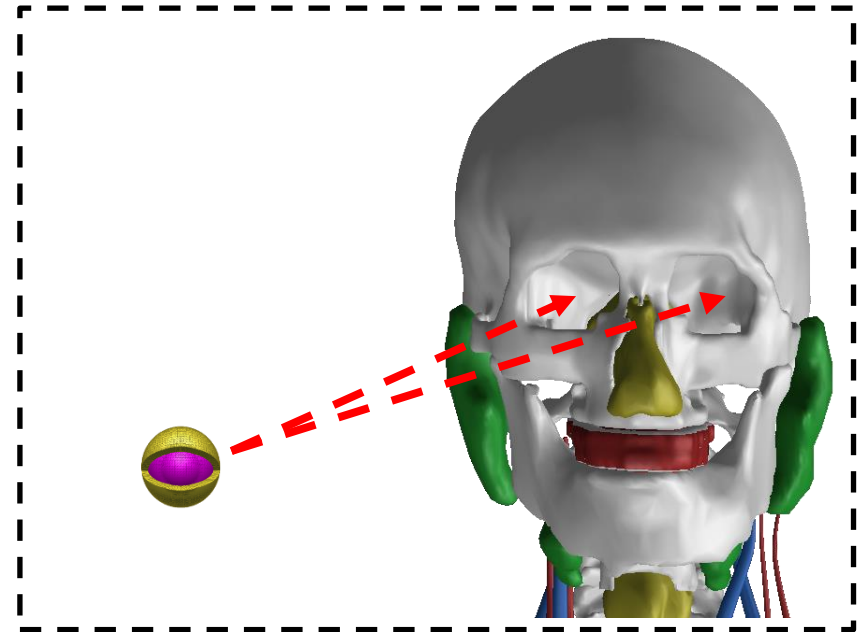
- The lenses of the eyes are directly exposed to air, which is anatomically incorrect, resulting in significant overestimation in lens dose calculation for weakly-penetrating radiations.



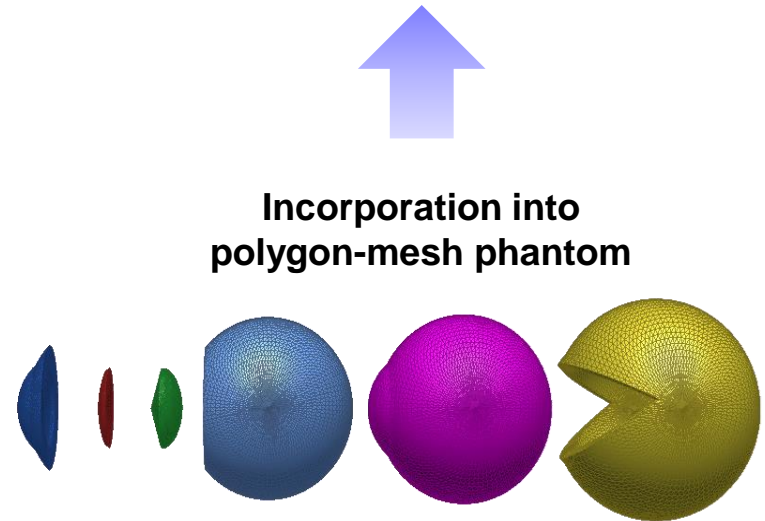
Behrens' eye model (ICRP-116)



Construction of NURBS surface model



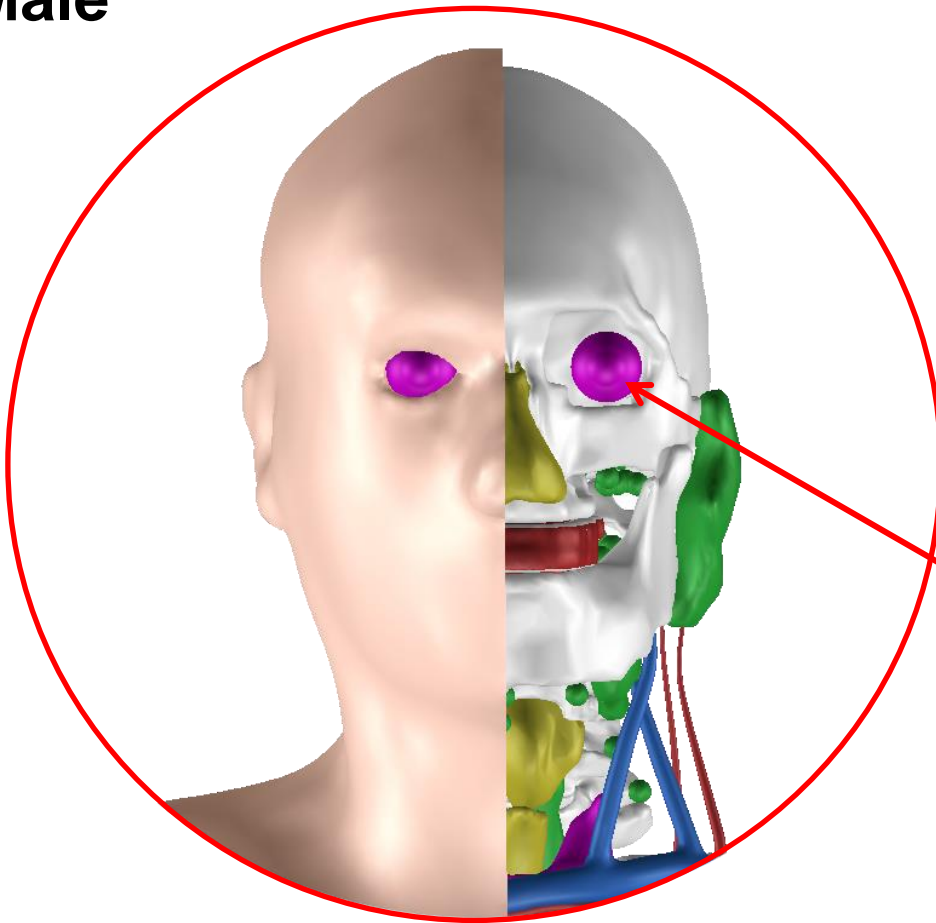
Conversion to polygon-mesh



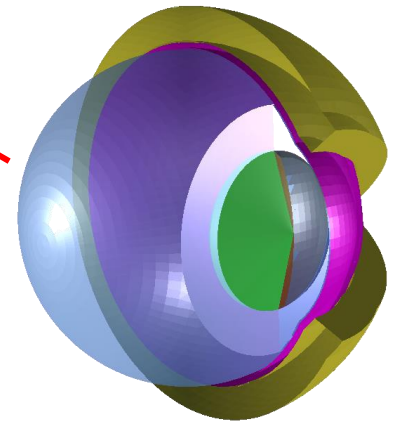
Incorporation into polygon-mesh phantom

Eyes - Male

Male

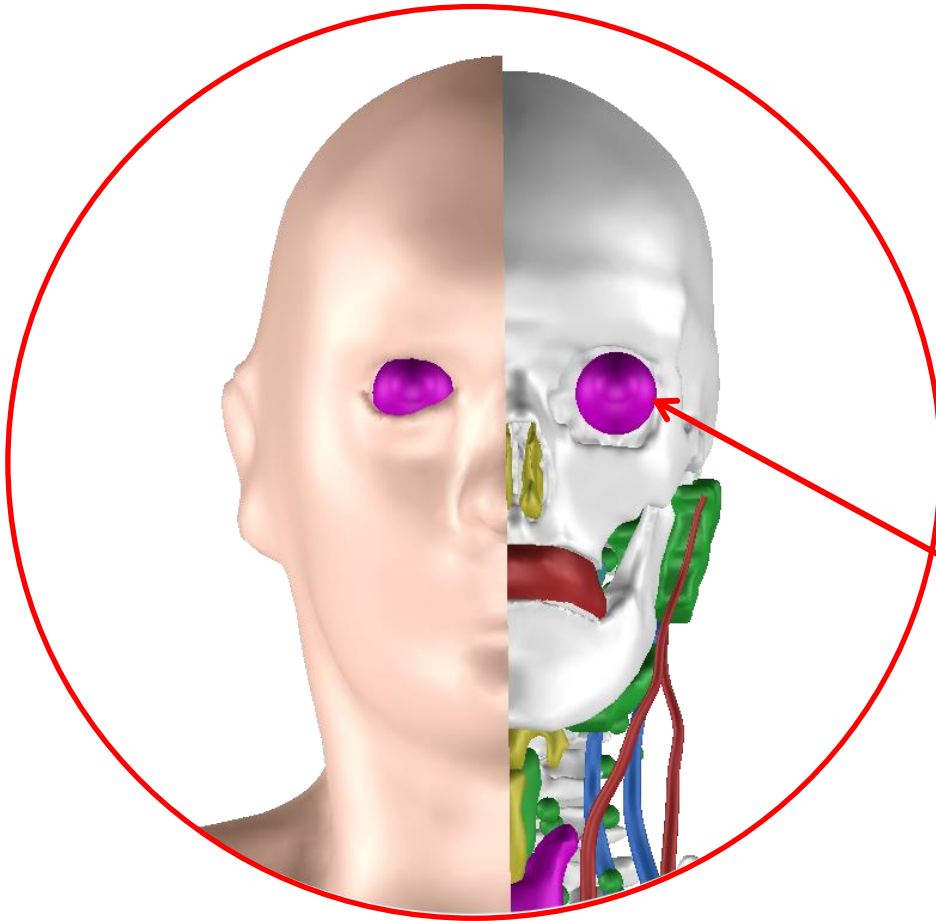


Detailed
eye model

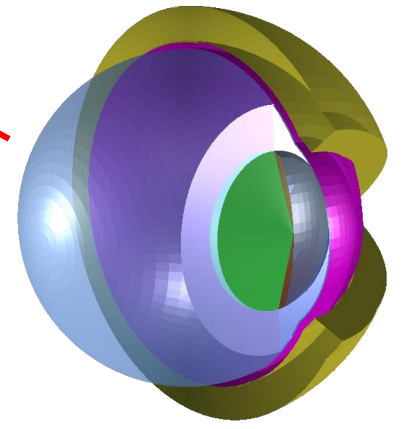


Eyes - Female

Female



Detailed
eye model



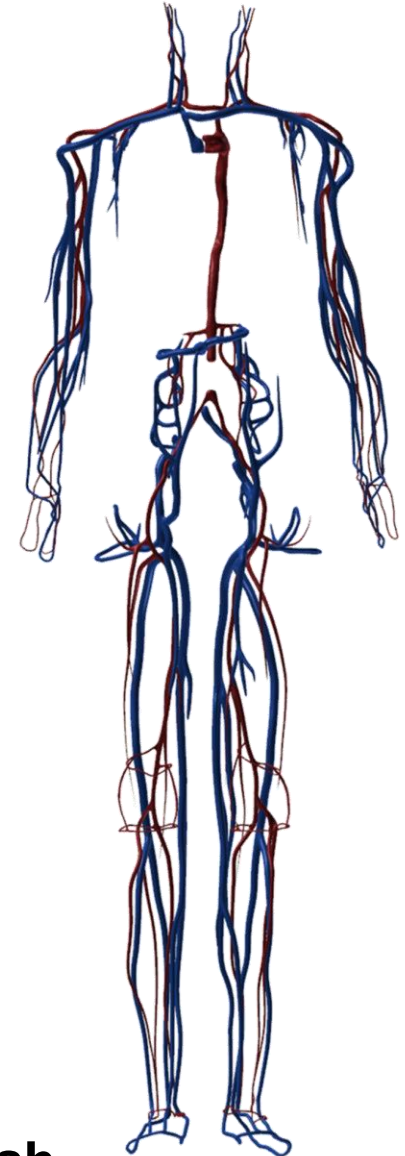
Blood in Large Arteries & Veins

Male

Female

Male

Female

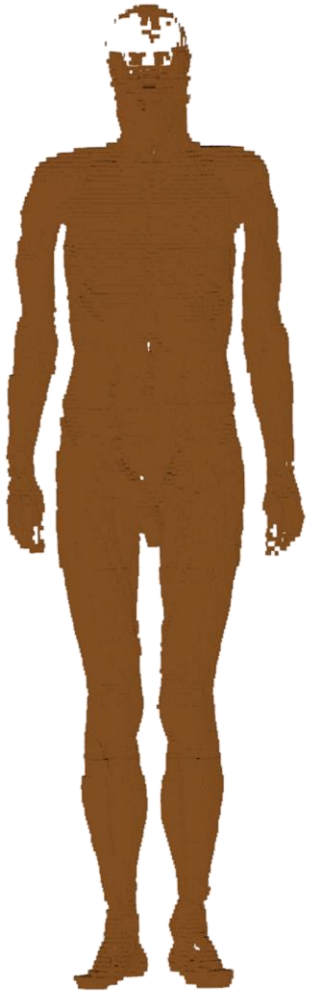


Voxel

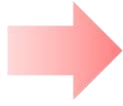
Mesh

Muscle

Male

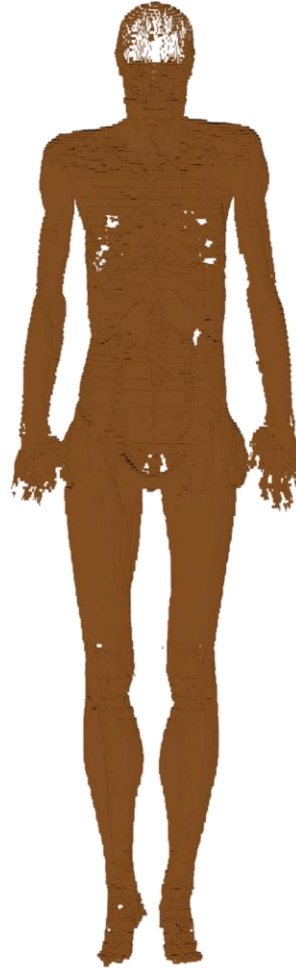


Voxel

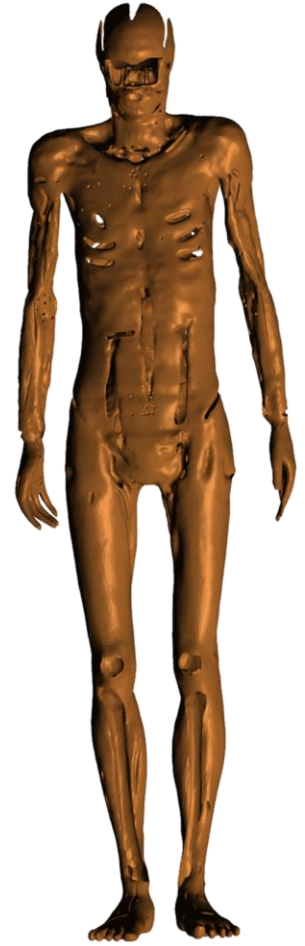


Mesh

Female



Voxel



Mesh

Development procedure – Part 2

1. Phantom conversion to mesh format

- Simple organs and tissues
- Complex organs and tissues
 - ✓ Skeletal system
 - ✓ Small intestine
 - ✓ Lymphatic nodes
 - ✓ Eyes
 - ✓ Blood in large vessels
 - ✓ Muscle

2. Inclusion of blood in organs and tissues

3. Inclusion of thin target and source regions

- Skin
- Alimentary tract system
- Respiratory tract system
- Urinary bladder

ICRP-89 Reference Organ/Tissue Mass

ICRP Publication 89

2.3. Postnatal period

2.3.1. Anatomical data

Table 2.8. Reference values for masses of organs and tissues as a function of age (g)

Organ/tissue	Newborn	1 year	5 years	10 years	15 years		Adult		See Section
					M	F	M	F	
Adipose tissue ^a	930	3800	5500	8600	12 000	18 700	18 200	22 500	11.1.2
Separable adipose tissue, excluding yellow marrow	890	3600	5000	7500	9500	16 000	14 500	19 000	11.1.2
Adrenals (2)	6	4	5	7	10	9	14	13	11.2.1
Alimentary system									
Tongue	3.5	10	19	32	56	53	73	60	6.3.4
Salivary glands	6	24	34	44	68	65	85	70	6.3.2
Oesophagus									
Wall	2	5	10	18	30	30	40	35	6.3.8
Stomach									
Wall	7	20	50	85	120	120	150	140	6.3.9
Contents	40	67	83	117	200	200	250	230	6.4.5
Small intestine									
Wall	30	85	220	370	520	520	650	600	6.3.10
Contents	56	93	117	163	280	280	350	280	6.4.5
Large intestine									
Right colon									
Wall	7	20	49	85	122	122	150	145	6.3.11
Contents	24	40	50	70	120	120	150	160	6.4.5
Left colon									
Wall	7	20	49	85	122	122	150	145	6.3.11
Contents	12	20	25	35	60	60	75	80	6.4.5
Rectosigmoid									
Wall	3	10	22	40	56	56	70	70	6.3.11
Contents	12	20	25	35	60	60	75	80	6.4.5
Liver	130	330	570	830	1300	1300	1800	1400	6.3.12
Gallbladder									
Wall	0.5	1.4	2.6	4.4	7.7	7.3	10	8	6.3.13
Contents	2.8	8	15	26	45	42	58	48	6.3.13
Pancreas	6	20	35	60	110	100	140	120	6.3.14
Brain	380	950	1310/1180	1400/1220	1420	1300	1450	1300	11.3.1
Breasts					15	250	25	500	11.4.1
Circulatory system									
Heart – with blood ^a	46	98	220	370	660	540	840	620	7.1.1
Heart – tissue only	20	50	85	140	230	220	330	250	7.1.1
Blood	290	530	1500	2500	4800	3500	5600	4100	7.4
Eyes (2)	6	7	11	12	13	13	15	15	11.7.1
Fat (storage fat) ^a	370	2300	3600	6000	9000	14 000	14 600	18 000	4.3.3
Integumentary system									
Skin	175	350	570	820	2000	1700	3300	2300	10.5
Muscle, skeletal	800	1900	5600	11 000	24 000	17 000	29 000	17 500	11.8.3
Pituitary gland	0.1	0.15	0.25	0.35	0.5	0.5	0.6	0.6	11.9

(continued on next page)

ICRP Publication 89

Table 2.8 (continued)

Organ/tissue	Newborn	1 year	5 years	10 years	15 years		Adult		See Section
					M	F	M	F	
Respiratory system									
Larynx	1.3	4	7	12	22	15	28	19	5.3.1
Trachea	0.5	1.5	2.5	4.5	7.5	6	10	8	5.3.2
Lung – with blood ^a	60	150	300	500	900	750	1200	950	5.3.3
Lung – tissue only	30	80	125	210	330	290	500	420	5.3.3
Skeletal system									
Total skeleton ^a	370	1170	2430	4500	7950	7180	10 500	7800	9.2.3
Bone, cortical	135	470	1010	1840	3240	2960	4400	3200	9.2.6
Bone, trabecular	35	120	250	460	810	740	1100	800	9.2.6
Bone, total ^a	170	590	1260	2300	4050	3700	5500	4000	9.2.11
Marrow, active	50	150	340	630	1080	1000	1170	900	9.2.13
Marrow, inactive	0	20	160	630	1480	1380	2480	1800	9.2.13
Cartilage	130	360	600	820	1140	920	1100	900	9.2.12
Teeth	0.7	5	15	30	45	35	50	40	9.2.14
Miscellaneous	20	45	55	90	155	145	200	160	9.2.15
Spleen	9.5	29	50	80	130	130	150	130	11.10.1
Thymus	13	30	30	40/35	35	30	25	20	11.11.1
Thyroid	1.3	1.8	3.4	7.9	12	12	20	17	11.12.1
Tonsils (2 palatine)	0.1	0.5	2	3	3	3	3	3	6.3.6
Urogenital system									
Kidneys (2)	25	70	110	180	250	240	310	275	8.2.1
Ureters (2)	0.77	2.2	4.2	7.0	12	12	16	15	8.2.2
Urinary bladder	4	9	16	25	40	35	50	40	8.2.3
Urethra	0.48/0.14 ^b	1.4/0.42	2.6/0.78	4.4/1.3	7.7	2.3	10	3	8.2.4
Testes (2)	0.85	1.5	1.7	2	16	16	35	35	8.2.5
Epididymes (2)	0.25	0.35	0.45	0.60	1.6	1.6	4	4	8.2.5
Prostate	0.8	1.0	1.2	1.6	4.3	4.3	17	17	8.2.6
Ovaries (2)	0.3	0.8	2.0	3.5	6	6	11	11	8.2.7
Fallopian tubes (2)	0.25	0.25	0.35	0.50	1.1	1.1	2.1	2.1	8.2.7
Uterus	4.0	1.5	3	4	30	30	80	80	8.2.8
Total body (kg) ^c	3.5	10	19	32	56	53	73	60	4.2.1

^a This entry duplicates other mass information in this table and should not be included in the whole-body sum of reference values for tissue masses.

^b Male (M)/female (F) values.

^c The body components listed above represent 96% of the total body mass. Separable connective tissues and certain lymphatic tissues account for most of the remaining 4% of body mass.

Table 2.9. Reference values for height, mass, and surface area of the total body (Sections 4.2.1 and 4.2.2)

Age	Height (cm)		Mass (kg)		Surface area (m ²)	
	Male	Female	Male	Female	Male	Female
Newborn	51	51	3.5	3.5	0.24	0.24
1 year	76	76	10	10	0.48	0.48
5 years	109	109	19	19	0.78	0.78
10 years	138	138	32	32	1.12	1.12
15 years	167	161	56	53	1.62	1.55
Adult	176	163	73	60	1.90	1.66

- The organ/tissue masses of the ICRP-110 voxel phantoms are matched to the ICRP-89 reference values (assumed as inclusive of **blood** together with parenchyma tissue).

ICRP-89 Reference Organ/Tissue Mass

- Finally, turned out that the ICRP-89 reference organ/tissue masses are **NOT inclusive of blood** (i.e., the organ/tissue masses of the ICRP-110 voxel phantoms are underestimated).

ICRP-89 Reference Organ/Tissue Mass

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- ICRP-133 SAFs (from the ICRP-110 voxel phantoms)

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- ICRP-133 SAFs (from the ICRP-110 voxel phantoms)
 - for **cross-fire-irradiation cases (e.g., Liver ← Lung)** derived by dividing the AF values by **the target organ/tissue mass of the ICRP-110 voxel phantoms (not inclusive of blood)**,

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 - but for **self-irradiation cases (e.g., Liver ← Liver)** derived by dividing the AF values by **the target organ/tissue masses increased to be inclusive of blood**.

ICRP-89 Reference Organ/Tissue Mass

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- ICRP-133 SAFs (from the ICRP-110 voxel phantoms)
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 - but for **self-irradiation cases (e.g., Liver ← Liver)** derived by dividing the AF values by **the target organ/tissue masses increased to be inclusive of blood**.



To overcome this issue, the mesh phantoms were also adjusted to increase **the organ/tissue masses for blood inclusion.**

Calculation of Blood Mass

ICRP-89 reference values for regional blood volume fractions



Total blood masses

- Male: 5.6 kg
- Female: 4.1 kg

ICRP Publication 89

Table 2.14. Reference values for regional blood volumes in adults (Section 7.7.2)

Organ or tissue	Blood content (% total blood volume)	
	Male	Female
Fat	5.0	8.5
Brain	1.2	1.2
Stomach and oesophagus	1.0	1.0
Small intestine	3.8	3.8
Large intestine	2.2	2.2
Right heart	4.5	4.5
Left heart	4.5	4.5
Coronary tissue	1.0	1.0
Kidneys	2.0	2.0
Liver	10	10
Pulmonary	10.5	10.5
Bronchial tissue	2.0	2.0
Skeletal muscle	14	10.5
Pancreas	0.6	0.6
Skeleton	7.0	7.0
Red marrow	4.0	4.0
Trabecular bone	1.2	1.2
Cortical bone	0.8	0.8
Other skeleton	1.0	1.0
Skin	3.0	3.0
Spleen	1.4	1.4
Thyroid	0.06	0.06
Lymph nodes	0.2	0.2
Gonads	0.04	0.02
Adrenals	0.06	0.06
Urinary bladder	0.02	0.02
All other tissues	1.92	1.92
Aorta and large arteries	6.0	6.0
Large veins	18	18

Calculation of Blood Mass

ICRP-89 reference values for regional blood volume fractions



ICRP Publication 89

Table 2.14. Reference values for regional blood volumes in adults (Section 7.7.2)

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Small intestine	3.8	3.8
Large intestine	2.2	2.2
Right heart	4.5	4.5
Left heart	4.5	4.5
Coronary tissue	1.0	1.0
Kidneys	2.0	2.0
Liver	10	10
Pulmonary	10.5	10.5
Bronchial tissue	2.0	2.0
Skeletal muscle	14	10.5
Pancreas	0.6	0.6
Skeleton	7.0	7.0
Red marrow	4.0	4.0
Trabecular bone	1.2	1.2
Cortical bone	0.8	0.8
Other skeleton	1.0	1.0
Skin	3.0	3.0
Spleen	1.4	1.4
Thyroid	0.06	0.06
Lymph nodes	0.2	0.2
Gonads	0.04	0.02
Adrenals	0.06	0.06
Urinary bladder	0.02	0.02
All other tissues	1.92	1.92
Aorta and large arteries	6.0	6.0
Large veins	18	18

Total blood masses

- Male: 5.6 kg
- Female: 4.1 kg

$$m_{\text{blood-in-liver}} = (m_{\text{total-blood}}^{\text{ICRP89}}) (f_{\text{liver}}^{\text{total-blood}}) \quad \text{Section 7.7.2 of ICRP89}$$

$$560 \text{ g} = 5.6 \text{ kg} \times 10\% \text{ (male)}$$

$$410 \text{ g} = 4.1 \text{ kg} \times 10\% \text{ (female)}$$

Calculation of Density and Elemental Composition

- The density and elemental composition were calculated based on data given in ICRP *Publication 89* and ICRU *Report 46*

Density for liver

$$d_{liver}^{with-blood} = \frac{m_{liver}^{ICRP89} + m_{blood-in-liver}}{\frac{m_{liver}^{ICRP89}}{d_{liver}^{ICRU46}} + \frac{m_{blood-in-liver}}{d_{blood}^{ICRU46}}}$$

Mass percentage of hydrogen in liver

$$(\%H)_{liver}^{with-blood} = \frac{(\%H)_{liver}^{ICRU46} m_{liver}^{ICRP89} + (\%H)_{blood}^{ICRU46} m_{blood-in-liver}}{m_{liver}^{ICRP89} + m_{blood-in-liver}}$$

Blood-in-Organ/Tissue Mass, Density, Compositions

Table 4.2 of ICRP 145

Annex B of ICRP 145

Table 4.2. Reference masses of organs and tissues for Reference Adult Male and Reference Adult Female.

Organ/tissue	Male		Female	
	Organ/tissue only (g)	Blood content (g)	Organ/tissue only (g)	Blood content (g)
Adipose tissue	14,500	280.000	19,000	348.500
Adrenals	14	3.360	13	2.460
Tongue	73	2.656	60	1.491
Salivary glands	85	3.093	70	1.739
Oesophagus, wall	40	11.789	35	8.200
Stomach, wall	150	44.211	140	32.800
Stomach, contents	250		230	
Small intestine, wall	650	212.800	600	155.800
Small intestine, contents	350		280	
Right colon, wall	150	49.946	145	36.331
Right colon, contents	150		160	
Left colon, wall	150	49.946	145	36.331
Left colon, contents	75		80	
Rectosigmoid, wall	70	23.308	70	17.539
Rectosigmoid, contents	75		80	
Liver	1800	560.000	1400	410.000
Gallbladder, wall	10	0.364	8	0.199
Gallbladder, contents	58		48	
Pancreas	140	33.600	120	24.600
Brain	1450	67.200	1300	49.200
Breasts, adipose	15	0.546	300	7.454
Breasts, glandular	10	0.364	200	4.969
Blood in heart chambers	510*	510.000	370*	370.000
Heart – tissue only	330	56.000	250	41.000
Total blood	5600	5600.000	4100	4100.000
Eyes	15	0.546	15	0.373
Skin	3300	168.000	2300	123.000
Muscle, skeletal	29,000	784.000	17,500	430.500
Pituitary gland	0.6	0.022	0.6	0.015
Larynx	28	1.019	19	0.472
Trachea	10	0.364	8	0.199
Blood in lung	700*	700.000	530*	530.000
Lung – tissue only	500		420	

(continued on next page)

ANNEX B. LIST OF MEDIA AND THEIR ELEMENTAL COMPOSITIONS

Table B.1. List of media, their elemental compositions (percentage by mass), and their densities for the adult male mesh-type reference phantom.

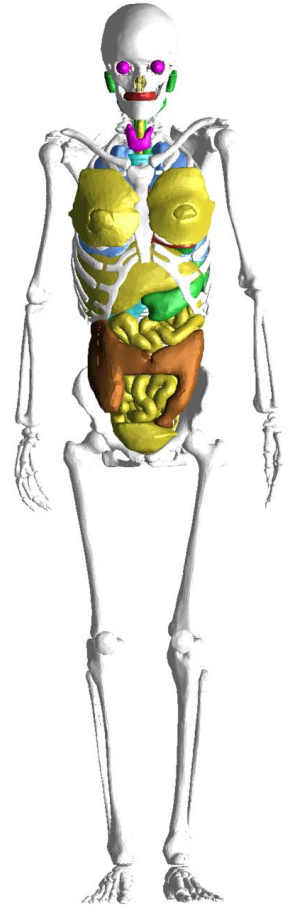
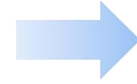
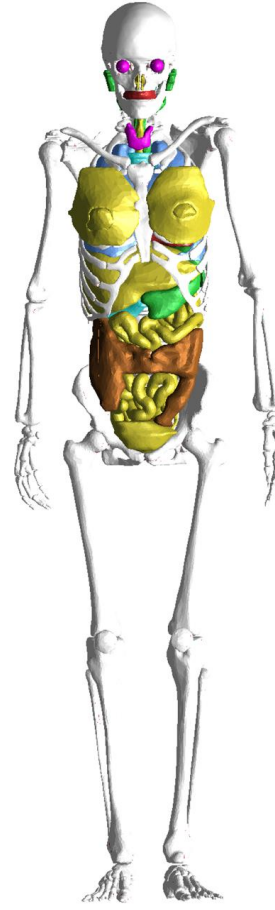
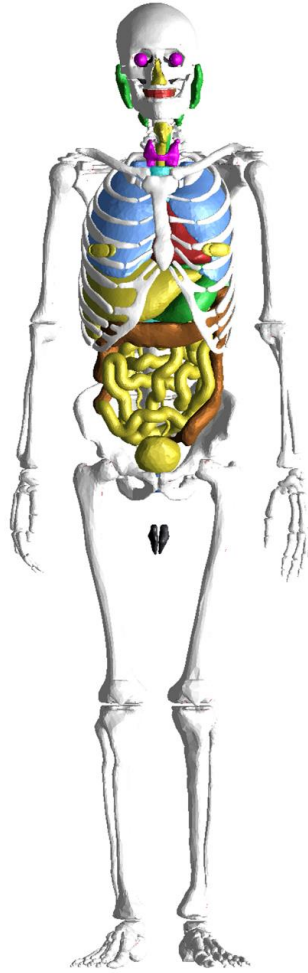
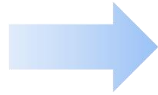
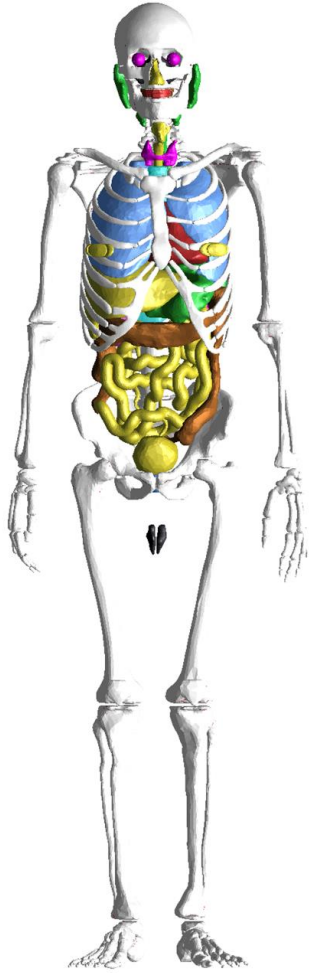
Medium no.		H	C	N	O	Na	Mg	P	S	Cl	K	Ca	Fe	I	Density (g cm ⁻³)
1	Adrenal	10.4	22.8	2.8	63.0	0.1		0.2	0.3	0.2	0.2				1.036
2	ET, trachea, BB, bb, gallbladder wall, pituitary gland, salivary glands, spinal cord, thymus, tonsils, ureter	10.5	25.1	2.7	60.7	0.1		0.2	0.3	0.2	0.2				1.031
3	Oral mucosa, tongue	10.2	14.2	3.4	71.1	0.1		0.2	0.3	0.1	0.4				1.050
4	Blood	10.2	11.0	3.3	74.5	0.1		0.1	0.2	0.3	0.2		0.1		1.060
5	Cortical bone	3.6	15.9	4.2	44.8	0.3	0.2	9.4	0.3			21.3			1.904
6	Medullary cavity	11.5	63.6	0.7	23.9	0.1			0.1	0.1					0.981
7	Humeri, upper, spongiosa	8.1	35.4	2.8	41.0	0.2	0.1	3.7	0.2	0.1	0.1	8.3			1.233
8	Humeri, lower, ulnae and radii, wrists and hand bones, femora, lower, tibiae, fibulae and patellae, ankles and foot, spongiosa	9.6	50.4	1.7	30.8	0.1		2.2	0.2	0.1		4.9			1.109
9	Clavicles, spongiosa	8.9	40.9	2.5	38.5	0.1		2.7	0.2	0.1	0.1	6.0			1.157
10	Cranium, spongiosa	8.8	39.5	2.6	39.5	0.1	0.1	2.8	0.2	0.1	0.1	6.2			1.165
11	Femora, upper, spongiosa	9.3	44.1	2.3	36.5	0.1	0.1	2.2	0.2	0.1	0.1	5.0			1.125
12	Mandible, spongiosa	7.7	33.2	3.0	42.0	0.2	0.1	4.1	0.2	0.1	0.1	9.3			1.271
13	Pelvis, spongiosa	9.4	40.9	2.6	40.0	0.1	0.1	2.0	0.2	0.1	0.1	4.5			1.121
14	Ribs, spongiosa	8.8	34.6	3.1	44.4	0.1	0.1	2.6	0.2	0.1	0.1	5.8	0.1		1.170
15	Scapulae, spongiosa	8.4	37.3	2.7	40.4	0.1	0.1	3.3	0.2	0.1	0.1	7.3			1.201
16	Cervical spine, spongiosa	10.3	41.6	2.8	42.8	0.1		0.6	0.2	0.2	0.1	1.2	0.1		1.049
17	Thoracic spine, spongiosa	10.0	40.3	2.8	43.1	0.1		1.0	0.2	0.2	0.1	2.1	0.1		1.070
18	Lumbar spine, spongiosa	9.5	38.0	3.0	43.6	0.1		1.6	0.2	0.2	0.1	3.6	0.1		1.108

(continued on next page)

Phantom Adjustment for Blood Inclusion

Male

Female



Before

After

Before

After

Development procedure – Part 3

1. Phantom conversion to mesh format

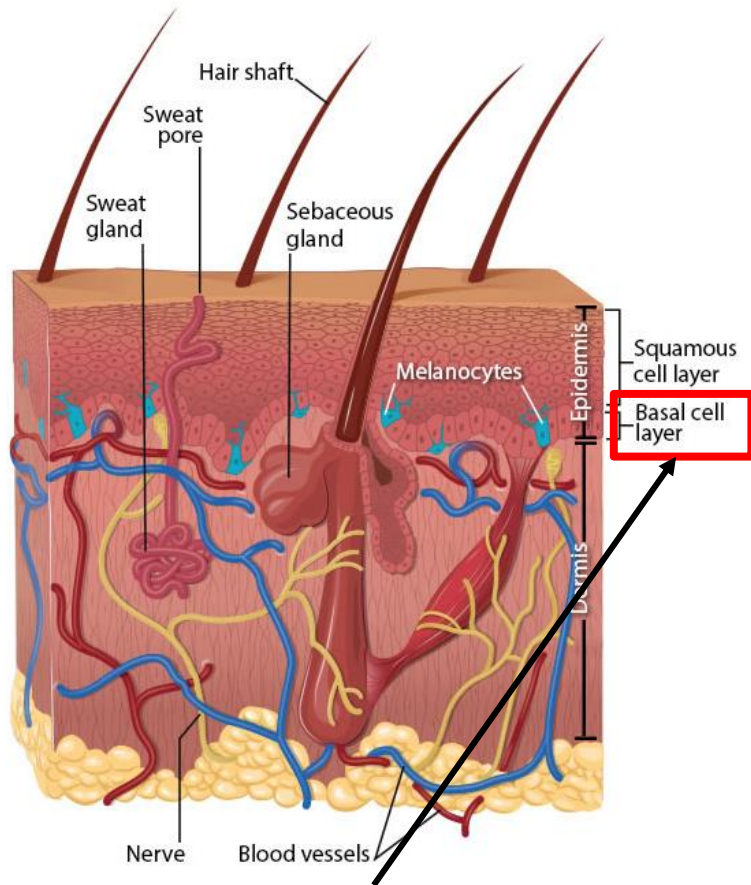
- Simple organs and tissues
- Complex organs and tissues
 - ✓ Skeletal system
 - ✓ Small intestine
 - ✓ Lymphatic nodes
 - ✓ Eyes
 - ✓ Blood in large vessels
 - ✓ Muscle

2. Inclusion of blood contents

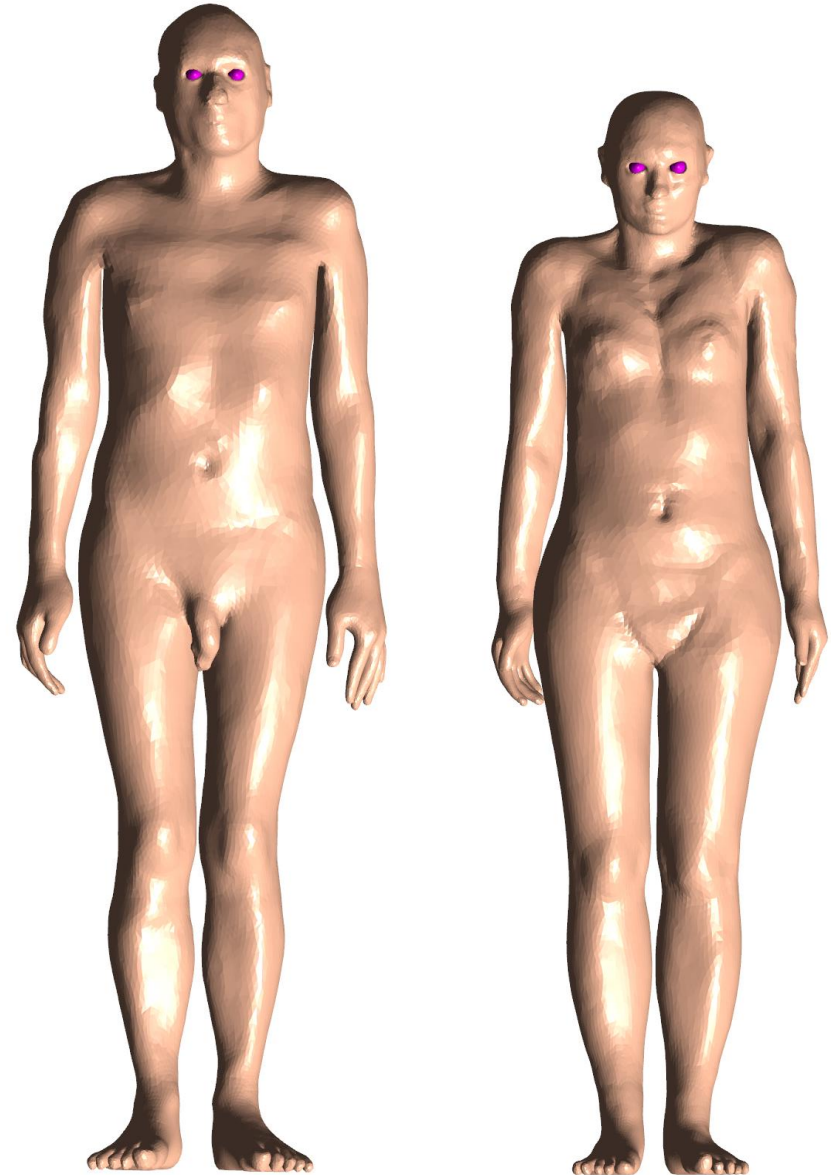
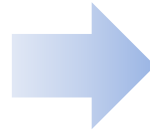
3. Inclusion of thin target and source regions

- Skin
- Alimentary tract system
- Respiratory tract system
- Urinary bladder

Skin – Basal Cell Layer



Include



A range from 50 to 100 μm is an appropriate depth recommended by ICRP

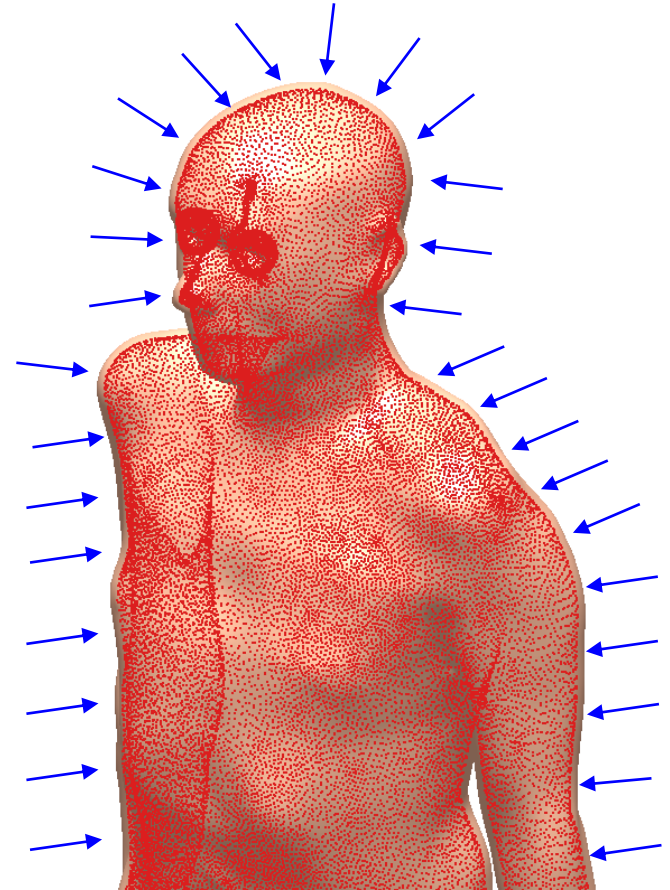
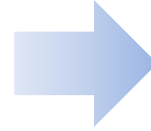
Skins of the mesh phantoms

Skin – Inclusion Method



Outer skin surface

Reduce

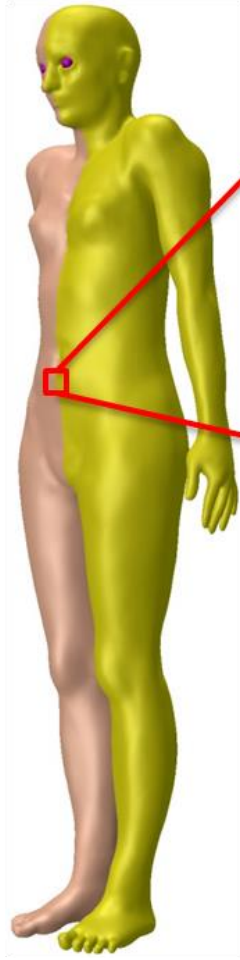


- The size of the outer skin surface of phantoms was reduced by using '**Offset**' *function* of *Rapidform* software to define the target layer within the skin.

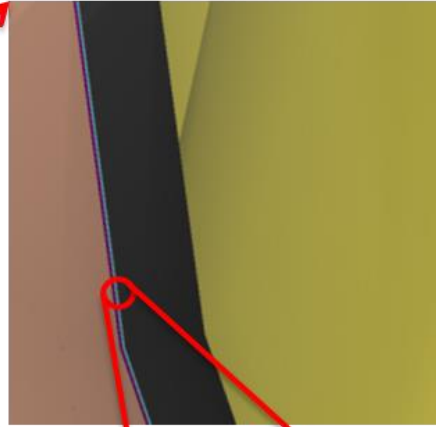
Skin (Target Layer)



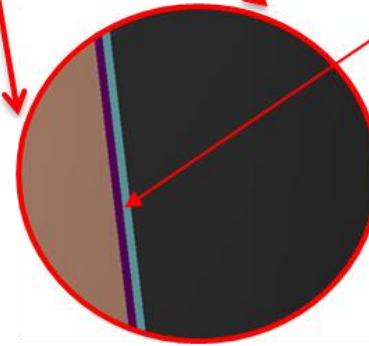
Male



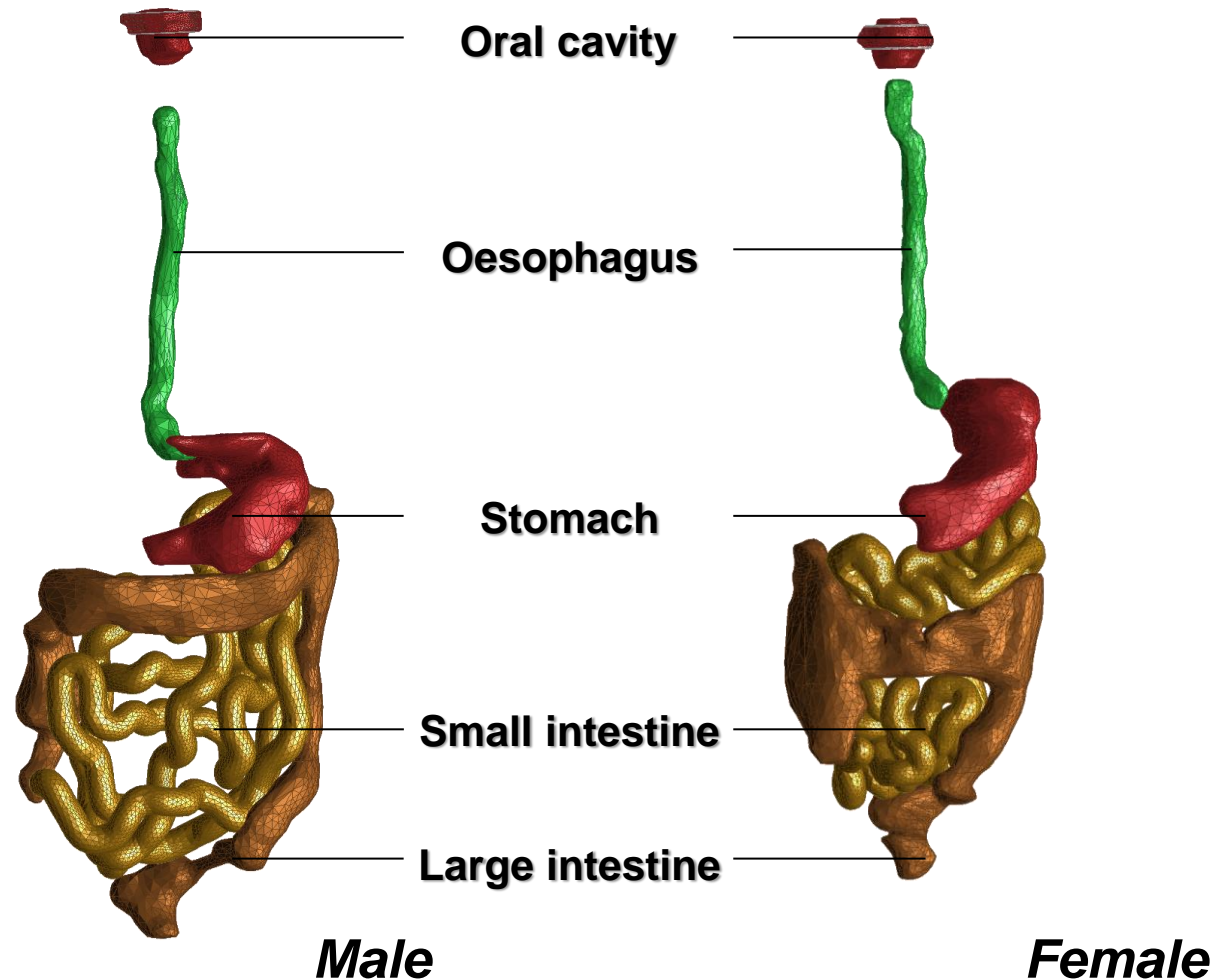
Female



Target layer
Depth: 50-100 μm
Thickness: 50 μm



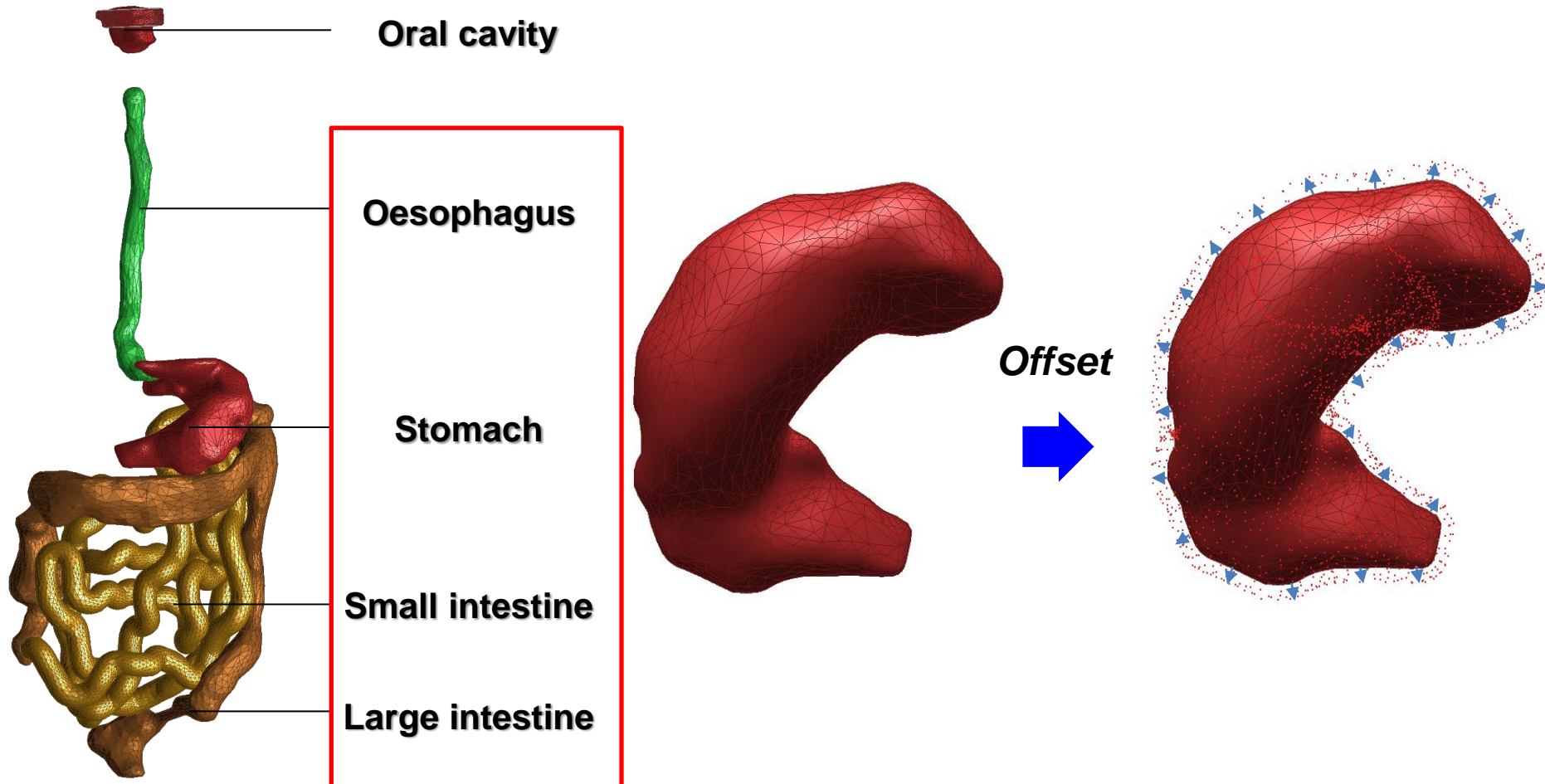
Alimentary Tract Organs



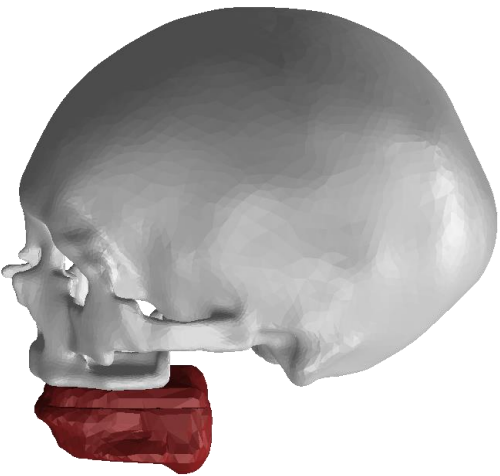
- Micron scales of target and source regions of the alimentary tract system **described in ICRP Publication 100** were included in the mesh phantoms

Alimentary Tract Organs (Except for Oral Cavity)

- Basically, '**Offset**' function with Rapidform™ software was used to model target and source regions in alimentary tract organs except for oral cavity



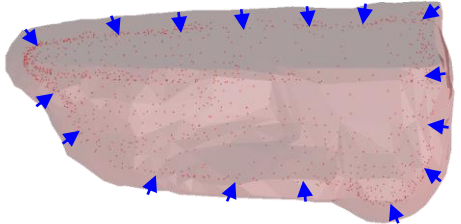
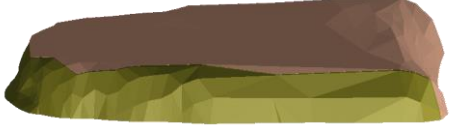
Oral Cavity



Definition of the food as the upper part of the tongue

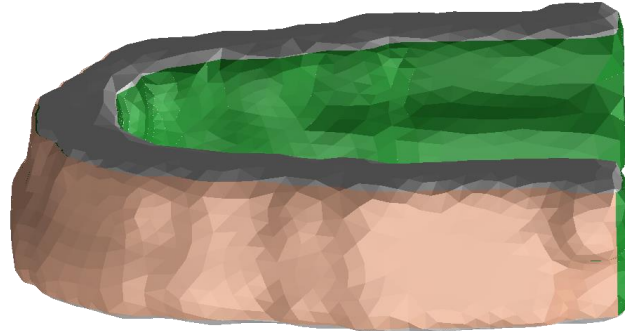
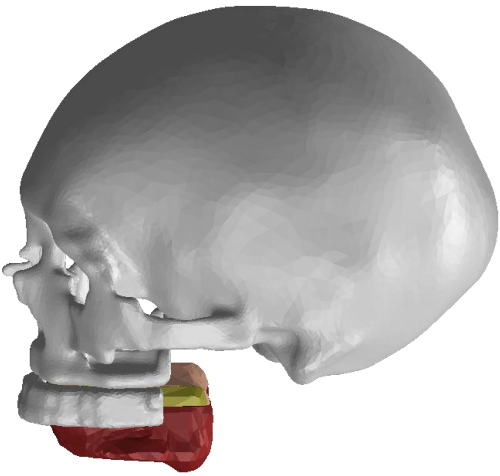


Definition of the oral mucosa in the roof of the mouth

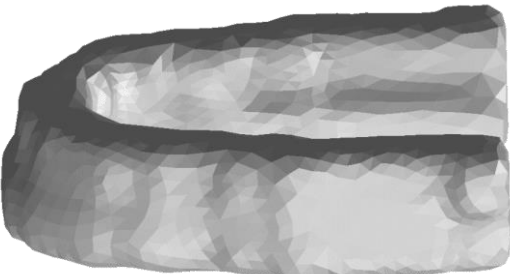


Definition of the oral mucosa in the inner tongue

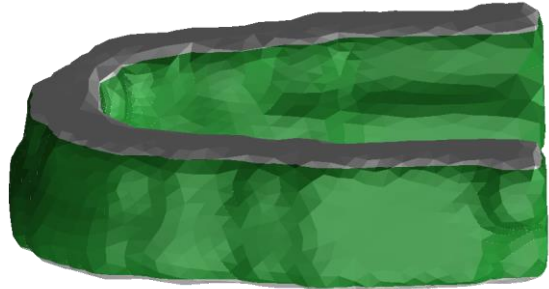
Oral Cavity



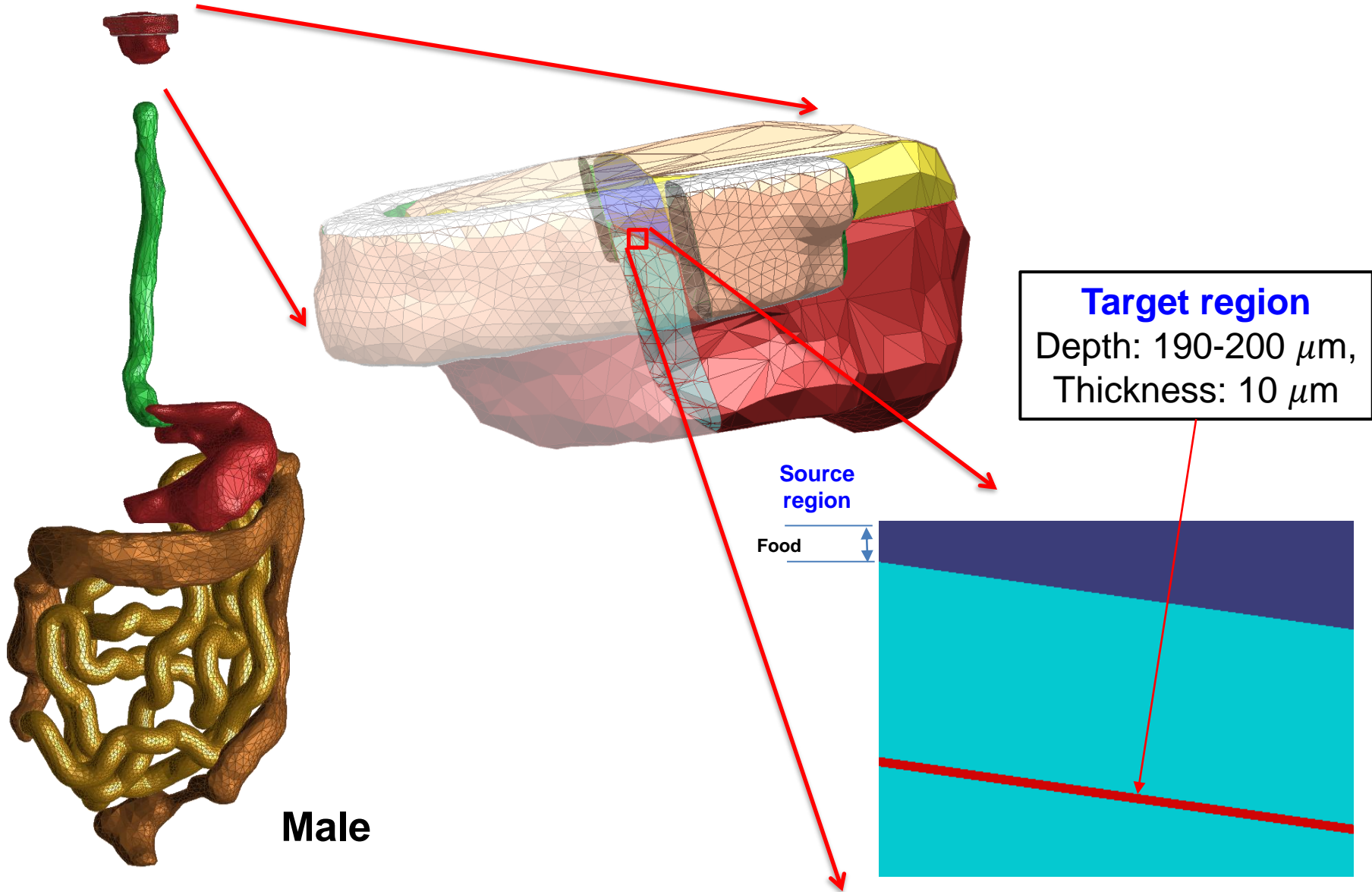
Definition of the oral mucosa in lips and cheek



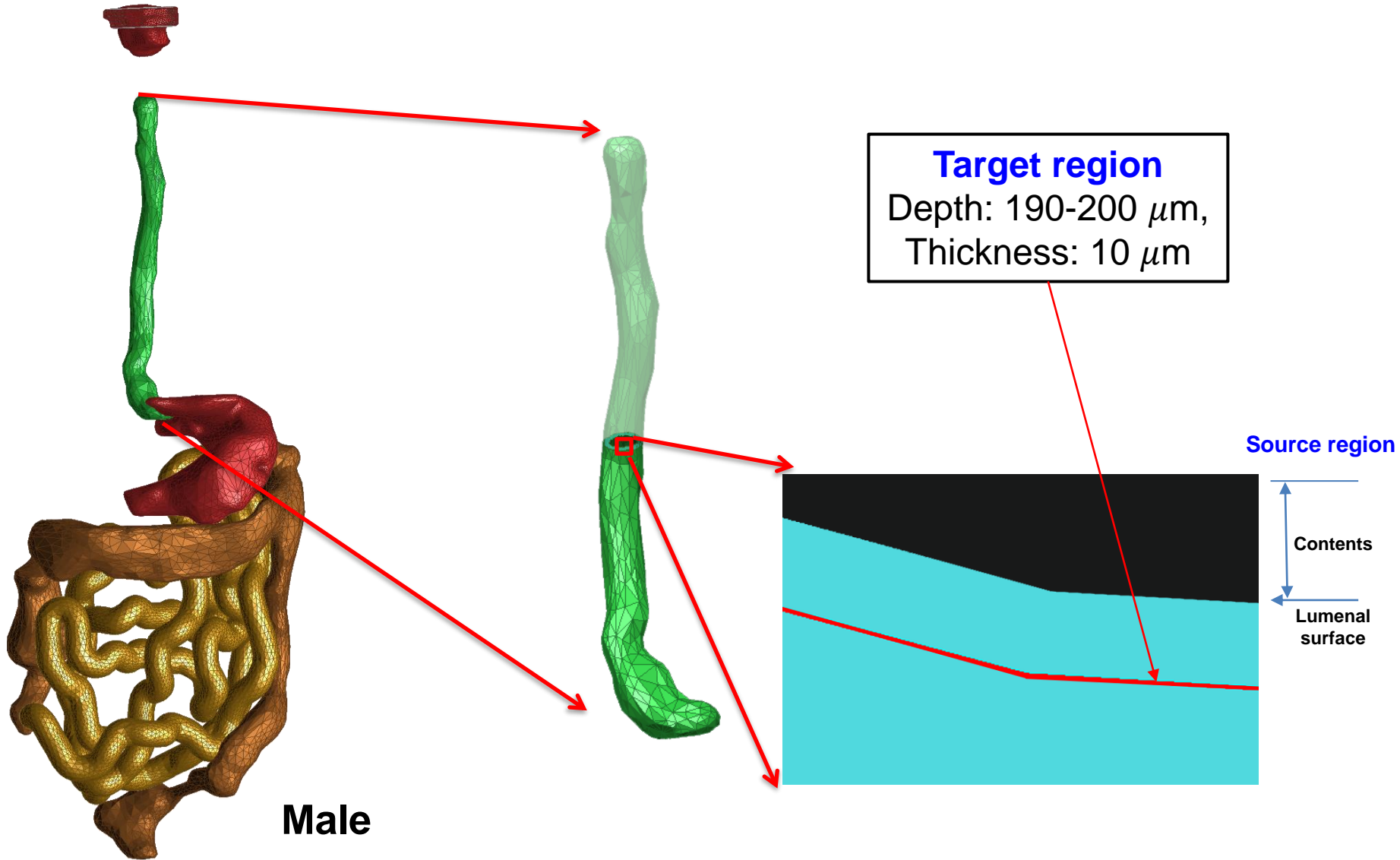
Definition of the radionuclide retention region



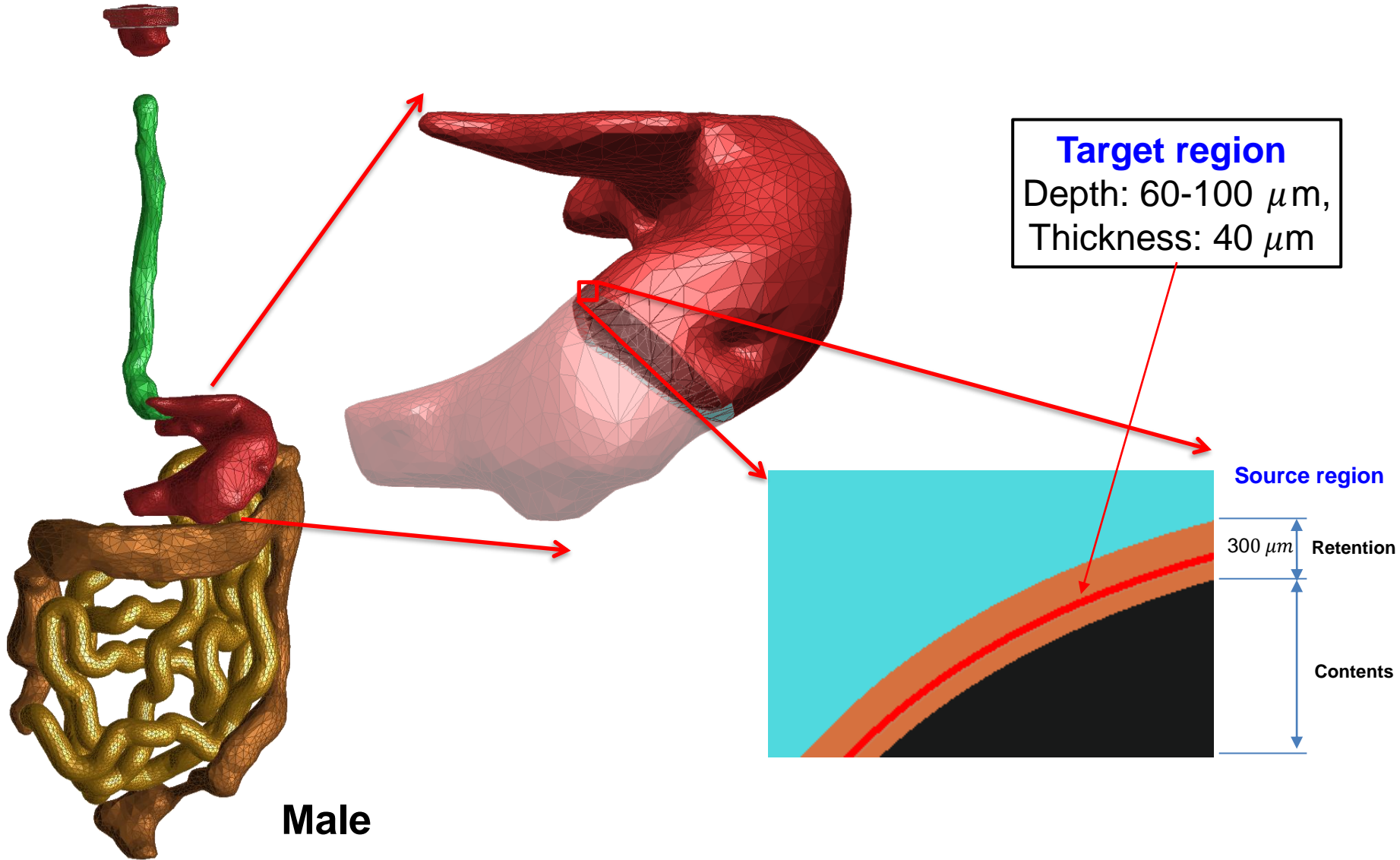
Oral Cavity (Target & Source)



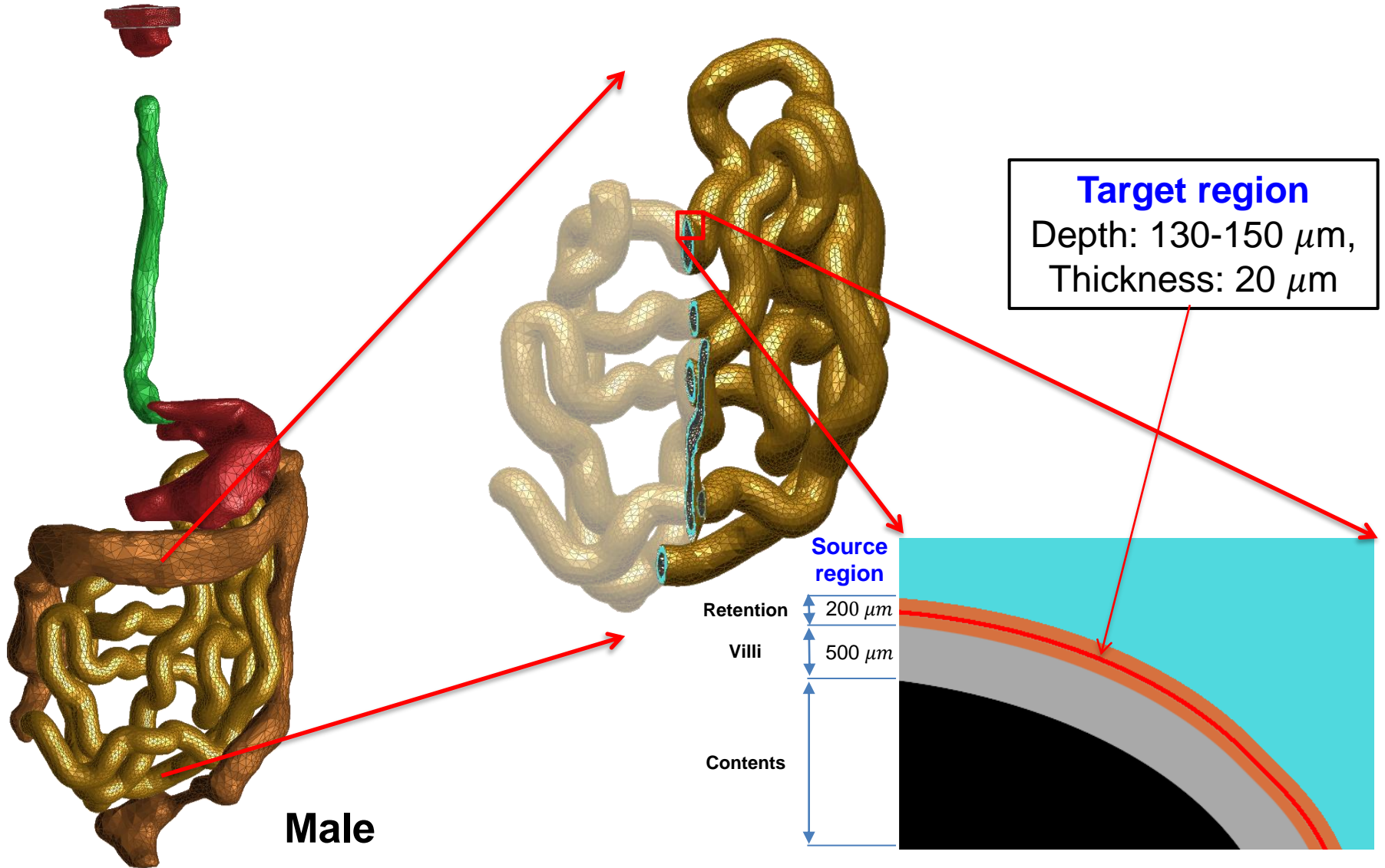
Oesophagus (Target & Source)



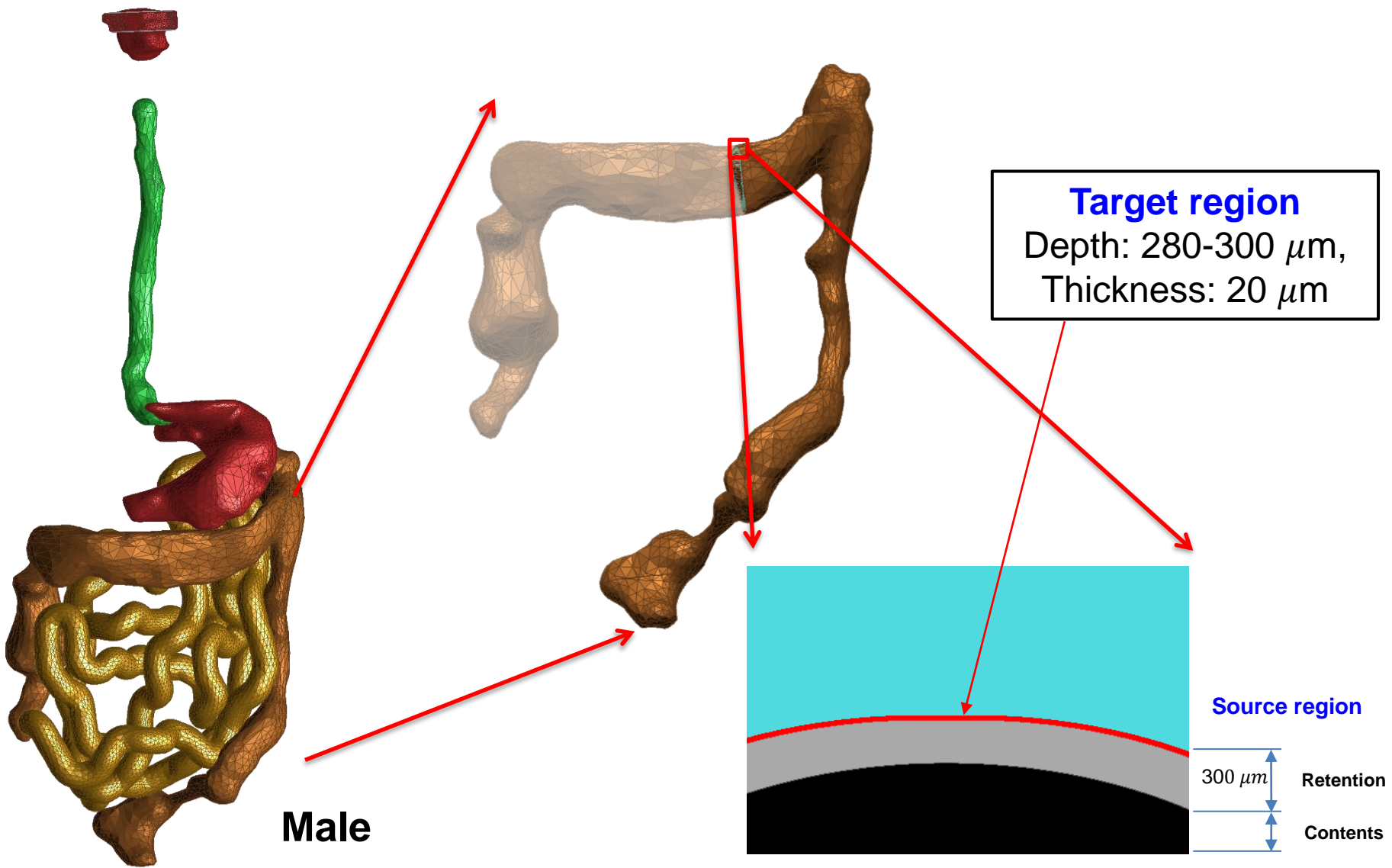
Stomach (Target & Source)



Small Intestine (Target & Source)

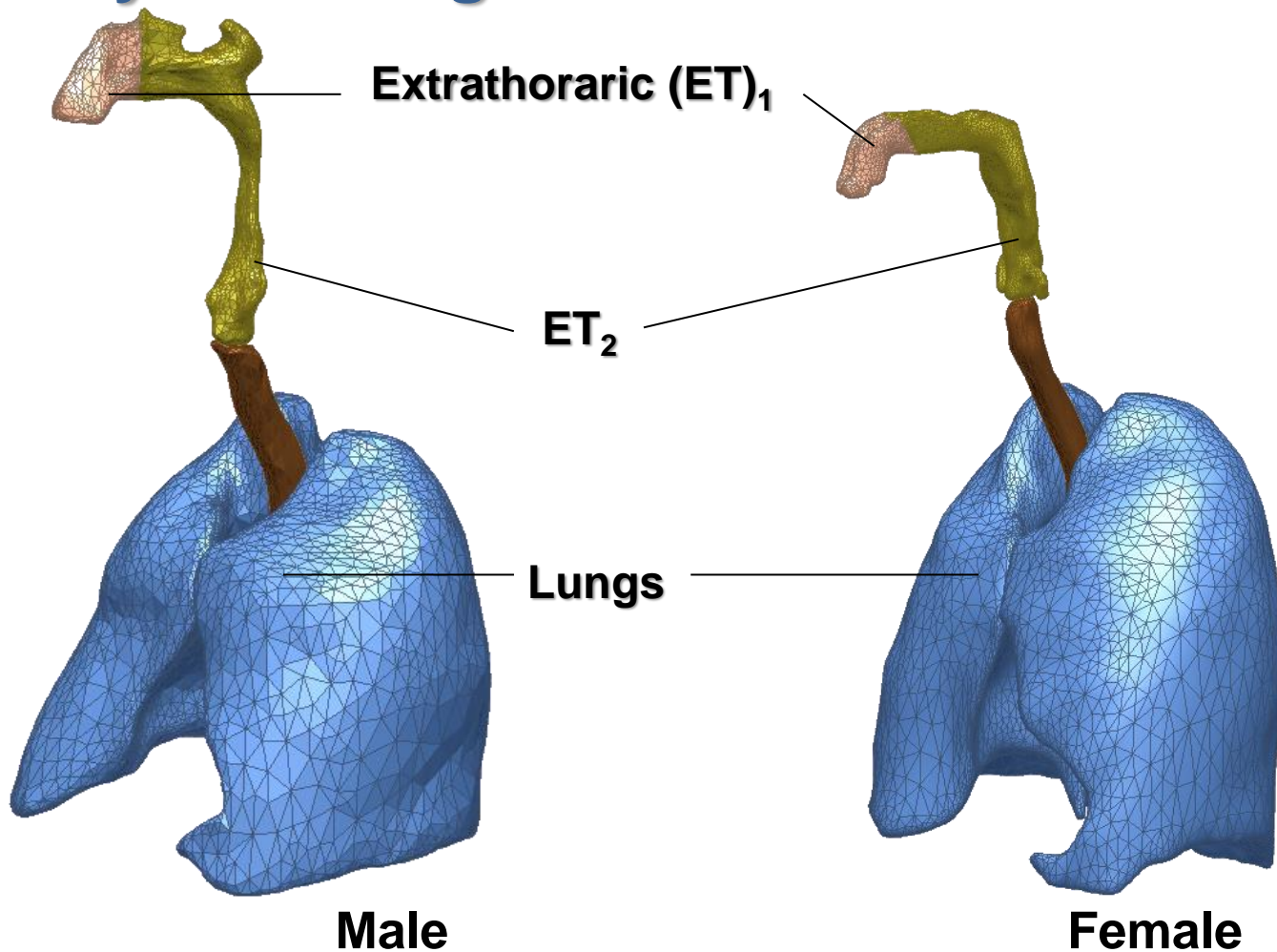


Large Intestine (Target & Source)



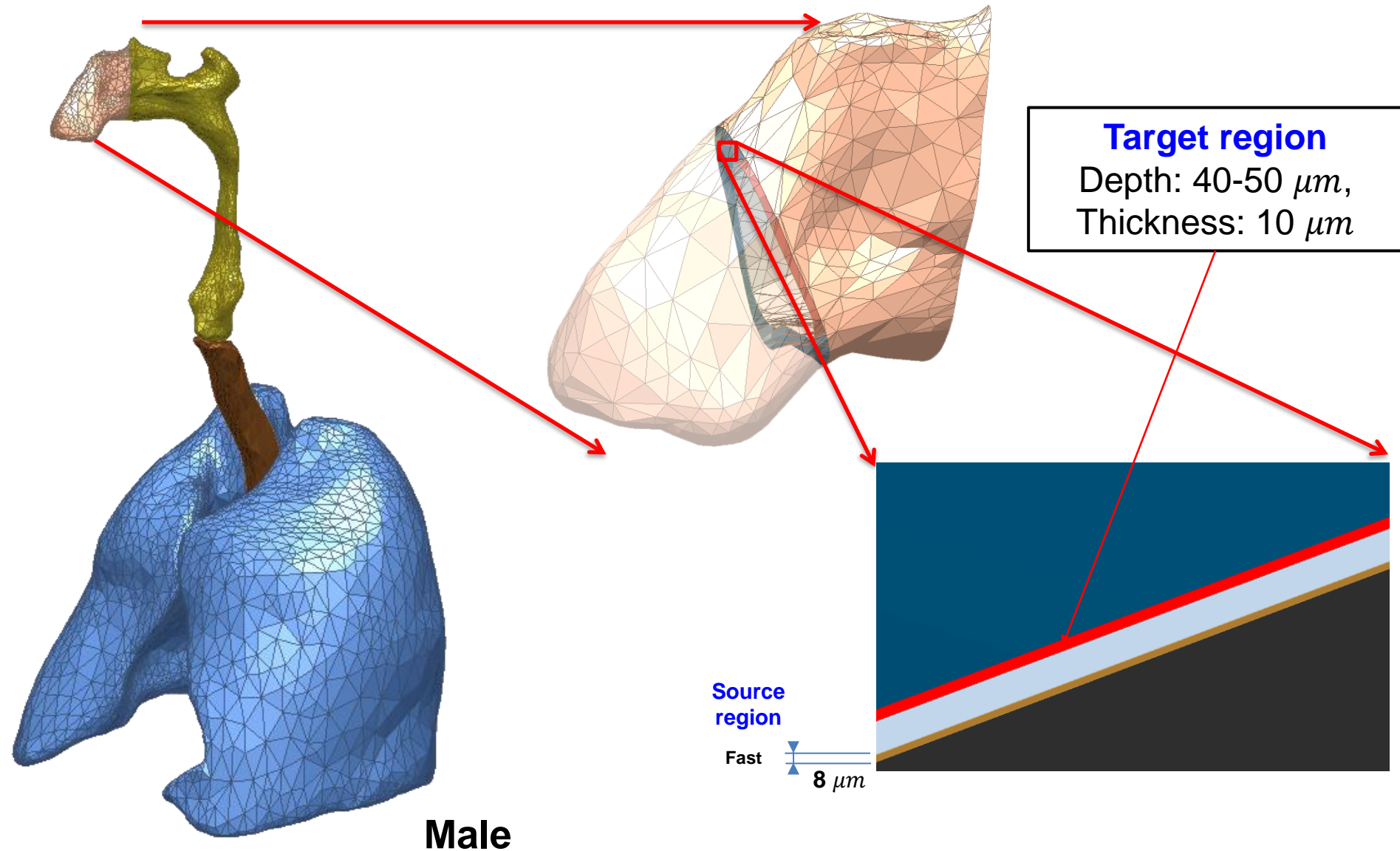
Male

Respiratory Tract Organs

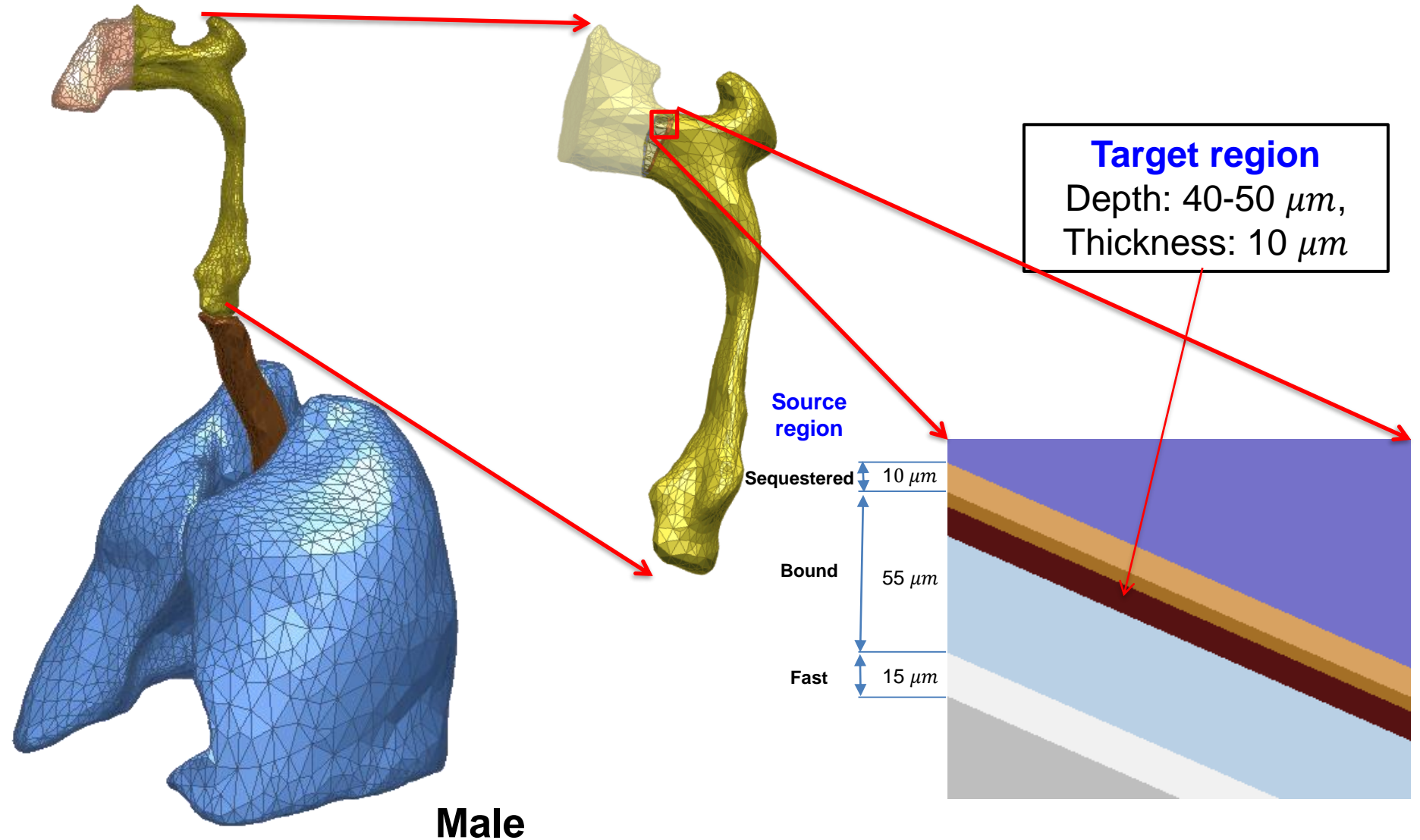


- Micron scales of target and source regions of the respiratory tract system **described in ICRP Publication 66** were included in the mesh phantoms

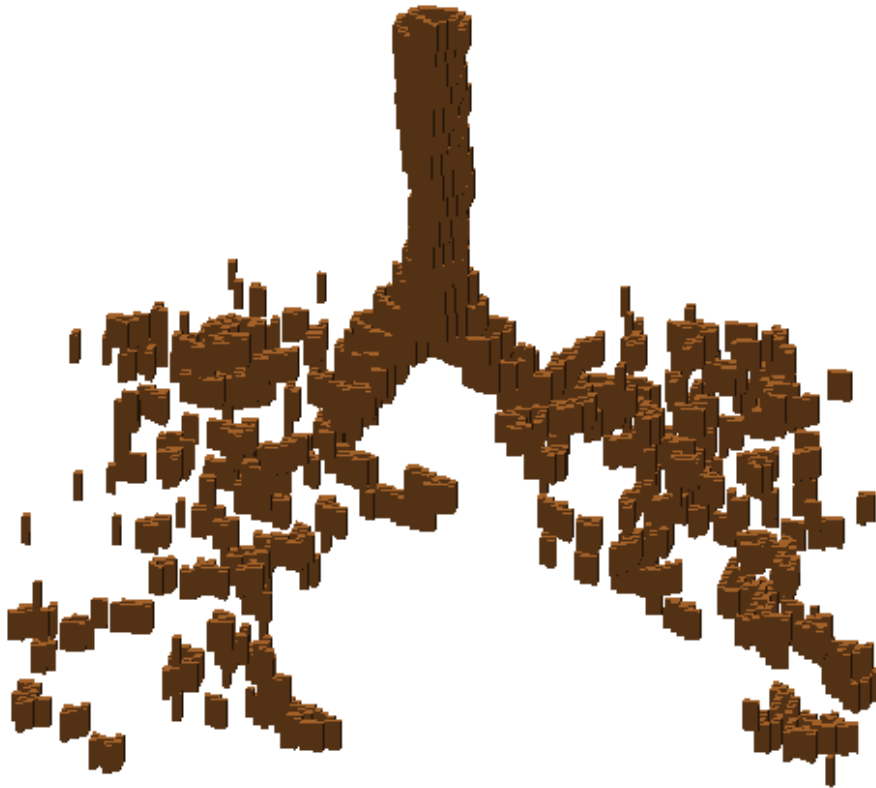
ET₁ (Target & Source)



ET₂ (Target & Source)

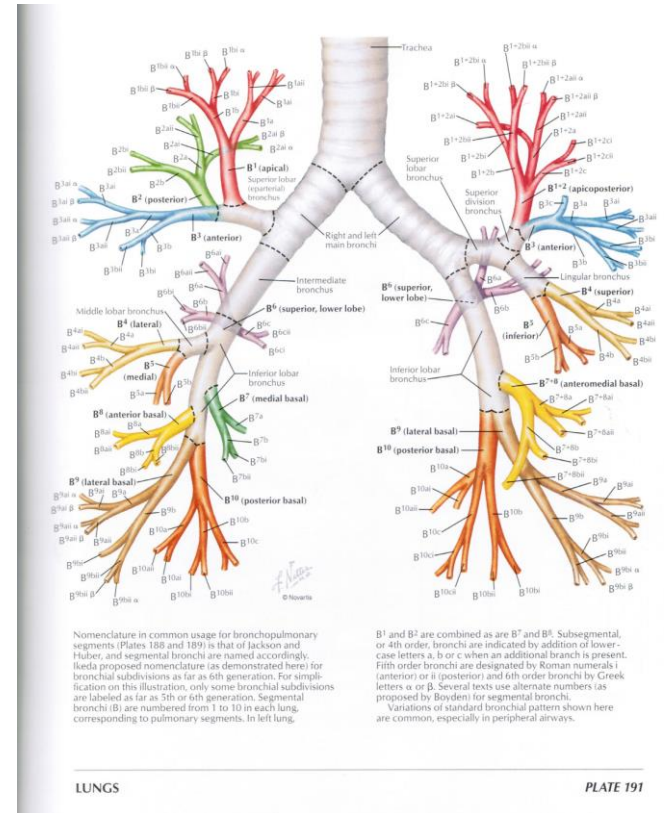


BB / bb (Issue)



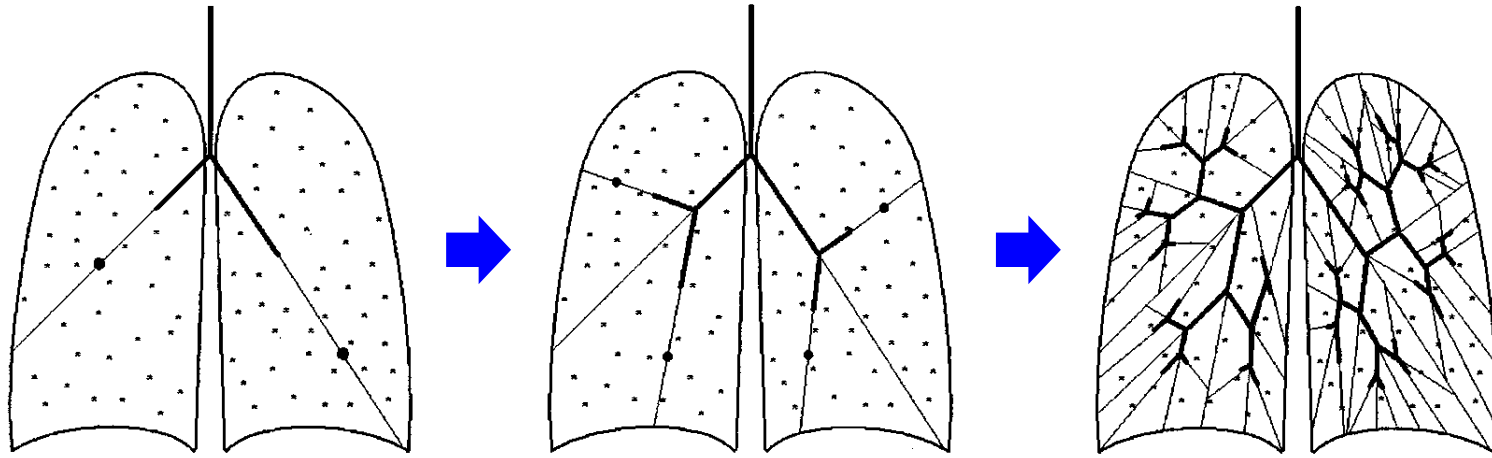
Bronchi (BB) / bronchioles (bb) regions of the ICRP-110 male voxel phantom

- The BB / bb regions cannot be converted to high-quality mesh models as like a realistic tree structure of the lung airways.

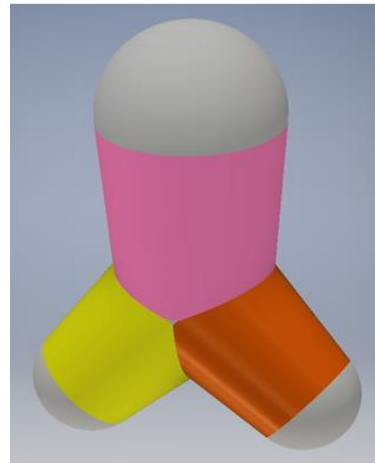
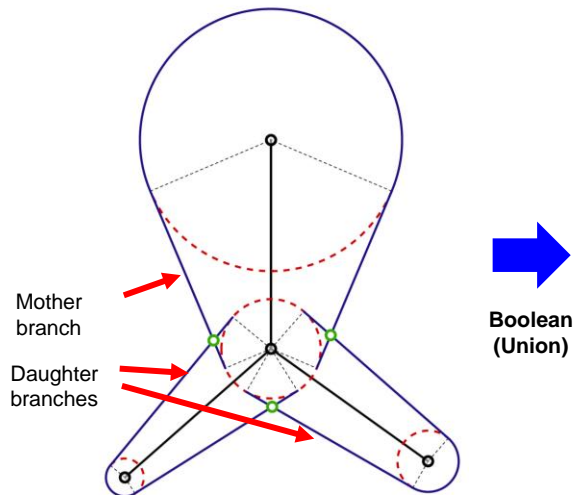


Netter, Frank H. *Atlas of human anatomy*. Elsevier Health Sciences, (2010)

BB / bb (Modeling)



Tawhai et al. "Generation of an anatomically based three-dimensional model of the conducting airways." *Annals of biomedical engineering* 28.7 (2000): 793-802.



Y-shape mathematical model based on truncated cones and spheres used for the smooth branch connections.

- The realistic lung airway models to represent the BB / bb regions were developed based on an airway center line generation algorithm and Y-shape mathematical models.

Dimensions of Airway for Adult Male

Table 2. Dimensional model of tracheobronchiolar tree in adult male adopted in this report to model aerosol deposition and bronchial-bronchiolar dose (James, 1988, adapted from Weibel, 1963; Yeh and Schum, 1980; and Phalen *et al.*, 1985)^a

Region	Generation	Diameter ^b (m)	Length ^b (m)	J branch ^c (degrees)	Gravity angle ^c (degrees)
Bronchial (BB)	0 Trachea	1.65×10^{-2d}	9.1×10^{-2}	0	0
	1 Main bronchi	1.20×10^{-2}	3.8×10^{-2}	36	20
	2	0.85×10^{-2}	1.5×10^{-2}	35	31
	3	0.61×10^{-2}	0.83×10^{-2}	28	43
	4	0.44×10^{-2}	0.90×10^{-2}	35	39
	5	0.36×10^{-2}	0.81×10^{-2}	39	39
	6	0.29×10^{-2}	0.66×10^{-2}	34	40
	7	0.24×10^{-2}	0.60×10^{-2}	48	36
	8	0.20×10^{-2}	0.53×10^{-2}	53	39
Bronchiolar (bb)	9 Bronchioles	0.1651×10^{-2e}	0.4367×10^{-2}	54	45
	10	0.1348×10^{-2}	0.3620×10^{-2}	51	45
	11	0.1092×10^{-2}	0.3009×10^{-2}	46	45
	12	0.0882×10^{-2}	0.2500×10^{-2}	47	45
	13	0.0720×10^{-2}	0.2069×10^{-2}	48	45
	14	0.0603×10^{-2}	0.1700×10^{-2}	52	45
	15 Terminal bronchioles	0.0533×10^{-2}	0.1380×10^{-2}	45	45

^a There are significant differences in the adult airway dimensions measured and published by Weibel (1963), Yeh and Schum (1980), and Phalen *et al.* (1985). Because it is not apparent which set of values more appropriately apply to reference man, the dimensions from the three sources were averaged after all were adjusted to a standard functional residual capacity (FRC) of $3.3 \times 10^{-3} \text{ m}^3$ (Yu and Dui, 1982; James, 1988).

^b These values are taken to be the reference values from which tissue masses (Table 5) and airway volumes (Table 6) are derived.

^c J branch: Branching angle of the daughter segment is defined as the change in direction of the bulk airflow from the segment into the daughter segment.

Gravity angle: The inclination of the segment to gravity = angle between the bulk airflow direction during inspiration and the force of gravity. (From Phalen *et al.*, 1985.)

Dimensions of Airway for Adult Female

Table 4. Constants used to calculate scaling* of airway diameter and length as a function of body height^b

Airway generation (z)	Constant (a)	
	Diameter	Length
0 Trachea	0.540	0.559
1 Main bronchi	0.530	0.468
2 Bronchi	0.507	0.474
3 Bronchi	0.489	0.502
4 Bronchi	0.429	0.431
5 Bronchi	0.441	0.476
6 Bronchi	0.452	0.441
7 Bronchi	0.405	0.359
8 Bronchi	0.333	0.273

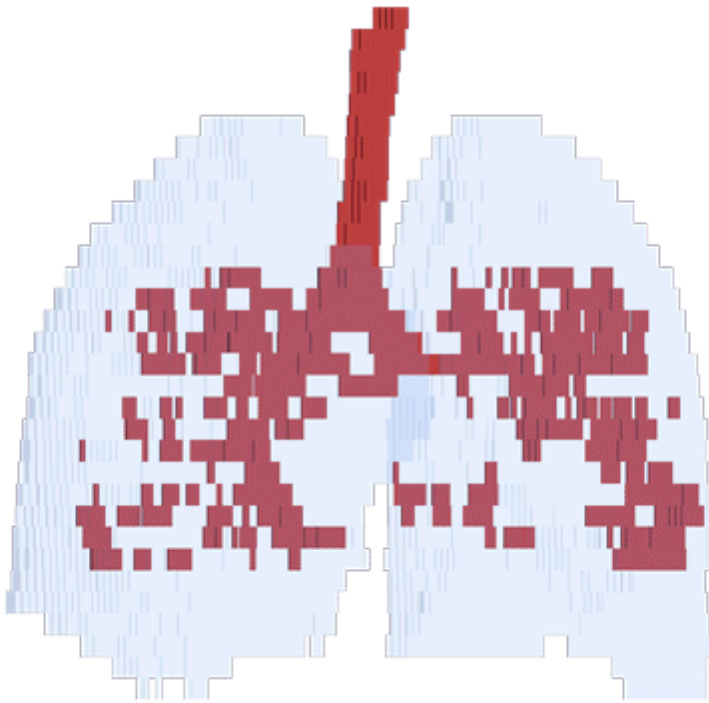
* Scaling factor, SF, is the ratio of airway diameter or length in the subject compared to that in reference man.

^b $SF = a(H_s - 1.76) + 1$, where H_s is height of subject in meters.

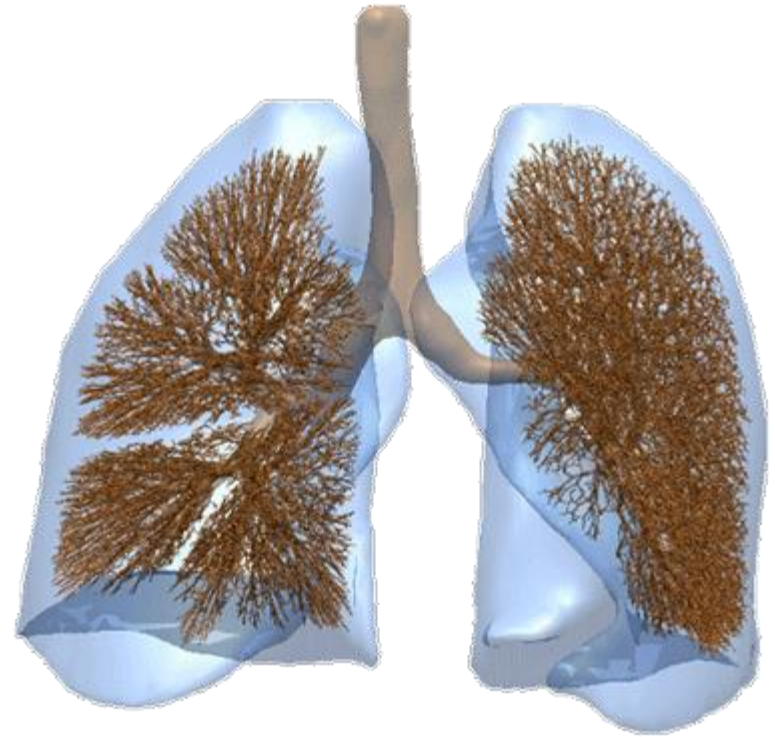
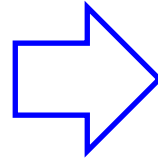
- The diameter and length of the **BB** were scaled by using the scaling factors given in ICRP Publication 66.
- The diameter and length of the **bb** were respectively obtained by parabolic and hyperbolic interpolation between those of generation 8 and 16.

BB / bb (Male)

Male



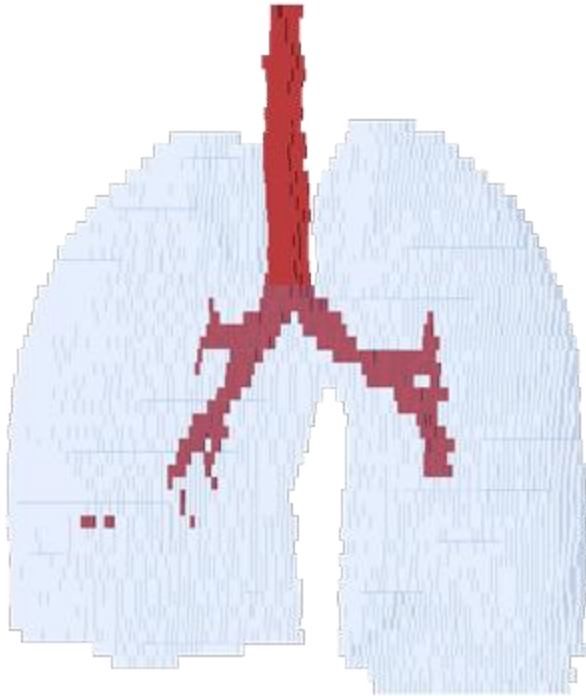
Voxel



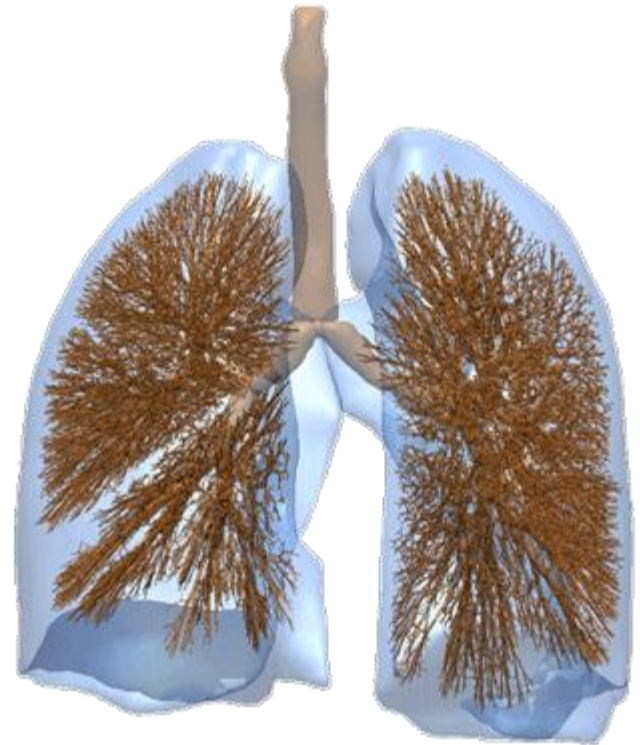
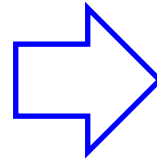
Mesh

BB / bb (Female)

Female



Voxel



Mesh

BB / bb (Target & Source)

Male

Target region

Secretory cells

$8 \mu m$

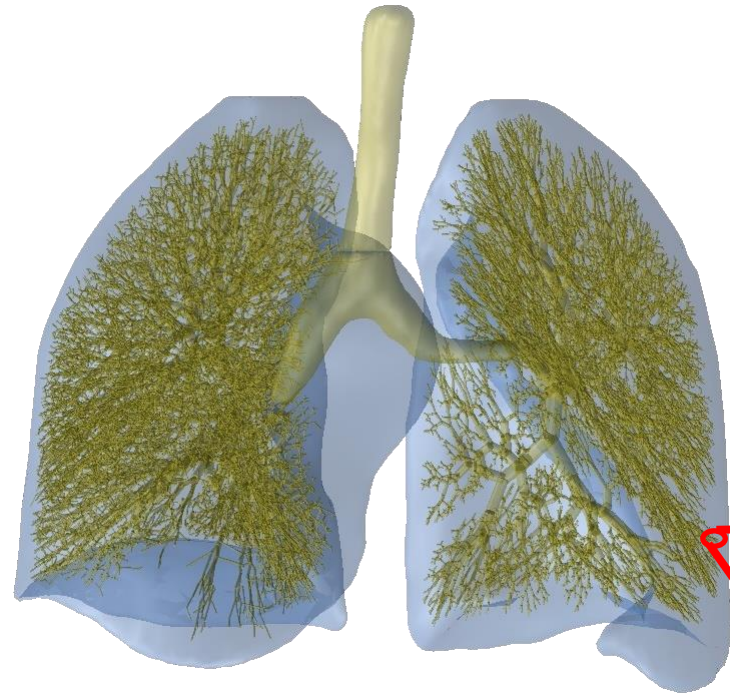
Source region

AI

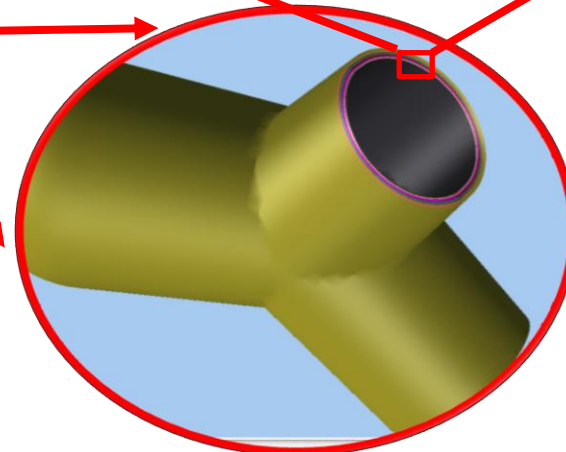
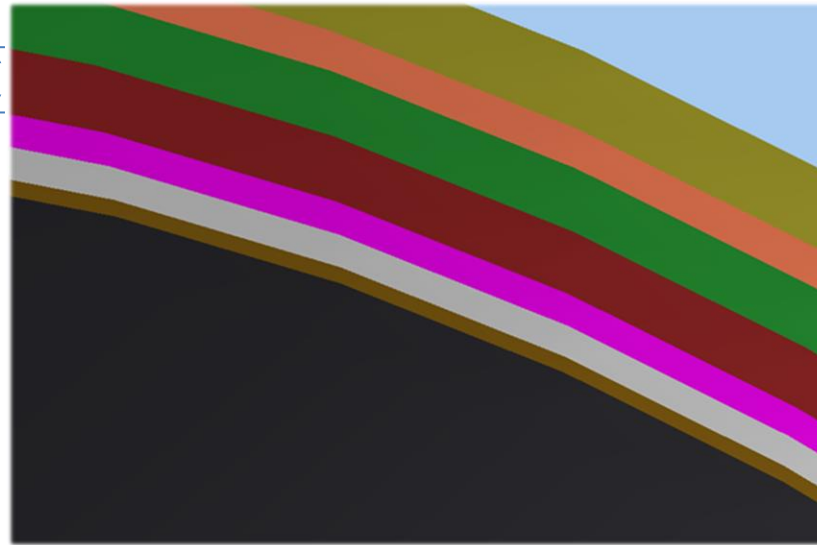
$5 \mu m$ Sequestered

$20 \mu m$ Bound

$6 \mu m$ Fast & slow mucus

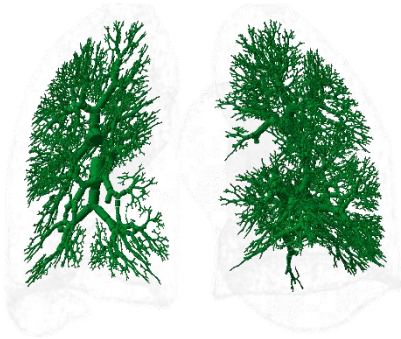


“Turn ON/OFF”

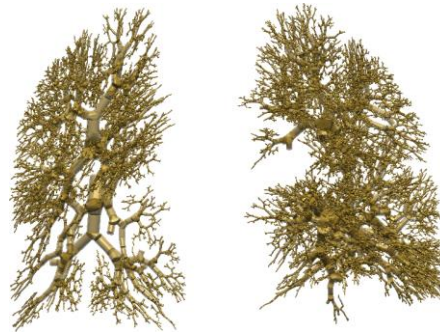
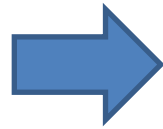


Bronchiolar (bb)

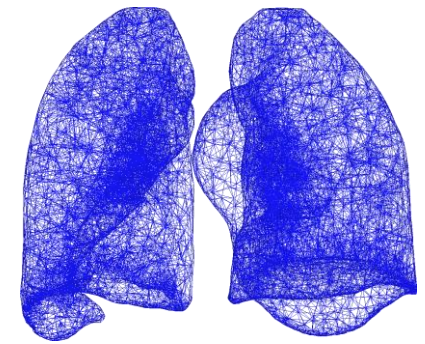
BB / bb – Memory Issue



Airway model in
mathematical format

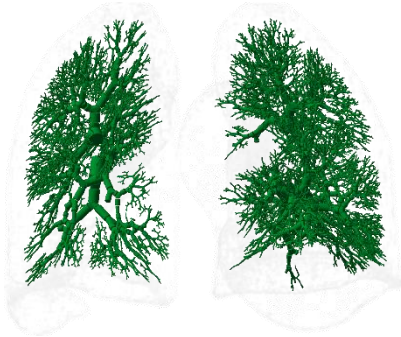


Airway model in
mesh format

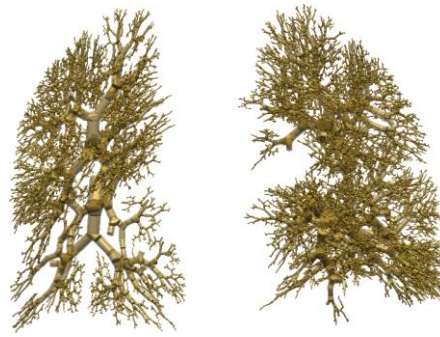
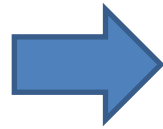


Lung model in
mesh format

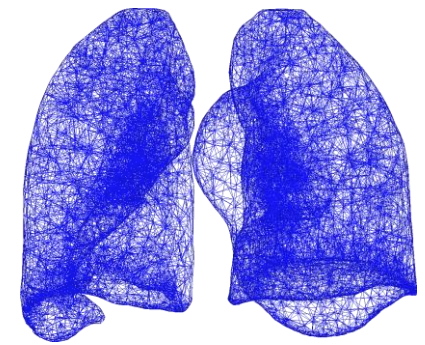
BB / bb – Memory Issue



Airway model in
mathematical format



Airway model in
mesh format



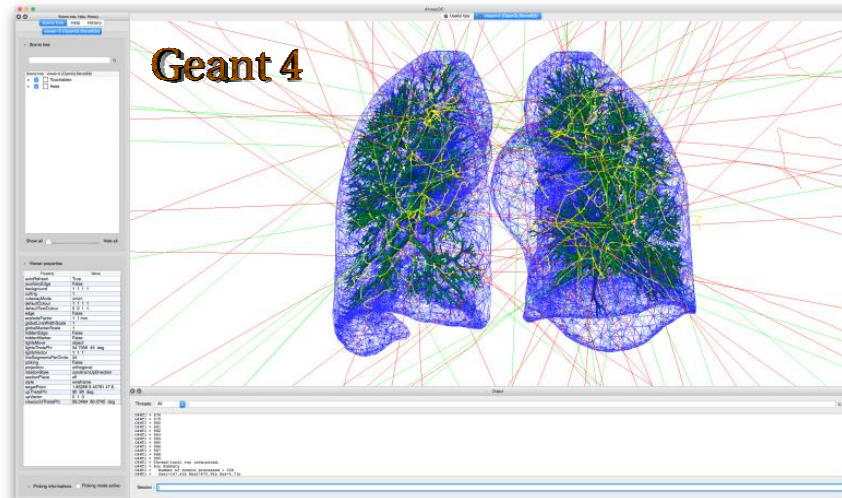
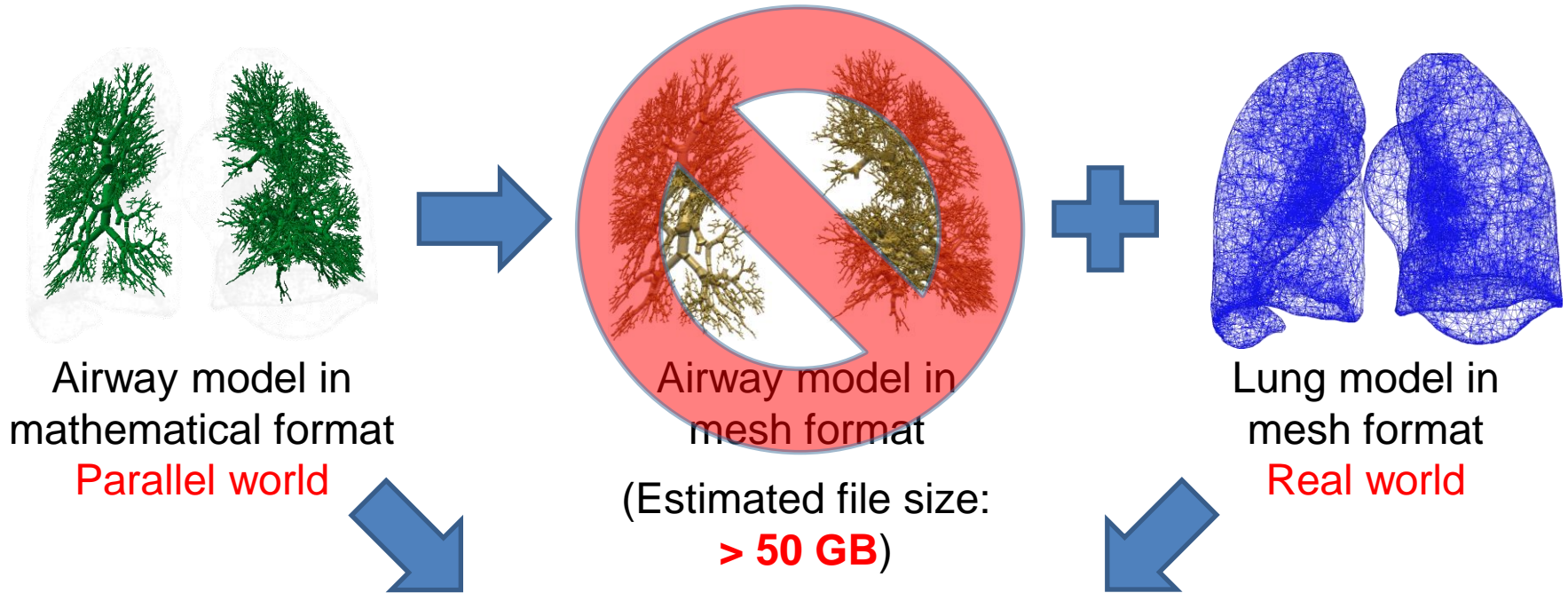
Lung model in
mesh format

(Estimated file size:
> 50 GB)



Impractical for Monte Carlo simulations

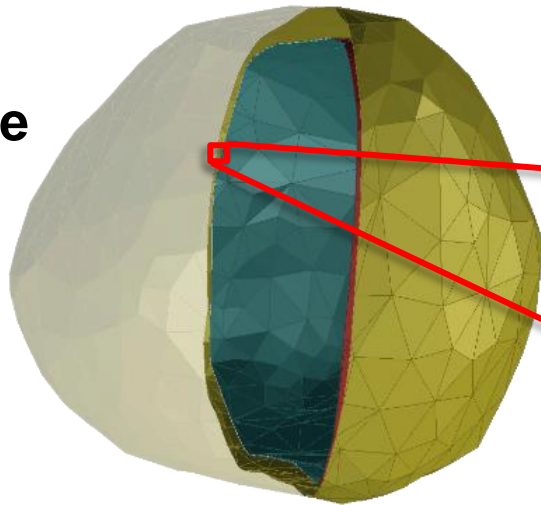
BB / bb – Memory Issue



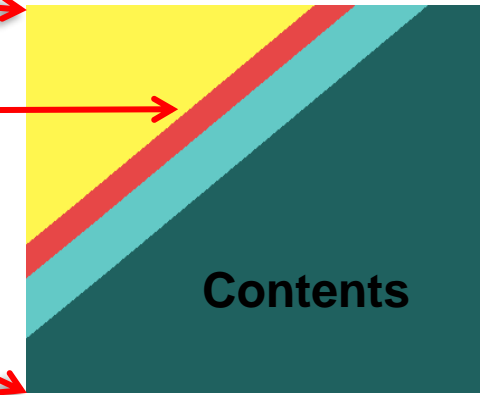
Simulated in Geant4

Urinary Bladder (Target Layer)

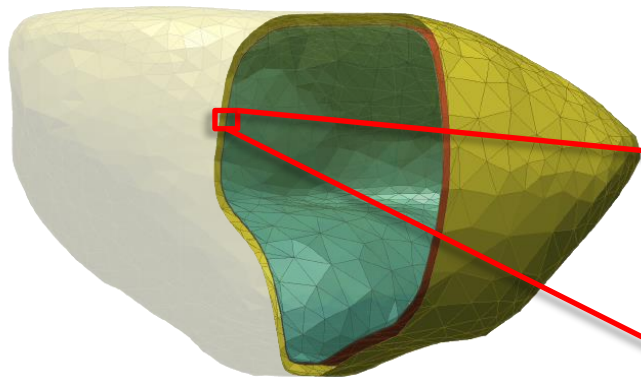
Male



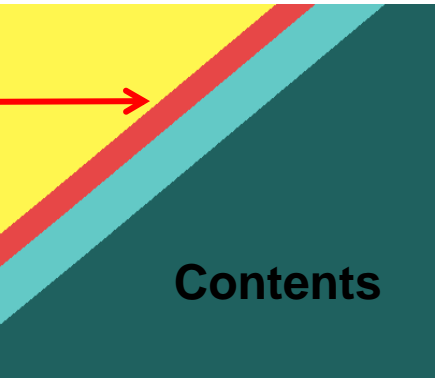
Target layer
Depth: 118-193 μm
Thickness: 75 μm



Female



Target layer
Depth: 116-185 μm
Thickness: 69 μm

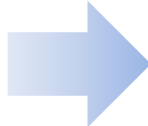
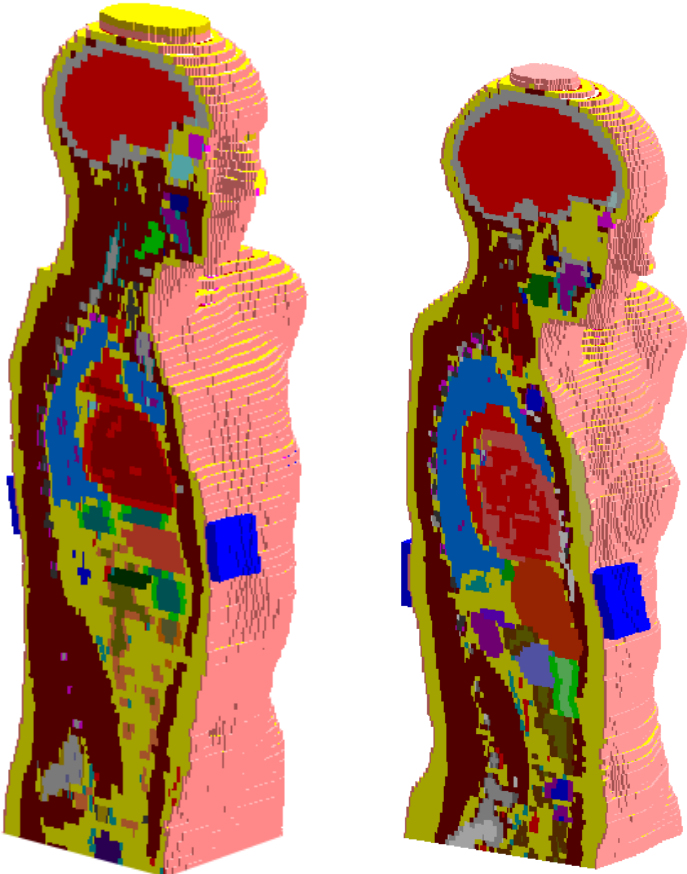


Eckerman, K.F., Veinot, K.G., 2018. Transitional epithelium of urinary bladder: dosimetric data for cells at risk. IEEE Trans. Radiat. Plasma Med. Sci. 3, 61–64.

Adult Mesh-type Reference Phantoms

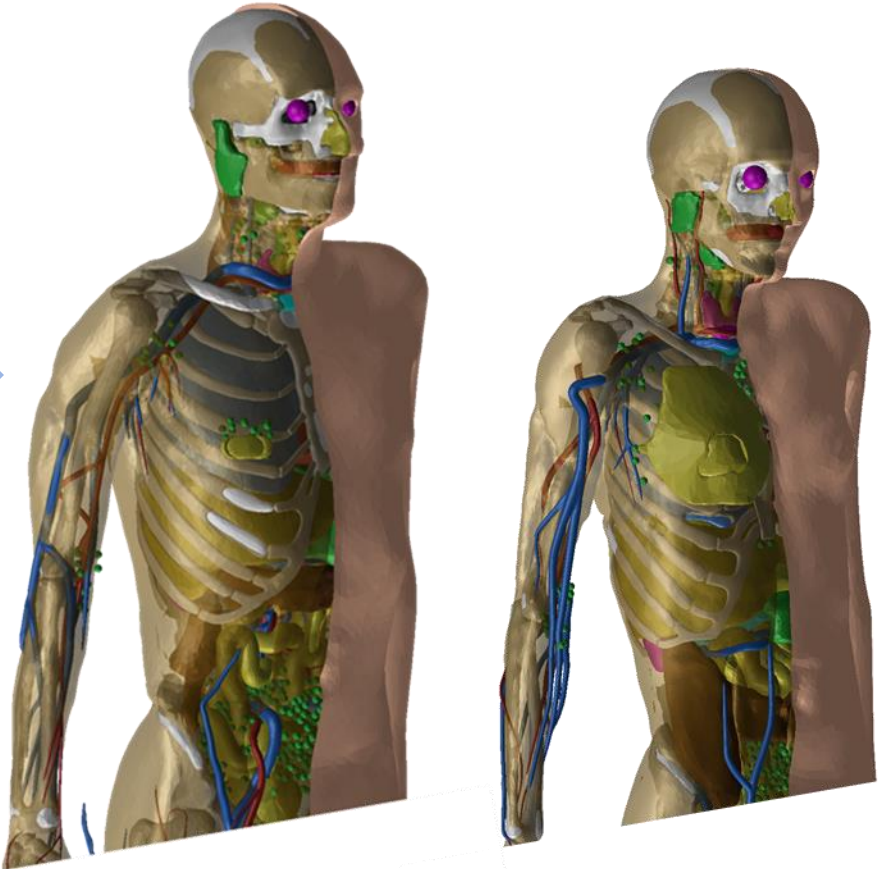
Male

Female



Male

Female



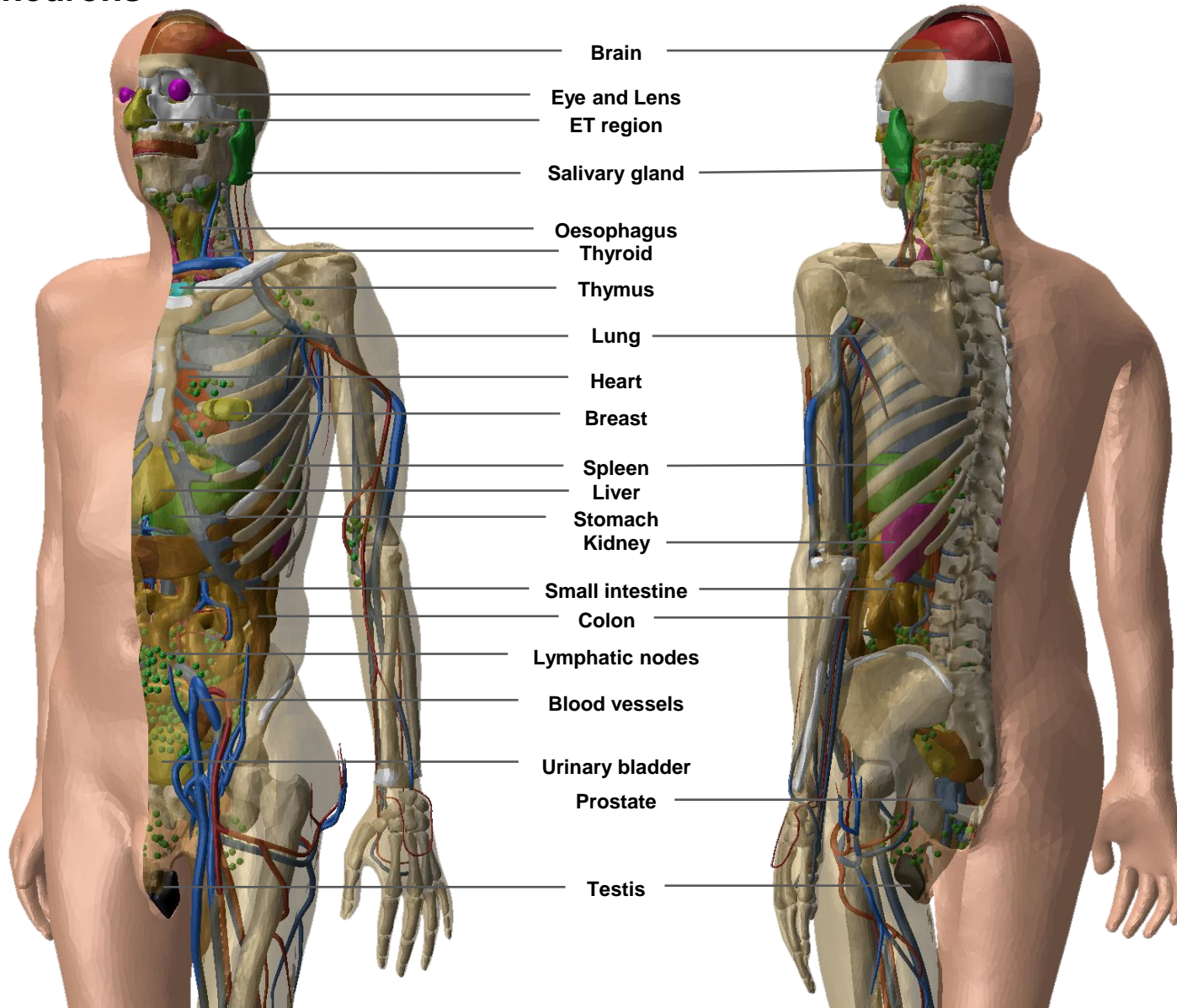
Adult voxel-type reference phantoms

Adult mesh-type reference phantoms

Adult Mesh-type Reference Phantoms - Male

2.5 M triangular facets

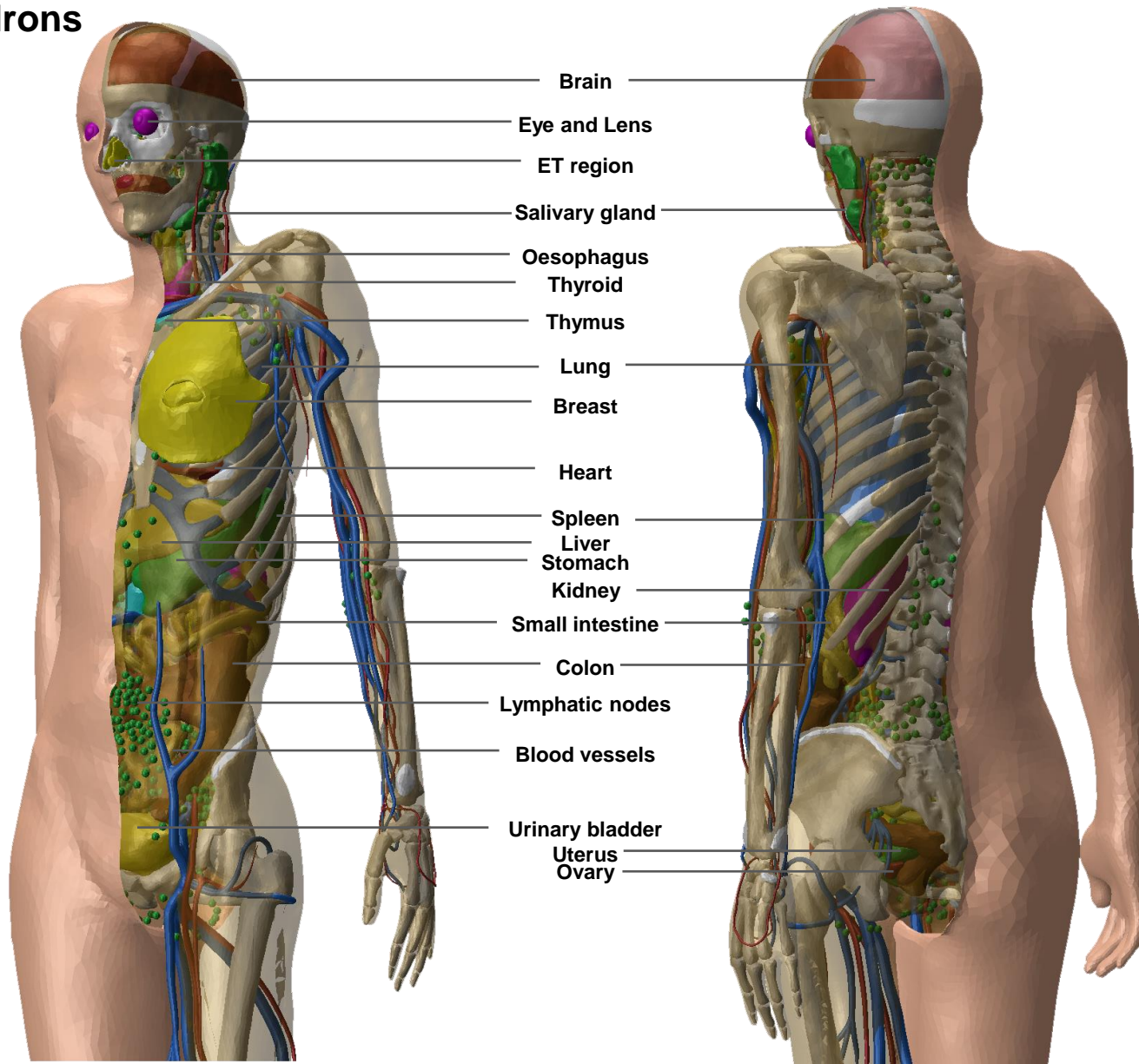
8.2 M tetrahedrons



Adult Mesh-type Reference Phantoms - Female

2.6 M triangular facets

8.6 M tetrahedrons



Organ ID, Mass, Density, Elemental Composition

ANNEX A. LIST OF ORGAN IDENTIFICATION NUMBERS, MEDIUM, DENSITY, AND MASS OF EACH ORGAN/TISSUE

Table A.1. List of organ identification (ID) number, medium, density, and mass of each organ/tissue in tetrahedral mesh (TM) phantoms.

Organ ID	Organ/tissue	Medium	Density (g cm ⁻³)		Mass (g)	
			Male	Female	Male	Female
100	Adrenal, left	1	1.036	1.035	8.683	6.817
200	Adrenal, right	1	1.036	1.035	8.683	8.649
300	ET ₁ , 0~8 μm	2	1.031	1.031	0.022	0.009
301	ET ₁ , 8~40 μm	2	1.031	1.031	0.090	0.035
302	ET ₁ , 40~50 μm	2	1.031	1.031	0.028	0.011
303	ET ₁ , 50 μm~surface	2	1.031	1.031	11.291	4.375
400	ET ₂ , -15~0 μm	52	1.000	1.000	0.141	0.104
401	ET ₂ , 0~40 μm	2	1.031	1.031	0.390	0.288
402	ET ₂ , 40~50 μm	2	1.031	1.031	0.098	0.072
403	ET ₂ , 50~55 μm	2	1.031	1.031	0.049	0.036
404	ET ₂ , 55~65 μm	2	1.031	1.031	0.098	0.072
405	ET ₂ , 65 μm~surface	2	1.031	1.031	28.808	14.180
500	Oral mucosa, tongue	3	1.050	1.050	0.086	0.066
501	Oral mucosa, mouth floor	3	1.050	1.050	0.024	0.016
600	Oral mucosa, lips, and checks	3	1.050	1.050	0.023	0.019
700	Trachea	2	1.031	1.031	10.364	8.201
800	BB ₁ [*] , -11~-6 μm	52	1.000	1.000	0.025	0.010
801	BB ₁ [*] , -6~0 μm	2	1.031	1.031	0.031	0.013
802	BB ₁ [*] , 0~10 μm	2	1.031	1.031	0.052	0.021
803	BB ₁ [*] , 10~35 μm	2	1.031	1.031	0.130	0.053
804	BB ₁ [*] , 35~40 μm	2	1.031	1.031	0.026	0.011
805	BB ₁ [*] , 40~50 μm	2	1.031	1.031	0.052	0.021
806	BB ₁ [*] , 50~60 μm	2	1.031	1.031	0.052	0.021
807	BB ₁ [*] , 60~70 μm	2	1.031	1.031	0.053	0.021
808	BB ₁ [*] , 70 μm~surface	2	1.031	1.031	2.777	1.179
900	Blood in large arteries, head	4	1.060	1.060	1.504	1.910
910	Blood in large veins, head	4	1.060	1.060	6.943	3.009

ANNEX B. LIST OF MEDIA AND THEIR ELEMENTAL COMPOSITIONS

Table B.1. List of media, their elemental compositions (percentage by mass), and their densities for the adult male mesh-type reference phantom.

Medium no.		Elemental Composition (%)											Density (g cm ⁻³)		
		H	C	N	O	Na	Mg	P	S	Cl	K	Ca		Fe	I
1	Adrenal	10.4	22.8	2.8	63.0	0.1		0.2	0.3	0.2	0.2				1.036
2	ET, trachea, BB, bb, gallbladder wall, pituitary gland, salivary glands, spinal cord, thymus, tonsils, ureter	10.5	25.1	2.7	60.7	0.1		0.2	0.3	0.2	0.2				1.031
3	Oral mucosa, tongue	10.2	14.2	3.4	71.1	0.1		0.2	0.3	0.1	0.4				1.050
4	Blood	10.2	11.0	3.3	74.5	0.1		0.1	0.2	0.3	0.2		0.1		1.060
5	Cortical bone	3.6	15.9	4.2	44.8	0.3	0.2	9.4	0.3				21.3		1.904
6	Medullary cavity	11.5	63.6	0.7	23.9	0.1			0.1	0.1					0.981
7	Humeri, upper, spongiosa	8.1	35.4	2.8	41.0	0.2	0.1	3.7	0.2	0.1	0.1	8.3			1.233
8	Humeri, lower, ulnae and radii, wrists and hand bones, femora, lower, tibiae, fibulae and patellae, ankles and foot, spongiosa	9.6	50.4	1.7	30.8	0.1		2.2	0.2	0.1		4.9			1.109
9	Clavicles, spongiosa	8.9	40.9	2.5	38.5	0.1		2.7	0.2	0.1	0.1	6.0			1.157
10	Cranium, spongiosa	8.8	39.5	2.6	39.5	0.1	0.1	2.8	0.2	0.1	0.1	6.2			1.165
11	Femora, upper, spongiosa	9.3	44.1	2.3	36.5	0.1	0.1	2.2	0.2	0.1	0.1	5.0			1.125
12	Mandible, spongiosa	7.7	33.2	3.0	42.0	0.2	0.1	4.1	0.2	0.1	0.1	9.3			1.271
13	Pelvis, spongiosa	9.4	40.9	2.6	40.0	0.1	0.1	2.0	0.2	0.1	0.1	4.5			1.121
14	Ribs, spongiosa	8.8	34.6	3.1	44.4	0.1	0.1	2.6	0.2	0.1	0.1	5.8	0.1		1.170
15	Scapulae, spongiosa	8.4	37.3	2.7	40.4	0.1	0.1	3.3	0.2	0.1	0.1	7.3			1.201
16	Cervical spine, spongiosa	10.3	41.6	2.8	42.8	0.1		0.6	0.2	0.2	0.1	1.2	0.1		1.049
17	Thoracic spine, spongiosa	10.0	40.3	2.8	43.1	0.1		1.0	0.2	0.2	0.1	2.1	0.1		1.070
18	Lumbar spine, spongiosa	9.5	38.0	3.0	43.6	0.1		1.6	0.2	0.2	0.1	3.6	0.1		1.108

Organ IDs for Source and Target Region

ANNEX C. LIST OF ANATOMICAL SOURCE REGIONS, ACRONYMS, AND IDENTIFICATION NUMBERS

Table C.1. List of anatomical source regions, their acronyms, and corresponding identification (ID) numbers in the tetrahedral mesh (TM) phantoms.

Source region	Acronym	ID number(s)
Oral cavity	O-cavity	13300
Oral mucosa	O-mucosa	500, 501, 600
Teeth surface	Teeth-S	12801
Teeth volume	Teeth-V	12800
Tongue	Tongue	500, 13300, 13301
Tonsils	Tonsils	13400
Oesophagus fast	Oesophag-f	11003
Oesophagus slow	Oesophag-s	11003
Oesophagus	Oesophagus-w	11000, 11001, 11002
Stomach contents	St-cont	7300
Stomach wall	St-wall	7200, 7201, 7202, 7203
Stomach mucosa	St-mucosa	7200, 7201, 7202
Small intestine contents	SI-cont	7501
Small intestine villi	SI-villi	7500
Small intestine wall	SI-wall	7400, 7401, 7402, 7403
Small intestine mucosa	SI-mucosa	7400, 7401, 7402
Right colon contents	RC-cont	7700, 7900
Right colon wall	RC-wall	7600, 7601, 7602, 7800, 7801, 7802
Right colon mucosa	RC-mucosa	7600, 7601, 7800, 7801
Left colon contents	LC-cont	8100, 8300
Left colon wall	LC-wall	8000, 8001, 8002, 8200, 8201, 8202
Left colon mucosa	LC-mucosa	8000, 8001, 8200, 8201
Rectosigmoid colon contents	RS-cont	8500
Rectosigmoid colon wall	RS-wall	8400, 8401, 8402, 8600
Rectosigmoid colon mucosa	RS-mucosa	8400, 8401
ET ₁ surface	ET1-sur	300
ET ₂ surface	ET2-sur	400
ET ₁ wall	ET1-wall	300, 301, 302, 303
ET ₂ wall	ET2-wall	401, 402, 403, 404, 405

ICRP Publication 145 (2020)

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ANNEX D. LIST OF ANATOMICAL TARGET REGIONS, ACRONYMS, AND IDENTIFICATION NUMBERS

Table D.1. List of target regions, their acronyms, and corresponding identification (ID) numbers in the tetrahedral mesh (TM) phantoms.

Target region	Acronym	ID number(s)
Red (active) marrow	R-marrow	*
Colon wall	Colon	7600, 7601, 7602, 7800, 7801, 7802, 8000, 8001, 8002, 8200, 8201, 8202, 8400, 8401, 8402, 8600
Stem cells of colon	Colon-stem	7601, 7801, 8001, 8201, 8401
RLung + LLung	Lungs	9700, 9900
Stomach wall	St-wall	7200, 7201, 7202, 7203
Stem cells of stomach	St-stem	7201
Breast-a + Breast-g	Breast	6200, 6300, 6400, 6500
ROvary + LOvary	Ovaries	11100, 11200
Testes	Testes	12900, 13000
Urinary bladder wall	UB-wall	13700, 13701
Urinary bladder basal cells	UB-basal	13701
Oesophagus wall	Oesophagus	11000, 11001, 11002
Oesophagus basal cells	Oesophagus-bas	11001
Liver	Liver	9500
Thyroid	Thyroid	13200
50- μ m endosteal region	Endost-BS	†
Brain	Brain	6100
Salivary glands	S-glands	12000, 12100
Skin	Skin	12200, 12201, 12300, 12301, 12400, 12401, 12500, 12501
Basal cells of skin	Skin-bas	12201, 12301, 12401, 12501
RArenal + LArenal	Adrenals	100, 200
ET region	ET	300, 301, 302, 303, 401, 402, 403, 404, 405
Gallbladder wall	GB-wall	7000
Heart wall	Ht-wall	8700
RKidney + LKidney	Kidneys	8900, 9000, 9100, 9200, 9300, 9400
Systemic lymph nodes	LN-Sys	10200, 10300, 10400, 10500
Muscle	Muscle	10600, 10700, 10800, 10900

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Authors on behalf of ICRP

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Abstract - Following the issuance of new radiological protection recommendations in ICRP Publication 103, the Commission released, in ICRP Publication 110, the adult male and female voxel-type reference computational phantoms to be used for calculation of the reference dose coefficients (DCs) for both external and internal exposures. While providing more anatomically realistic representations of internal anatomy than the older stylised phantoms, the voxel phantoms have their limitations, mainly due to voxel resolution, especially with respect to small tissue structures (e.g. lens of the eye) and very thin tissue layers (e.g. stem cell layers in the stomach wall mucosa and intestinal epithelium).

This publication describes the construction of the adult mesh-type reference computational phantoms (MRCPs) that are the modelling counterparts of the Publication 110 voxel-type reference computational phantoms. The MRCPs include all source and target regions needed for estimating effective dose, even the micrometre-thick target regions in the respiratory and alimentary tract organs, skin, and urinary bladder, assimilating the supplementary stylised models. The MRCPs can be implemented directly into Monte Carlo particle transport codes for dose calculations (i.e. without voxelisation), fully maintaining the advantages of the mesh geometry. DCs of organ dose and effective dose and specific absorbed fractions (SAFs) calculated with the MRCPs for some external and internal exposures show that - while some differences were observed for small tissue structures and for weakly-penetrating radiations - the MRCPs provide the same or very similar values as the previously published reference DCs and SAFs, which were calculated with the Publication 110 reference phantoms and supplementary stylised models, for most tissues and penetrating radiations. Consequently, the DCs for effective dose (i.e. the fundamental protection quantity) were not found to be different. The DCs of ICRP Publication 116 and the SAFs of ICRP Publication 133 thus remain valid.

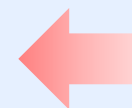


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Other Resources

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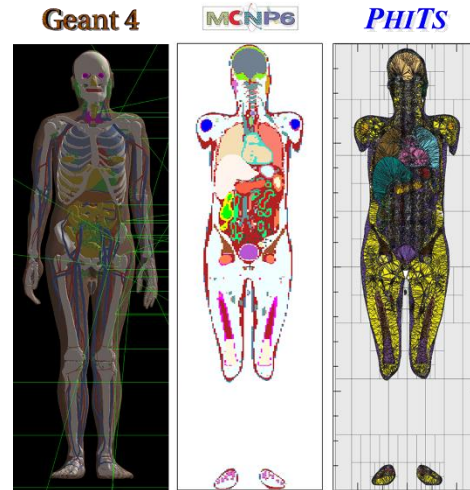
[Resolution of Comments](#)



Compatibility with Monte Carlo Codes

❖ Monte Carlo codes

- Geant4
- PHITS
- MCNP6



❖ Run time

- Geant4 (ver. 10.02) \approx PHITS (ver. 2.92) $>$ MCNP6 (ver. 2.0)*

❖ Memory usage

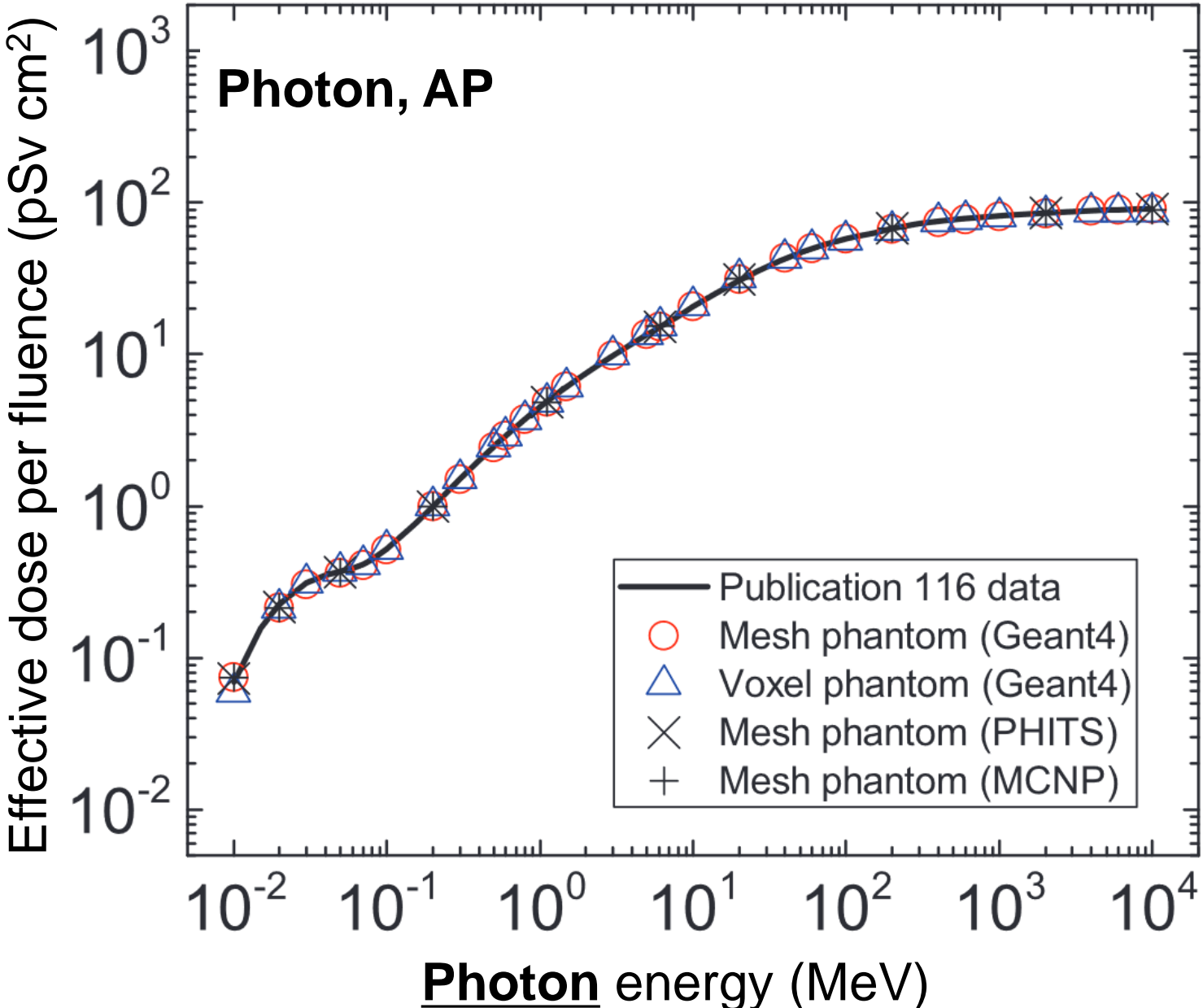
- PHITS (ver. 2.92): \sim 1 GB
- Geant4 (ver. 10.02): \sim 11 GB
- MCNP6 (ver. 2.0): \sim 14 GB*

$<$ A personal computer
(maximum: 64 GB)

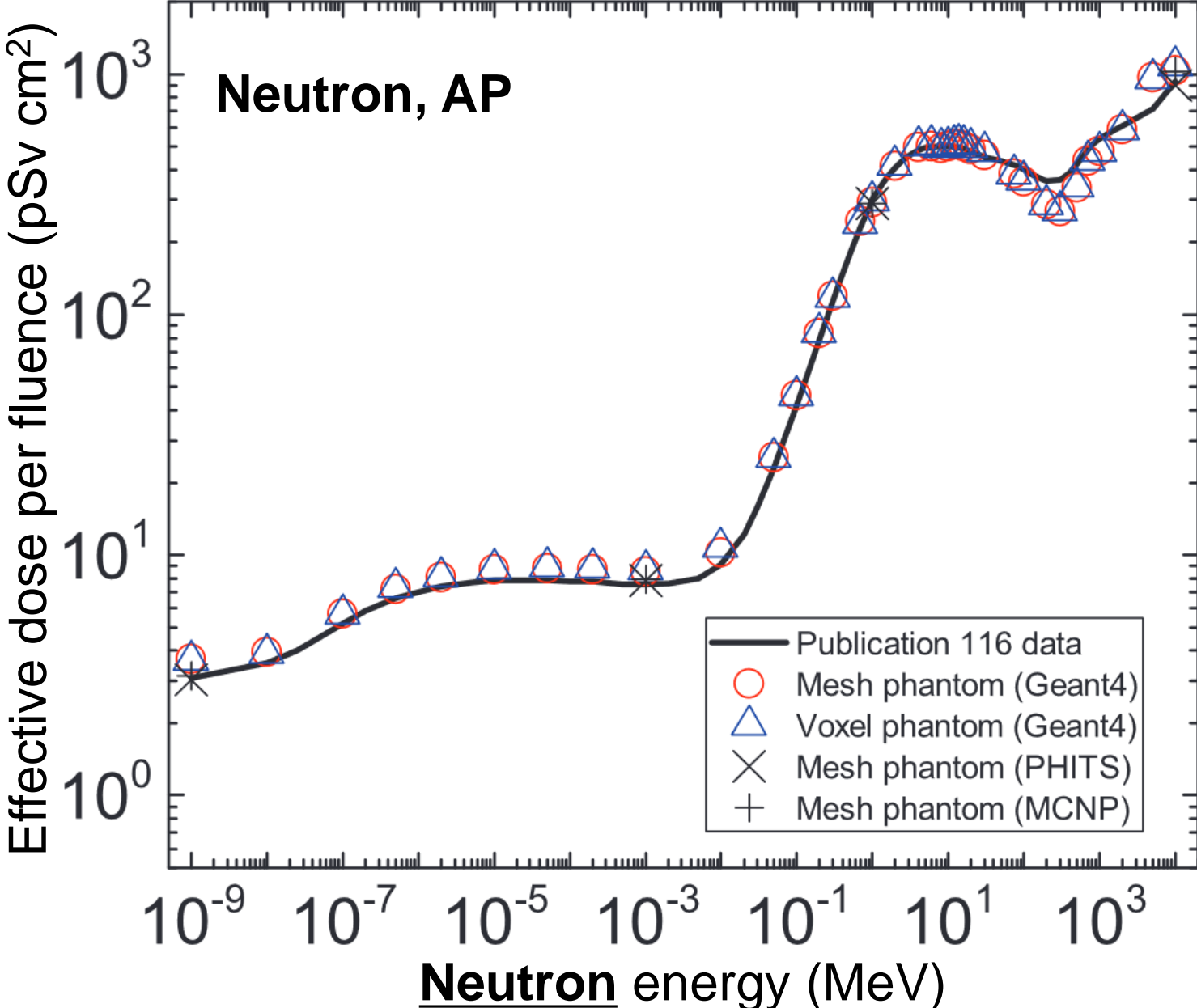
**Version 3.0 is coming soon and expected to improve the simulation performance of “unstructured mesh” in general (from personal communication with a MCNP developer)*

Example input/code files for Geant4, PHITS, and MCNP6 are also provided in the supplemental material of ICRP Publication 145

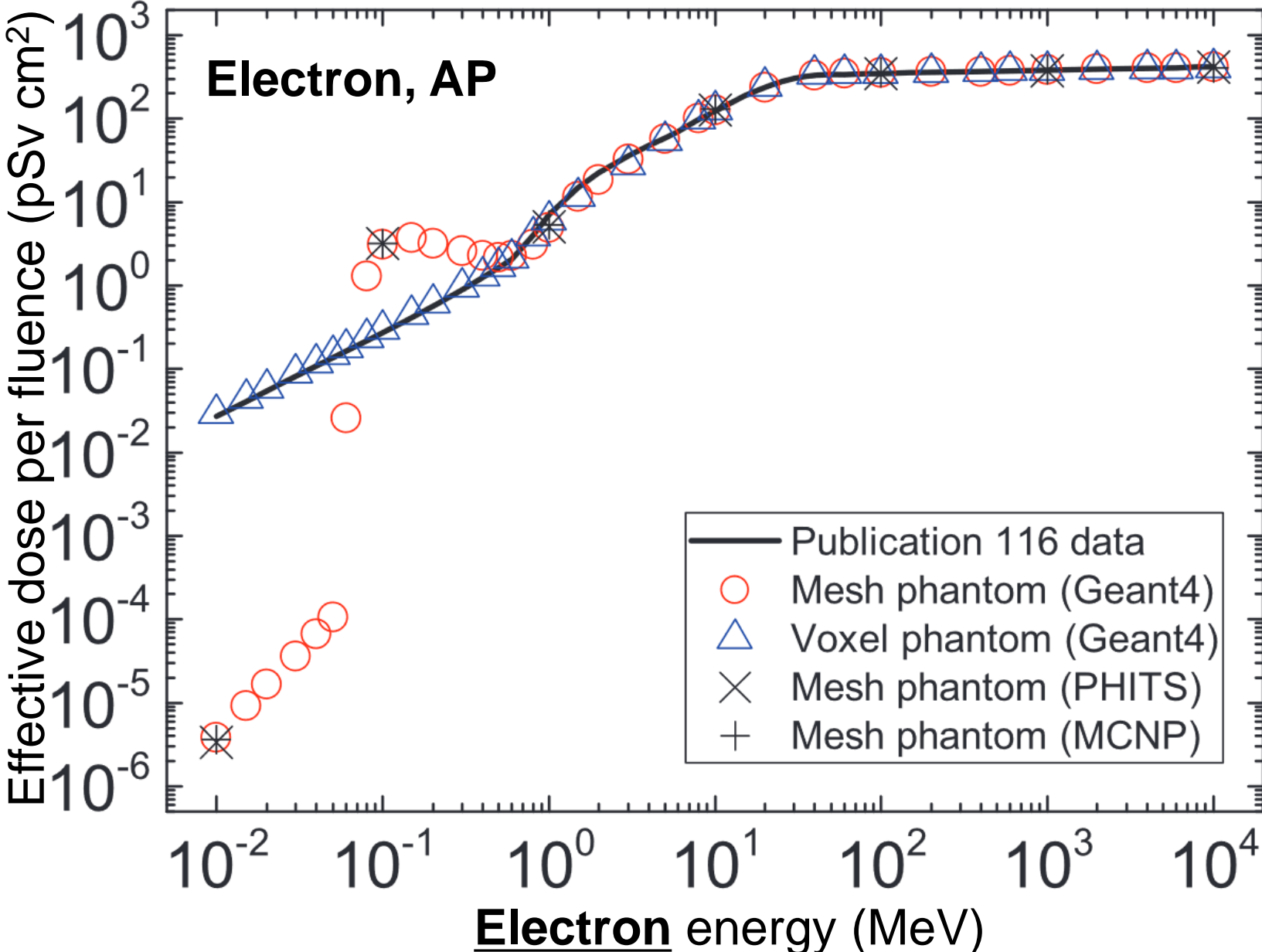
Dosimetry Impact – External (Photon)



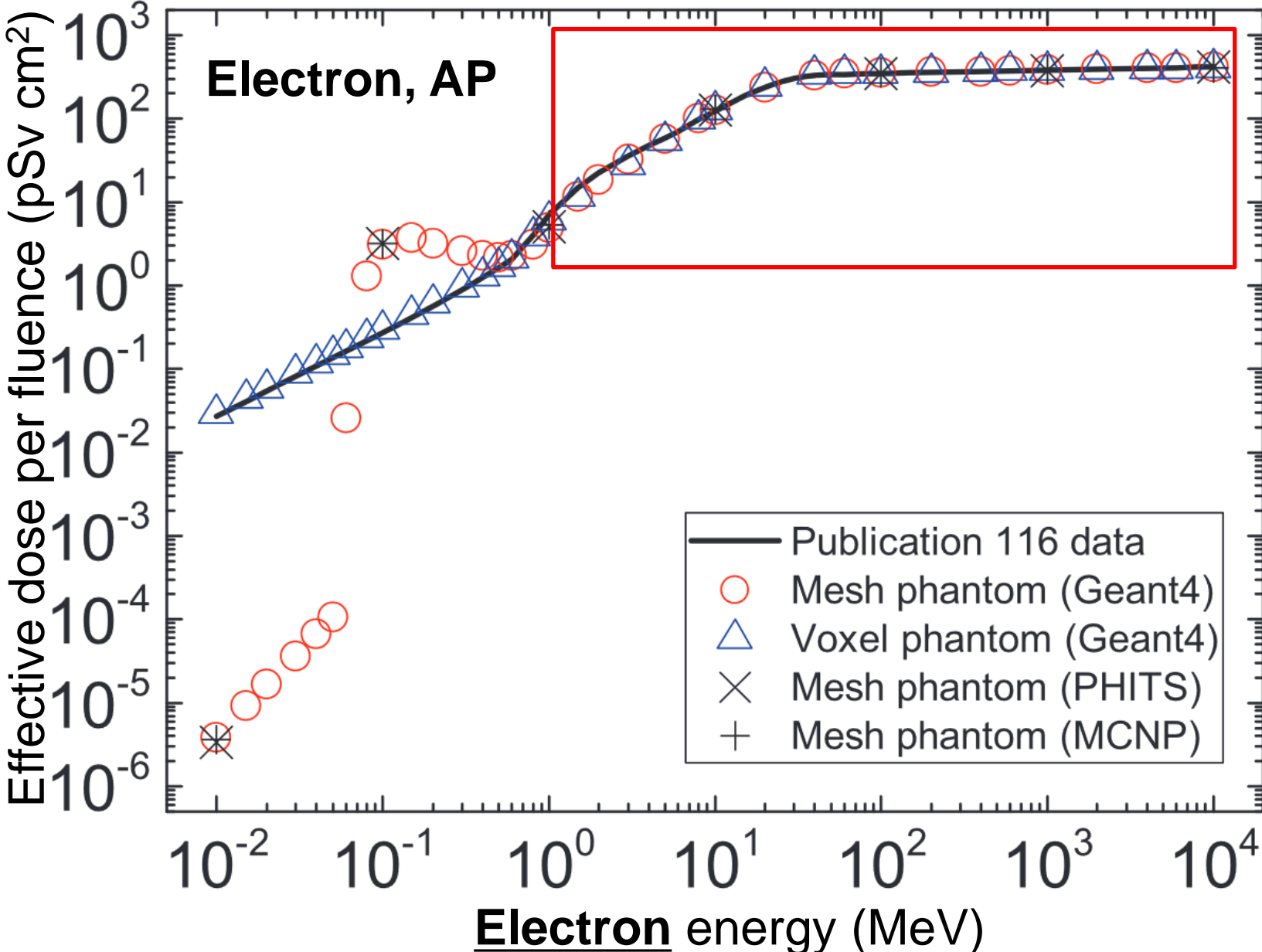
Dosimetry Impact – External (Neutron)



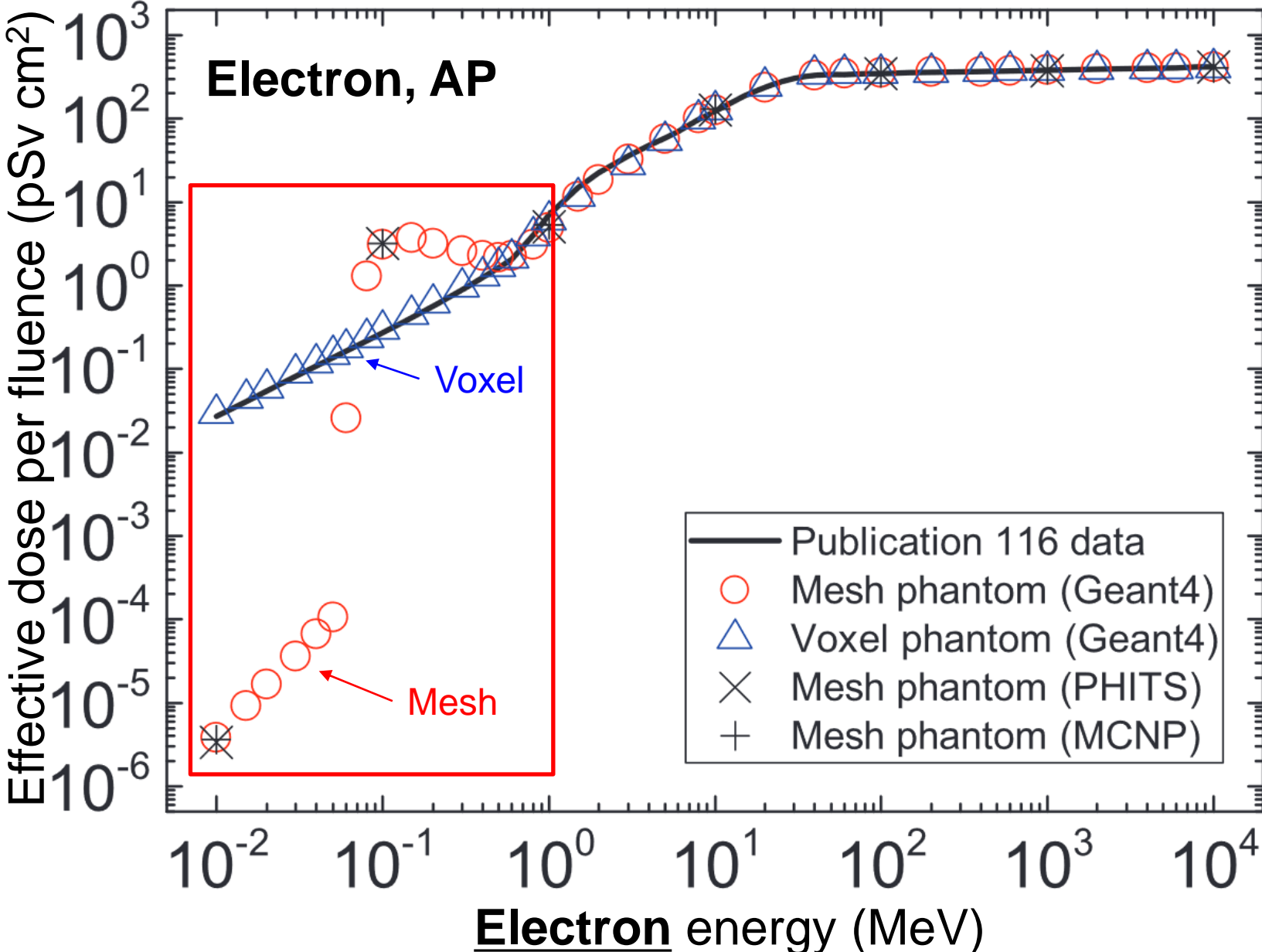
Dosimetry Impact – External (Electron)



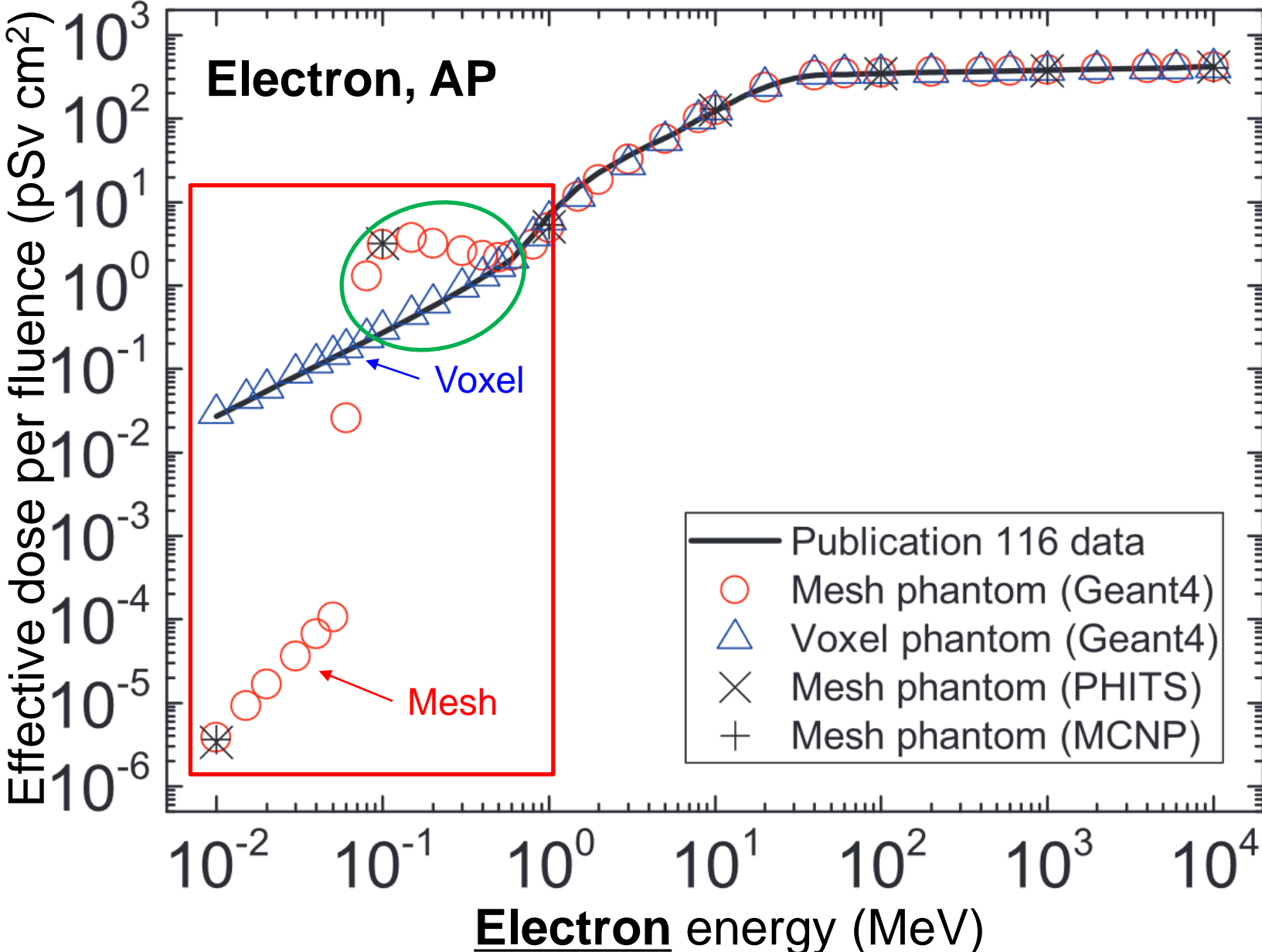
Dosimetry Impact – External (Electron)



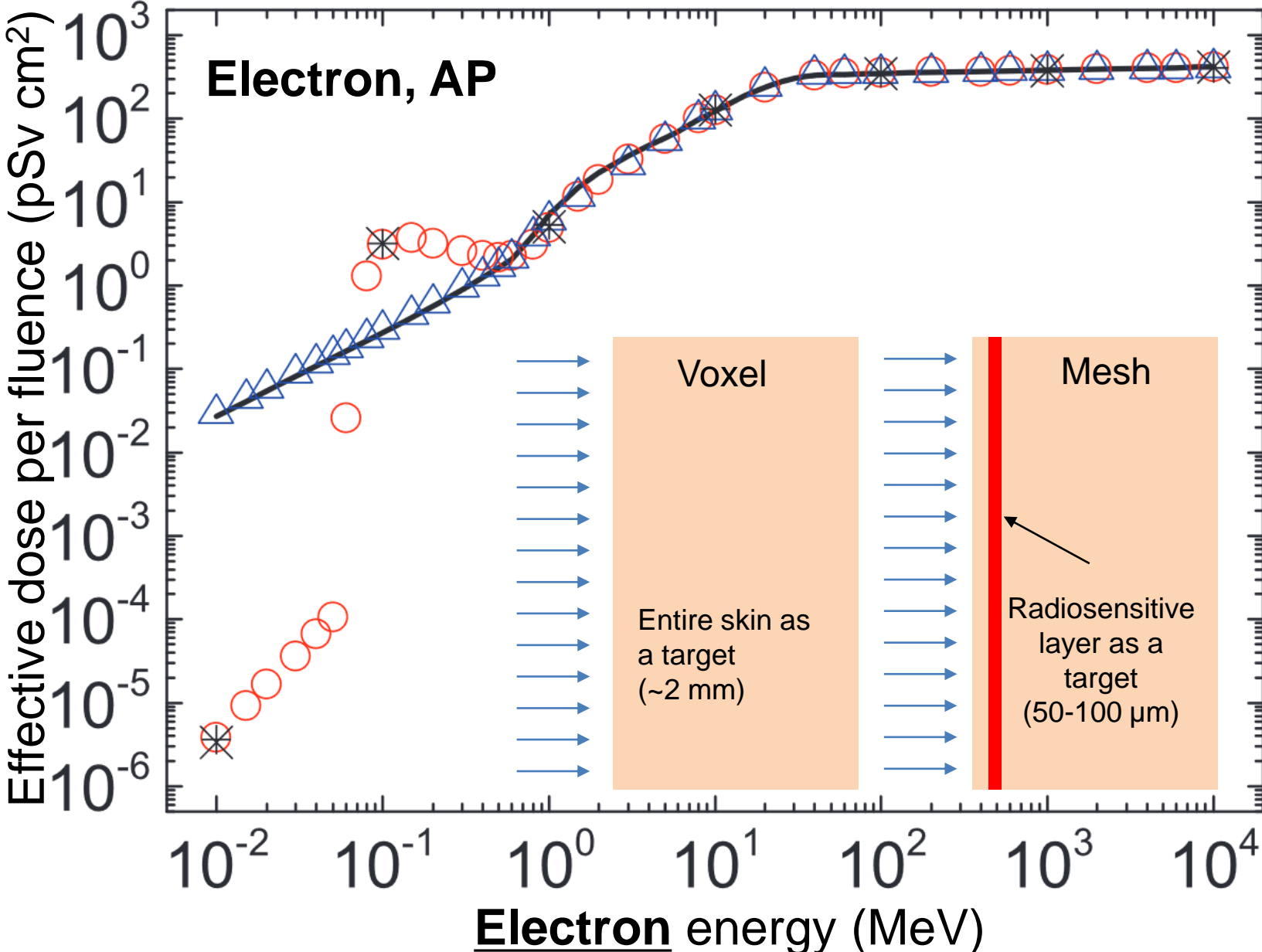
Dosimetry Impact – External (Electron)



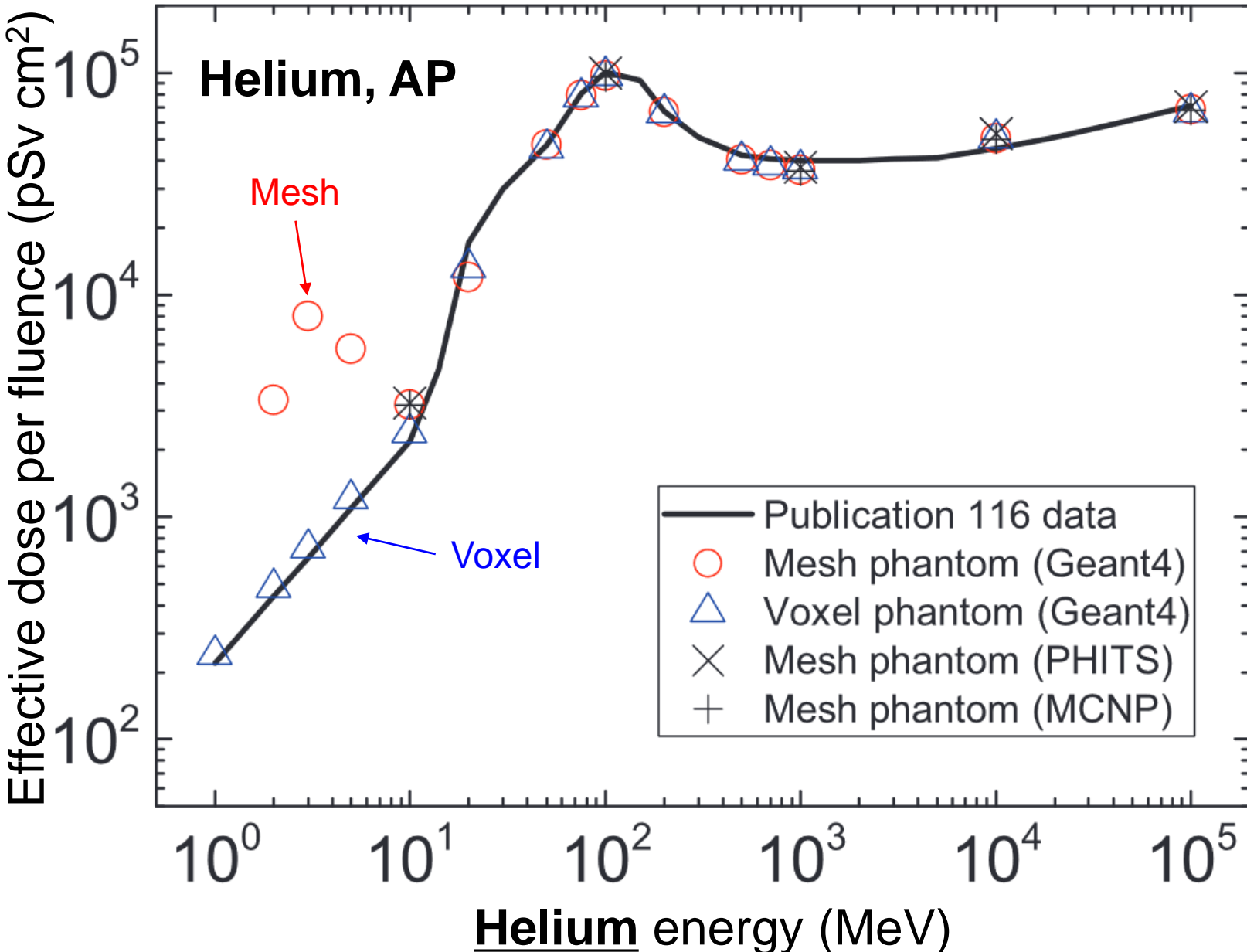
Dosimetry Impact – External (Electron)



Dosimetry Impact – External (Electron)



Dosimetry Impact – External (Helium)

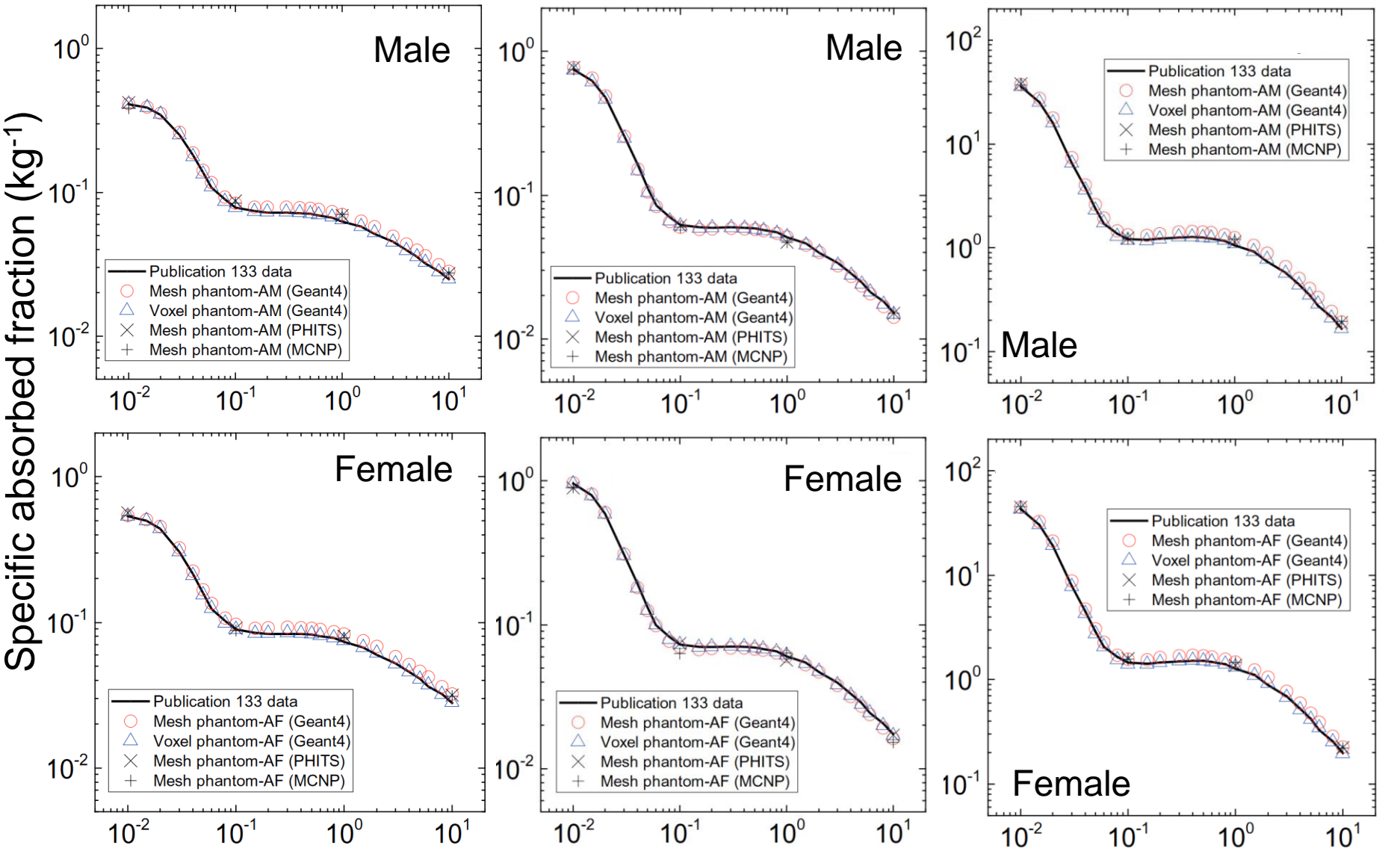


Dosimetry Impact – Internal (Self-irradiation)

Liver ← Liver

Lung ← Lung

Thyroid ← Thyroid



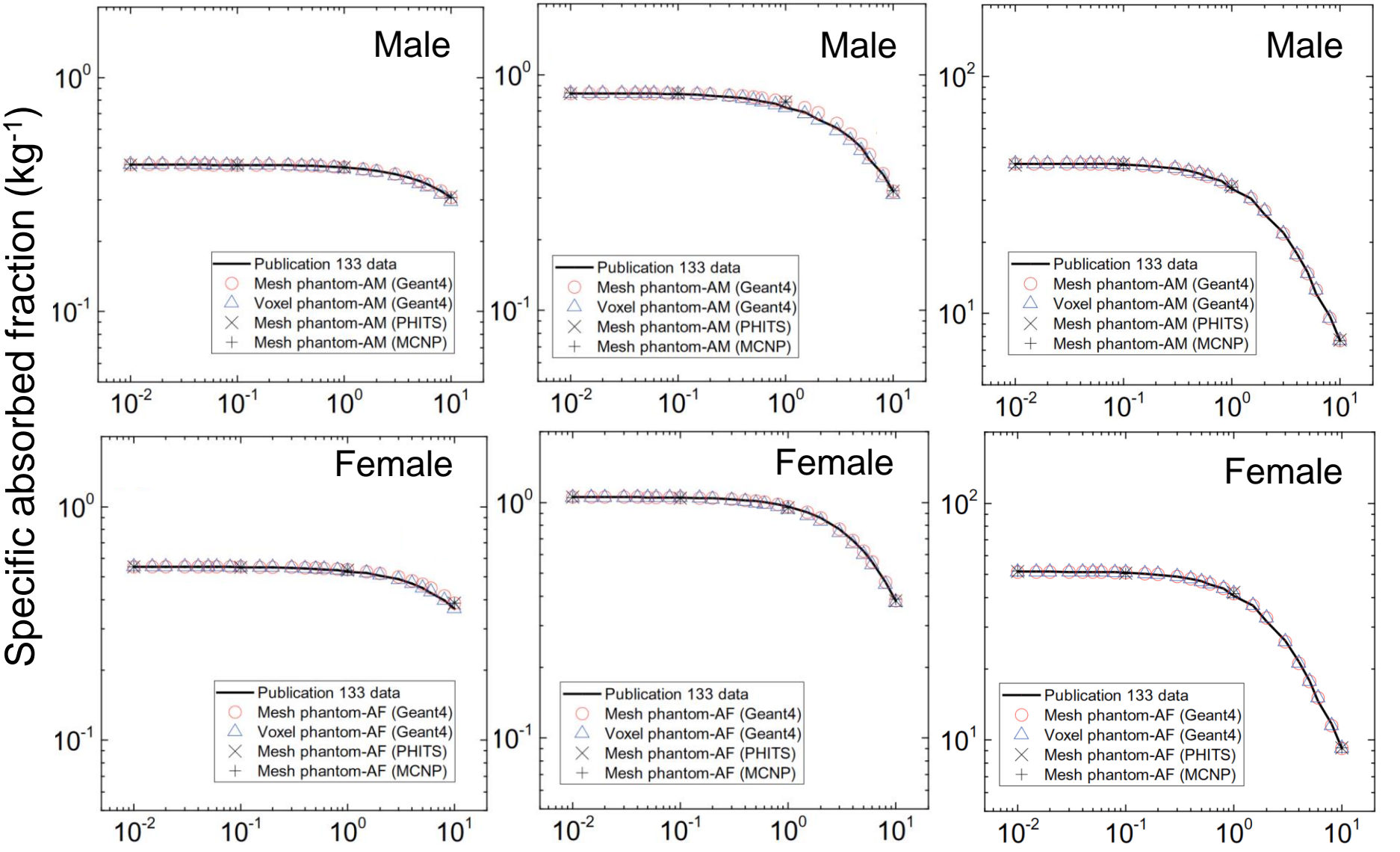
Photon energy (MeV)

Dosimetry Impact – Internal (Self-irradiation)

Liver ← Liver

Lung ← Lung

Thyroid ← Thyroid



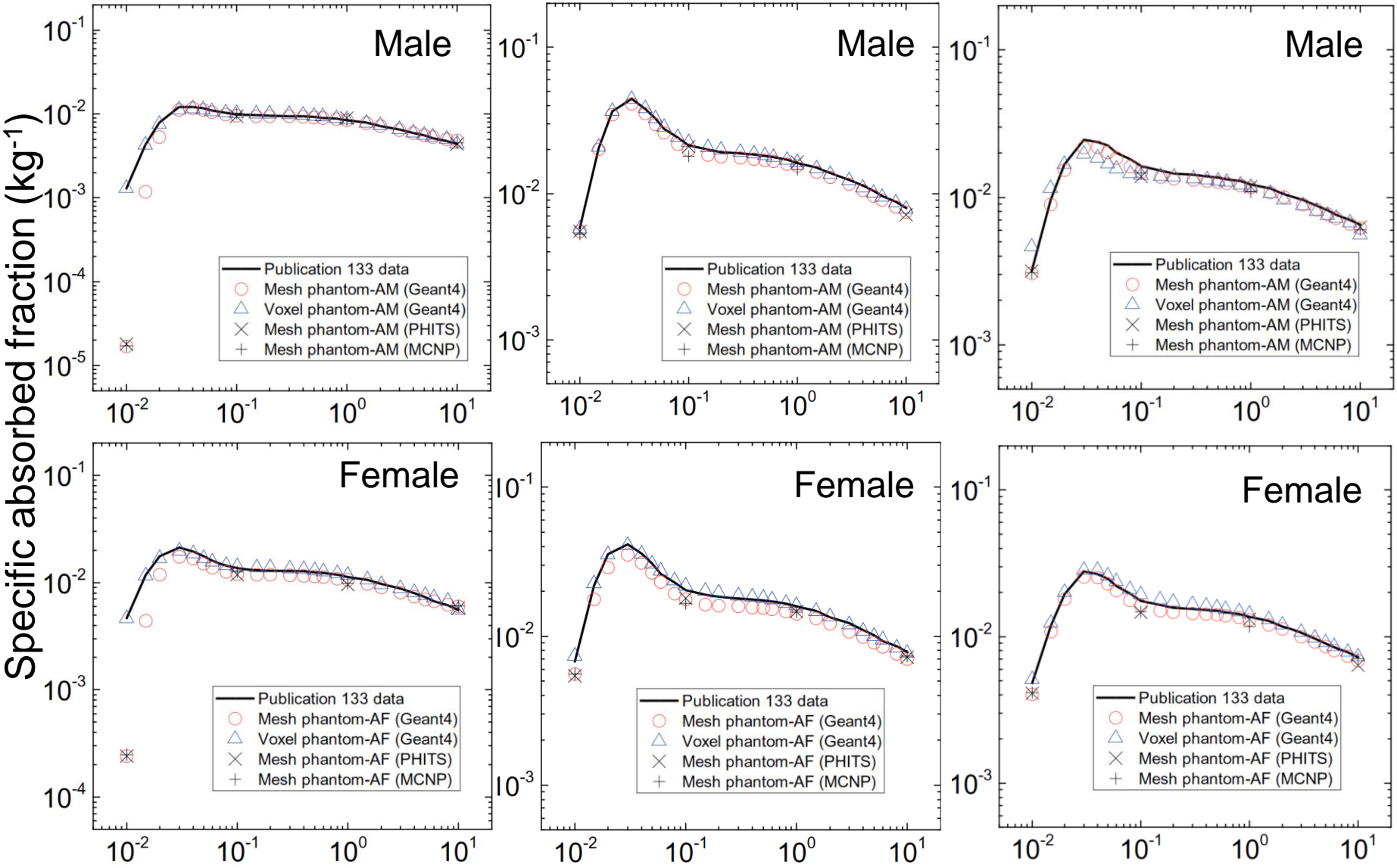
Electron energy (MeV)

Dosimetry Impact – Internal (Cross-fire-irradiation)

RBM ← Lung

Spleen ← Lung

Liver ← Lung



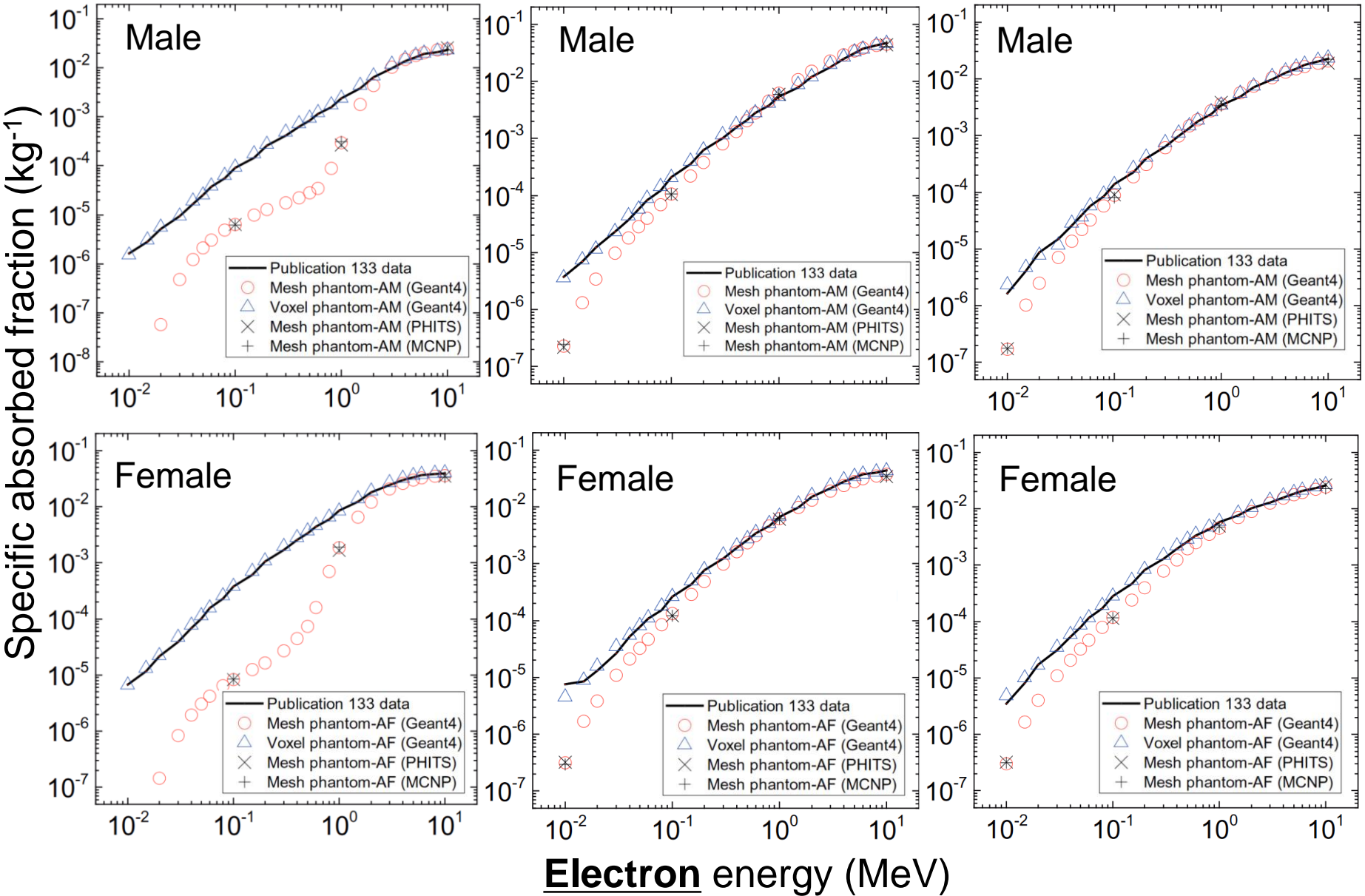
Photon energy (MeV)

Dosimetry Impact – Internal (Cross-fire-irradiation)

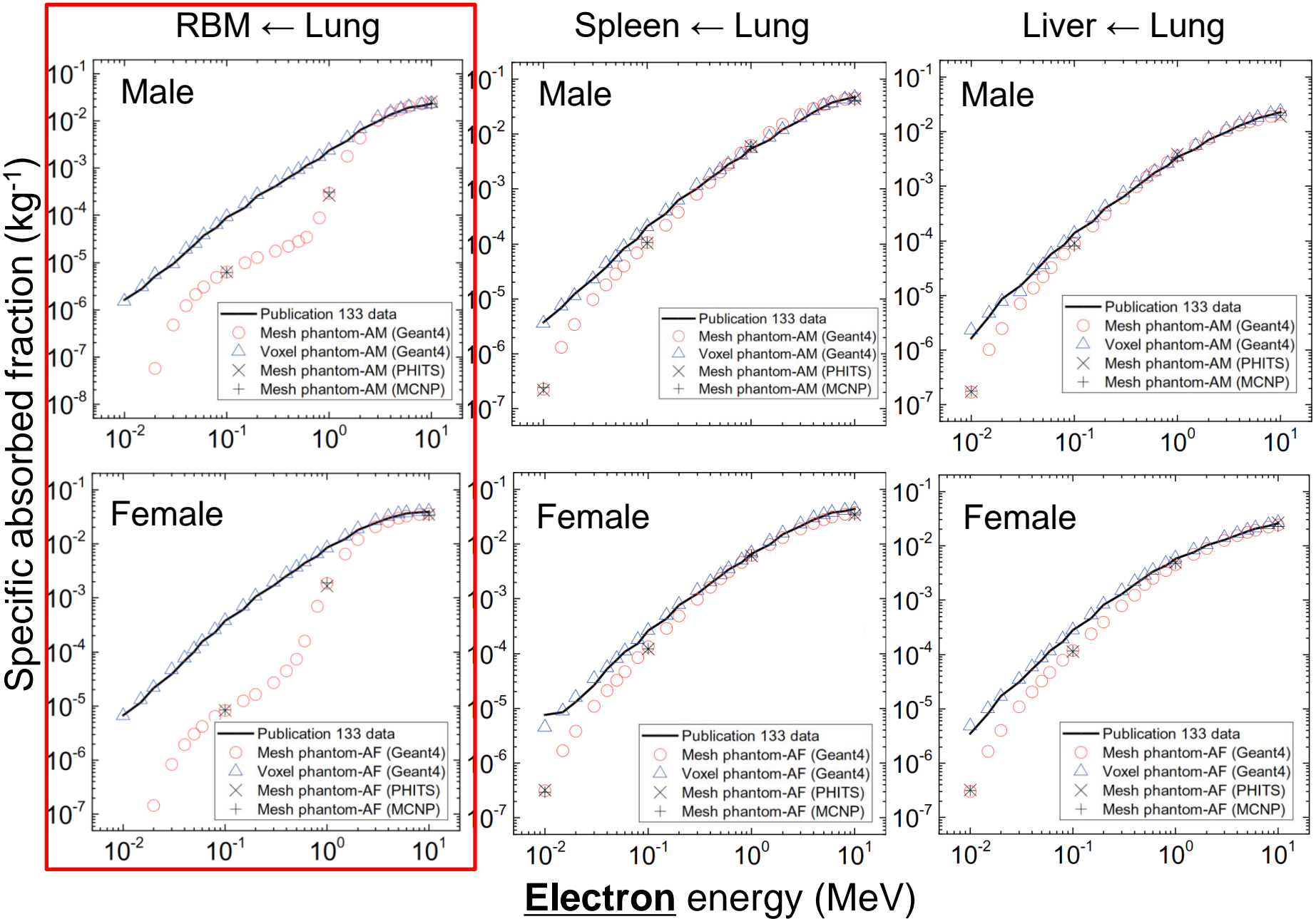
RBM ← Lung

Spleen ← Lung

Liver ← Lung

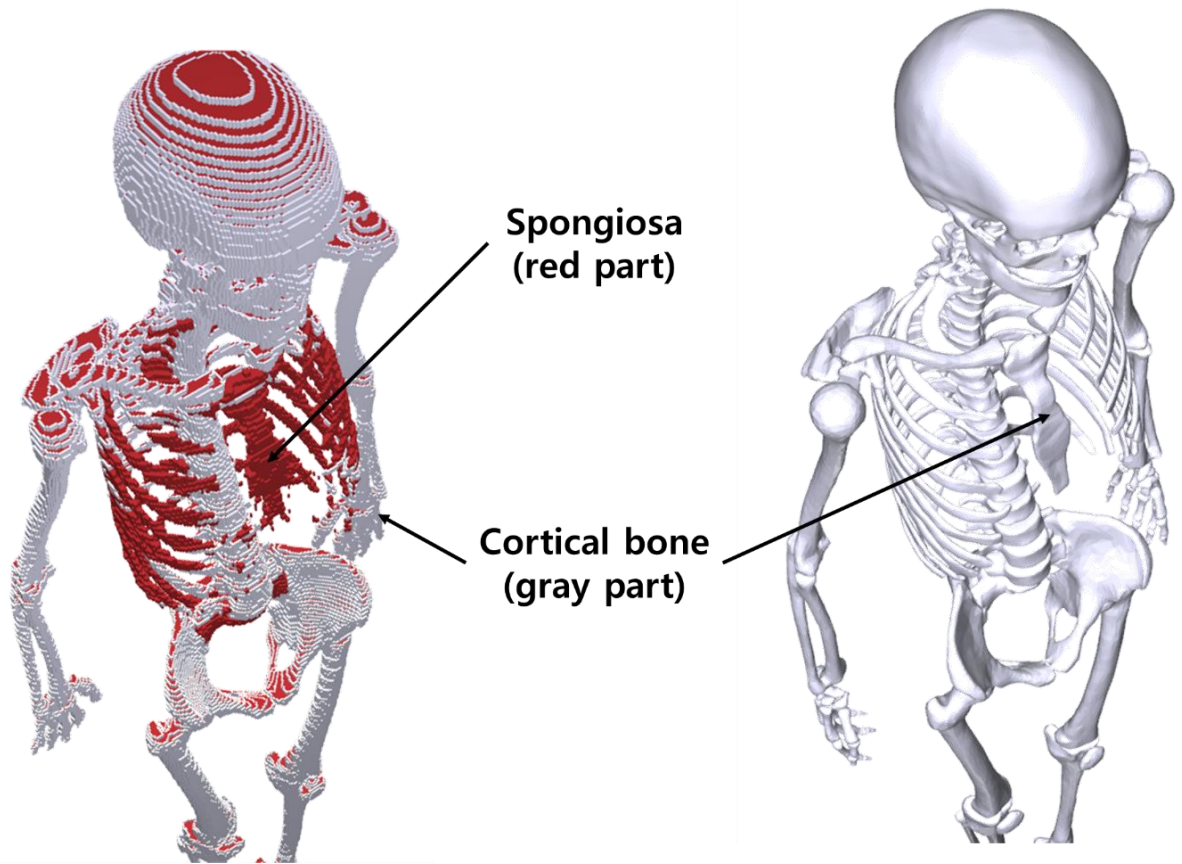
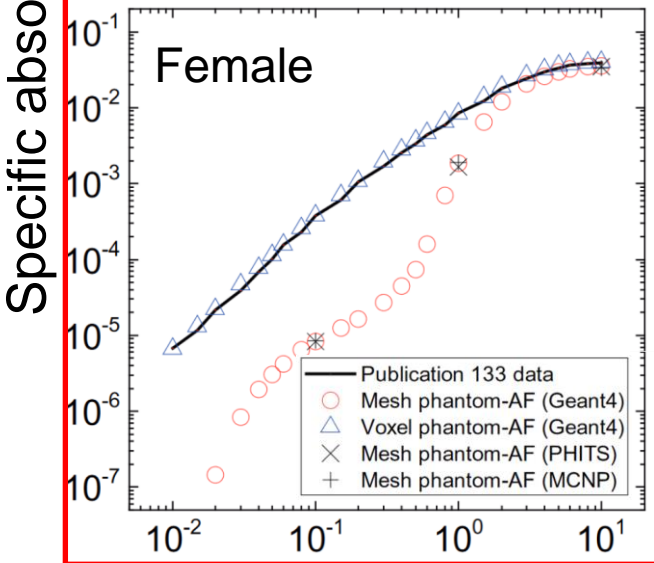
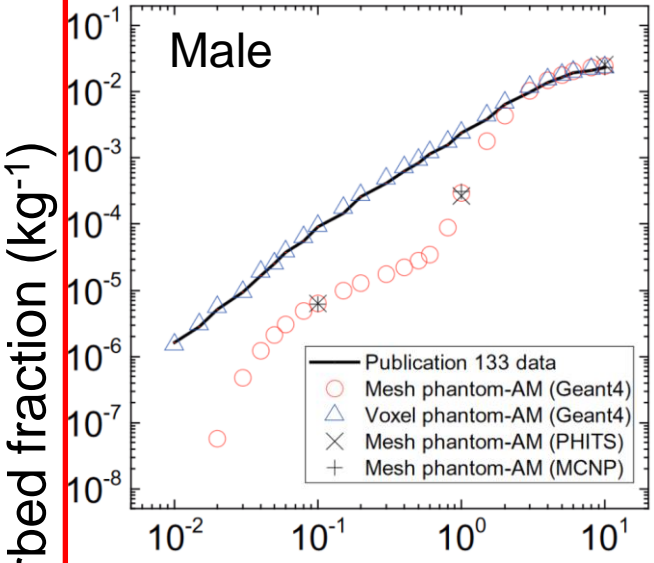


Dosimetry Impact – Internal (Cross-fire-irradiation)



Dosimetry Impact – Internal (Cross-fire-irradiation)

RBM ← Lung



Voxel

Mesh

Electron energy (MeV)

Key References

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Thank you!