Development and Significance of Paediatric Mesh-type Reference Computational Phantoms

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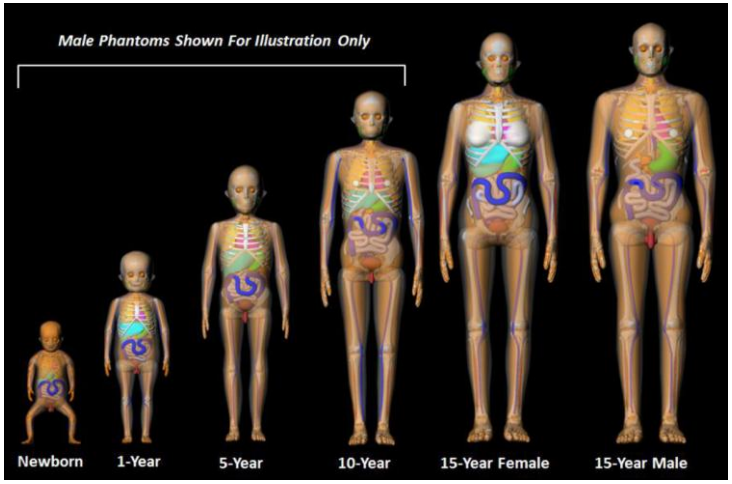
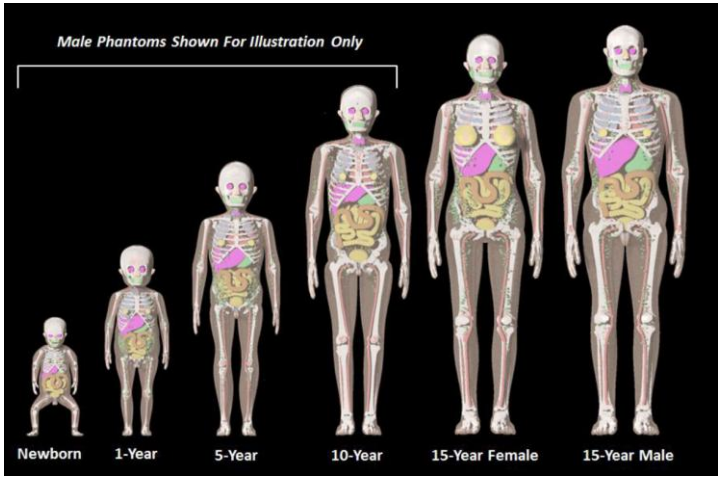
Approach to Produce Mesh Replica of Paediatric VRCPs

- Paediatric VRCPs were produced from the UF/NCI paediatric phantoms[1] through voxelization process.
- After the voxelization, some organs or tissues (e.g., muscle, breasts, colon, lymph nodes, …) were modified or added in the paediatric VRCPs.



UF/NCI paediatric phantoms*



Paediatric VRCPs

* NURBS: most organs/tissues
PM: skeleton, brain, extrathoracic (ET) region

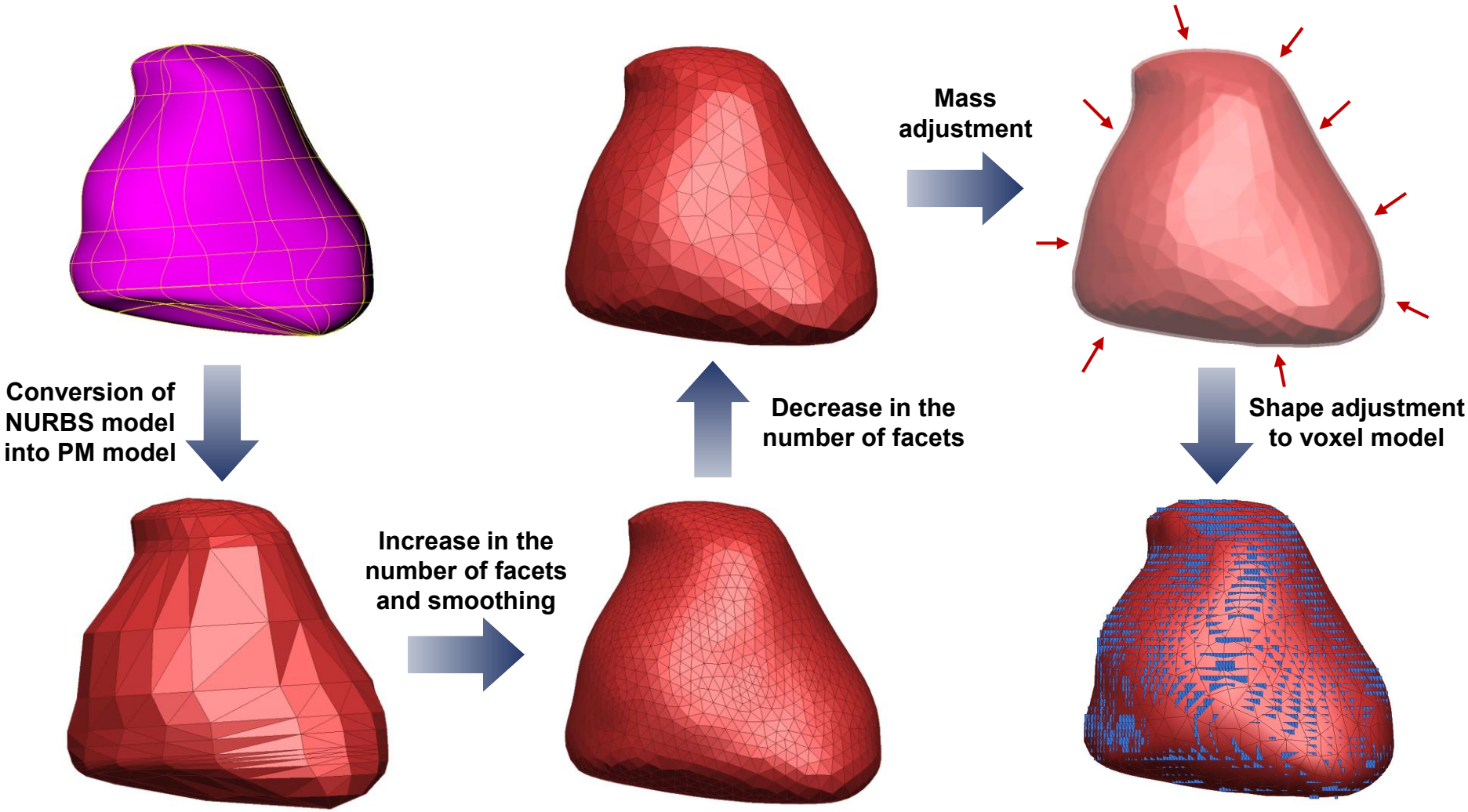
➢ Use as a **"starting point"** of conversion project

➢ Use as a **"target geometry"**

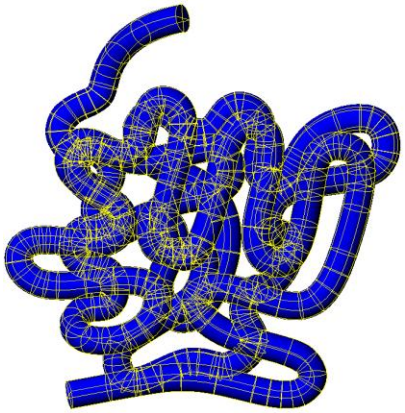
[1] Lee, C., Lodwick, D., Hurtado, J., et al., 2010. The UF family of reference hybrid phantoms for computational radiation dosimetry. Phys. Med. Biol. 55, 339–363.

Example of Conversion

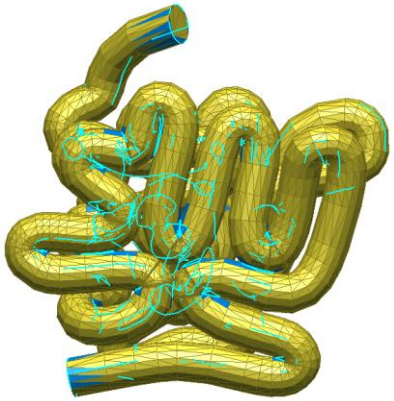
- **NURBS format – example 1 (heart)**



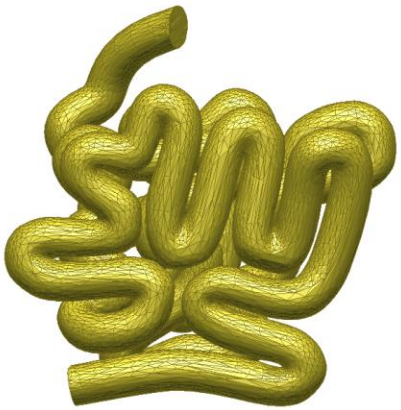
- **NURBS format – example 2 (small intestine)**



Conversion of NURBS model into PM model and detect self intersections

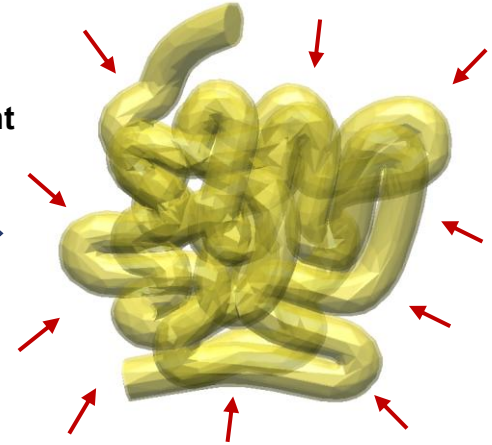


Removal of self intersections and smoothing

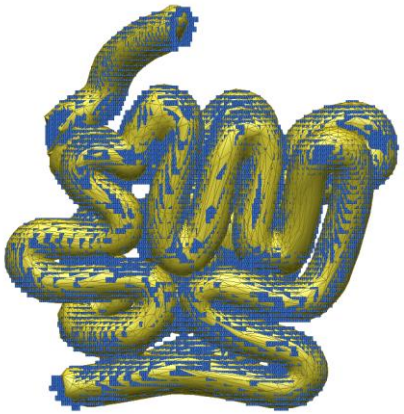


Decrease in the number of facets

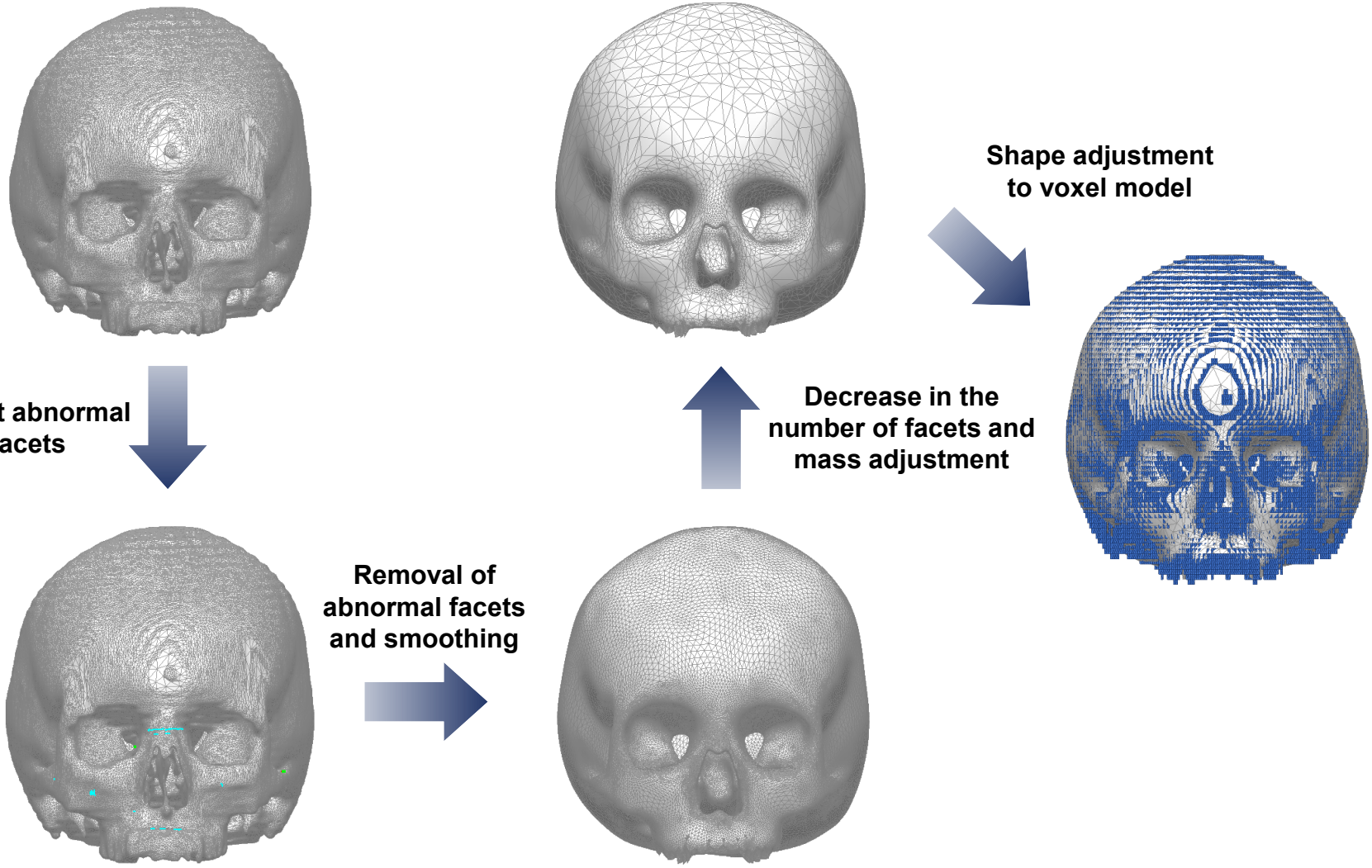
Mass adjustment



Shape adjustment to voxel model

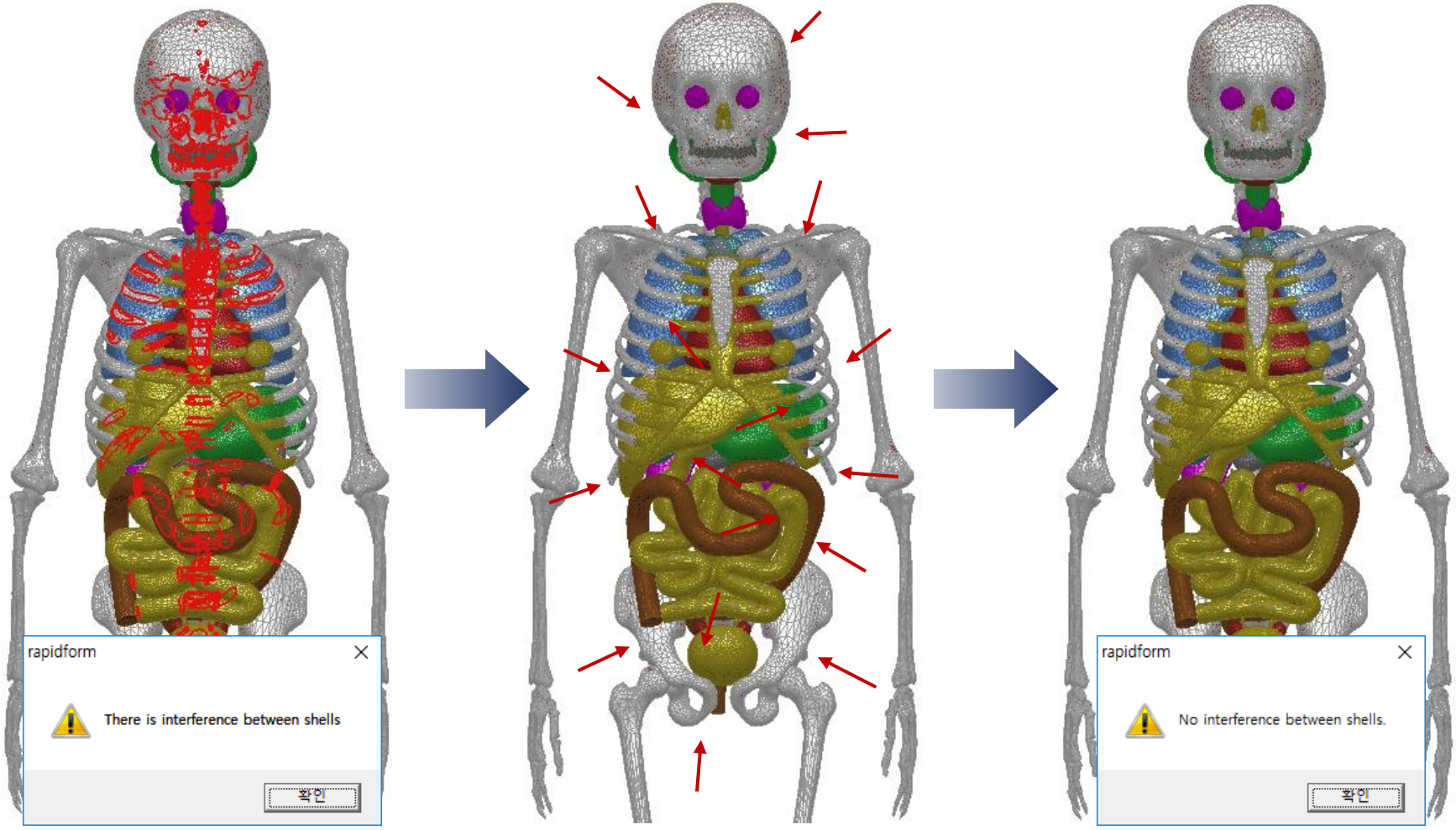


- **PM format – example (cranium)**



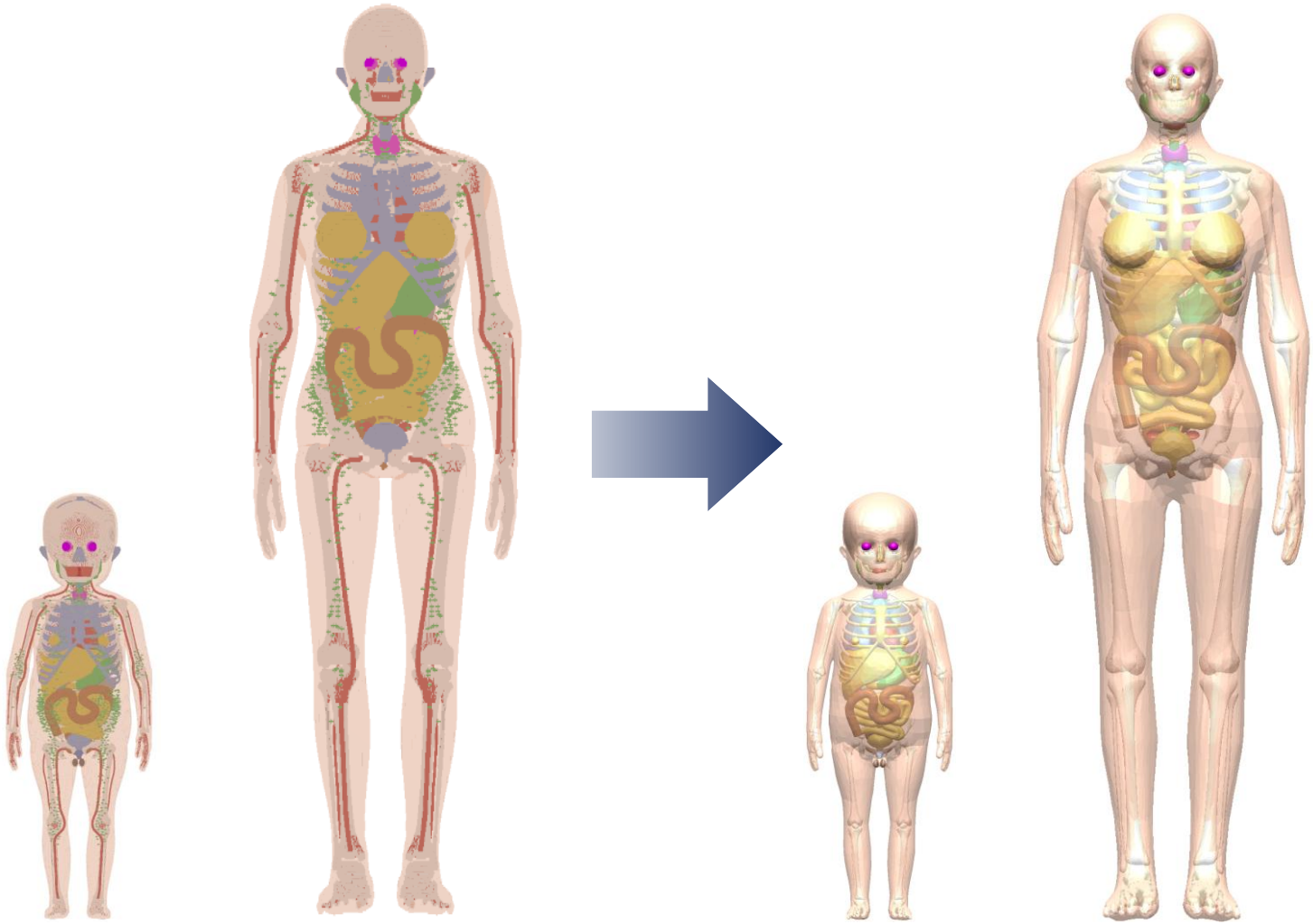
Topological Adjustment of Organs and Tissues

- Constructed PM models were slightly adjusted to avoid the interferences between organs and tissues.



Mesh Replica of Paediatric VRCPs

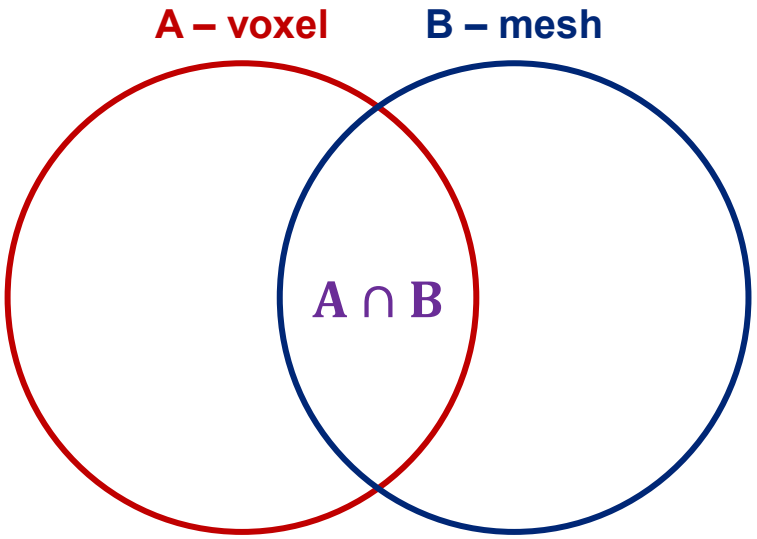
Example: 1-year male and 15-year female phantoms



Paediatric VRCPs **Mesh replica of paediatric VRCPs**

Conversion Criteria

- **Dice index (DI)[2]**
  - Overlapping volume fraction of two objects (mesh vs. voxel)
  - DI > 0.9 of the maximum achievable Dice index (MADI)



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

- **Centroid distance (CD)**
  - Distance between the centroids of two objects (mesh vs. voxel)
  - CD ≤ 2 mm

[2] Dice, L.R., 1945. Measures of the amount of ecologic association between species. Ecology 26, 297–302.

Ⅰ. Conversion of Paediatric VRCPs to Mesh Format

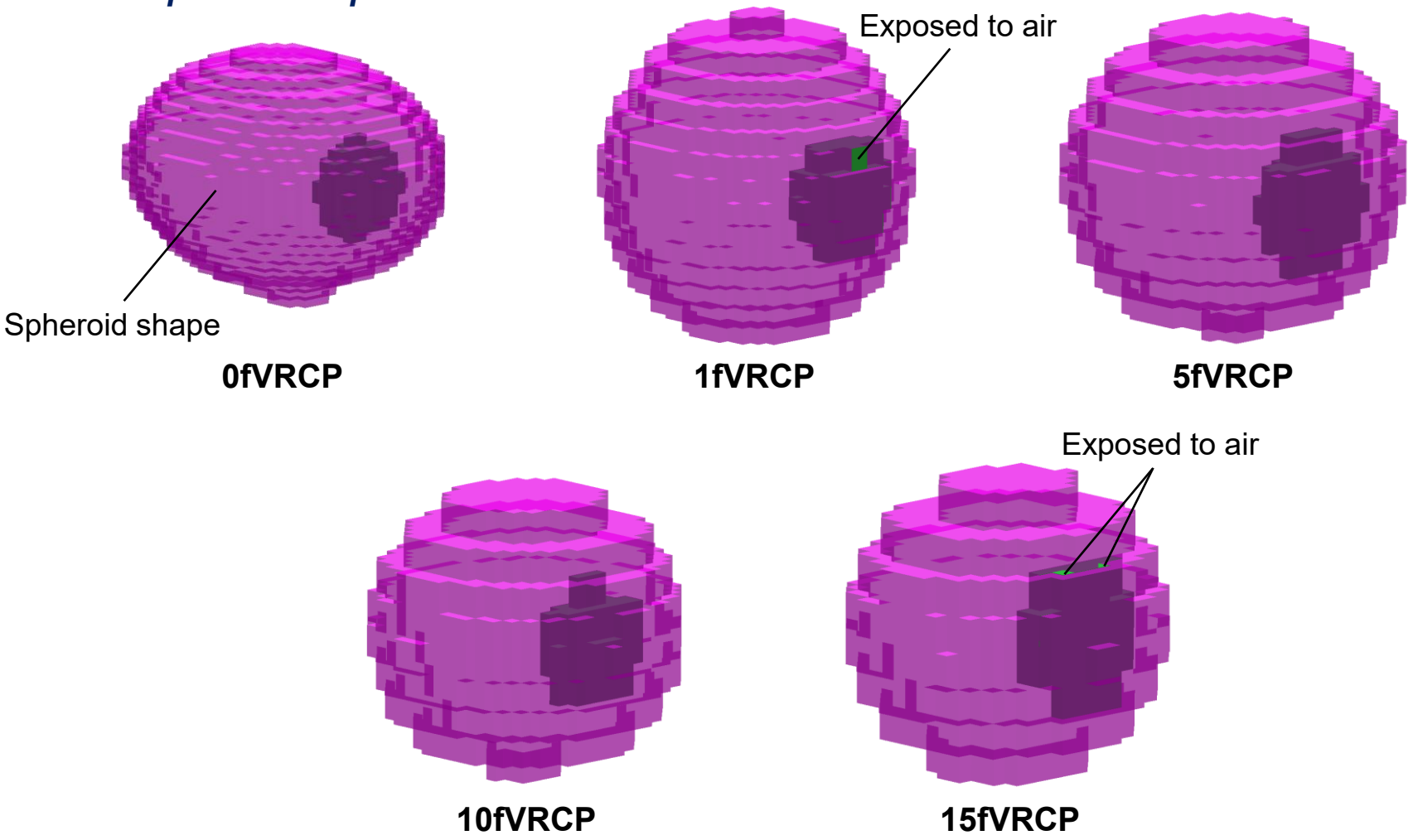
1. Production of mesh replica of paediatric VRCPs

2. Remodeling or modification of organs and tissues with anatomical or dosimetric issues (e.g., eyes, teeth, colon, thyroid, …)

1) Eyes

- Due to finite voxel resolutions, the detailed structures of the eyes were not fully modeled in the paediatric VRCPs.

Example: female phantoms

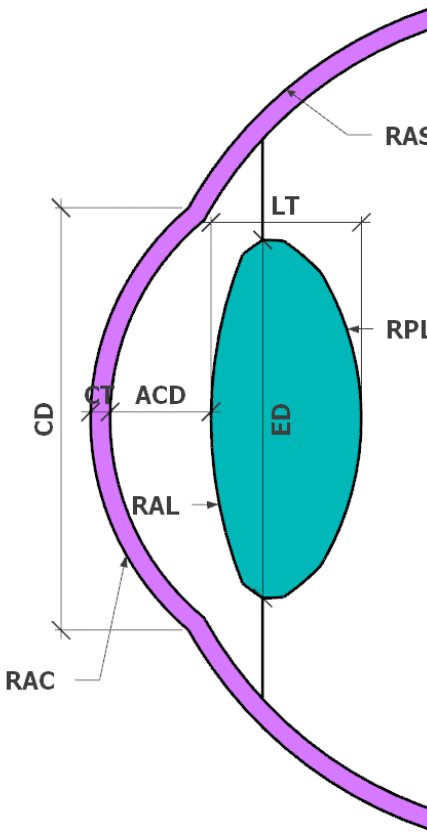


0fVRCP **1fVRCP** **5fVRCP**

10fVRCP **15fVRCP**

- **Selection of nine anatomical parameters[3]**

	Parameters	Description
Lens	ACD	anterior chamber depth along the optical axis
	LT	lens thickness along the optical axis
	ED	equatorial diameter of the lens
	RAL	radius of curvature of the anterior surface of the lens
	RPL	radius of curvature of the posterior surface of the lens
Cornea	RAC	radius of curvature of the anterior surface of the cornea
	CT	corneal thickness along the optical axis
	CD	corneal diameter
	RAS	radius of curvature of the anterior surface of the sclera



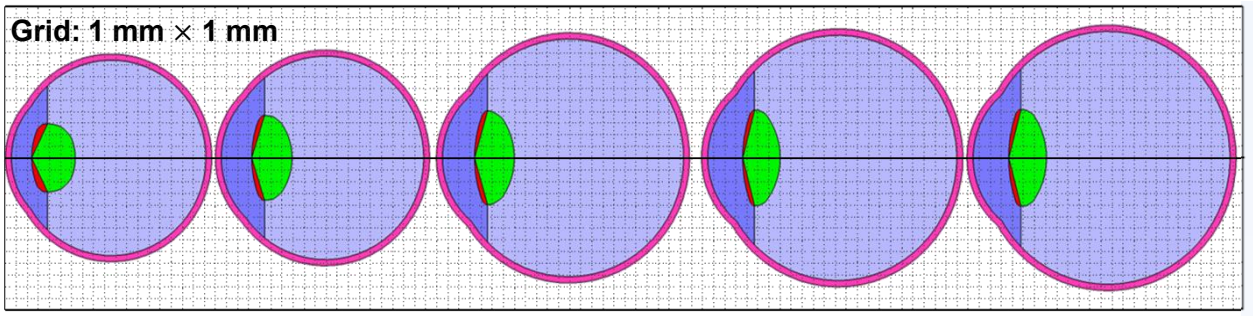
- **Data selection criteria**
  - The large number of samples
  - Data measured in vivo
  - Unaccommodated eyes
  - Normal eyes without any eye disease
  - Caucasian paediatric eyes
  - Full-term newborns

[3] Behrens, R., Dietze, G., Zankl, M., 2009. Dose conversion coefficients for electron exposure of the human eye lens. Phys. Med. Biol. 54, 4069–4087.

Determination of anatomical parameters

(Unit: mm)

Parameters	Newborn	1 year	5 years	10 years	15 years	References
ACD	1.83	2.75	2.90	3.16	3.21	[4–6]
LT	3.96	3.66	3.61	3.41	3.44	
RAL	6.33	9.23	10.51	11.45	11.72	[7, 8]
RPL	4.48	5.27	6.05	6.24	6.55	
RAC	7.11	7.82	7.72	7.72	7.72	[8–10]
CT	0.55	0.55	0.56	0.57	0.57	[11]
CD	9.66	11.15	11.80	11.80	11.80	[12, 13]
ED	5.95	7.40	8.20	8.37	8.43	[14–19]
RAS	9.10	9.45	10.96	11.30	11.63	Reference eye mass

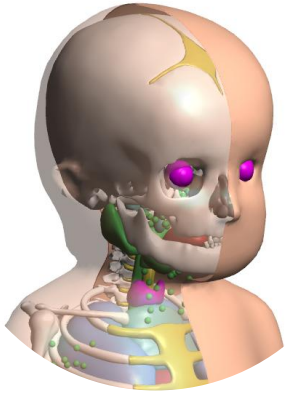


[4] Larsen, J., 1971. The sagittal growth of the eye: 1. ultrasonic measurement of the depth of the anterior chamber from birth to puberty. Acta Ophthalmol. 49, 239–262.
[5] Larsen, J., 1971. The sagittal growth of the eye: 2. ultrasonic measurement of the axial diameter of the lens and the anterior segment from birth to puberty. Acta Ophthalmol. 49, 427–440.
[6] Zadnik, K., Mutti, D.O., Mitchell, G.L., et al., 2004. Normal eye growth in emmetropic schoolchildren. Optom. Vis. Sci. 81, 819–828.
[7] Mutti, D.O., Zadnik, K., Fusaro, R.E., et al., 1998. Optical and structural development of the crystalline lens in childhood. Invest. Ophthalmol. Vis. Sci. 39, 120–133.
[8] Frane, S.L., Sholtz, R.I., Lin, W.K., et al., 2000. Ocular components before and after acquired, nonaccommodative esotropia. Optom. Vis. Sci. 77, 633–636.
[9] Ehlers, N., Sorensen, T., Bramsen, T., et al., 1976. Central corneal thickness in newborns and children. Acta Ophthalmol. 54, 285–290.
[10] Friedman, N.E., Mutti, D.O., Zadnik, K., 1996. Corneal changes in schoolchildren. Optom. Vis. Sci. 73, 552–557.
[11] PEDIG, 2011. Central corneal thickness in children. Arch. Ophthalmol. 129, 1132–1138.
[12] Müller, A., Doughty, M.J., 2002. Assessments of corneal endothelial cell density in growing children and its relationship to horizontal corneal diameter. Optom. Vis. Sci. 79, 762–770.
[13] Charles, M.W., Brown, N., 1975. Dimensions of the human eye relevant to radiation protection (dosimetry). Phys. Med. Biol. 20, 202–218.
[14] Atchison, D.A., Markwell, E.L., Kasthurirangan, S., et al., 2008. Age-related changes in optical and biometric characteristics of emmetropic eyes. J. Vis. 8, 1–20.
[15] Dilmen, G., Koktener, A., Turhan, T.O., et al., 2002. Growth of the fetal lens and orbit. Int. J. Genecol. Obstet. 76, 267–271.
[16] Goldstein, I. Tamir, A., Zimmer, E.Z., et al., 1998. Growth of the fetal orbit and lens in normal pregnancies. Ultrasound Obstet. Gynecol. 12, 175–179.
[17] Ishii, K., Yamanari, M., Iwata, H., et al., 2013. Relationship between changes in crystalline lens shape and axial elongation in young children. Invest. Ophthalmol. Vis. Sci. 54, 771–777.
[18] Paquette, L.B., Jackson, H.A., Tavaré, C.J., et al., 2009. In utero eye development documented by fetal MR imaging. Am. J. Neuroradiol. 30, 1787–1791.
[19] Sukonpan, K., Phupong, V., 2009. A biometric study of the fetal orbit and lens in normal pregnancies. J. Clin. Ultrasound 37, 69–74.

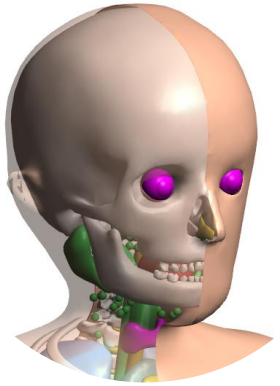
- **Conversion to mesh format and installation in paediatric MRCPs**

Example: female phantoms

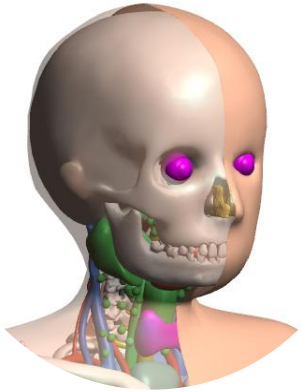
0fMRCP



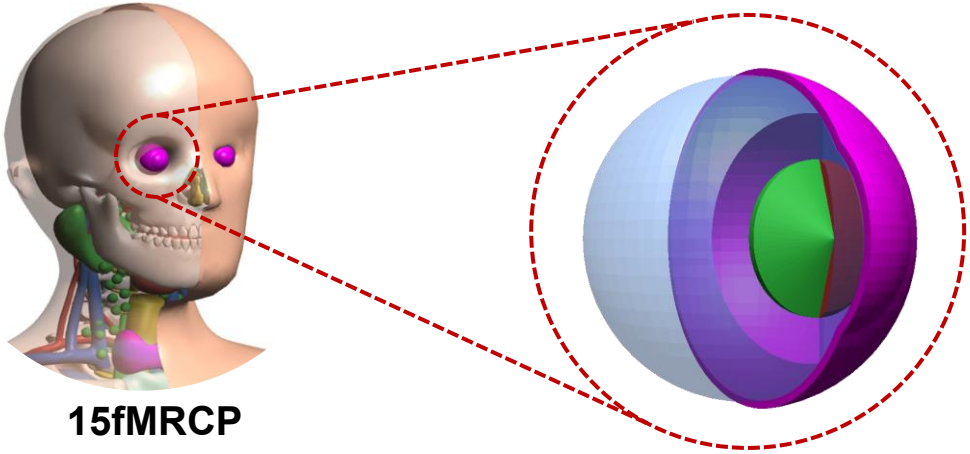
1fMRCP



5fMRCP



10fMRCP

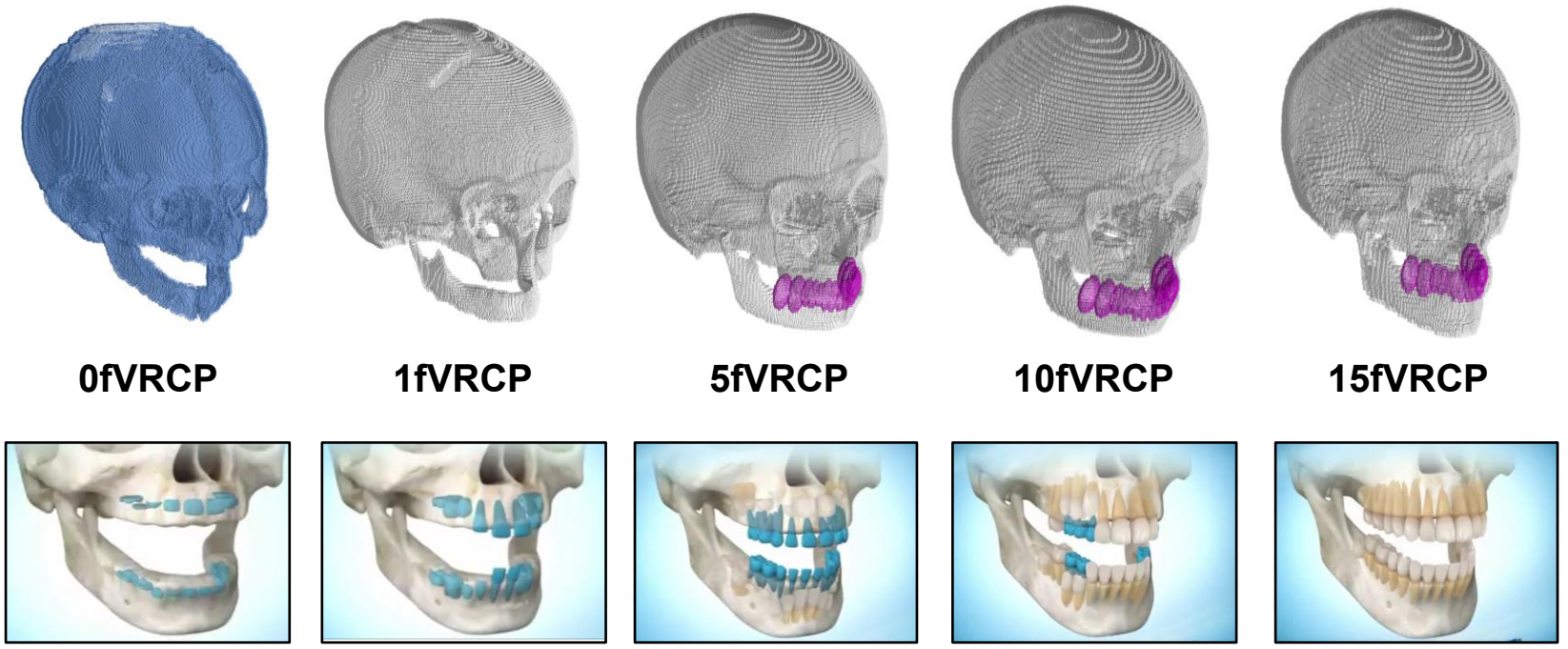


15fMRCP

2) Teeth

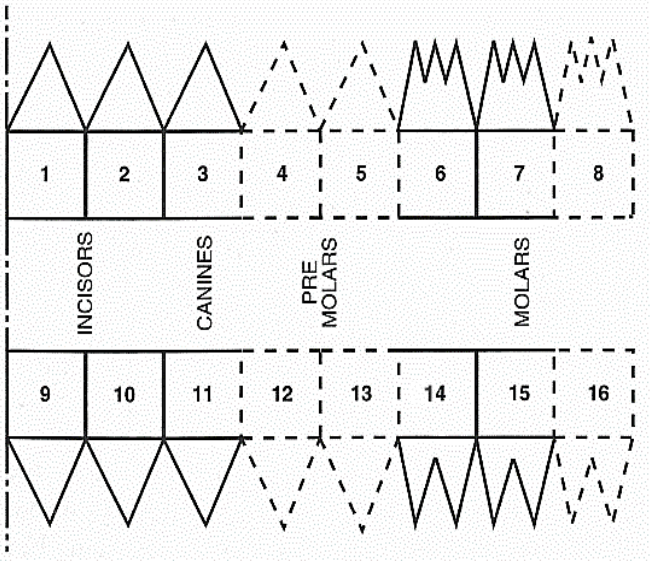
- Teeth of the paediatric VRCPs were defined as a single homogeneous region with a simplified geometry, and anatomical changes with ages were not reflected.

Example: female phantoms



- In the paediatric MRCPs, detailed tooth tissues (i.e., enamel, dentin, cementum, and pulp) were defined, which can be used for separately EPR/ESR dosimetry.

- **Determination of eruption period of teeth[20, 21]**



Tooth eruption time			
Deciduous teeth		Permanent teeth	
Tooth (i)	Eruption time (months)	Tooth (i)	Eruption time (years)
Upper teeth		Upper teeth	
1	8-11	1	7-8
2	8-11	2	8-10
3	16-24	3	11-12
4		4	10-11
5		5	10-12
6	9-21	6	6-7
7	20-36	7	12-13
8		8	17-30
Lower teeth		Lower teeth	
9	4-8	9	6-7
10	7-12	10	7-10
11	16-25	11	9-10
12		12	10-12
13		13	11-12
14	9-21	14	6-7
15	20-36	15	11-13
16		16	16-30

- **Calculation of mass of growing teeth[21]**

$$m_i = m_{0i}[1 - \exp(-\frac{t - T_{0i}}{\tau_i})]$$

m_i: the mass of tooth (i is defined as the relaxational time of the respective tooth(i))

m_0: the average mass of fully developed permanent and deciduous teeth

T_{0i}: the time when the mineralization of the formation of the tooth mass is observed

τ_i: the relaxational time when m_i is 63.2% of the final mass m_0

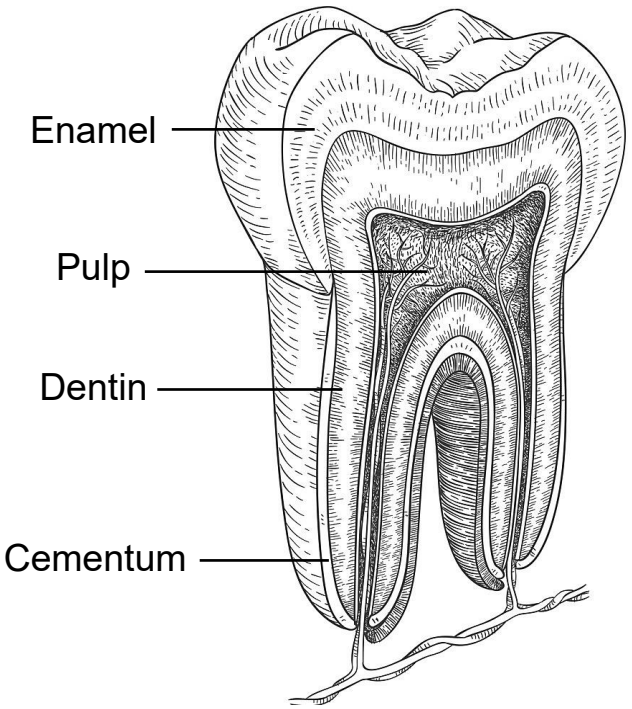
***t*: the time at the moments**

[20] Schwartz, J.H., 1995. Skeleton keys: an introduction to human skeletal morphology, development, and analysis. Oxford University Press, Oxford.
[21] Ogorelec, Z., 1997. The growth of human teeth: a simple description of its kinetics. Acta Stomatol. Croat. 31, 389–395.

Calculated individual tooth mass

Mass of teeth (left + right, g)												
Teeth	**Newborn**		**1-year male/female**		**5-year male/female**		**10-year male/female**		**15-year male**		**15-year female**	
Upper teeth	**Erupted**	**Unerupted**	**Erupted**	**Unerupted**	**Erupted**	**Unerupted**	**Erupted**	**Unerupted**	**Erupted**	**Unerupted**	**Erupted**	**Unerupted**
1	-	0.0347	0.2838	0.2864	0.4400	0.5292	1.9800	-	2.2296	-	1.7304	-
2	-	0.0310	0.2044	0.0253	0.3200	0.3416	1.2694	-	1.5990	-	1.2410	-
3	-	0.0447	-	0.2416	0.5800	0.5848	0.5800	1.2862	2.9504	-	2.2896	-
4	-	-	-	-	-	0.4106	1.7840	-	2.4098	-	1.8702	-
5	-	-	-	-	-	0.3680	-	1.0750	2.5674	-	1.9926	-
6	-	0.1111	-	0.8044	1.1400	1.1842	4.1198	-	5.1124	-	3.9676	-
7	-	0.1092	-	0.5135	1.1600	0.4617	1.1600	1.7649	4.1562	-	3.2256	-
8	-	-	-	-	-	-	-	0.5336	-	2.7232	-	2.1135
Lower teeth	**Erupted**	**Unerupted**	**Erupted**	**Unerupted**	**Erupted**	**Unerupted**	**Erupted**	**Unerupted**	**Erupted**	**Unerupted**	**Erupted**	**Unerupted**
9	-	0.0398	0.1420	0.1684	0.2200	0.2953	1.0400	-	1.1712	-	0.9088	-
10	-	0.0355	0.1864	0.1903	0.2800	0.3497	1.3000	-	1.4638	-	1.1362	-
11	-	0.0512	-	0.2240	0.5200	0.5352	2.0026	-	2.6350	-	2.0450	-
12	-	-	-	-	-	0.3402	-	0.8562	1.9818	-	1.5382	-
13	-	-	-	-	-	0.3298	-	0.9671	2.3198	-	1.8002	-
14	-	0.1271	-	0.8607	1.1400	1.2109	4.4000		4.9548	-	3.8452	-
15	-	0.1251	-	0.9125	1.9200	0.5368	1.9200	1.9697	4.5278	-	3.5140	-
16	-	-	-	-	-	-	-	0.4062	-	2.8802	-	2.2354
Total teeth	0.7094		5.0437		15.1980		30.4147		45.6824		35.4535	
Reference teeth mass	**0.7094**		**5.0437**		**15.1980**		**30.4147**		**45.6824**		**35.4535**	

Determination of tooth tissue parameters



Tooth anatomy

- **Density of tooth tissues[22–25]**

Tooth type	Density of tooth tissue (g/cm^3)			
	Enamel	Dentin	Cementum	Pulp
Deciduous	2.840	2.185	2.030	1.021
Permanent	3.000	2.140	2.030	1.021

- **Volume ratio of tooth tissues[26, 27]**

Tooth type	Tooth tissue		
	Enamel	Dentin*	Pulp
Deciduous	0.199	0.625	0.177
Permanent	0.161	0.791	0.047

** According to consultation with our dental anatomist, it was considered as the ratio inclusive of cementum.*

- **Cementum thickness[28]**

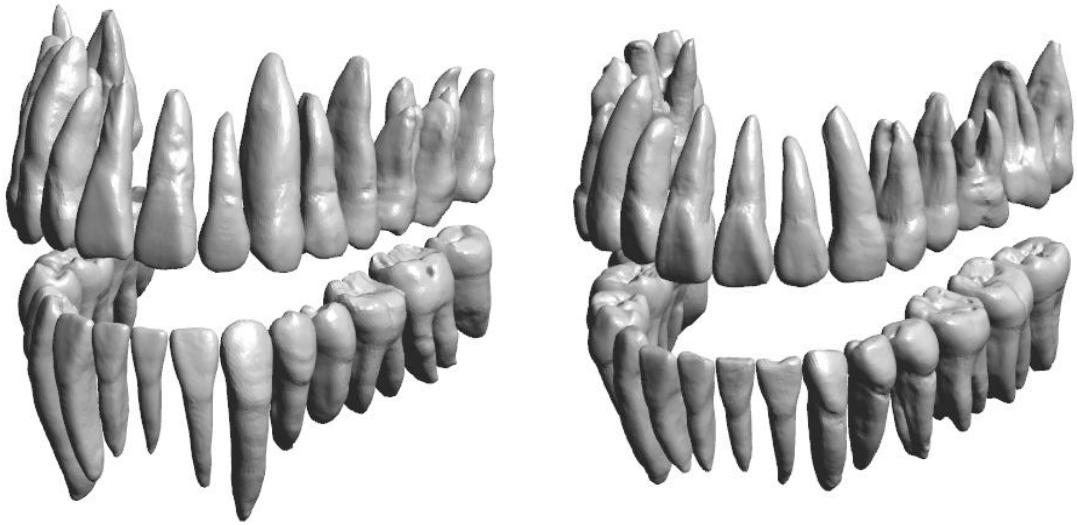
$$y = 0.0325 + 0.00307x$$

$$y: thickness\ of\ cementum\ (mm), x: age\ (year)$$

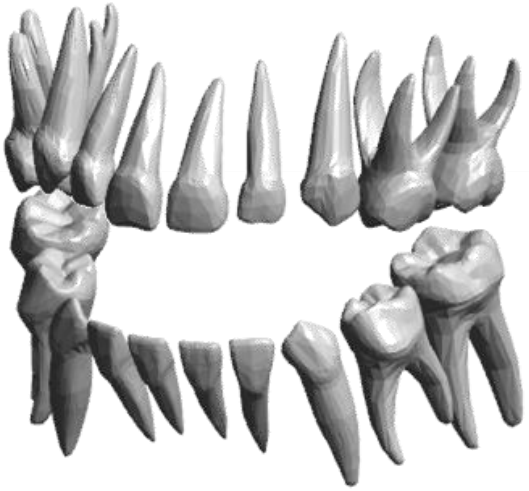
Determine target mass (or volumes) of tooth tissues for each individual tooth

[22] ICRP, 2002. Basic anatomical and physiological data for use in radiological protection reference values. ICRP Publication 89. Ann. ICRP 32.
[23] Bhussry, B.R., 1958. Chemical and physical studies of enamel from human teeth: 1. Specific gravity and nitrogen content of nemael from different surfaces. J. Dental Research 37, 832–836.
[24] Berghash, S.R. and Hodge, H.C., 1940. Density and refractive index studies of dental hard tissues: III. Density distribution of deciduous enamel and dentin. J. Dental Research 19, 487–495.
[25] Trudnowski, R.J. and Rico, R.C., 1974. Specific gravity of blood and plasma at 4 and 37 ℃. Clin. Chem. 20, 615–616.
[26] Bayle, P., Braga, J., Mazurier, A., et al., 2009. Brief communication: high-resolution assessment of the dental developmental pattern and characterization of tooth tissue proportions in the late Upper Paleolithic child from La Madeleine, France. Am. J. Phys. Anthropol. 138, 493–498.
[27] ICRP, 1975. Report on the task group on reference man. ICRP Publication 23. Pergamon Press, Oxford.
[28] Zander, H.A., Hürzeler, B., 1958. Continuous cementum apposition. J. Dent. Research. 37, 1035–1044.

- **High-quality PM tooth models used to develop the teeth of paediatric MRCPs**



Permanent teeth model: male (left) and female (right)[29]

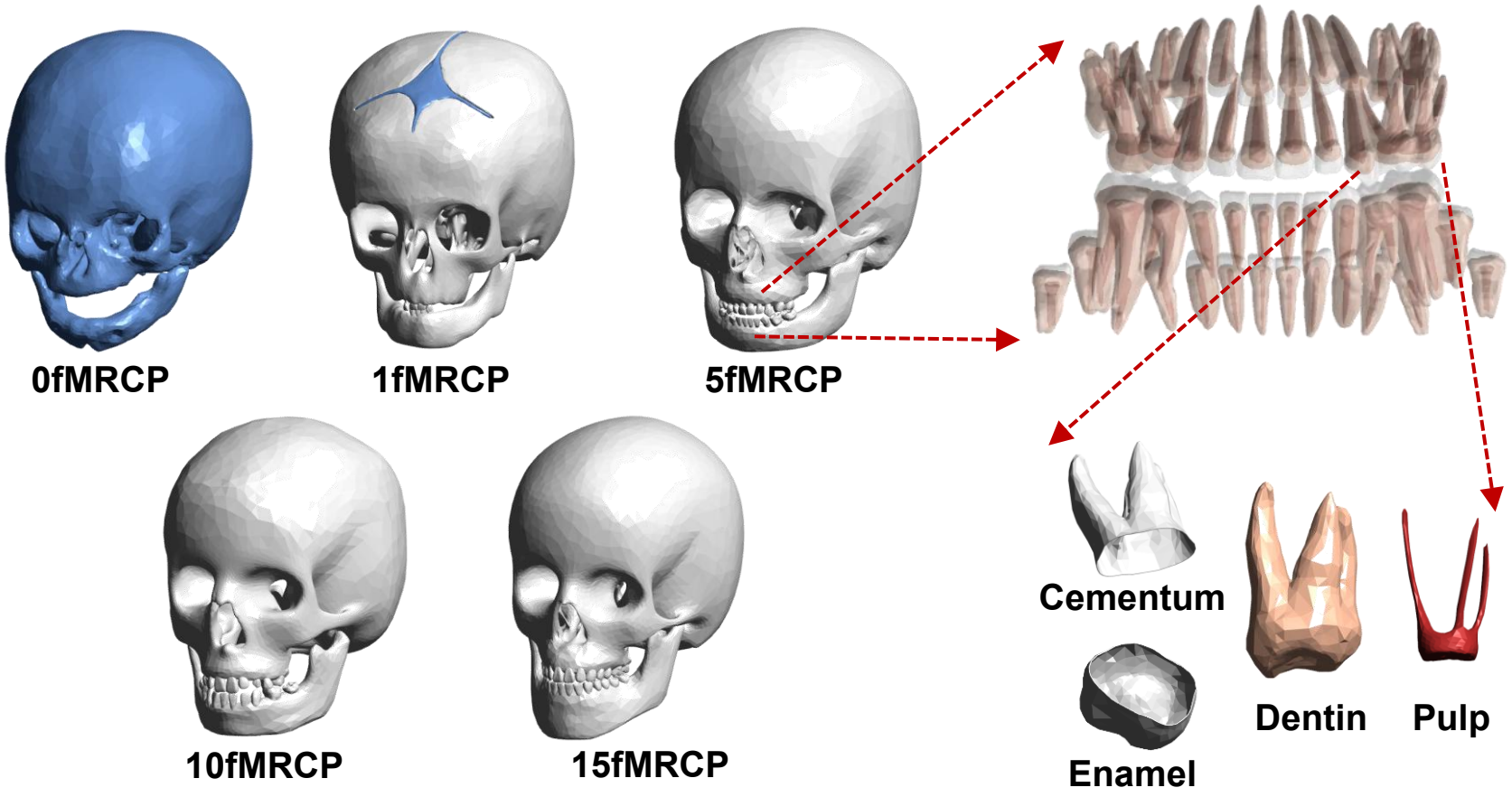


Deciduous teeth model[30]

[29] Digital Korean Project. http://dk.kisti.re.kr
[30] TurboSquid. Primary Teeth 3D Model. https://www.turbosquid.com/3d-models/primary-teeth-dentition-max/953912

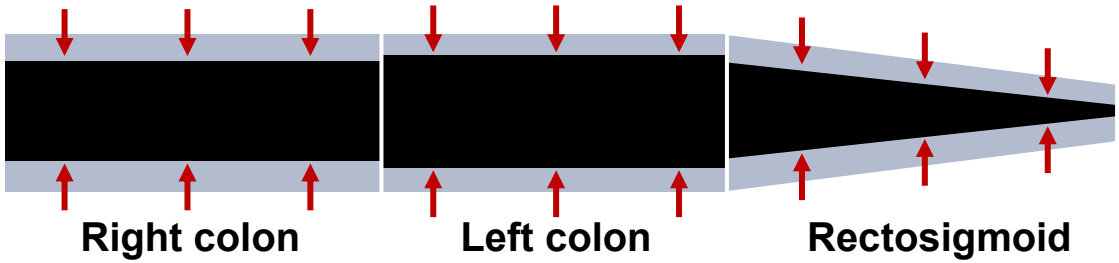
- **Construction and installation in paediatric MRCPs**
  - A total of 332 detailed tooth models (i.e., newborn: 20, 1-year: 28, 5-year: 48, 10-year: 38, 15-year: 32 for male and female, respectively) were constructed individually and then installed into the paediatric MRCPs.

Example: female phantoms

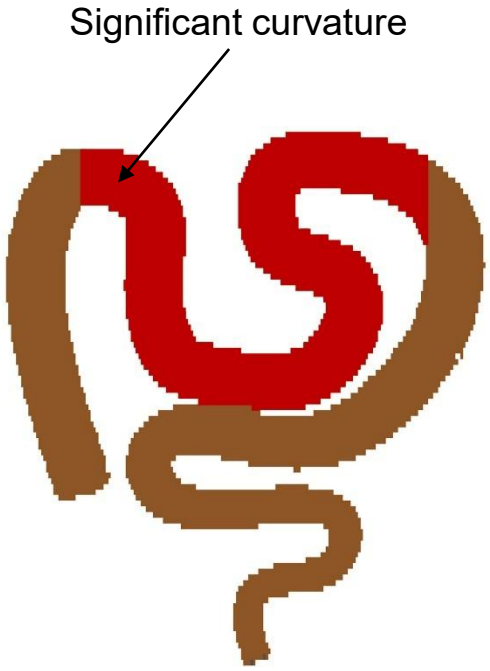


3) Colon

- In the paediatric VRCPs, either the mass or the density of the colon contents was significantly different from the reference values, due to the limitation of the modeling approach using a simple cylinder[1].
- In addition, the middle part of the transverse colon showed significantly downward curvature.



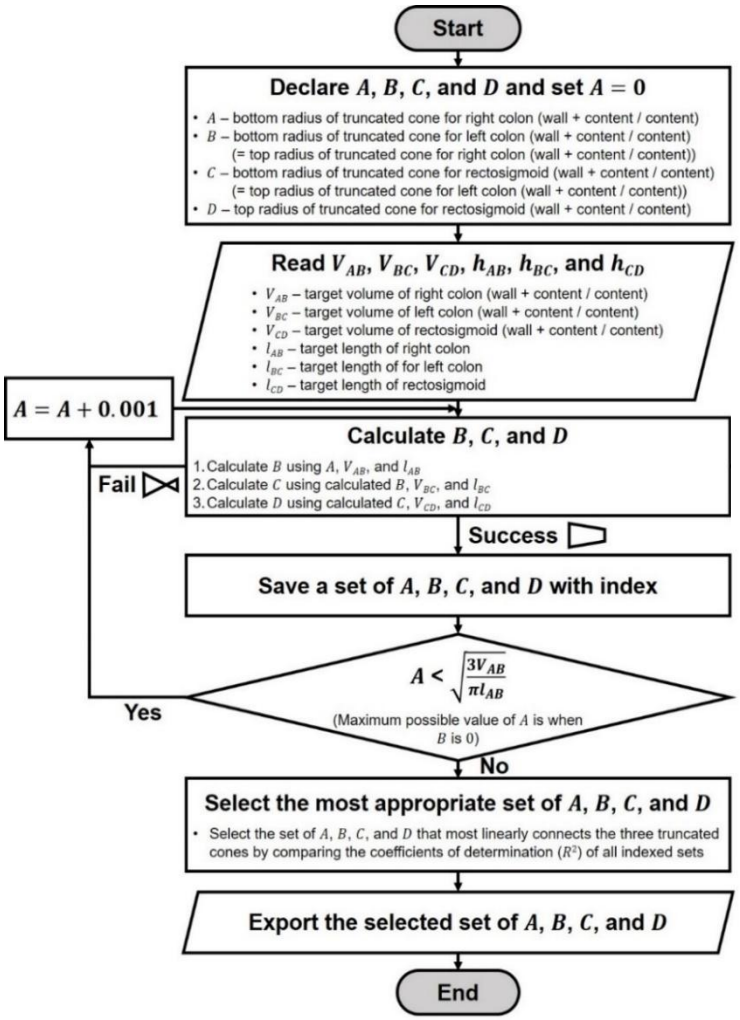
→ **Only matched to reference length and wall mass**



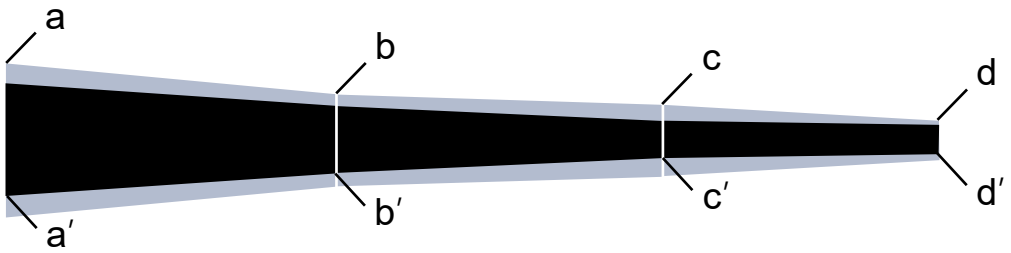
Example: 1-year male

Content	Volume (cm^3)	Density (g/cm^3)	Mass (g)	Reference mass (g)	Mass ratio
Right colon	15	1.03	**15.4**	40	2.6
Left colon	21	**0.95**	19.9	20	1.0
Rectosigmoid	14	1.03	**14.6**	20	1.4

Development of truncated cone model for each colon region



Program flowchart



- **Radii of colon wall**

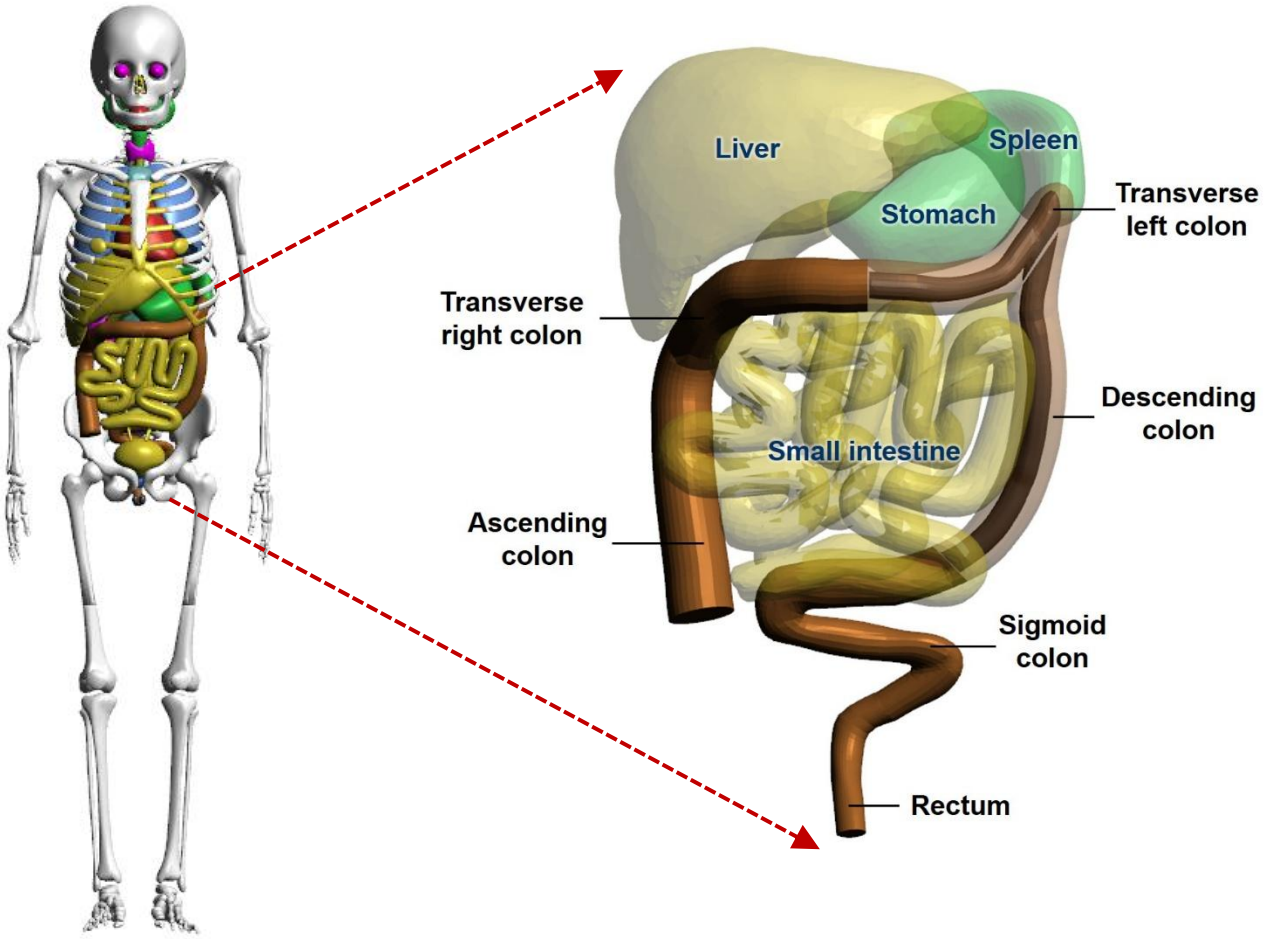
Age/sex	Determined radius (cm)			
	a	b	c	d
Newborn male/female	1.011	0.681	0.587	0.554
1-year male/female	1.214	0.861	0.734	0.630
5-year male/female	1.368	1.074	0.953	0.617
10-year male/female	1.555	1.231	1.145	0.678
15-year male	1.901	1.499	1.298	0.865
15-year female	1.856	1.452	1.249	0.861

- **Radii of colon content**

Age/sex	Determined radius (cm)			
	a′	b′	c′	d′
Newborn male/female	0.938	0.495	0.468	0.526
1-year male/female	1.069	0.562	0.522	0.562
5-year male/female	1.054	0.560	0.530	0.560
10-year male/female	1.128	0.604	0.578	0.604
15-year male	1.430	0.760	0.696	0.760
15-year female	1.430	0.760	0.696	0.760

- **Construction and installation in paediatric MRCPs**

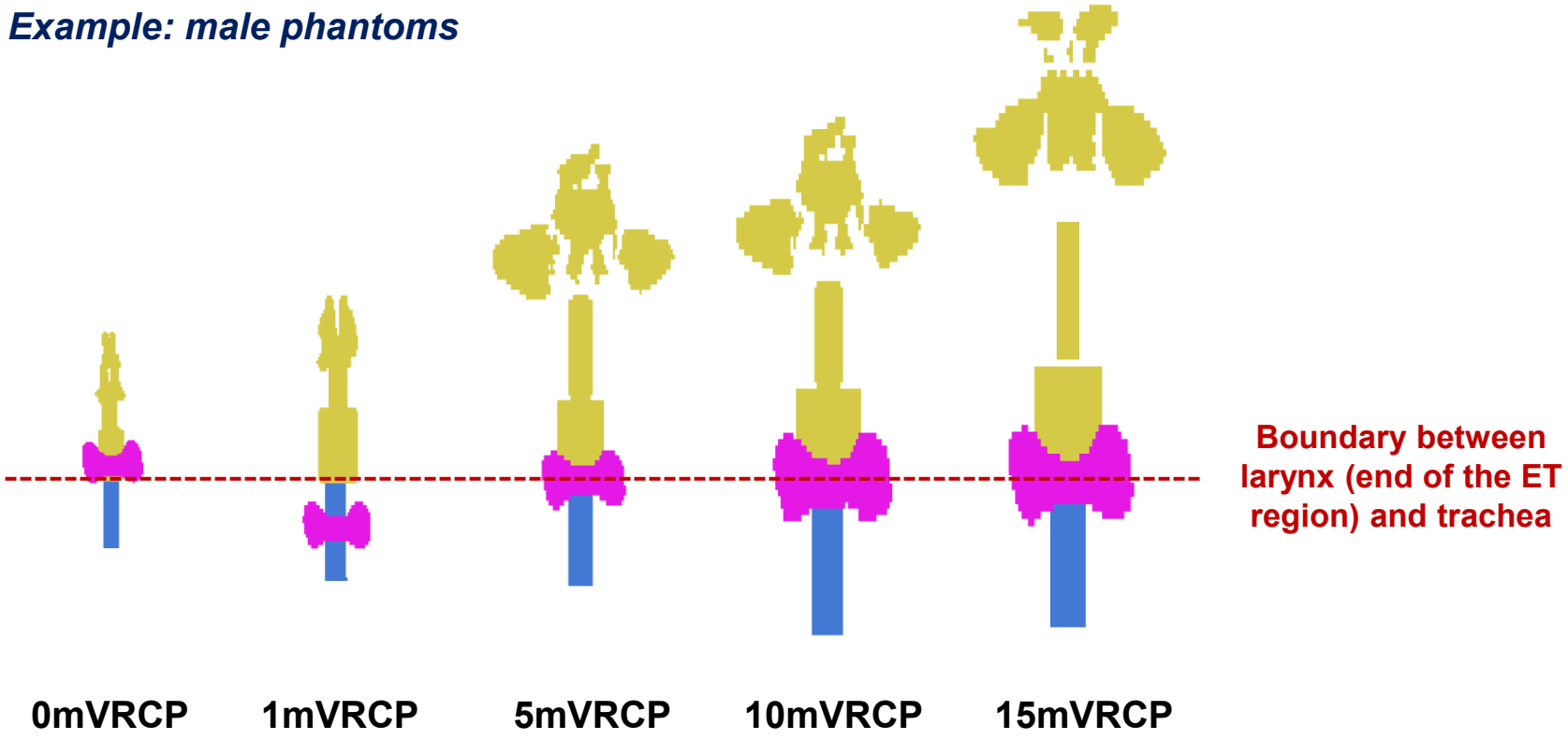
Example: 10mMRCP



4) Thyroid

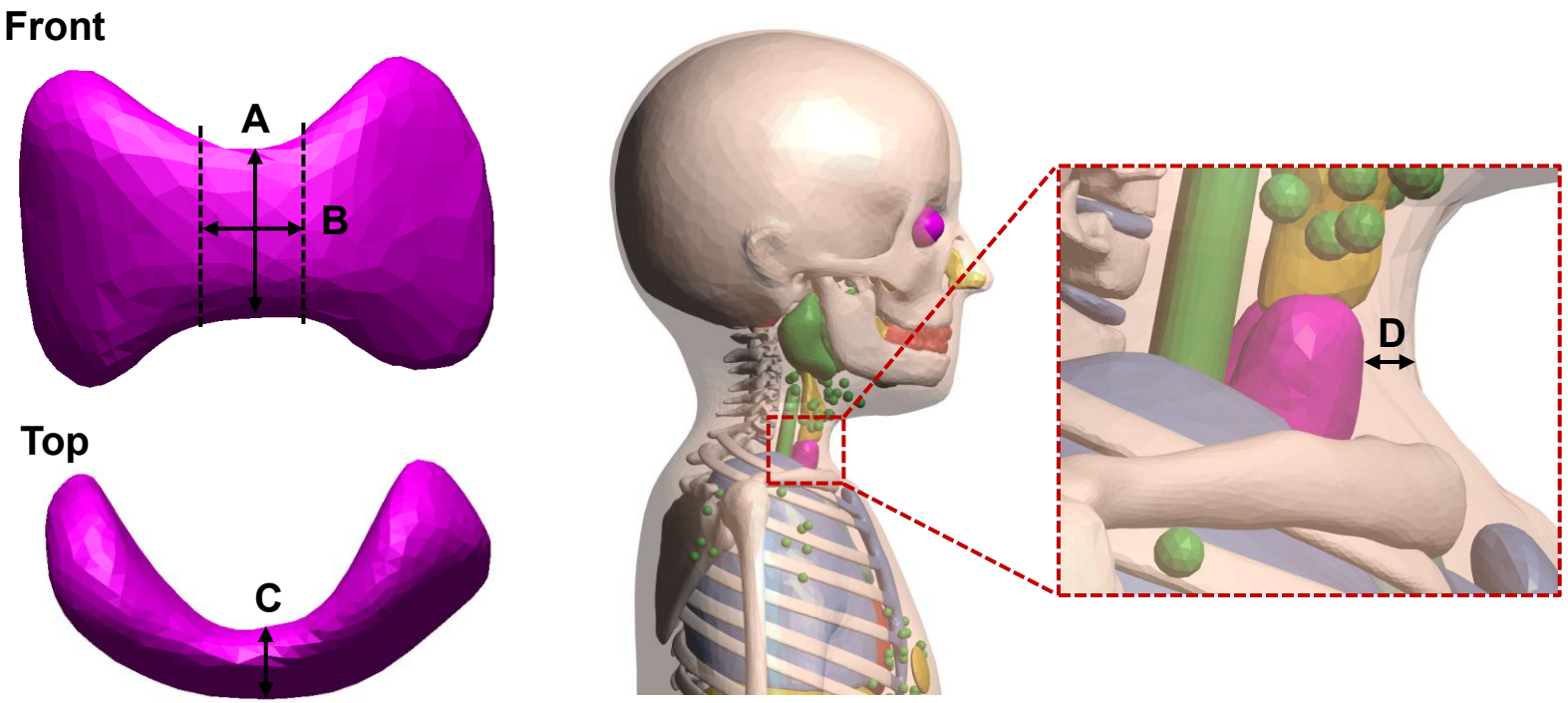
- For some ages, the thyroid of the paediatric VRCPs is located in an untypical position.

Example: male phantoms



- In addition, the isthmus region of the thyroid of the paediatric VRCPs is thicker than the typical shape.

- **Selection of five anatomical parameters**
  - Isthmus height (A)
  - Isthmus width (B)
  - Isthmus thickness (C)
  - Overlying tissue thickness (D)
  - Anatomical location



- **Determination of anatomical parameters**
  - **Isthmus dimensions**

Dimensions	Newborn	1 year	5 years	10 years	15 years	Adult*
Height	[31]	← Linear interpolation →				[32−36]
Width						
Thickness	[37]					

** For the interpolation, the adult values were assumed to be the same for 18 years of age, considering that the shape of the thyroid gland hardly changes after reaching young adulthood[33, 36, 38].*

Dimensions	Newborn	1 year	5 years	10 years	15 years
Height	8.6 mm	8.9 mm	10.2 mm	11.8 mm	13.5 mm
Width	9.2 mm	9.5 mm	10.4 mm	11.5 mm	12.6 mm
Thickness	1.5 mm	1.5 mm	2.0 mm	3.0 mm	3.0 mm

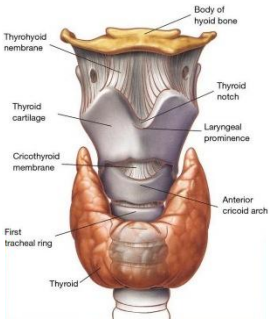
  - **Overlying tissue thickness[39]**

$$d = 0.0007a^2 + 0.025a + 5.2$$

$d = overlying\ tissue\ thickness\ (mm)$

$a = age\ (y)$

  - **Anatomical location[40, 41]**
    - Typically located in front of the second and third tracheal cartilage.



[31] Ozguner, G., Sulak, O., 2014. Size and location of thyroid gland in the fetal period. Surg. Radiol. Anat. 36, 359–367.
[32] Tong, E.C.K., Rubenfeld, S., 1972. Scan measurements of normal and enlarged thyroid gland. Am. J. Roentgenol. Radium Ther. Nucl. Med. 115, 706–708.
[33] Harjeet, A., Sahni, D., Jit, I., et al., 2004. Shape, measurements and weight of the thyroid gland in northwest Indians. Surg. Radio. Anat. 26, 91–95.
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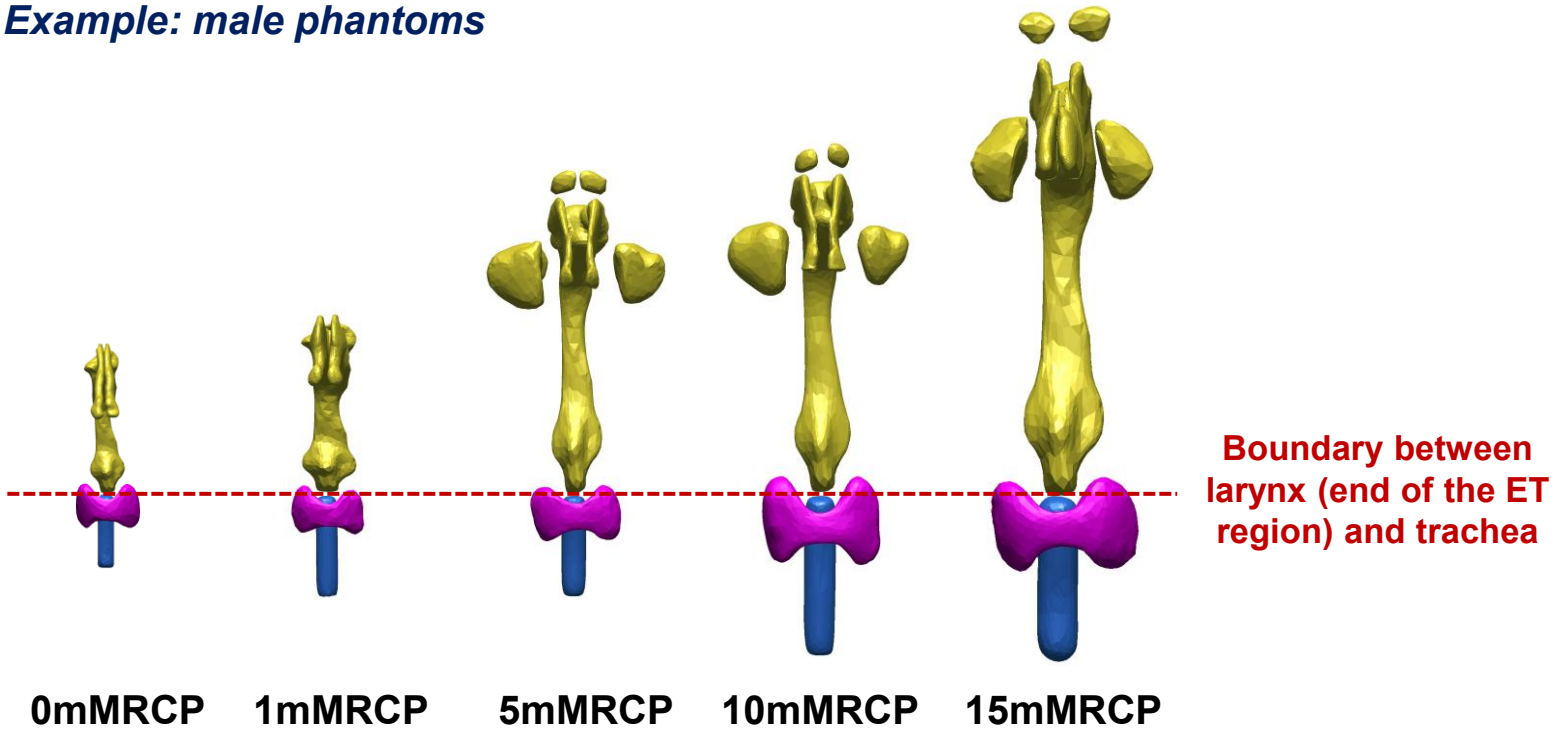
[36] Won, H.S., Han, S.H. Oh, C.S., et al., 2013. The location and morphometry of the thyroid isthmus in adult Korean cadavers. Anat. Sci. Int. 88, 212–216.
[37] Sea, J.H., Ji, H., You, S.K., et al. 2019. Age-dependent reference values of the thyroid gland in paediatric population; from routine computed tomography data. Clin. Imag. 56, 88–92.
[38] Sultana, S.Z., Khalil, M., Khan, M.K., et al., 2011. Morphometry of isthmus of thyroid gland in Bangladeshi cadaver. Mymensingh Med. J. 20, 366–370.
[39] Likhtarev, I.A., Gulko, G.M., Sobolev, B.G., et al., 1995. Evaluation of the 131I thyroid-monitoring measurements performed in Ukraine during May and June of 1986. Health Phys. 69, 6–15.
[40] Ellis, H, 2007. Anatomy of the thyroid and parathyroid glands. Surgery, Oxford 25, 467–468.
[41] Naqshi, B.F., Seth, S., Shah, A.B., et al., 2016. Thyroid hemiagenesis with agenesis of isthmus a case report. J. Med. Sci. Clin. Res. 4, 10799–10801.

- **Modification in paediatric MRCPs**
  - The height, width, and thickness of the isthmus and the overlying tissue thickness for the thyroid were adjusted to match the target values with the deviations below 3%.
  - Thyroids were located in front of the second and third tracheal cartilages.

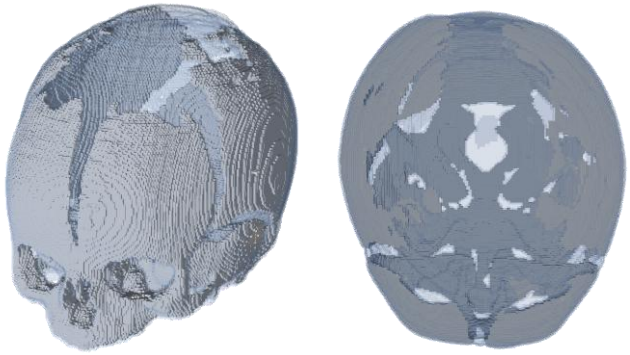
Example: male phantoms

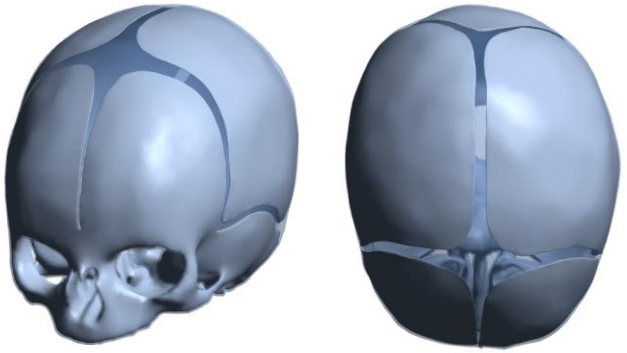


5) Cranium (Newborn and 1 year)

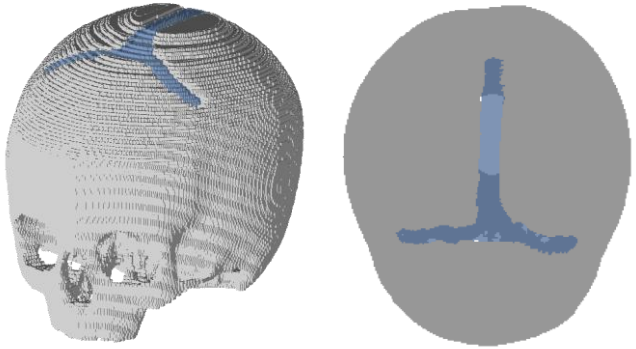
- For the paediatric MRCPs, the cranium was remodeled for newborn and 1 year, referring to anatomical literature[42−46].

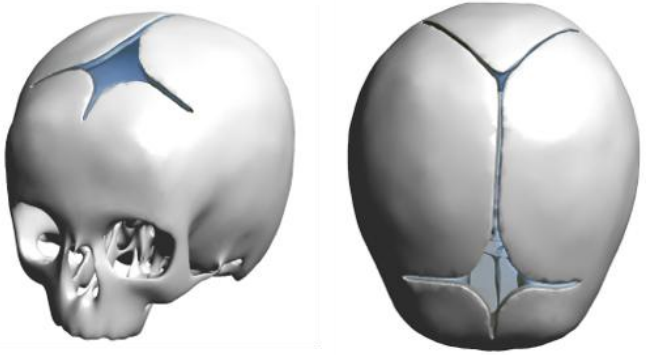
Example: newborn male phantom





Example: 1-year male phantom





Paediatric VRCPs

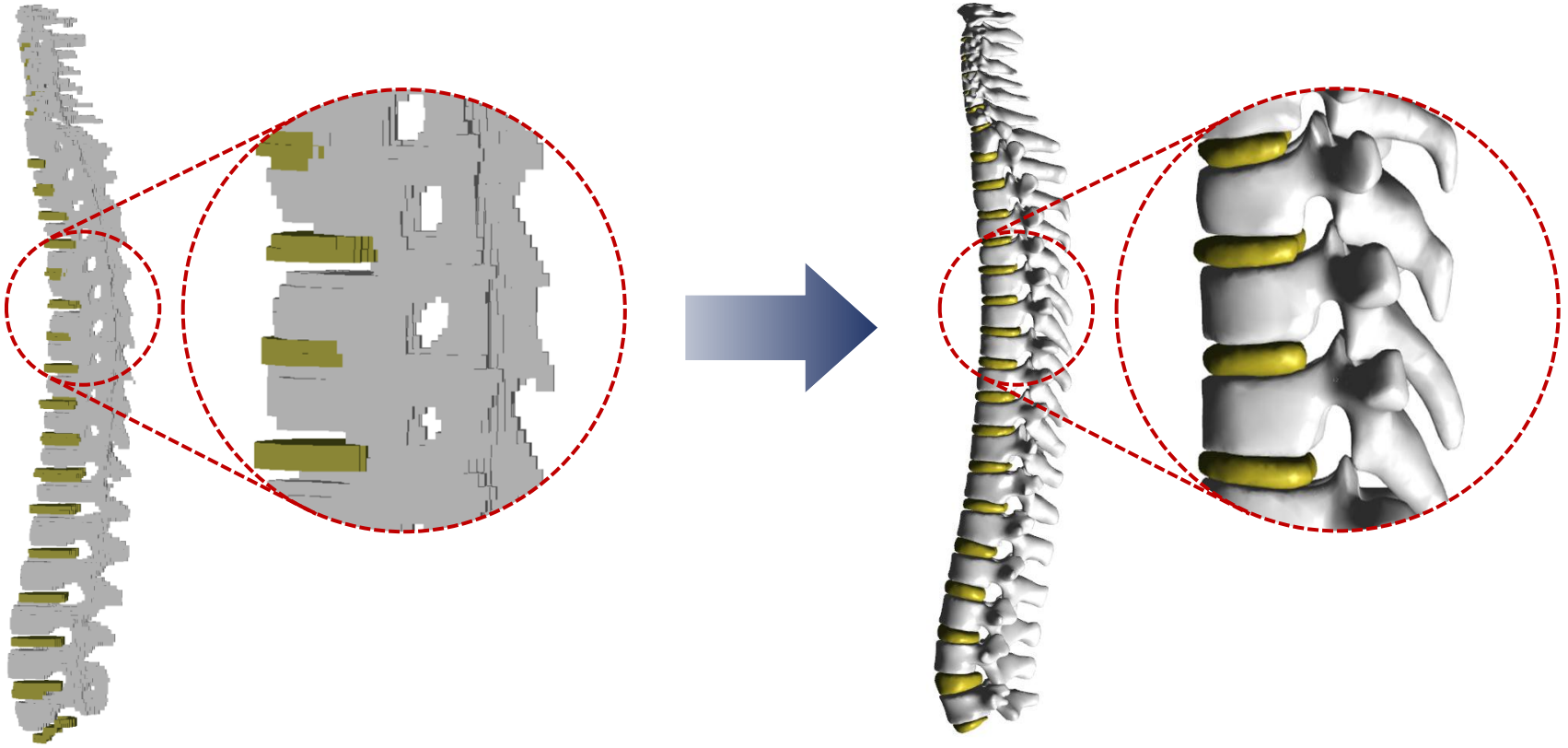
Paediatric MRCPs

[42] Noorizadeh, N., Kazemi, K., Grebe, R., et al., 2015. Evaluation of anterior fontanel size and area in the newborn using CT images. J. Intell. Fuzzy. Syst. 29, 443–450.
[43] Duc, G., Largo, R.H., 1986. Anterior fontanel: size and closure in term and preterm infants. Pediatrics 78, 904–908
[44] Faix, R.G., 1982. Fontanelle size in black and white term newborn infants. J. Pediatr. 100, 304–306.
[45] Usman, N., Dilkash, N.A., Khan, S., et al. 2011. Study of relationship between changes in size of posterior fontanelle with gestational age. Natl. J. Integr. Res. Med. 2, 1–3.
[46] Li, Z., Park, B.K., Liu, W., et al., 2015. A statistical skull geometry model for children 0–3 years old. PLoS One 10, 1–13.

6) Spine (1, 5, 10, and 15 years)

- For the paediatric MRCPs, the spine was developed by adjusting the high-quality spine models[47] to the paediatric VRCPs, piece by piece[48].

Example: 5-year male phantom



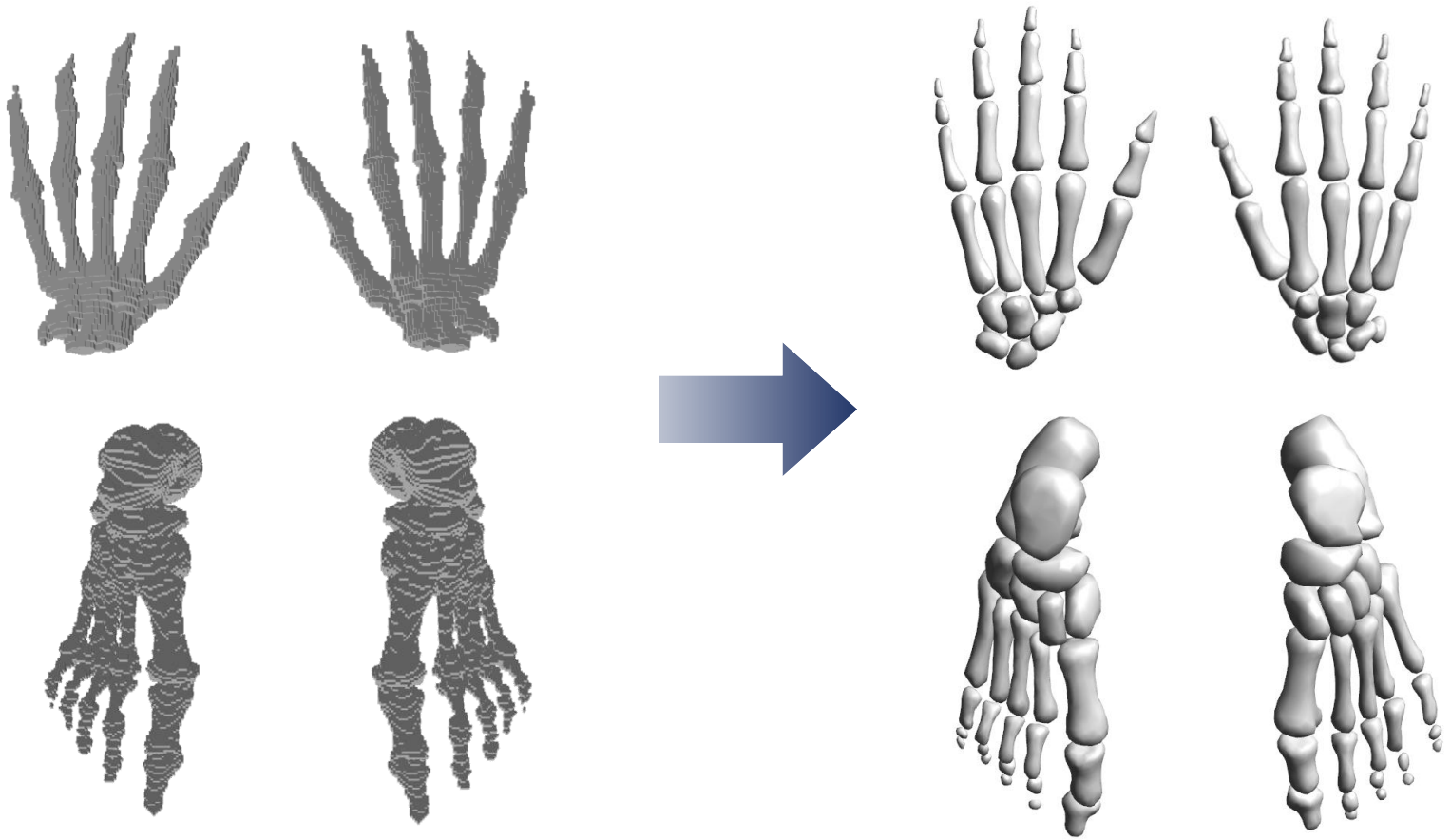
Paediatric VRCPs **Paediatric MRCPs**

[47] Park, J.S., Chung, M.S., Hwang, S.B., et al., 2005. Visible Korean Human: improved serially sectioned images of the entire body. IEEE Trans. Med. Imaging 24, 352–360.
[48] Taylor, J.R., 1975. Growth of human intervertebral discs and vertebral bodies. J. Anat. 120, 49–68.

7) Hand/Foot Bones (1, 5, 10, and 15 years)

- For the paediatric MRCPs, the same approach was used for the hand and foot bones[29].

Example: 10-year male phantom

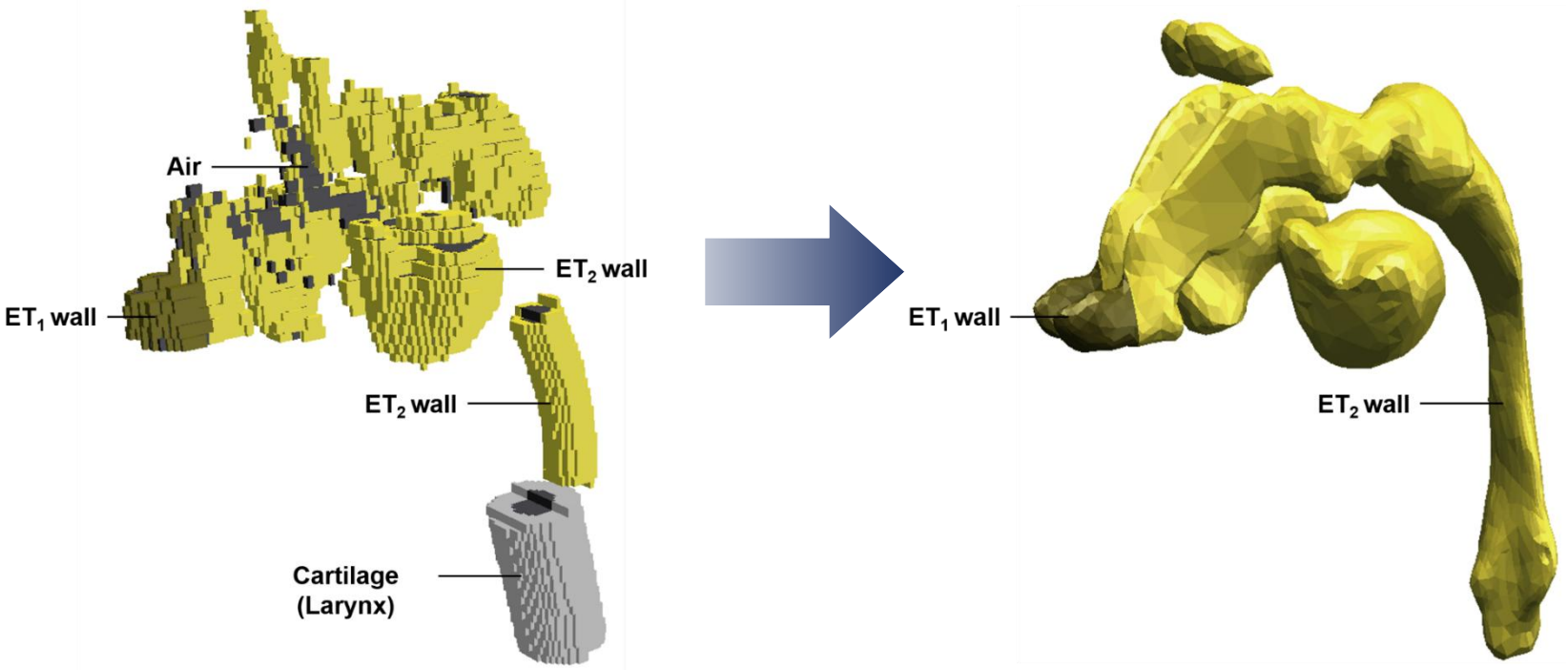


Paediatric VRCPs **Paediatric MRCPs**

8) Extrathoracic (ET) Region

- For the paediatric MRCPs, the ET region was remodeled; the anterior nose and the posterior nasal passage were modified referring to anatomical literature[49], and the remaining parts were constructed by scaling down those of the adult MRCPs.

Example: 5-year male phantom



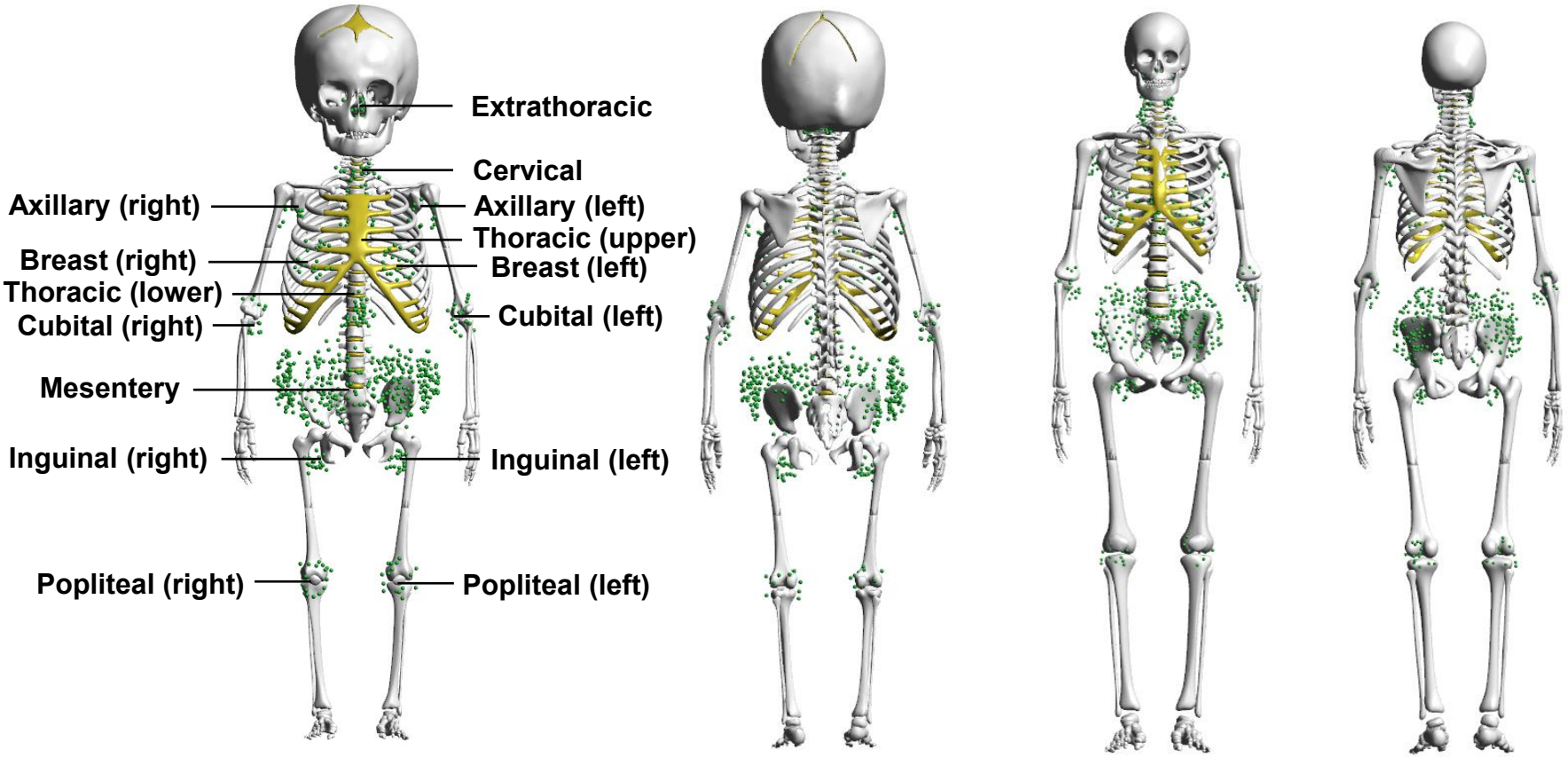
Paediatric VRCPs **Paediatric MRCPs**

[49] Kozak, F.K., Ospina, J.C., 2014. Characteristics of normal and abnormal postnatal craniofacial growth and development. Cummings Paediatric Otolaryngology, Elsevier, 55–80.

9) Lymphatic Nodes

- For the paediatric MRCPs, the lymphatic nodes were generated using the same computer program that was used for the adult MRCPs.

Example: 1mMRCP (left) and 15fMRCP (right)



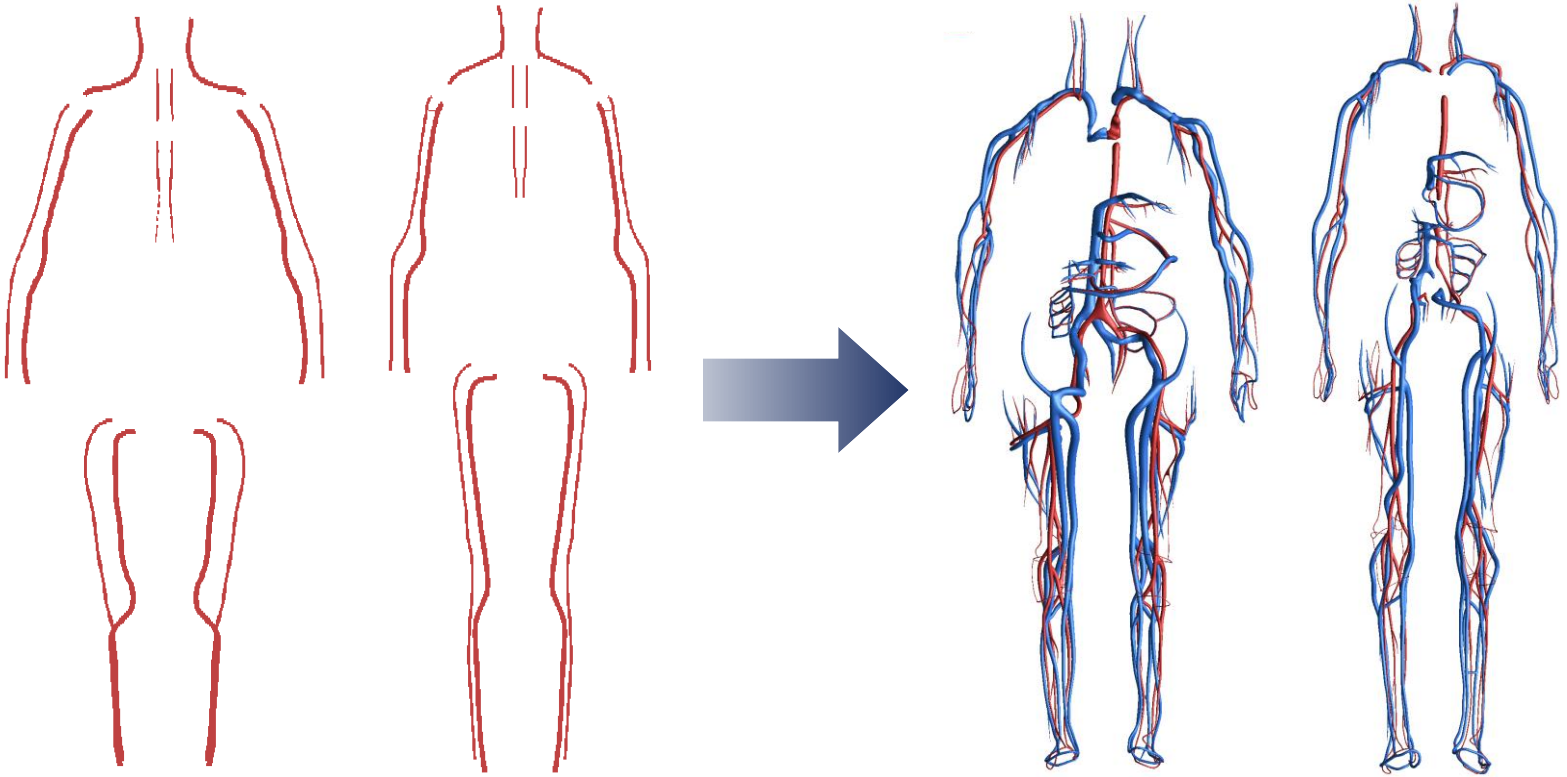
10) Blood in Large Vessels

- For the paediatric MRCPs, the blood in large vessels was remodeled referring to anatomical literature[50] and in consultation with the anatomist.

Example: 1-year male (left) and 15-year female (right) phantoms

Red: arteries

Blue: veins



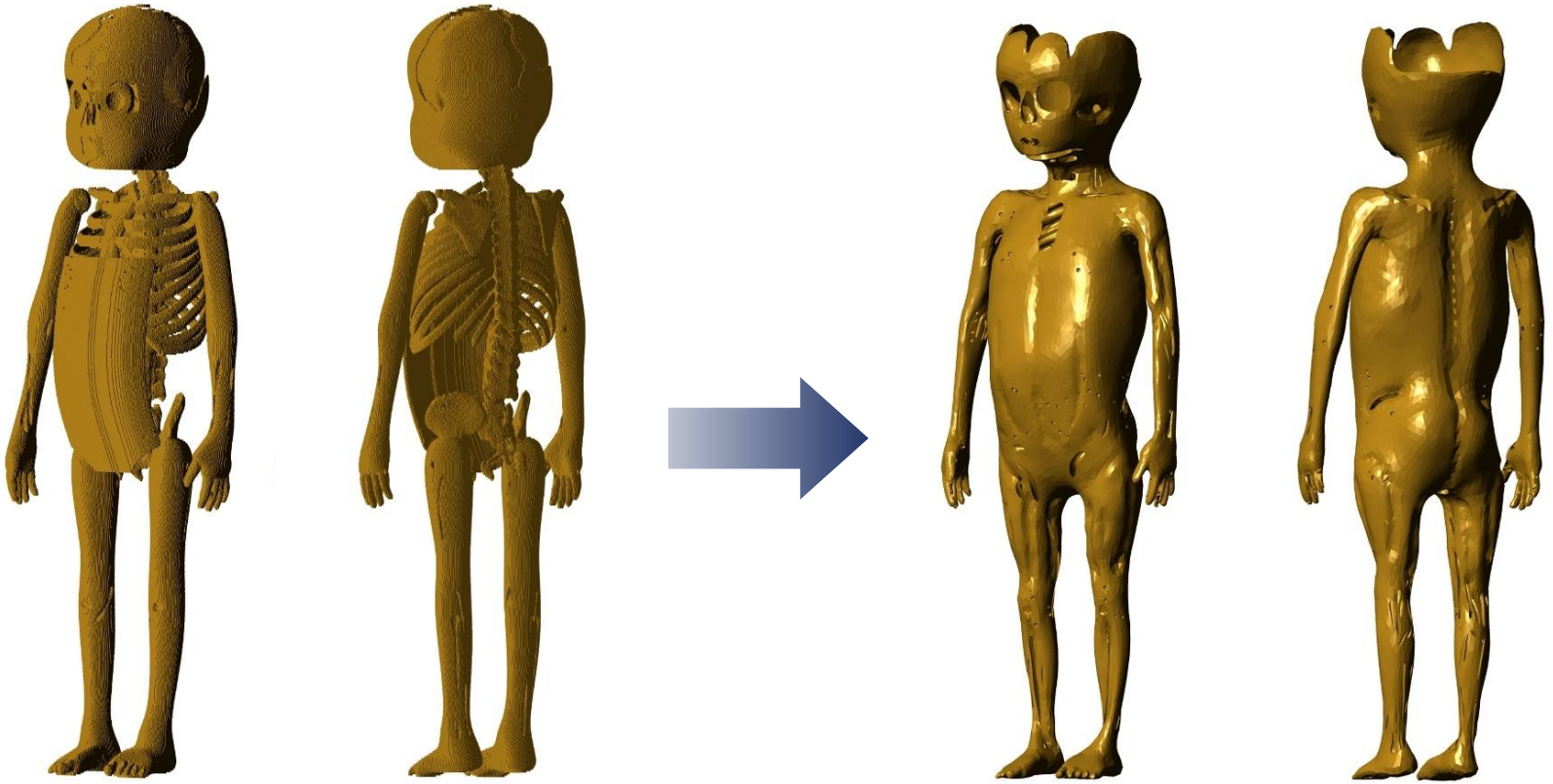
Paediatric VRCPs **Paediatric MRCPs**

[50] BioDigital Human, http://www.biodigital.com

11) Muscle

- For the paediatric MRCPs, the muscle was constructed in consultation with the anatomist.

Example: 1-year female phantom

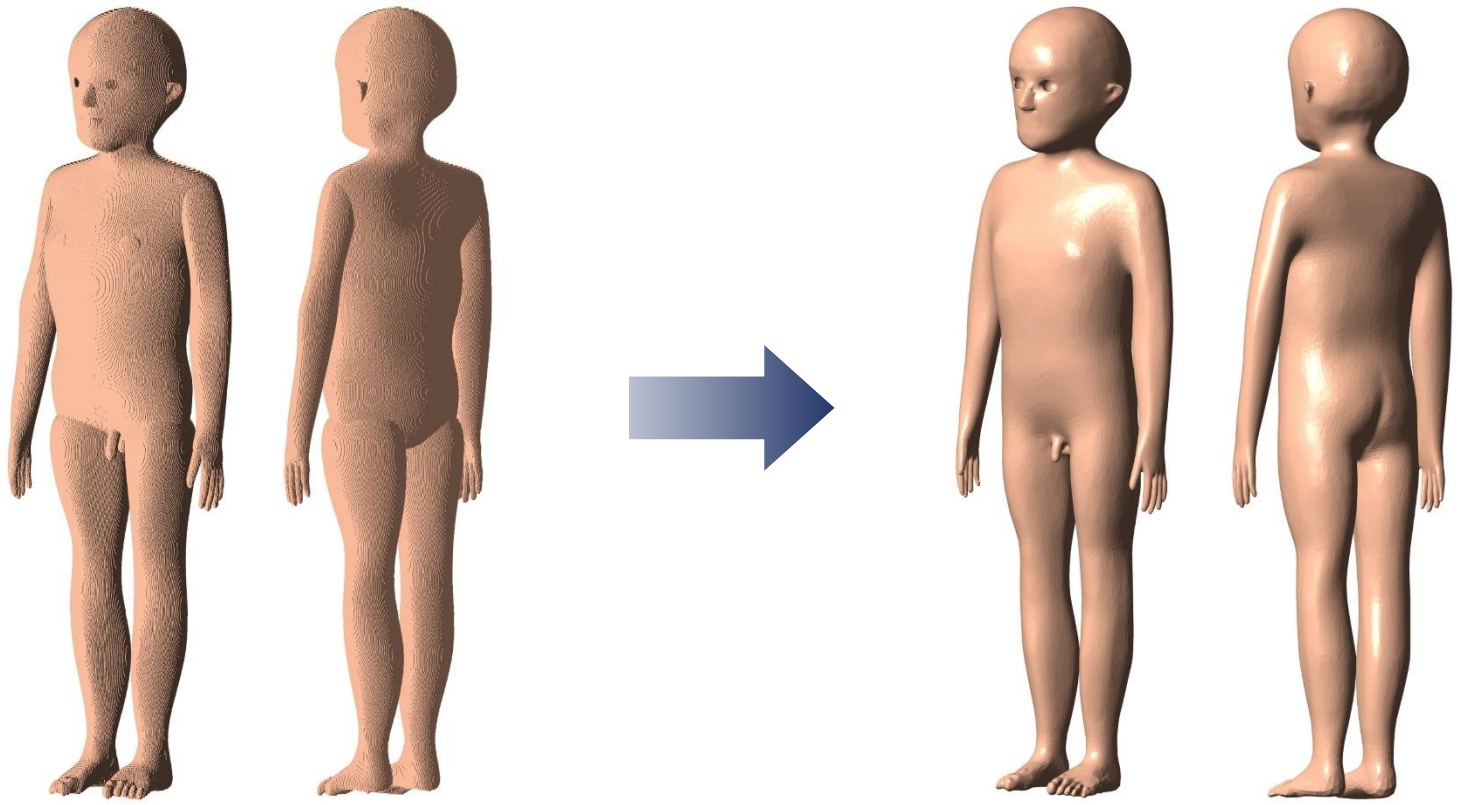


Paediatric VRCPs **Paediatric MRCPs**

12) Exterior Body Contour

- For the paediatric MRCPs, the exterior body shape was modified to have more natural shape, matching the reference morphometric values within 5% of difference.

Example: 5-year male phantom



Paediatric VRCPs **Paediatric MRCPs**

Other Organs

- **Oesophagus**
- **Tongue**
- **Sacrum (1, 5, 10, and 15 years)**
- **Sternum (1, 5, and 10 years)**
- **Mandible (1 and 10 years)**
- **Liver (newborn)**

Ⅱ. Inclusion of Blood in Organs and Tissues

Necessity to Consider Intra-organ Blood Content

- Organs of the VRCPs are generally based on the ICRP-89 reference masses[22], which are not inclusive of intra-organ blood content.
- In a living person, a considerable amount of blood is situated in the small vessels and capillaries in the organs.
- Consideration of the blood content is necessary in phantom construction, especially for the purpose of internal dosimetry (e.g., cross-fire of weakly-penetrating radiations and self-irradiation).

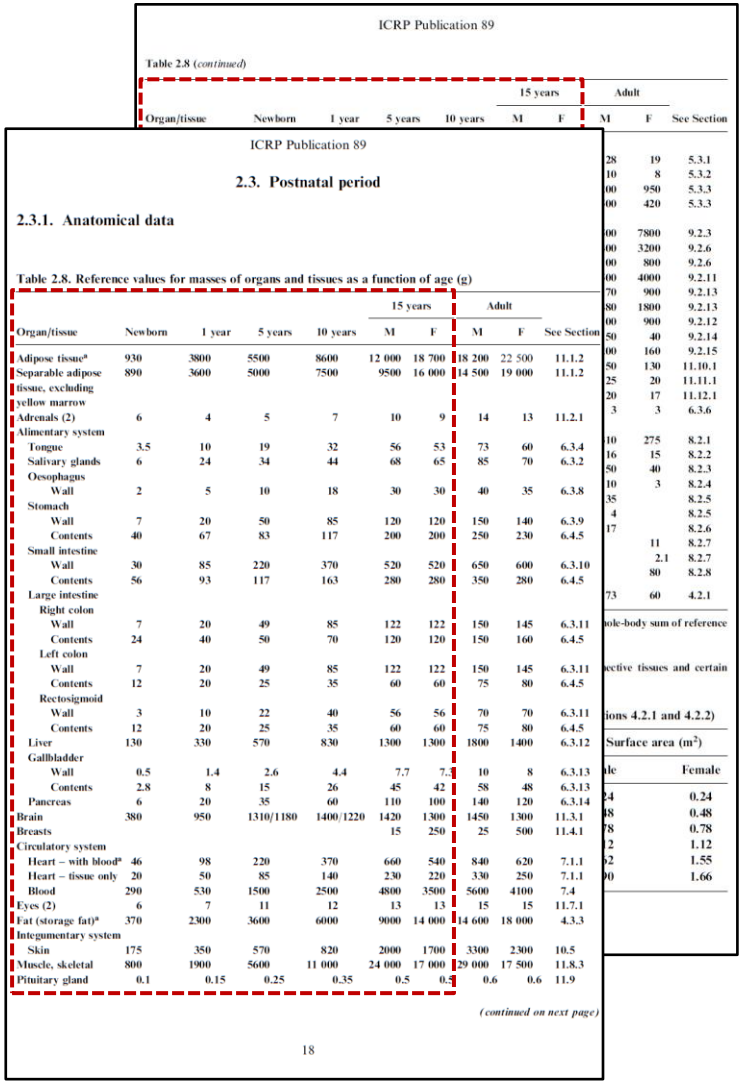


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Table 2.8 (*continued*)

Organ/tissue	Newborn	1 year	5 years	10 years	15 years M	15 years F	Adult M	Adult F	See Section
									28 19 5.3.1
									10 8 5.3.2
									00 950 5.3.3
									00 420 5.3.3
									00 7800 9.2.3
									00 3200 9.2.6
									00 800 9.2.6
									00 4000 9.2.11
									70 900 9.2.13
									80 1800 9.2.13
									00 900 9.2.12
									50 40 9.2.14
									00 160 9.2.15
									50 130 11.10.1
									25 20 11.11.1
									20 17 11.12.1
									3 3 6.3.6
									10 275 8.2.1
									16 15 8.2.2
									50 40 8.2.3
									10 3 8.2.4
									35 8.2.5
									4 8.2.5
									17 8.2.6
									11 8.2.7
									2.1 8.2.7
									80 8.2.8
									73 60 4.2.1
									ole-body sum of reference
									ective tissues and certain
									ions 4.2.1 and 4.2.2)
									Surface area (m^2)
									ale Female
									24 0.24
									48 0.48
									78 0.78
									2 1.12
									62 1.55
									90 1.66

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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 M	15 years F	Adult M	Adult F	See Section
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	7.7	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*)

18

ICRP-89 reference organ masses

Calculation of Blood Content Mass

- Blood-content masses were calculated based on ICRP-89 reference blood masses and regional blood volume fractions[51].

ICRP-89 reference blood masses

- Newborn male/female: 290 g
- 1-year male/female: 530 g
- 5-year male/female: 1500 g
- 10-year male/female: 2500
- 15-year male: 4800
- 15-year female: 3500

Table 6. Suggested reference values for regional blood distribution (% total BV) for the ICRP reference persons.

	Newborn	1 year	5 year	10 year	15 year		Adult	
Organ or tissue	Male/female	Male/female	Male/female	Male/female	Male	Female	Male	Female
Fat	2.2	5.0	4.1	4.2	3.6	6.6	5.0	8.5
Brain	5.4	5.3	4.3	2.7	1.6	1.4	1.2	1.2
Stomach & esophagus wall	0.8	0.7	0.9	1.0	0.9	0.9	1.0	1.0
Small intestine wall	2.8	2.8	3.8	3.9	3.6	3.3	3.8	3.8
Colon wall	1.6	1.6	2.1	2.2	2.1	1.8	2.2	2.2
Right heart contents	*4.5*	*4.5*	*4.5*	*4.5*	*4.5*	*4.5*	*4.5*	*4.5*
Left heart contents	*4.5*	*4.5*	*4.5*	*4.5*	*4.5*	*4.5*	*4.5*	*4.5*
Coronary tissues	1.1	0.9	0.8	0.9	0.8	0.9	1.0	1.0
Kidneys	0.7	1.8	2.2	2.2	1.9	1.8	2.0	2.0
Liver	12.9	11.4	10.3	9.2	8.5	9.4	10.0	10.0
Lungs								
Pulmonary gas exchange blood	*10.5*	*10.5*	*10.5*	*10.5*	*10.5*	*10.5*	*10.5*	*10.5*
Pulmonary nutrient blood	*2.0*	*2.0*	*2.0*	*2.0*	*2.0*	*2.0*	*2.0*	*2.0*
Skeletal muscle	6.8	5.5	8.5	10.3	13.7	10.3	14.0	10.5
Pancreas	0.4	0.5	0.5	0.5	0.6	0.5	0.6	0.6
Skeletal tissues								
Active marrow	5.2	5.0	4.9	4.9	4.8	5.0	4.0	4.0
Trabecular bone	3.6	4.4	4.4	4.4	4.0	4.4	1.2	1.2
Cortical bone	1.3	1.6	1.6	1.6	1.4	1.5	0.8	0.8
Other skeletal tissues	0.7	0.7	0.7	0.8	0.9	0.9	1.0	1.0
Skin	3.0	2.0	1.8	1.6	2.2	2.2	3.0	3.0
Spleen	1.5	1.6	1.4	1.4	1.4	1.4	1.4	1.4
Thyroid	0.07	0.03	0.03	0.04	0.04	0.04	0.06	0.06
Lymphatic nodes	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Testes or ovaries	0.01	0.01	0.01	0.01	0.02	0.01	0.04	0.02
Adrenal glands	0.4	0.1	0.1	0.1	0.1	0.04	0.06	0.06
Urinary bladder wall	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
All other tissues	3.8	3.3	1.9	2.4	2.2	1.9	1.9	1.9
Aorta and large arteries	*6.0*	*6.0*	*6.0*	*6.0*	*6.0*	*6.0*	*6.0*	*6.0*
Large veins	*18.0*	*18.0*	*18.0*	*18.0*	*18.0*	*18.0*	*18.0*	*18.0*
	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Regional blood volume fractions

Example: liver

$$m_{blood-in-liver} = \left(m_{total-blood}^{ICRP89}\right)\left(f_{liver}^{total-blood}\right)$$

[51] Wayson, M.B., Leggetti, R.W., Jokisch, D.W., et al., 2018. Suggested reference values for regional blood volumes in children and adolescents. Phys. Med. Biol. 63, 155022.

Calculation of Density and Elemental Composition

- Subsequently, densities and elemental compositions of the organs inclusive of blood content were calculated using data given in the scientific literature[22, 52, 53], assuming that the blood content is uniformly distributed within the organs.

Example: brain

- **Density**

$$\rho_{brain}^{with-blood} = \frac{m_{brain}^{ICRP89} + m_{blood-in-brain}}{\frac{m_{brain}^{ICRP89}}{\rho_{brain}^{ICRU46}} + \frac{m_{blood-in-brain}}{\rho_{blood}^{ICRU46}}}$$

- **Mass percentage of hydrogen**

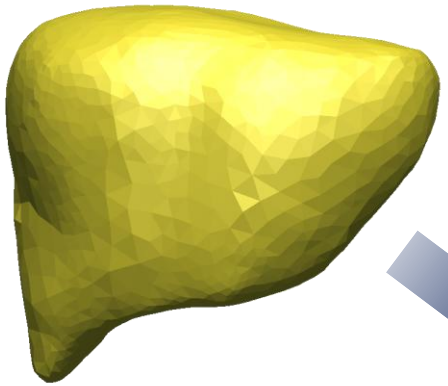
$$(\%H)_{brain}^{with-blood} = \frac{(\%H)_{brain}^{ICRU46} m_{brain}^{ICRP89} + (\%H)_{blood}^{ICRU46} m_{blood-in-brain}}{m_{brain}^{ICRP89} + m_{blood-in-brain}}$$

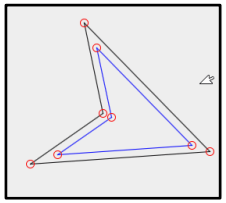
[52] ICRU, 1992. Photon, electron, proton, and neutron interaction data for body tissues. ICRU Report 46. International Commission on Radiation Units and Measurements, Bethesda, MD.
[53] White, D.R., Woodard, H.Q. and Hammond, S.M., 1987. Average soft-tissue and bone models for use in radiation dosimetry. Br. J. Radiol. 60, 907–9013.

Adjustment for Blood Inclusion

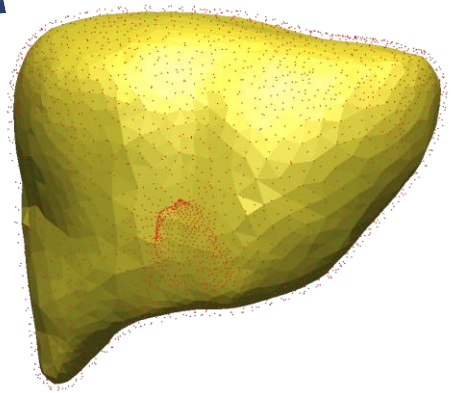
- Organs were isotropically increased, preserving the original shape and centroid of the organs.
- After enlargement, resulting overlaps between some of the neighboring organs were eliminated by preferentially modifying the larger organs, rather than the smaller ones.

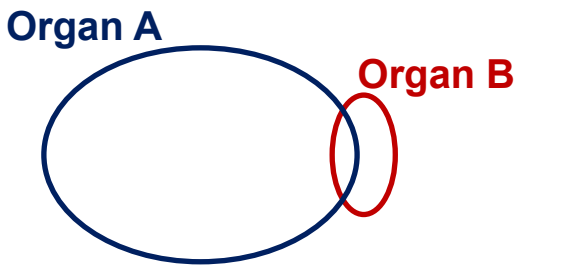
Example: liver



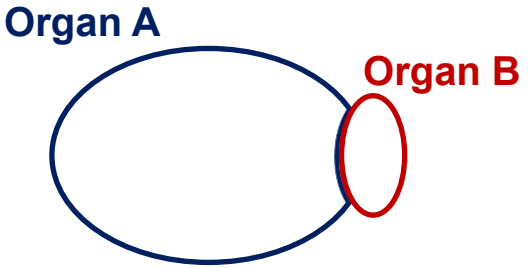


Enlargement of surface using *Offset* function





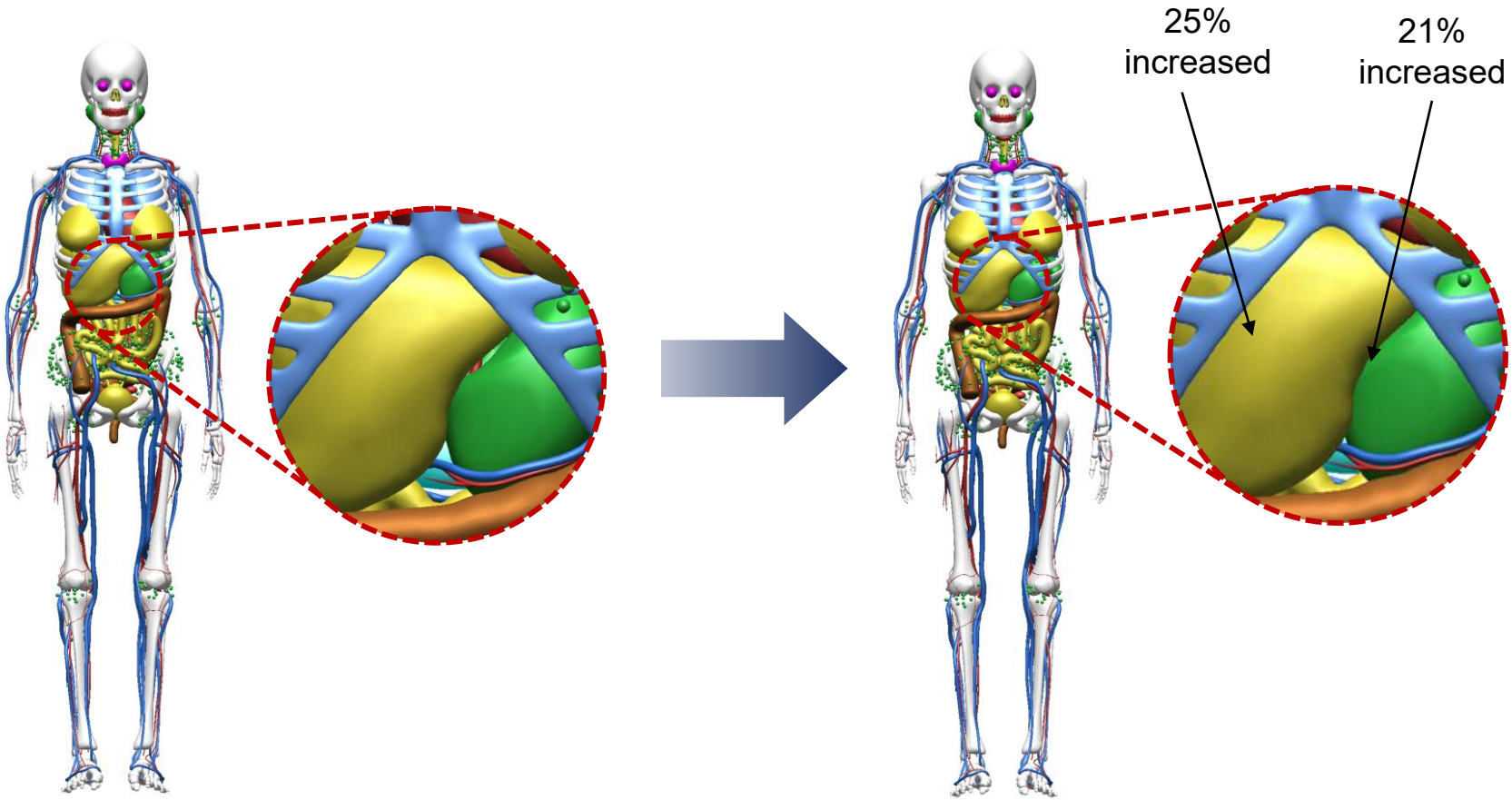
Elimination of overlaps using *Boolean* function



Comparison of Changes Caused by Blood Inclusion

- Most of internal organs were increased by 20−30% in size.

Example: 15fMRCP



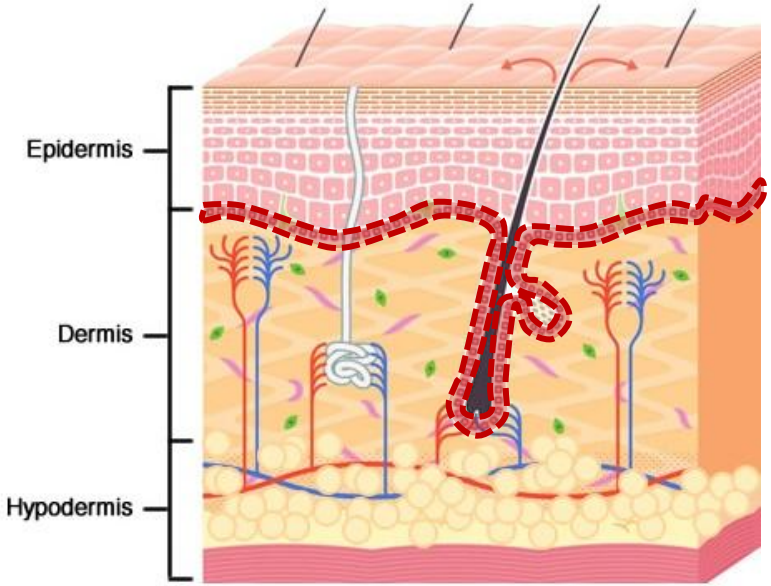
Organs exclusive of blood content

Organs inclusive of blood content

Ⅲ. Inclusion of Thin Target and Source Regions

Skin

- **Target region in skin**
  - The ICRP assumes that the target region of the skin is at a depth of 50 to 100 μm below the skin surface for the adult[54, 55].
  - Dr. John Harrison and Dr. John Hopewell carefully discussed the skin target layer issue and decided to use the skin target layer of 50–100 μm for the 15 years and 40–100 μm for the 10 years and younger.



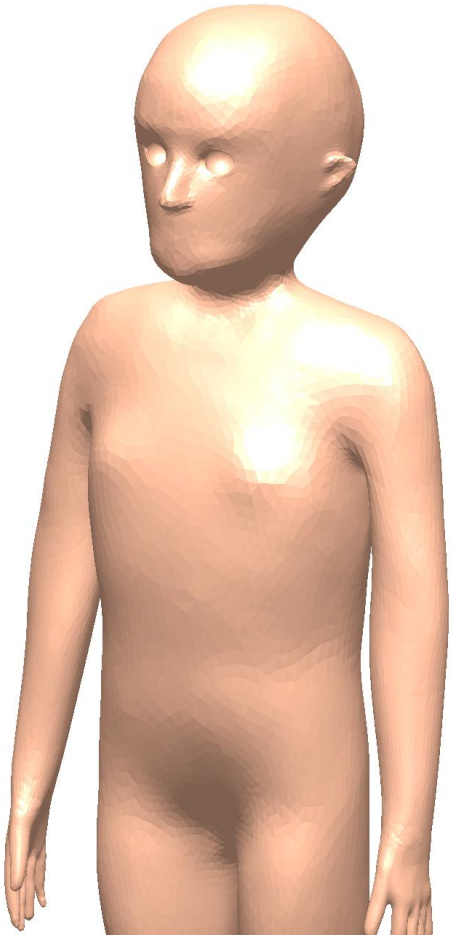
Anatomical structure of the skin

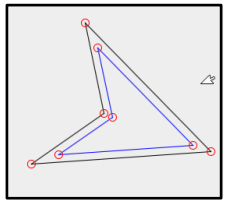
'We came to the conclusion that it would not make sense to use the shallower depths in the way we had tentatively discussed in Beijing. This is because a substantial proportion of the target cells for skin cancer are not in the inter-follicular basal layer between hair follicles but in the hair follicles themselves that penetrate through the dermis. John points out that the hair follicles are closer together in the skin of children and so a greater proportion of target cells will actually be at greater depths. Given that we are committed to previous use of 50–100 μm for adults (nominal 70 μm), we propose that this depth should also be used for the 15 y old, and that a slightly wider band of 40–100 μm should be used for ages 10 y and younger.'

Mail from Dr. John Harrison (30 September 2018)

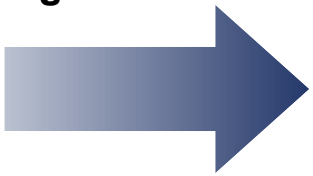
[54] ICRP, 2015. Occupational intakes of radionuclides: part 1. ICRP Publication 130. Ann. ICRP 44.
[55] ICRP, 1977. Recommendations of the International Commission on Radiological Protection. ICRP Publication 26. Ann. ICRP 1.

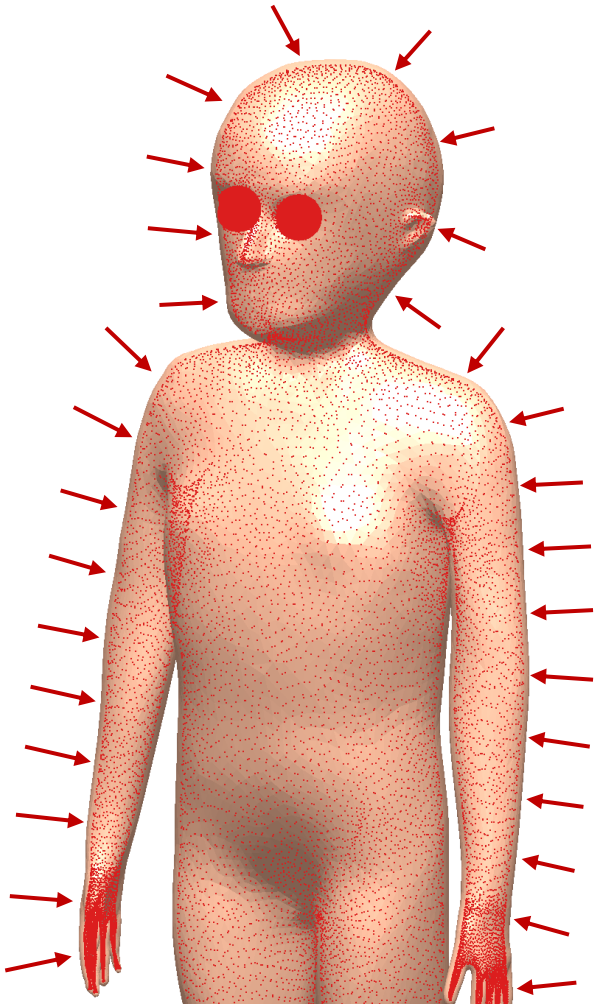
- **Construction of target region in skin**





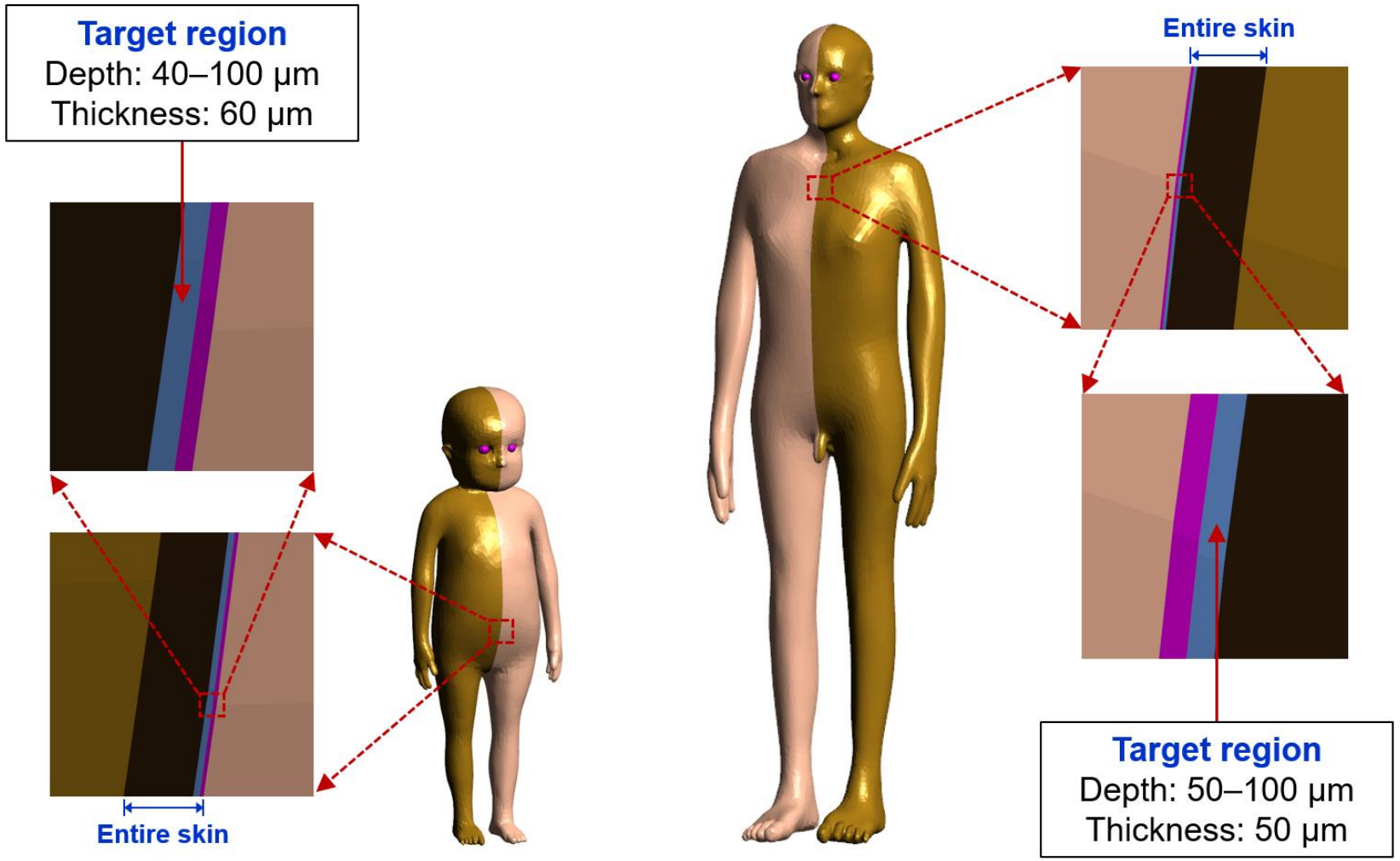
Reduction of skin surface using *Offset* function





- **Target region defined in skin of paediatric MRCPs**

Example: 1fMRCP (left) and 15mMRCP (right)



Urinary Bladder

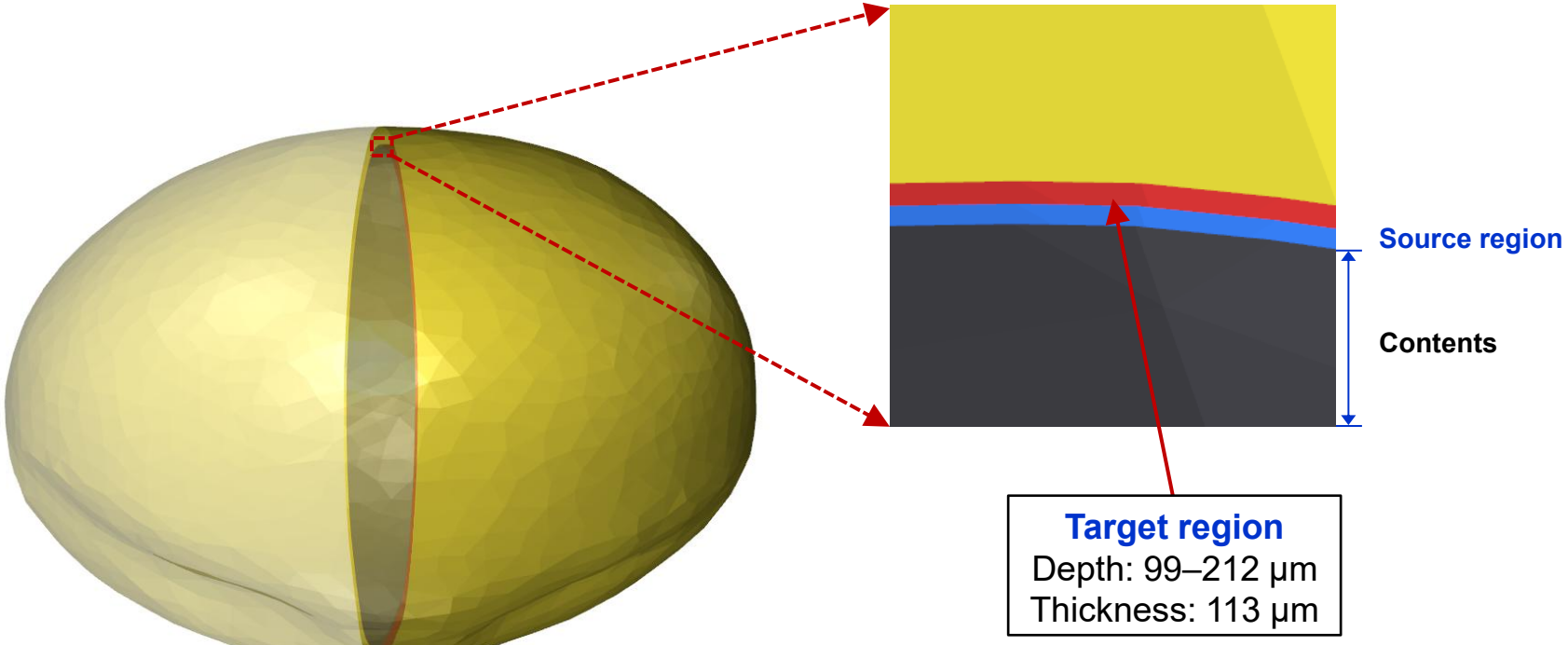
- **Target region in urinary bladder**
  - Eckerman and Veinot[56] derived the depth and thickness of the target region of the urinary bladder for adults.
  - In their subsequent study, the depth and thickness of the target region for children and adolescents were also derived.

Age/sex	Depth (μm)	Thickness (μm)
Newborn male/female	54	178
1-year male/female	71	167
5-year male/female	86	107
10-year male/female	99	113
15-year male	116	122
15-year female	111	116

[56] 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.

- **Target region defined in urinary bladder of paediatric MRCPs**

Example: 10mMRCP



Alimentary Tract Organs

- **Source and target regions in alimentary tract organs**
  - The ICRP provides the information on the source and target regions of the alimentary tract organs through ICRP *Publication 100*.
  - ICRP *Publication 100* assumes that the depth of the target and source regions are the same for all ages, except for the villi.

Alimentary tract organ	Source	Source location¶
Oral Cavity	Food (or liquid)	5 mm (on top of the tongue, outward)
	Retention on teeth	10 μm (on inner and outer surfaces of the teeth, outward)
Oesophagus	Contents (fast)	*
	Luminal surface (slow)	**
Stomach	Mucosa	0–300 μm (outward)
	Contents	*
Small intestine	Villi	0–400†/500†† μm (inward)
	Mucosa	0–200 μm (outward)
	Contents	*
Right colon	Mucosa	0–300 μm (outward)
	Contents	*
Left colon	Mucosa	0–300 μm (outward)
	Contents	*
Rectosigmoid	Mucosa	0–300 μm (outward)
	Contents	*

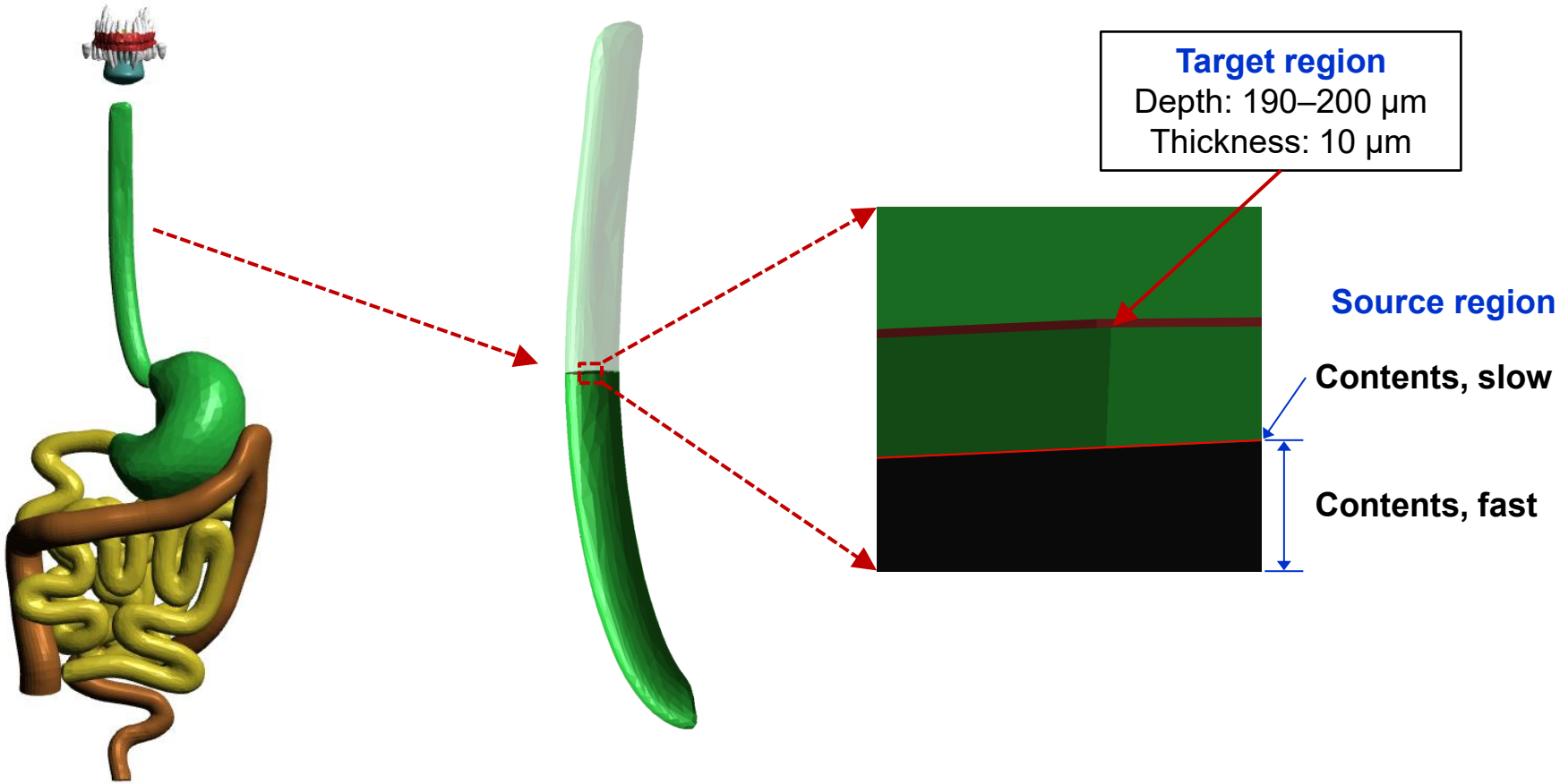
¶ *Default depth is from the luminal surface.*
* *Volume of the contents is the source region.*
** *Surface of the contents is the source region.*

Alimentary tract organ	Target region	Target location¶
Oral Cavity	Roof of mouth	190–200 μm (from the top surface of the food, outward)
	Tongue	190–200 μm (from the surface of the tongue, inward)
	Lips and cheek	190–200 μm (from the outer surface of retention on teeth, outward)
Oesophagus	Basal cells	190–200 μm (outward)
Stomach	Stem cells	60–100 μm (outward)
Small intestine	Stem cells	130–150 μm (outward)
Right colon	Stem cells	280–300 μm (outward)
Left colon	Stem cells	280–300 μm (outward)
Rectosigmoid	Stem cells	280–300 μm (outward)

† *Depth of the small intestine villi for newborn, 1 year and 5 years.*
†† *Depth of the small intestine villi for 10 years and 15 years.*

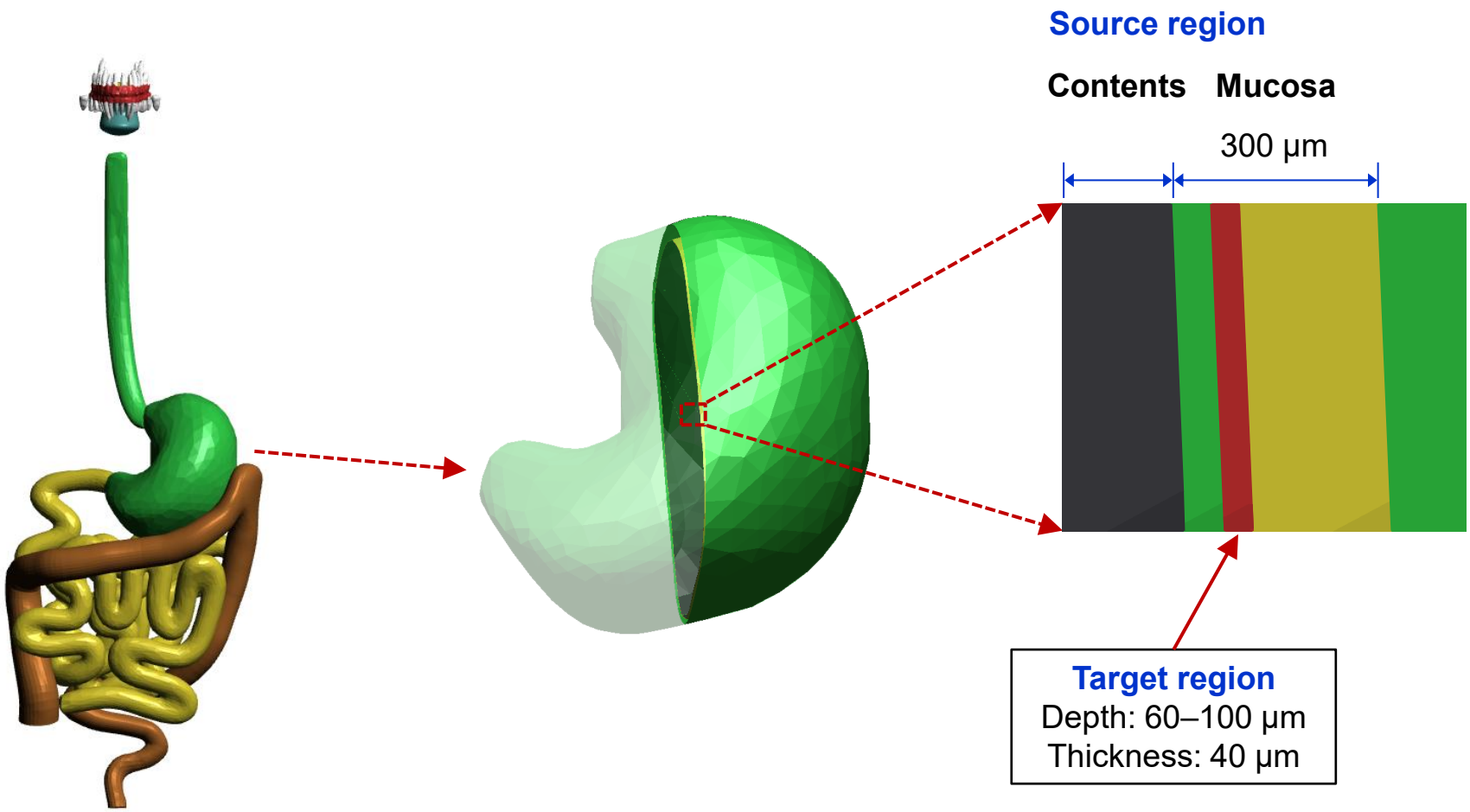
- **Source and target regions defined in oesophagus of paediatric MRCPs**

Example: 15mMRCP



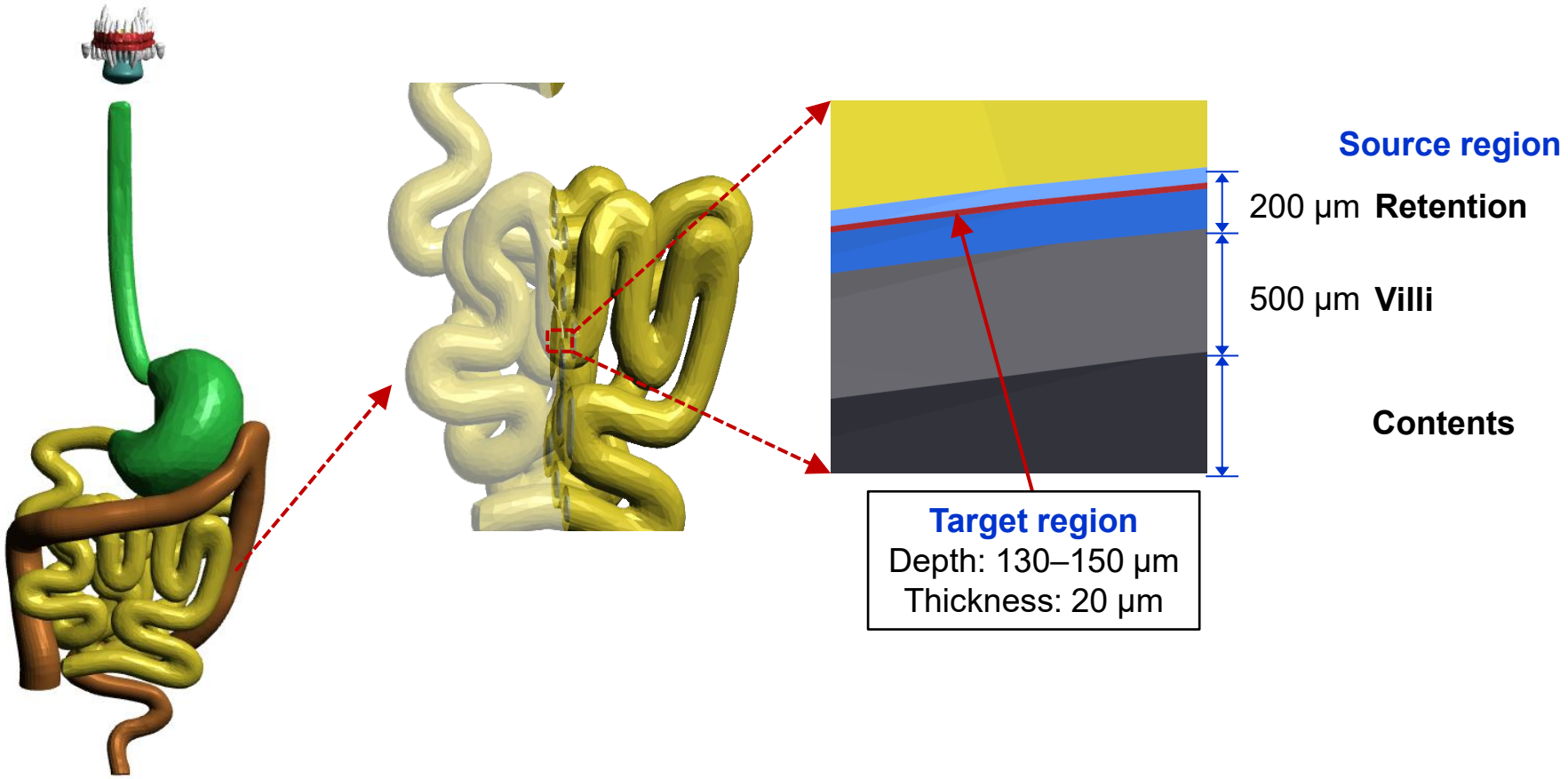
- **Source and target regions defined in stomach of paediatric MRCPs**

Example: 15mMRCP



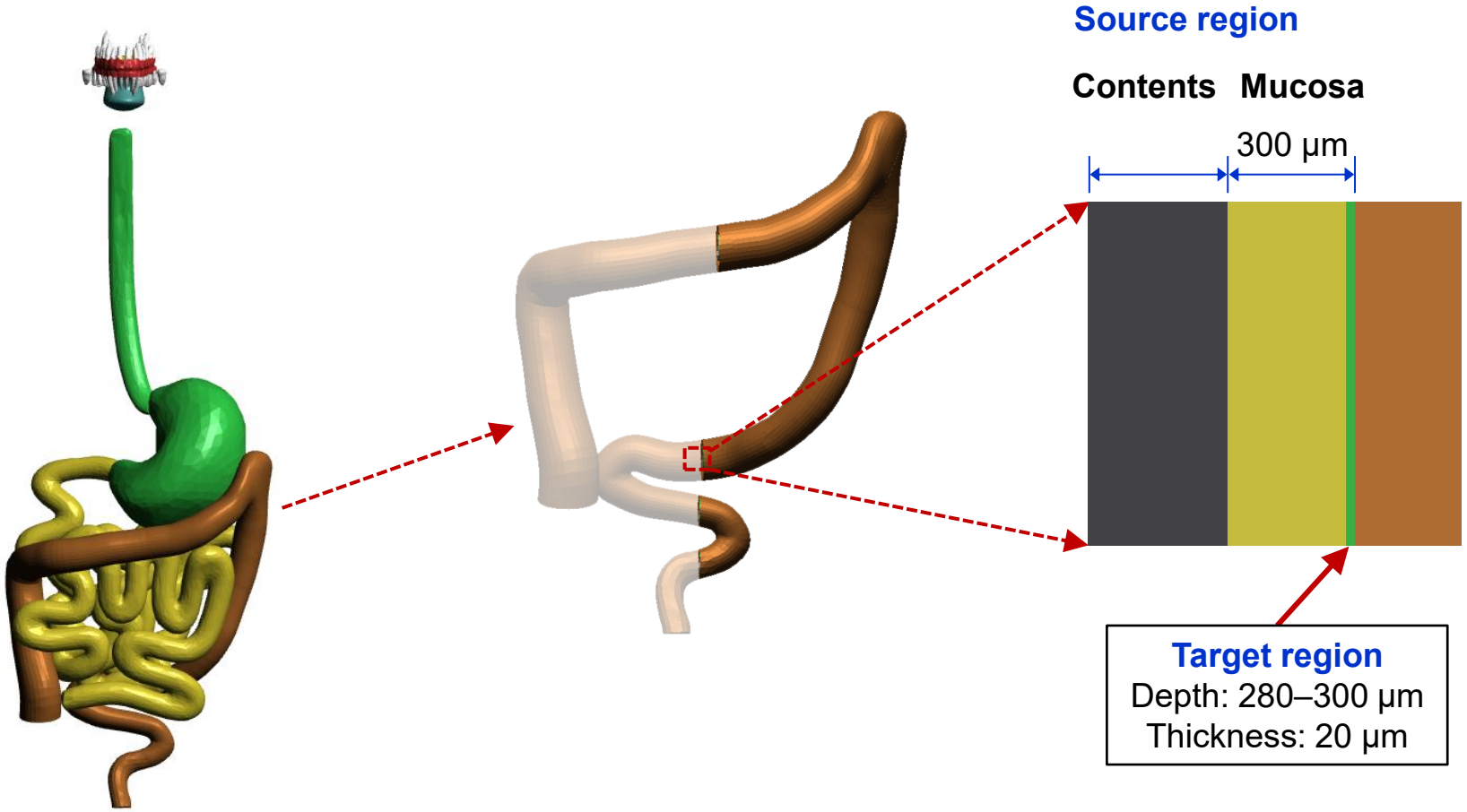
- **Source and target regions defined in small intestine of paediatric MRCPs**

Example: 15mMRCP

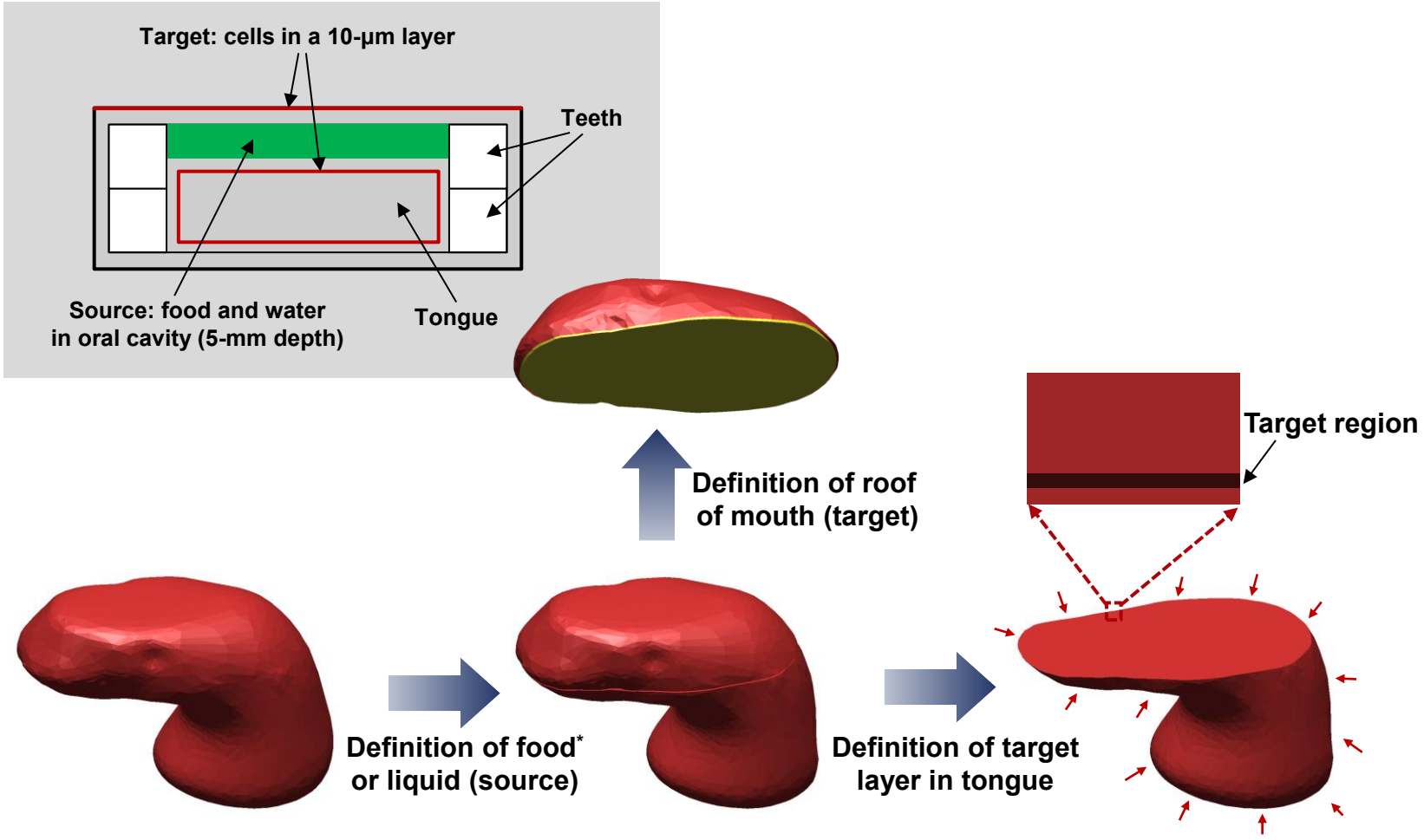


- **Source and target regions defined in colon of paediatric MRCPs**

Example: 15mMRCP

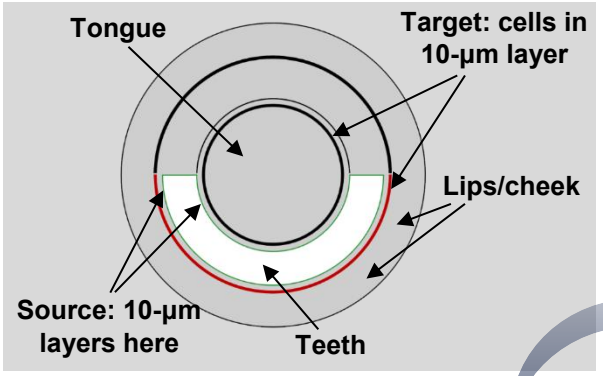


Construction of target and source regions in oral cavity (1)



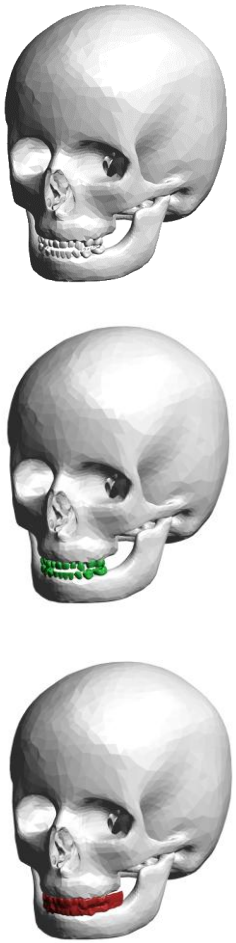
* *The food volume has been estimated only for the adults (= 20 cm^3); for the paediatric MRCPs, therefore, the food volume was estimated by scaling in proportion to the area of the tongue, assuming that the thickness of the food region (= 5 mm) is identical for all ages.*

Construction of target and source regions in oral cavity (2)

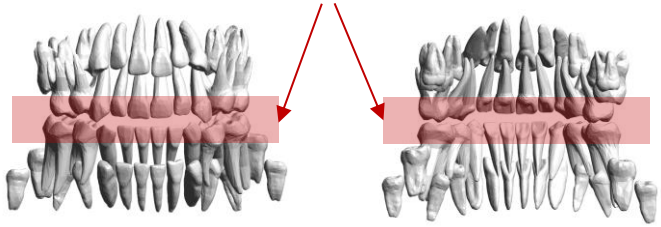


Definition of retention region on teeth (source)

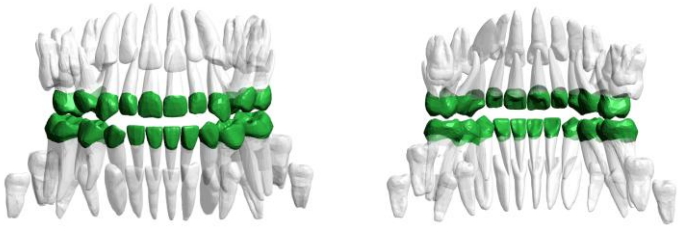
Definition of oral mucosa in lips/cheek (target)



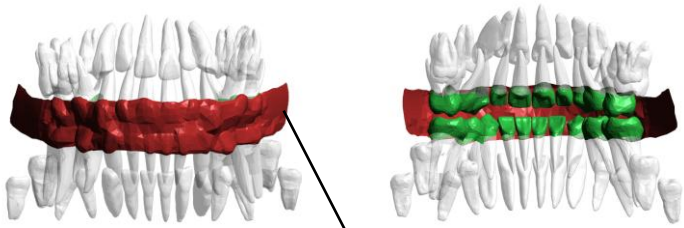
Erupted region (enamel region)



Front Back



Front Back

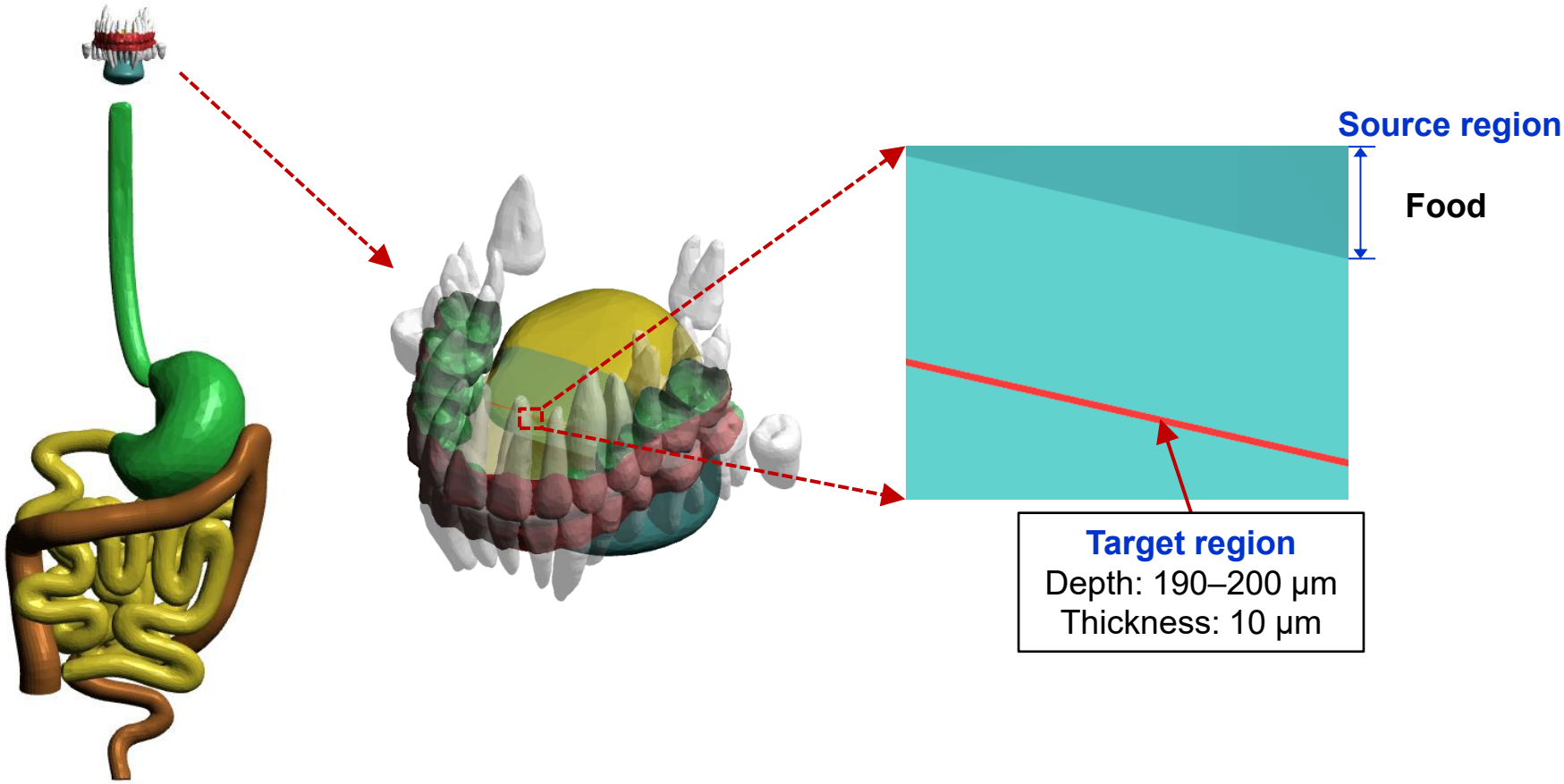


Front Back

This region was manually constructed along cranium and mandible for ages whose teeth on the side are not erupted.

- **Source and target regions defined in oral cavity of paediatric MRCPs**

Example: 15mMRCP



Respiratory Tract Organs

- **Source and target regions in respiratory tract organs**
  - The ICRP provides the information on the source and target regions of the respiratory tract organs through ICRP *Publication 66*.
  - ICRP *Publication 66* assumes that the depth of the target and source regions are the same for all ages.

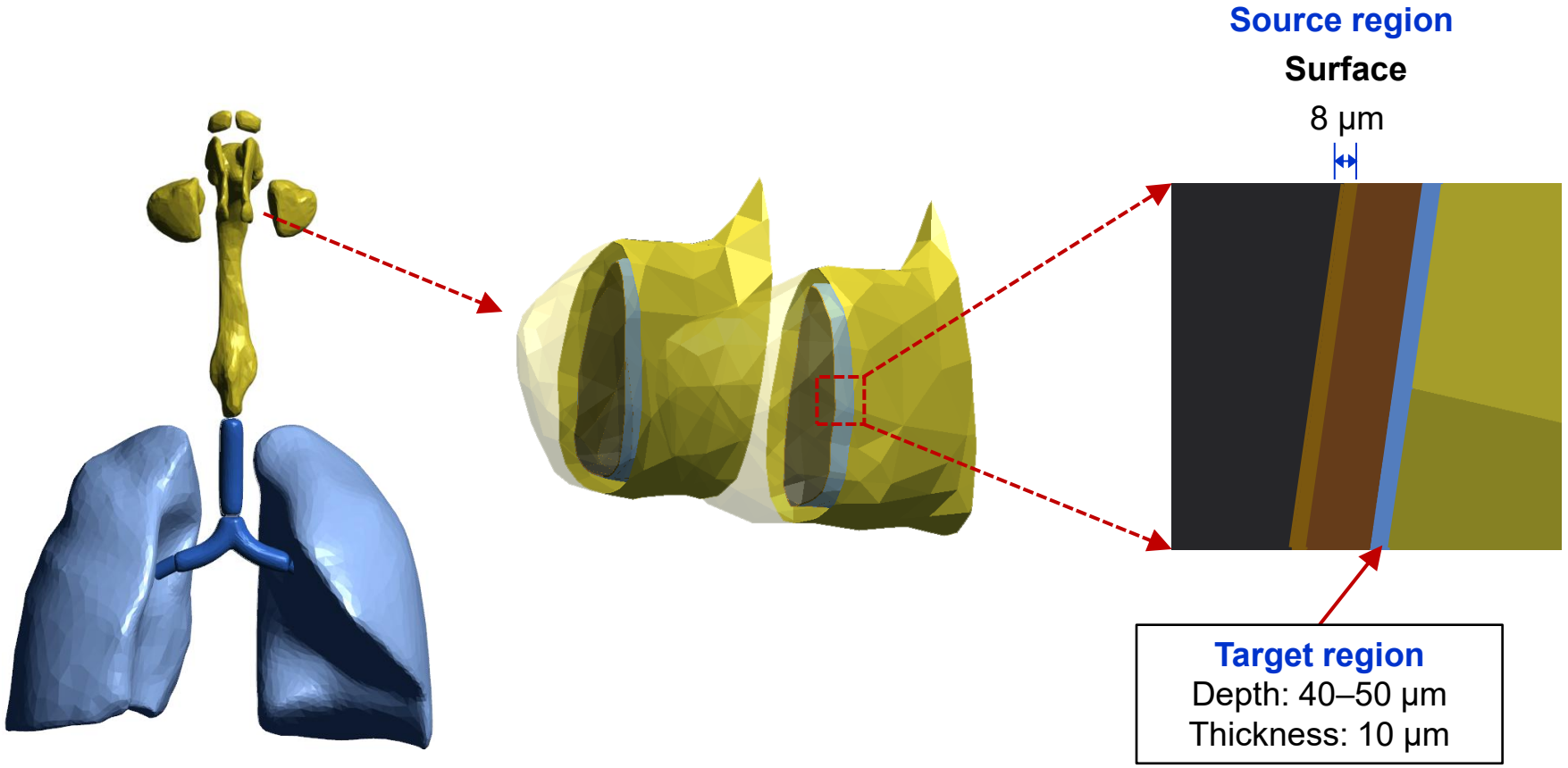
Respiratory tract organ	Source	Source location¶
ET_1	Surface	0–8 μm (outward)
ET_2	Surface	0–15 μm (inward)
	Bound	0–55 μm (outward)
	Sequestered	55–65 μm (outward)
BB	Fast mucus	6–11 μm (inward)
	Slow mucus	0–6 μm (inward)
	Bound	0–60 μm (outward)
	Sequestered	60–70 μm (outward)
	AI	*
bb	Fast mucus	4–6 μm (inward)
	Slow mucus	0–4 μm (inward)
	Bound	0–20 μm (outward)
	Sequestered	20–25 μm (outward)
	AI	*

Respiratory tract organ	Target region	Target location¶
ET_1	Basal cells	40–50 μm (outward)
ET_2	Basal cells	40–50 μm (outward)
BB	Basal cells	35–50 μm (outward)
	Secretory cells	10–40 μm (outward)
bb	Secretory cells	4–12 μm (outward)

¶ *Default depth is from the airway surface.*
* *AI as a source region is determined by radiation types and energies.*

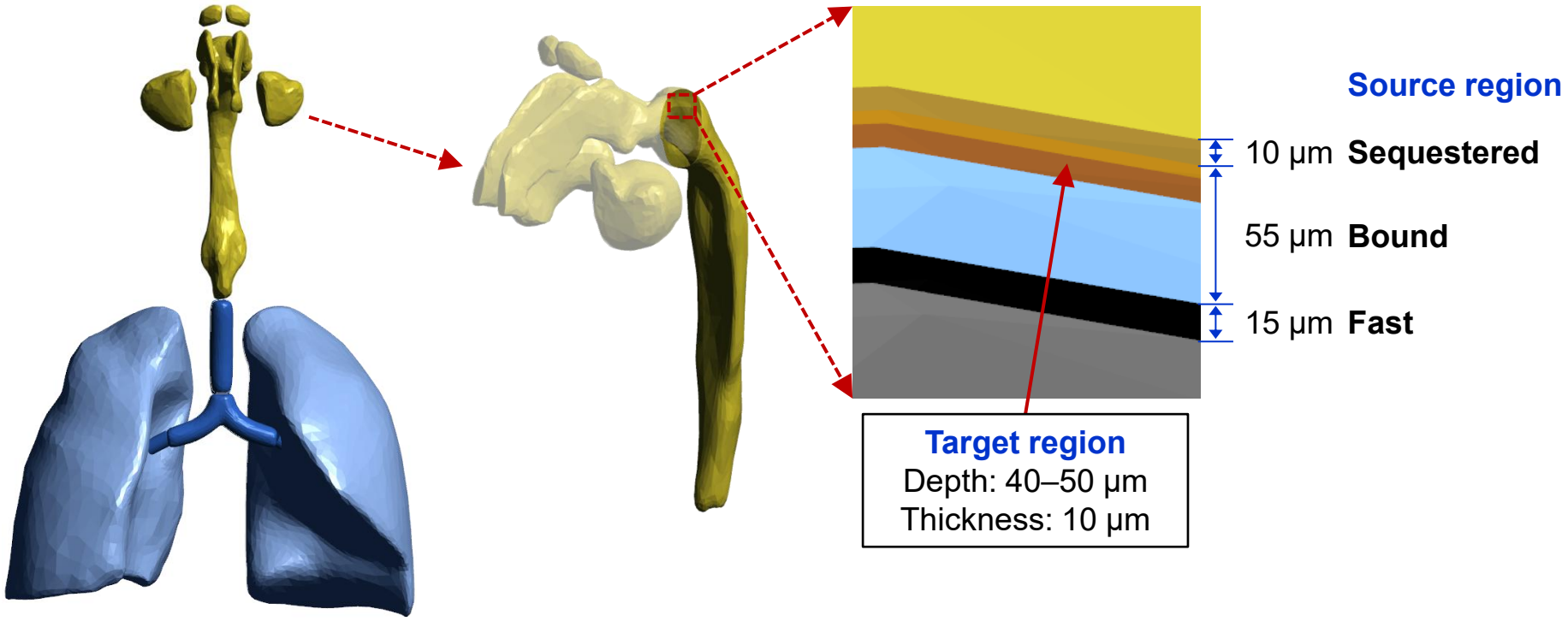
- **Source and target regions defined in ET_1 region of paediatric MRCPs**

Example: 5mMRCP

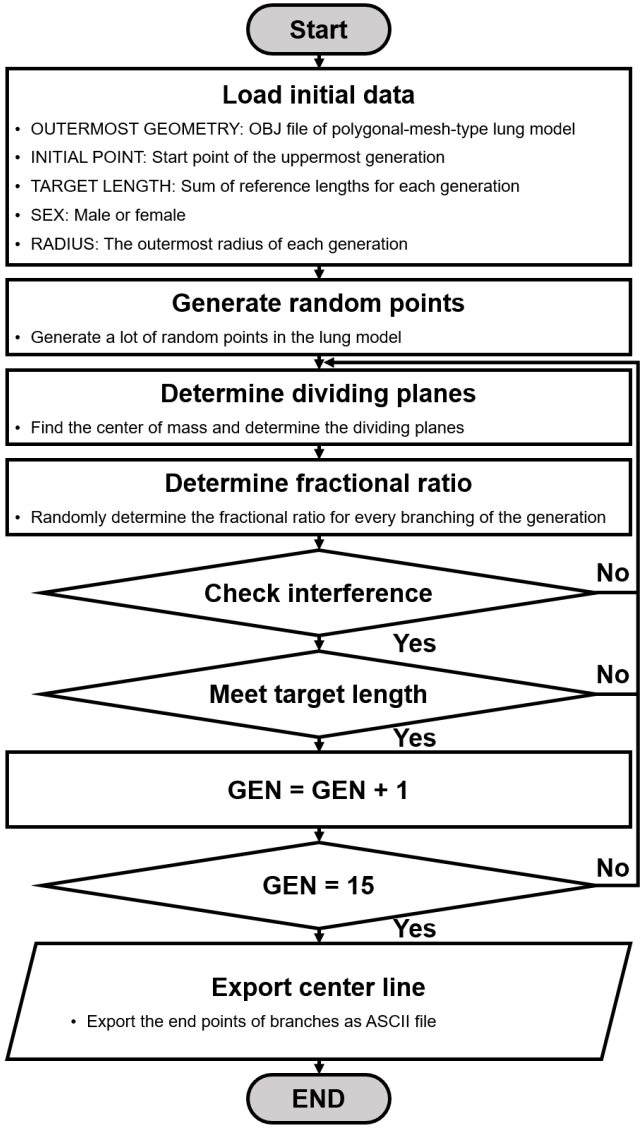


- **Source and target regions defined in ET_2 region of paediatric MRCPs**

Example: 5mMRCP



- **Construction of BB/bb regions in paediatric MRCPs**
  - BB/bb regions were modeled in constructive solid geometry (CSG) format based on airway dimensions (i.e., lengths and diameters) derived using the scaling method of ICRP *Publication 66*, using the computer program applied for adult MRCPs[57].
  - As an exception, newborn airway dimensions were derived by scaling the adult male values in proportion to the cube root of lung volume.

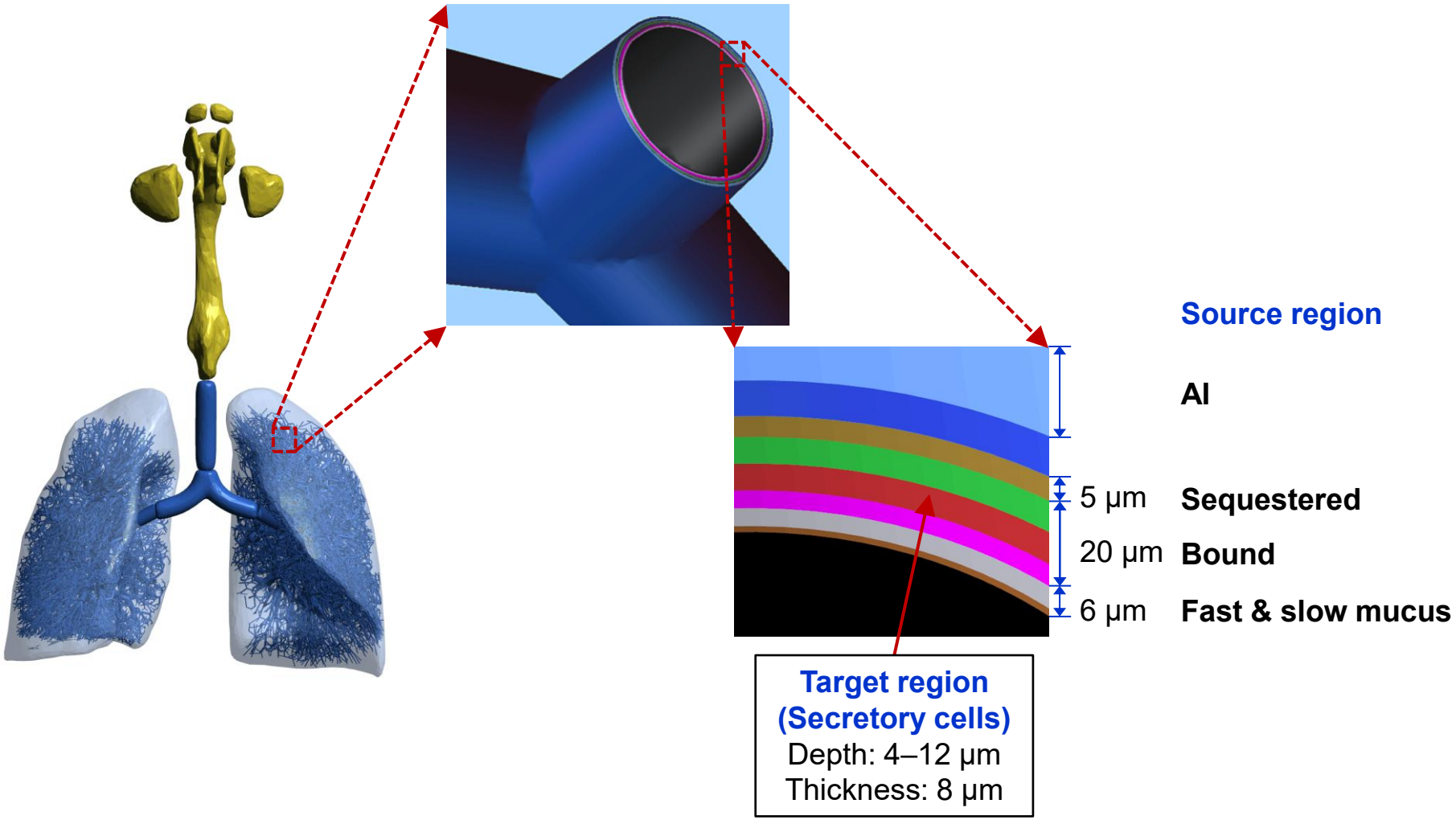


Program flowchart

[57] Kim, H.S., Yeom, Y.S., Nguyen, T.T., et al., 2017. Inclusion of thin target and source regions in alimentary and respiratory tract systems of mesh-type ICRP adult reference phantoms. Phys. Med. Biol. 62, 2132–2152.

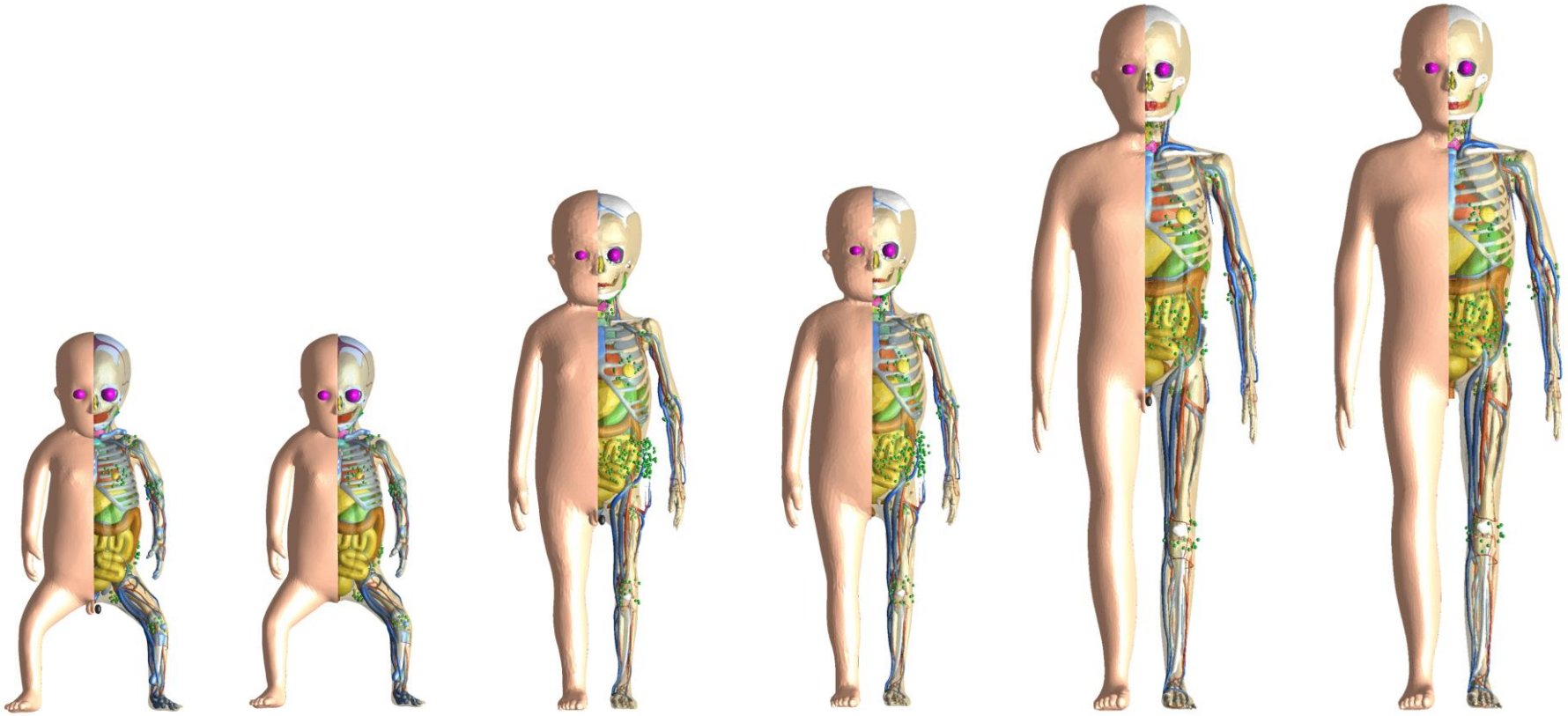
- **Source and target regions defined in BB/bb regions of paediatric MRCPs**

Example: bb region of 5mMRCP



Ⅳ. Paediatric MRCP

Paediatric MRCPs – Rotational View (1)

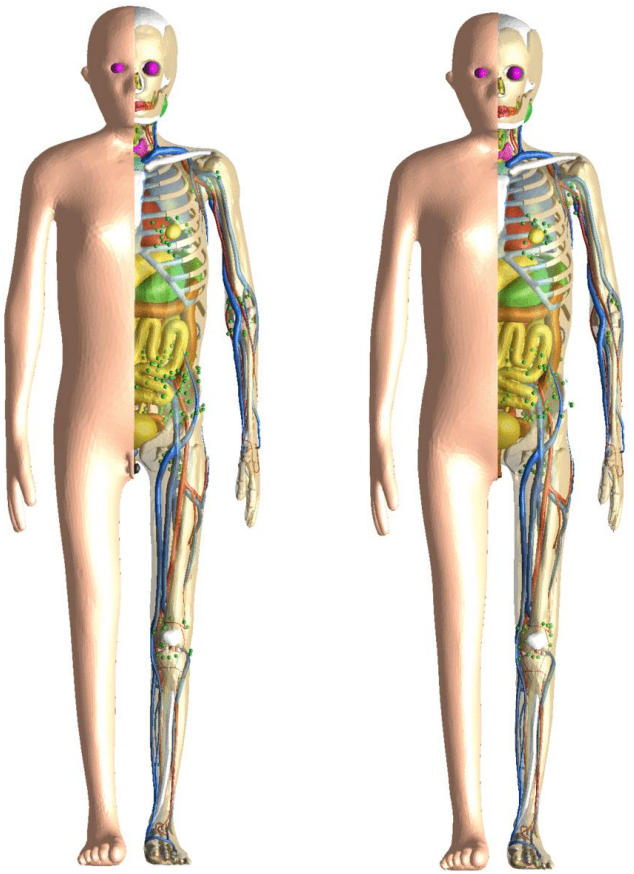


Newborn male/female

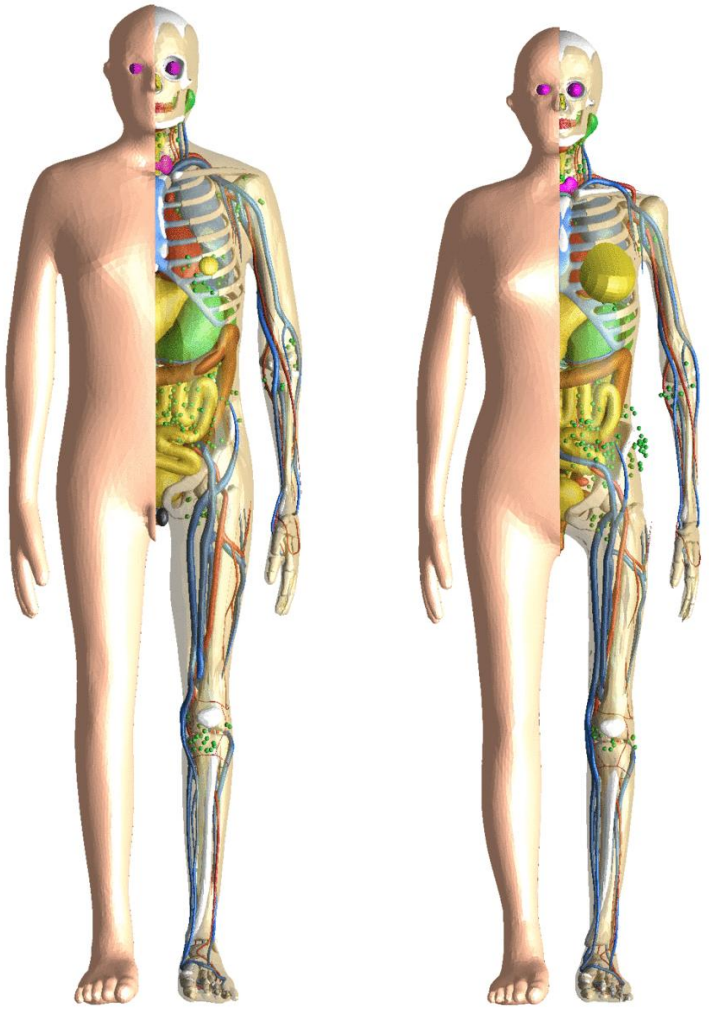
1-year male/female

5-year male/female

Paediatric MRCPs – Rotational View (2)



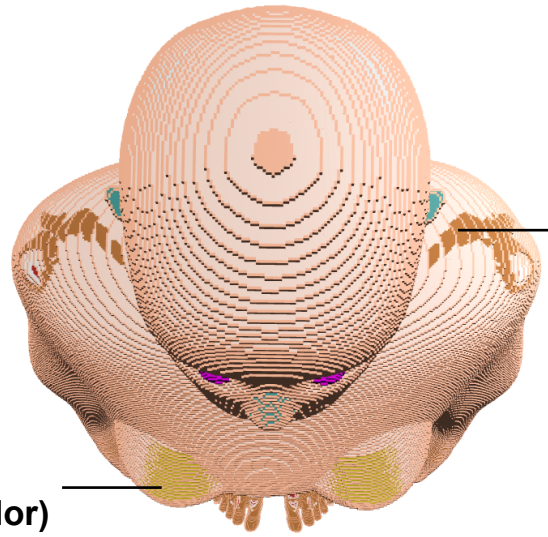
10-year male/female



15-year male/female

Improvement of Paediatric MRCPs (1)

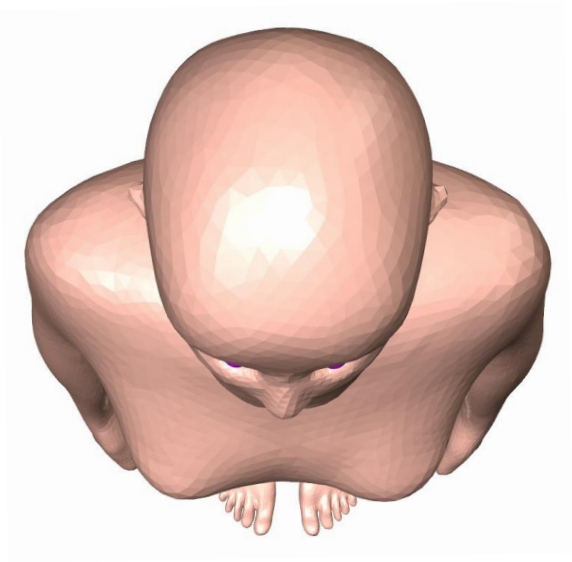
Example: 15-year female phantom



Muscle (brown color)

Breasts (yellow color)

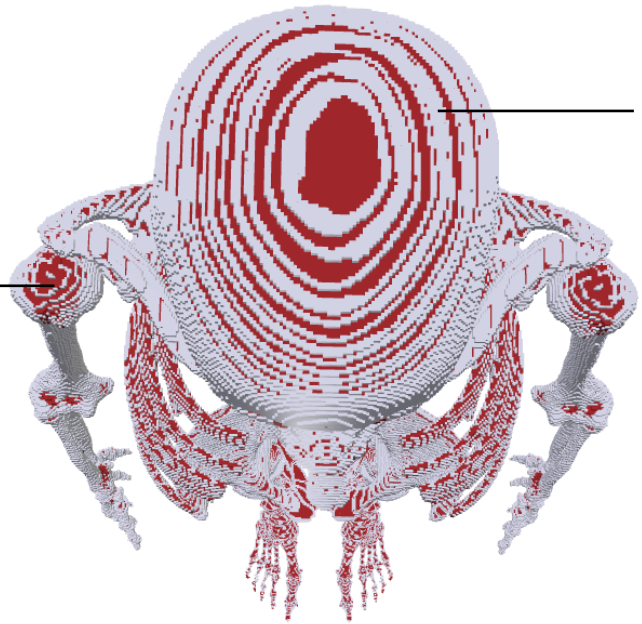
Paediatric VRCPs



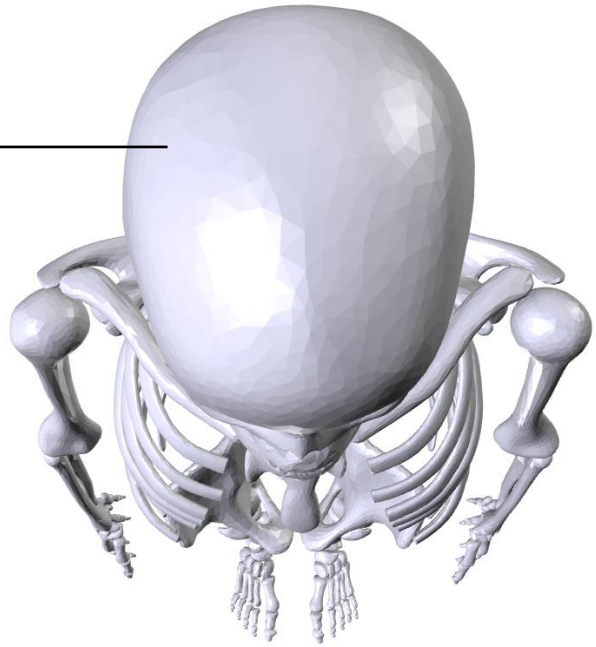
Paediatric MRCPs

Improvement of Paediatric MRCPs (2)

Example: 15-year female phantom



Paediatric VRCPs



Paediatric MRCPs

Numerical Data

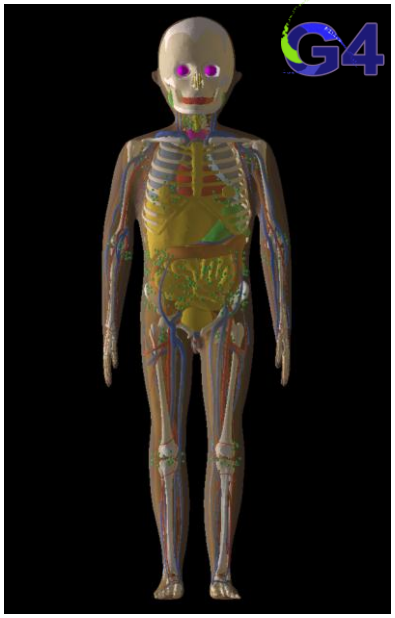
Phantom		Height / Weight	Number of organs	Deviation from ICRP reference data*	Number of tetrahedra	Avg. volume of tetrahedron	File size (ASCII)
Newborn	Male	– / 3.5 kg	48	< 0.1%	7,556,192	0.45 mm^3	423 MB
	Female	– / 3.5 kg	48	< 0.1%	7,650,313	0.44 mm^3	407 MB
1 year	Male	76 cm / 10 kg	48	< 0.1%	6,715,716	1.47 mm^3	373 MB
	Female	76 cm / 10 kg	48	< 0.1%	6,943,945	1.42 mm^3	387 MB
5 years	Male	109 cm / 19 kg	48	< 0.1%	8,178,096	2.27 mm^3	462 MB
	Female	109 cm / 19 kg	48	< 0.1%	8,440,293	2.19 mm^3	478 MB
10 years	Male	138 cm / 32 kg	48	< 0.1%	6,925,977	4.48 mm^3	385 MB
	Female	138 cm / 32 kg	48	< 0.1%	7,103,129	4.37 mm^3	396 MB
15 years	Male	167 cm / 56 kg	48	< 0.1%	7,366,440	7.43 mm^3	412 MB
	Female	161 cm / 53 kg	48	< 0.1%	7,519,627	6.96 mm^3	422 MB

* *Organ mass deviation from the reference organ masses inclusive of blood content*

Ⅴ. Computational Performance in Monte Carlo Codes

Simulation Conditions

- **Used phantom**
  - 5mMRCP and 5mVRCP



- **Used computer**
  - CPU: Intel® Xeon® CPU E5-2698 v4 @ 2.20 GHz × 2
  - RAM: 512 GB DDR4 memory
  - OS: CentOS 7.8

- **Monte Carlo code setting (default setting except for the following)**
  - Geant4 (10.06.p01)
    - The physics library of *G4EmLivermorePhysics* was used for photons and electrons, and the physics models and cross-sections of *NeutronHPThermalScattering*, *NeutronHPElastic*, *ParticleHPInelastic*, *NeutronHPCapture* and *NeutronHPFission* were used for neutrons.
    - The range cutoff of 1 μm was applied for the production of secondary particles.

- PHITS (3.10)
  - The *EGS5* physics library was used for the transportation of photons and electrons and the *JENDL-4.0* physics library and the event generator mode version 2 were used for the transportation of neutrons.
  - Considering the range cutoff value of 1 μm used for Geant4 calculations, the equivalent energy cut values were applied.
- MCNP6 (2.0)
  - The default physics libraries based on Lawrence Livermore National Laboratory evaluated data were used for the transportation of photons and electrons and *ENDF70* physics library were used for the transportation of neutrons.
  - Considering the range cutoff value of 1 μm used for Geant4 calculations, the equivalent energy cut values were applied.

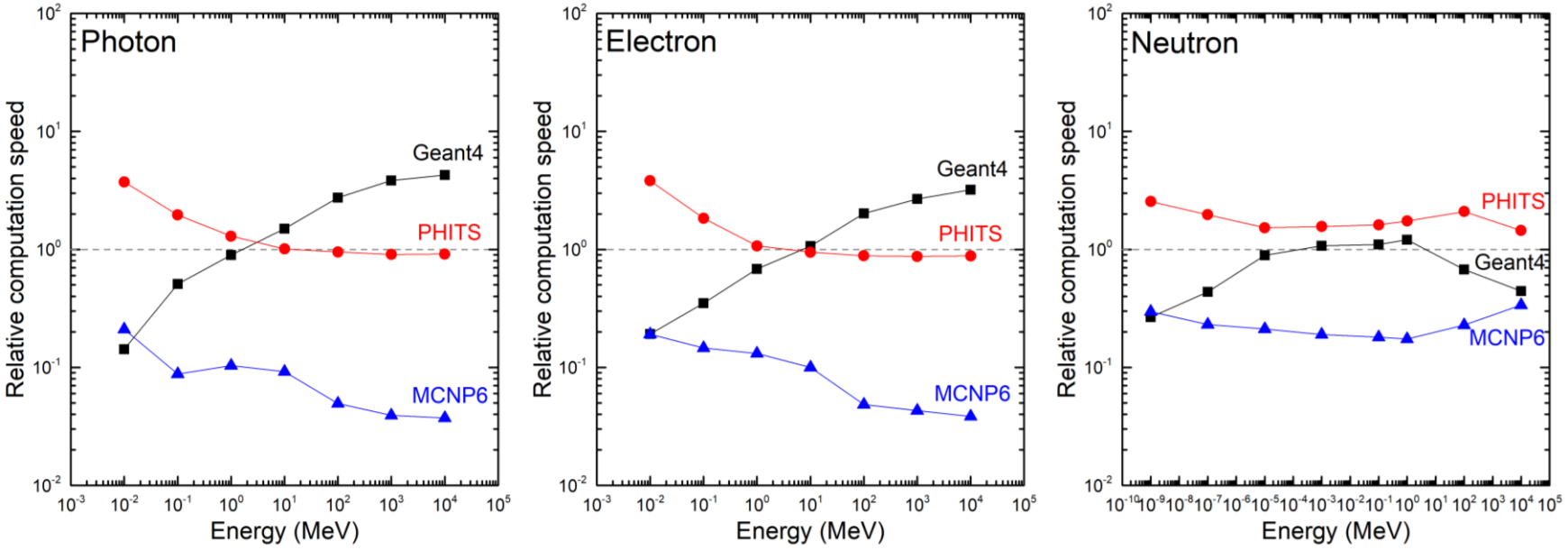
Computational Performance

- **Memory requirement**

Monte Carlo code	5mMRCP	5mVRCP
Geant4	8.5 GB	0.7 GB
PHITS	1.4 GB	2.2 GB
MCNP6	4.5 GB	1.9 GB

**Much lower than the maximum memory (128 GB) that can be equipped in a personal computer these days*

- **Computation speed (S_{5mMRCP}/S_{5mVRCP})**



Ⅵ. Dosimetric Impact

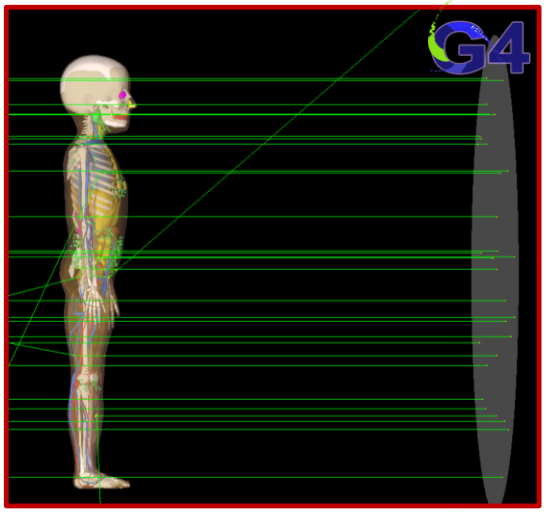
VI. Dosimetric Impact

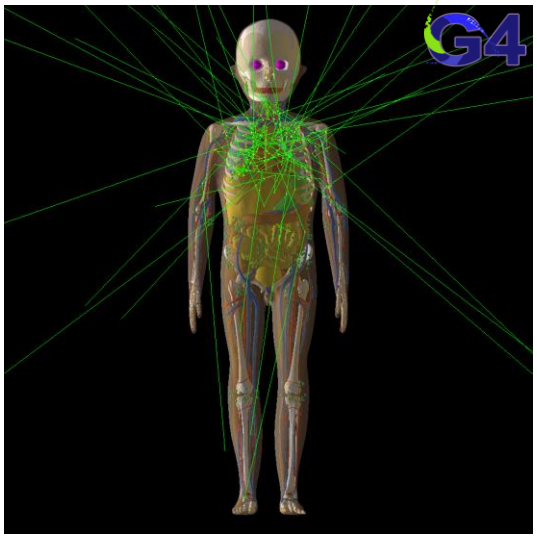
1. External exposures

- **Organ (RBM and skin) DCs**
  - Photons and electrons
  - Compared with paediatric VRCPs
- **Effective DCs**
  - Photons and electrons
  - Compared with paediatric VRCPs

2. Internal exposures

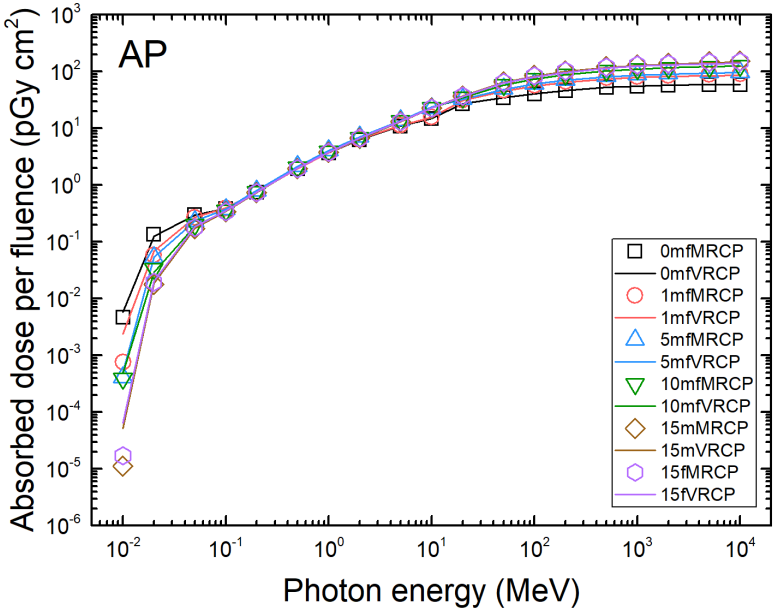
- **SAFs for general cases**
  - Photons and electrons
  - Compared with paediatric VRCPs
- **SAFs for alimentary tract system**
  - Electrons
  - Compared with ICRP-100 model
- **SAFs for respiratory tract system**
  - Electrons
  - Compared with ICRP-66 model

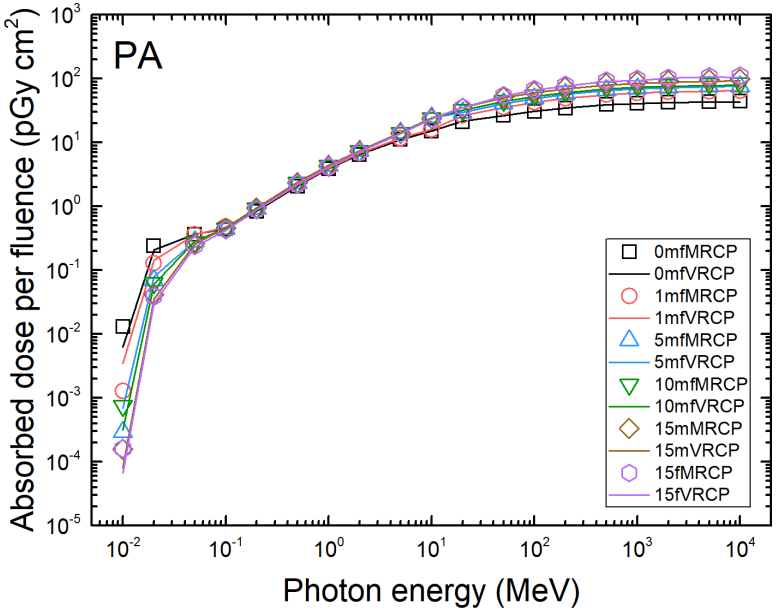


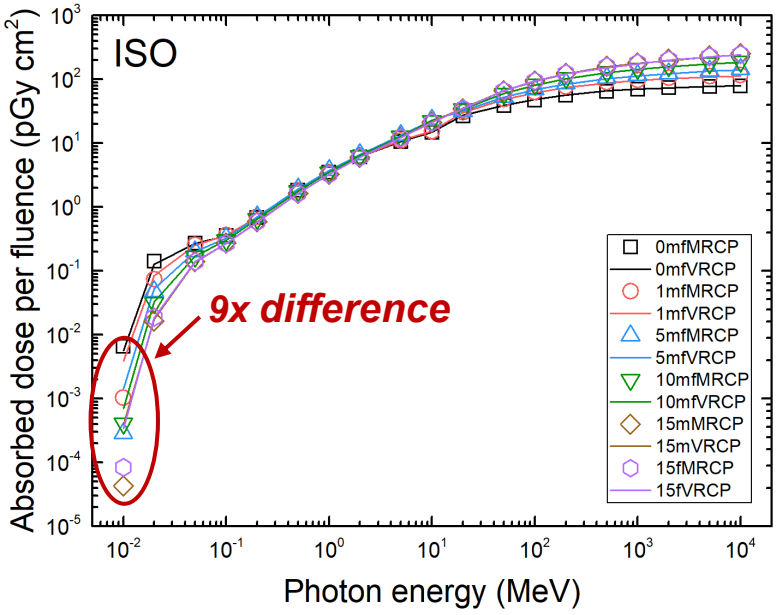


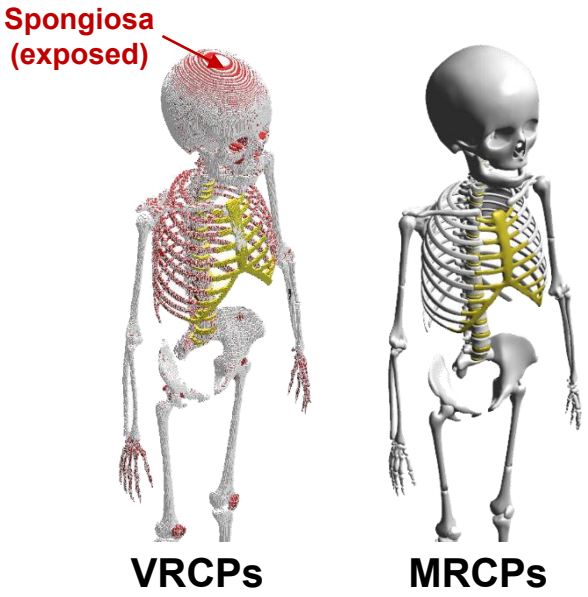
DC: dose coefficient, SAF: specific absorbed fraction
Geant4 version: 10.06.p01, Physics library: G4EmLivermorePhysics, secondary range cut: 1 μm.

RBM DCs – Photons

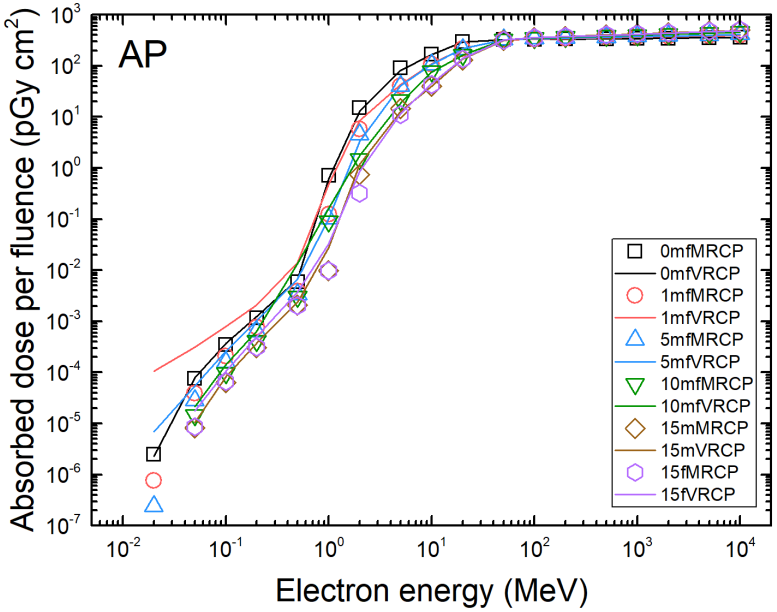


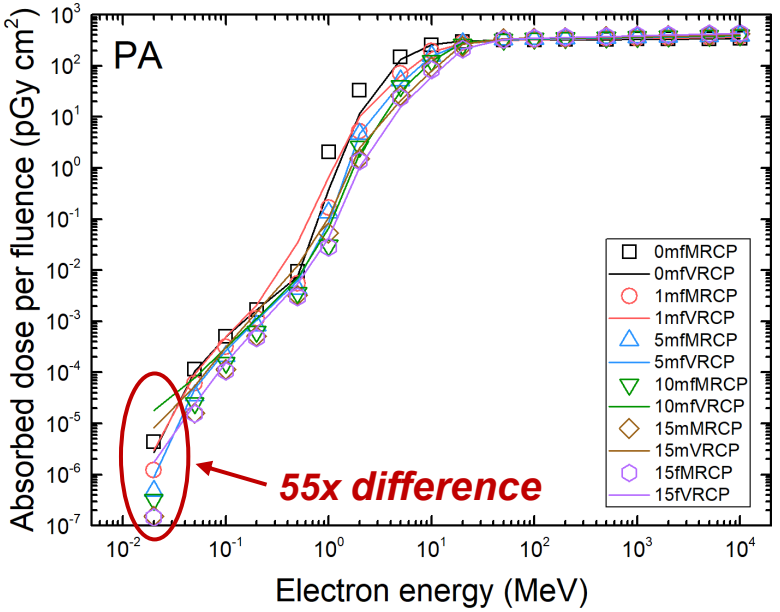


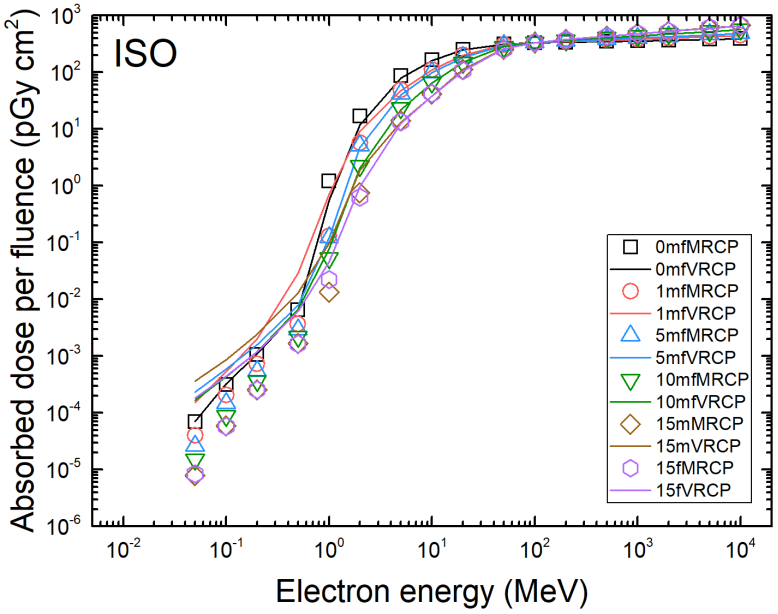


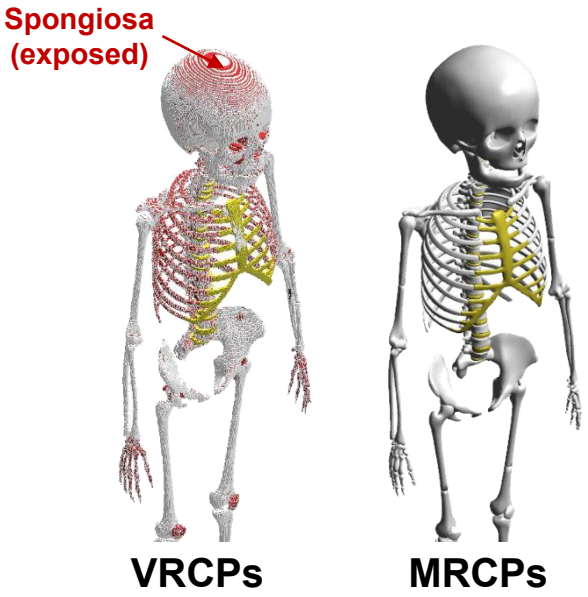


RBM DCs – Electrons

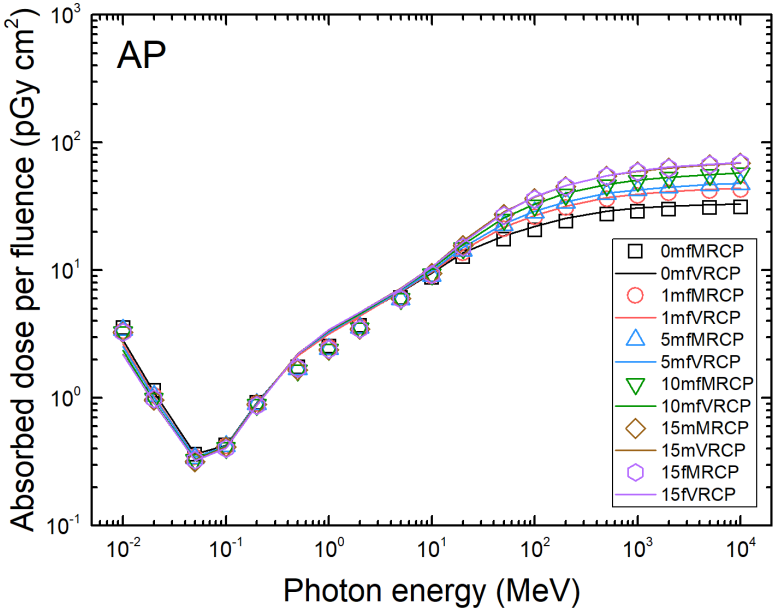


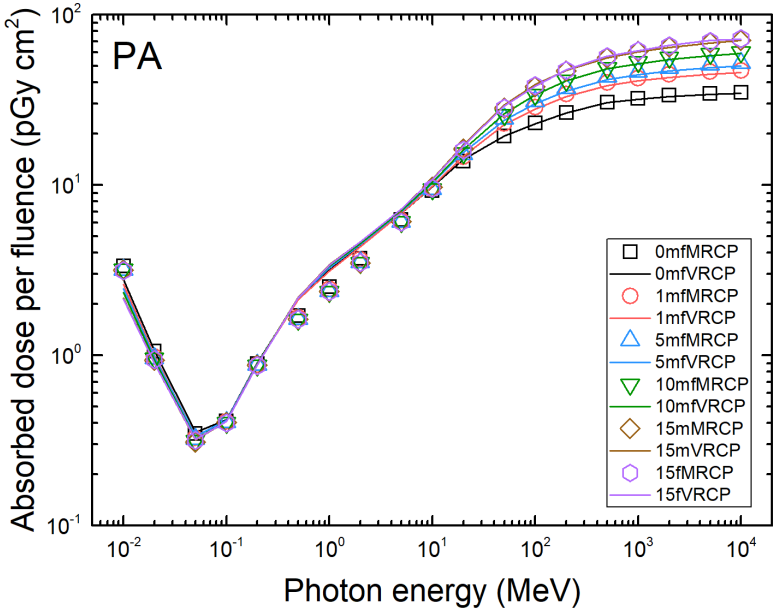


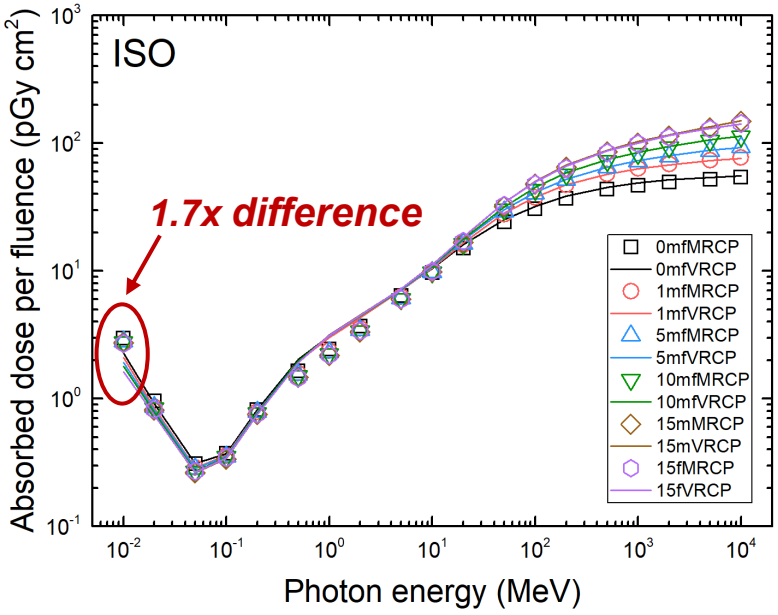


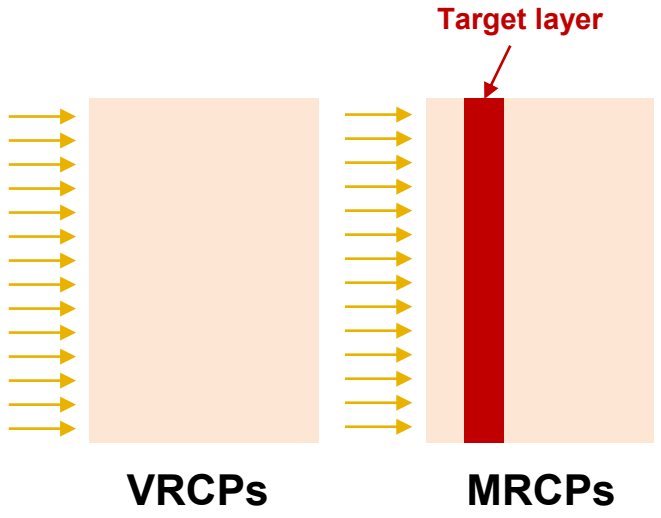


Skin DCs – Photons

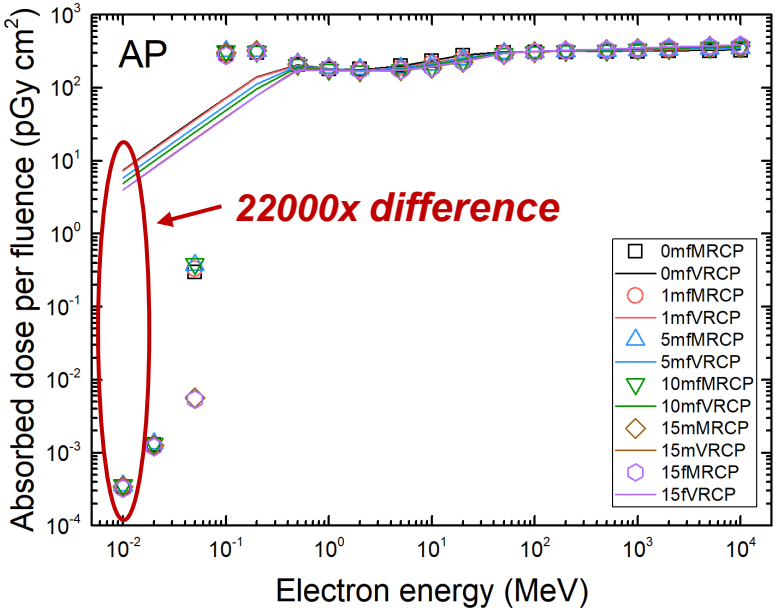


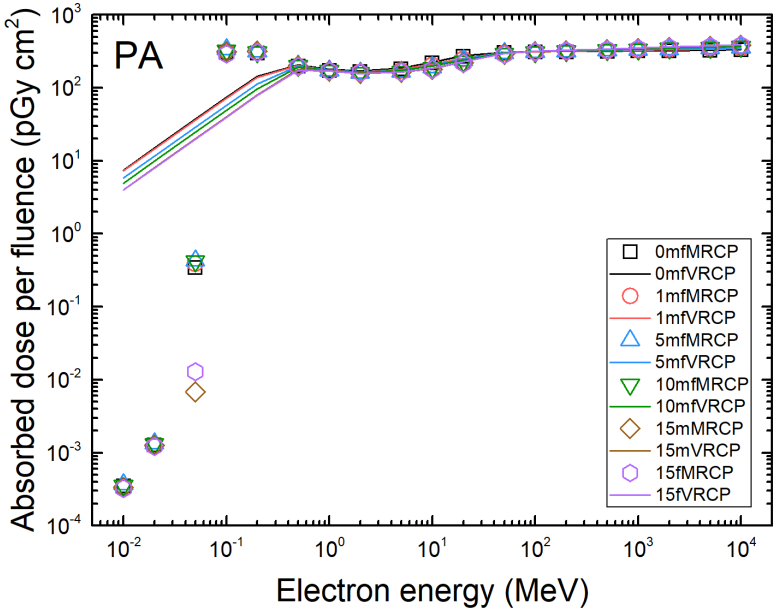


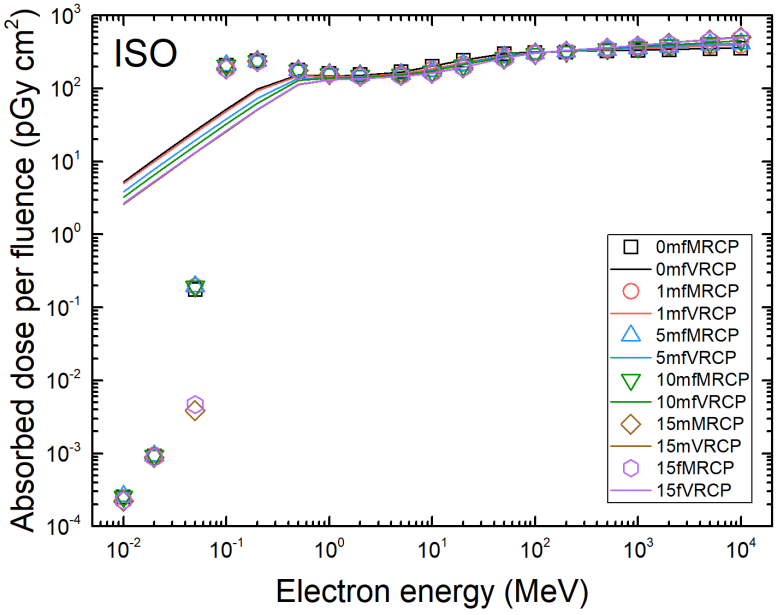


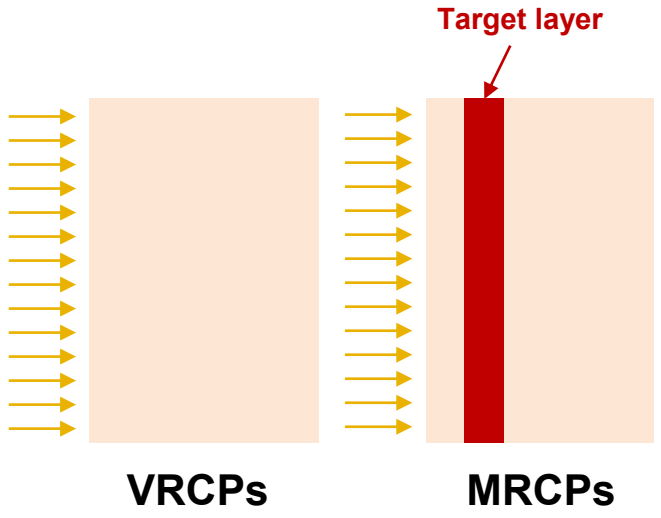


Skin DCs – Electrons

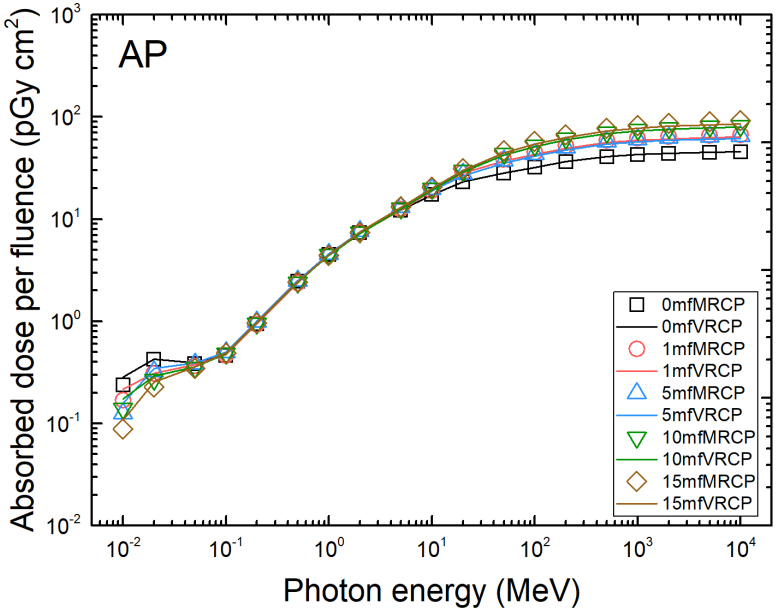


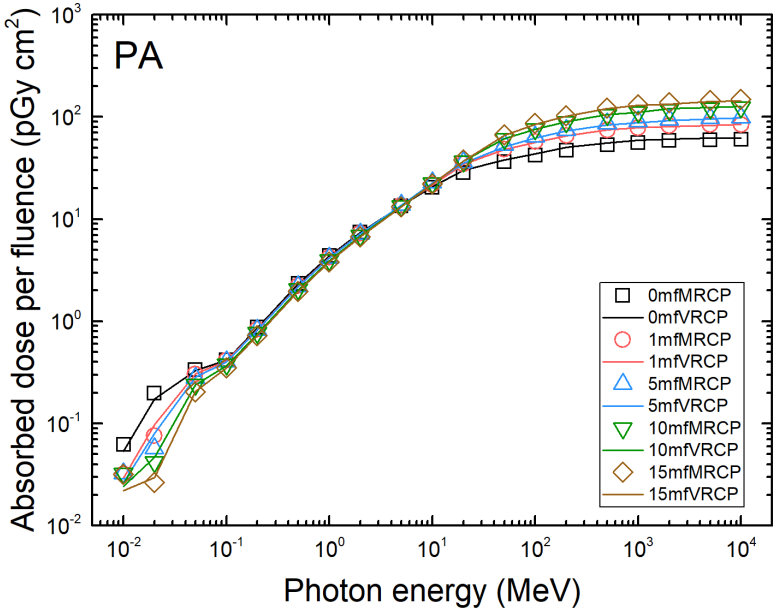


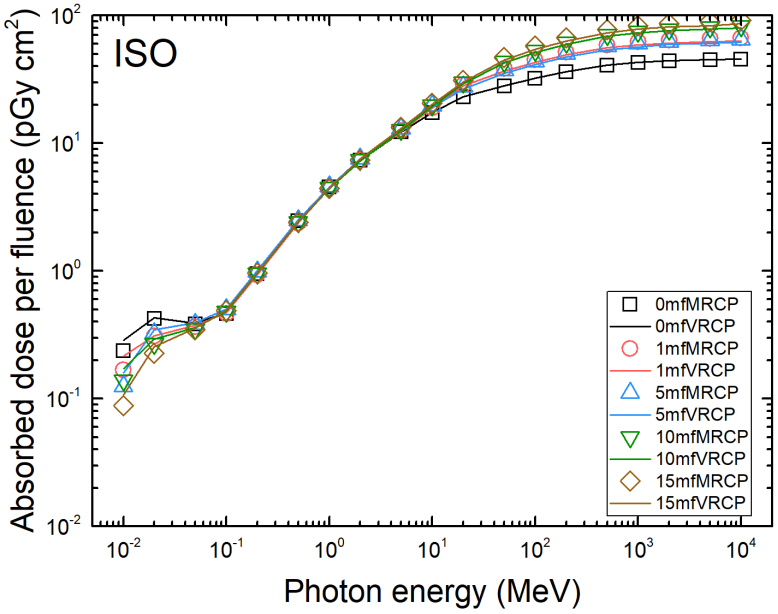




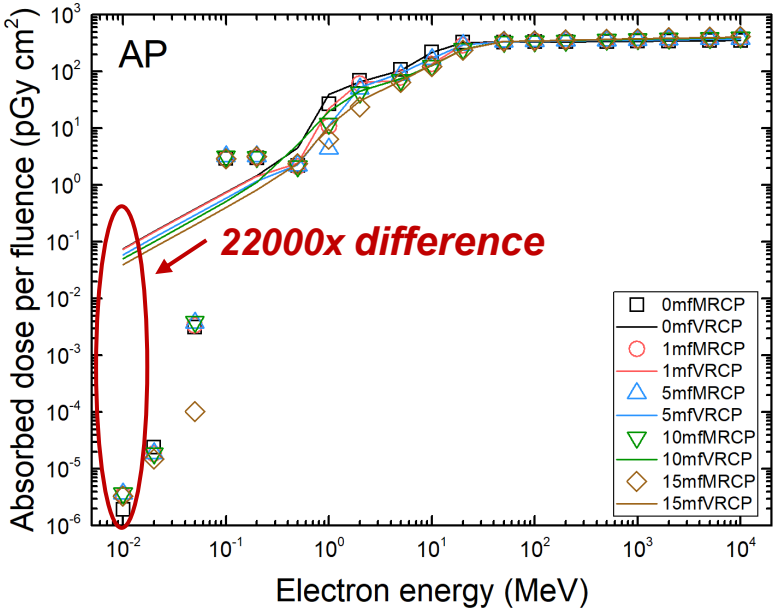
Effective DCs – Photons

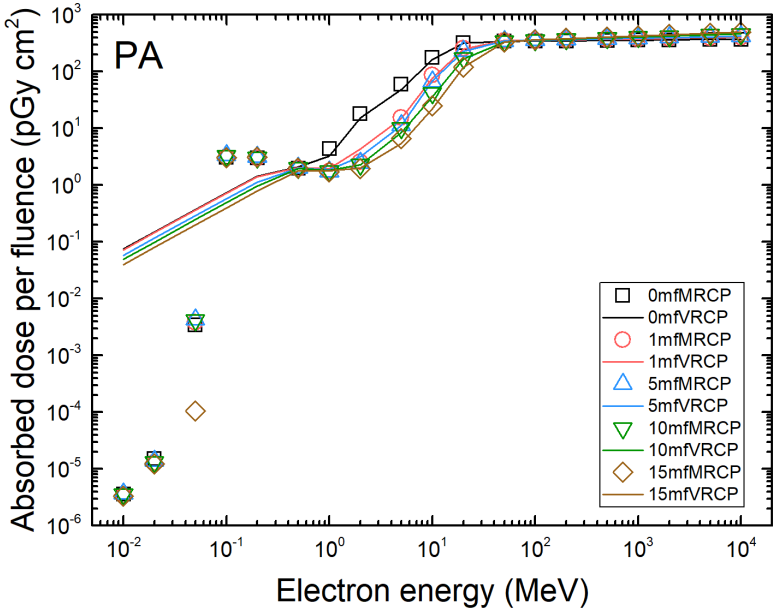


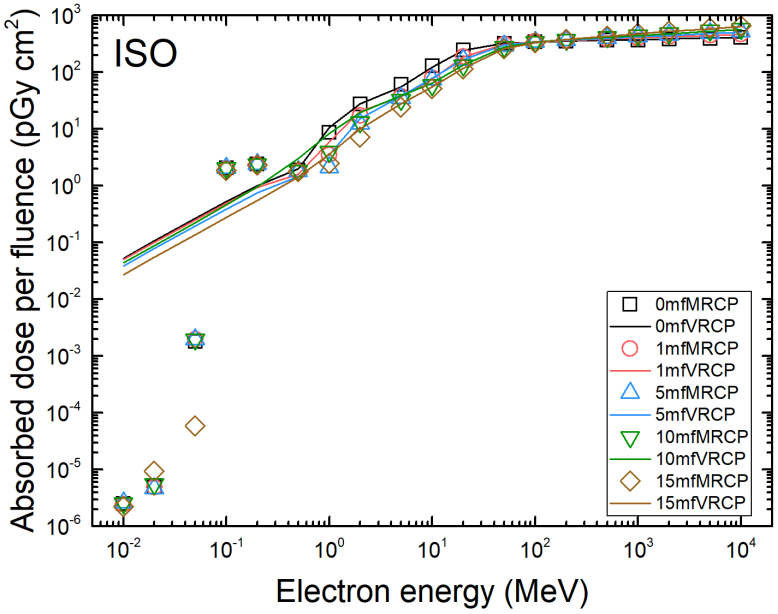


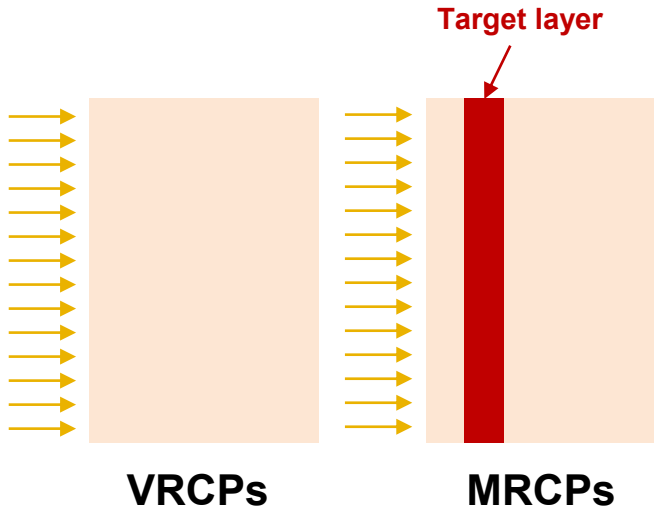


Effective DCs – Electrons









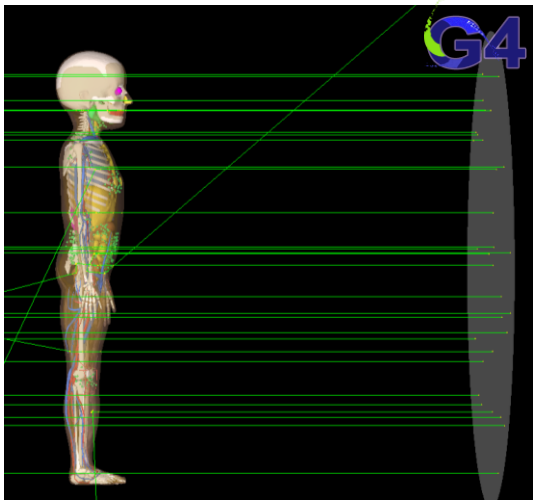
VI. Dosimetric Impact

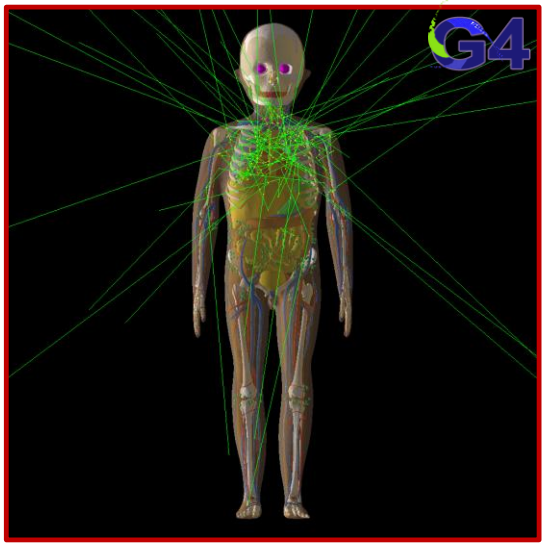
1. External exposures

- **Organ (RBM and skin) DCs**
  - Photons and electrons
  - Compared with paediatric VRCPs
- **Effective DCs**
  - Photons and electrons
  - Compared with paediatric VRCPs

2. Internal exposures

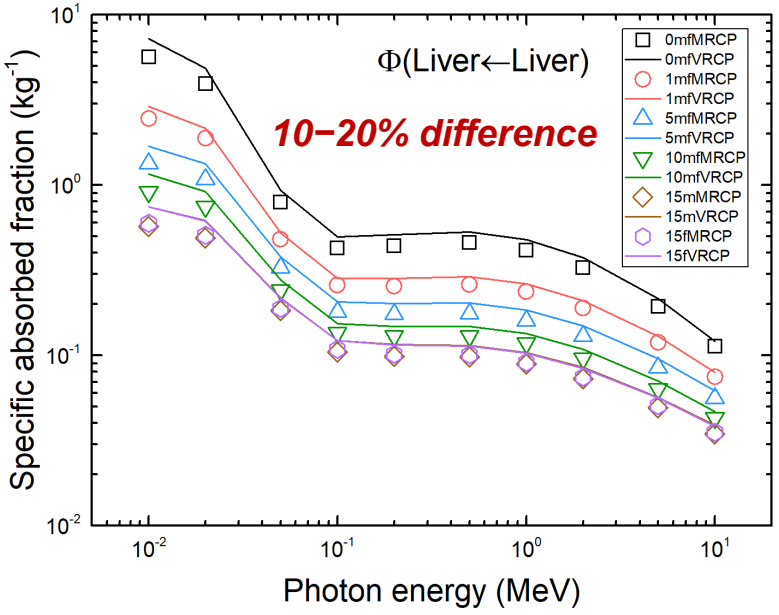
- **SAFs for general cases**
  - Photons and electrons
  - Compared with paediatric VRCPs
- **SAFs for alimentary tract system**
  - Electrons
  - Compared with ICRP-100 model
- **SAFs for respiratory tract system**
  - Electrons
  - Compared with ICRP-66 model

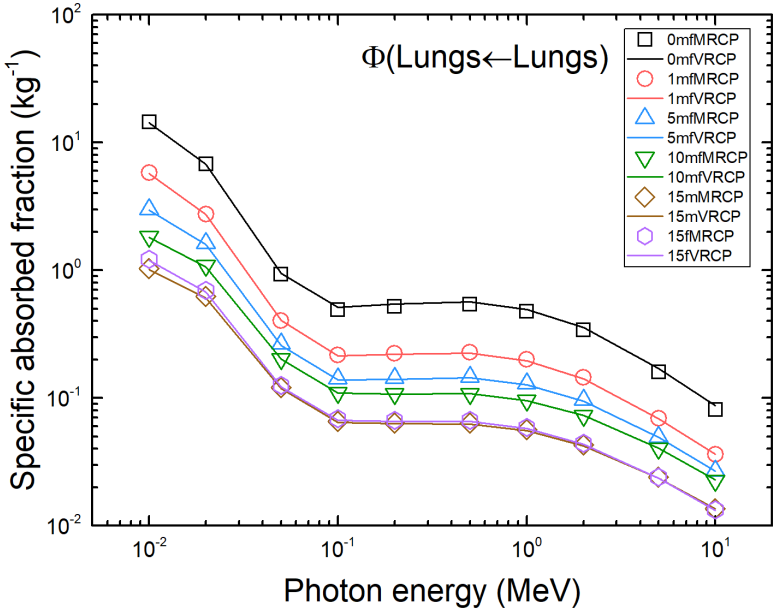


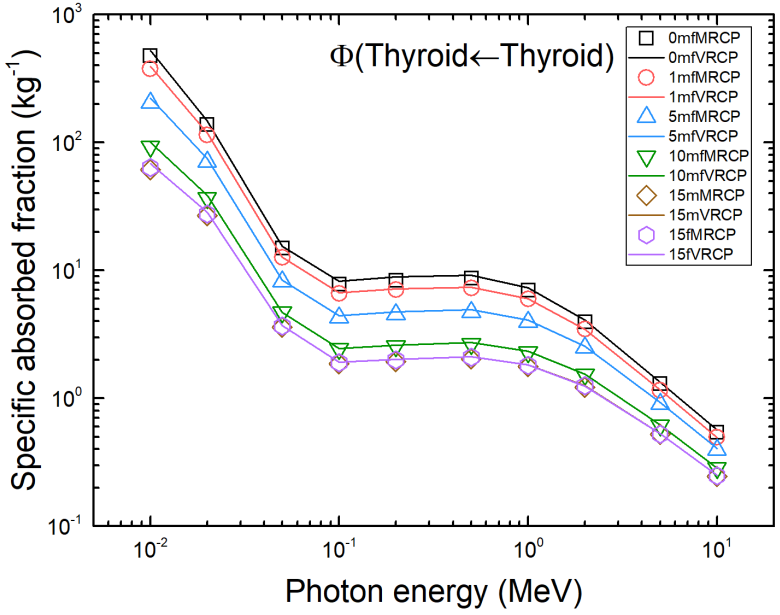


DC: dose coefficient, SAF: specific absorbed fraction
Geant4 version: 10.06.p01, Physics library: G4EmLivermorePhysics, secondary range cut: 1 μm.

SAFs for Self-irradiation Cases – Photons

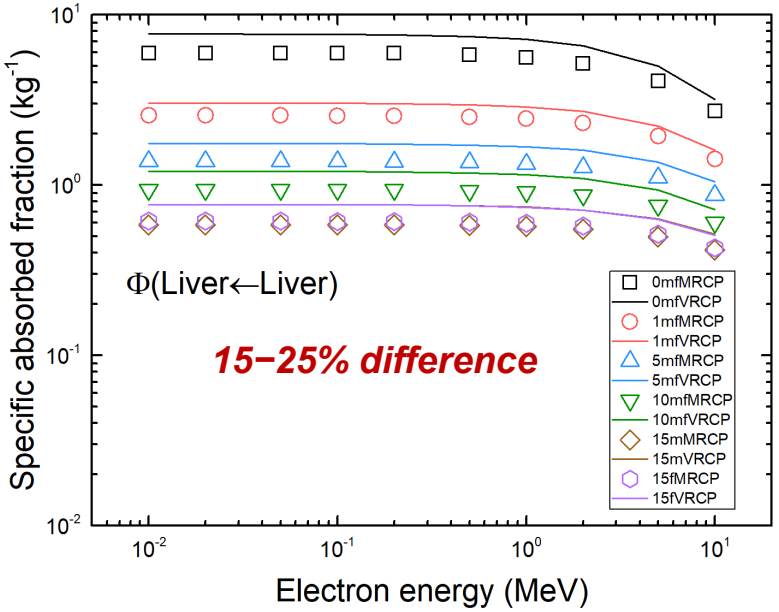


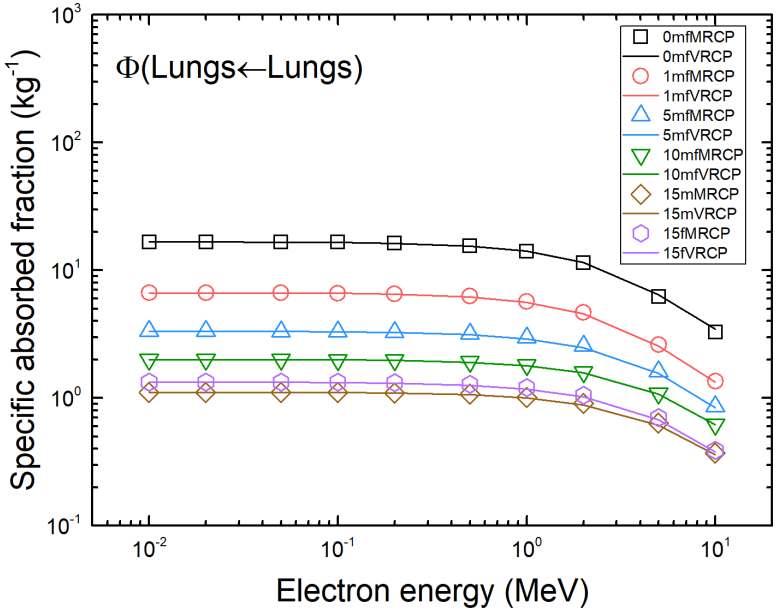


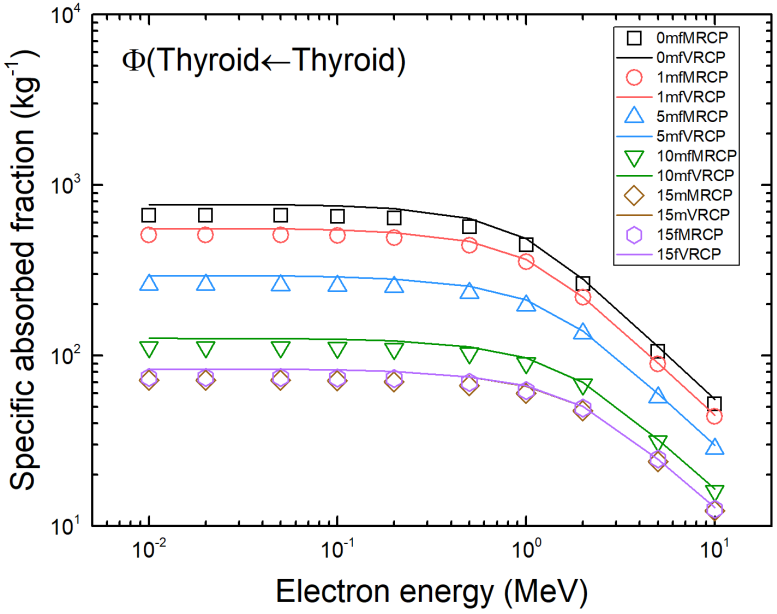


	Liver of VRCPs (g)	Liver of MRCPs (g)	Difference
Newborn M/F	130.000	167.475	**25%**
1-year M/F	330.000	390.205	**17%**
5-year M/F	570.000	724.019	**24%**
10-year M/F	830.000	1059.688	**24%**
15-year M	1300.000	1709.440	**27%**
15-year F	1300.000	1628.278	**22%**

SAFs for Self-irradiation Cases – Electrons







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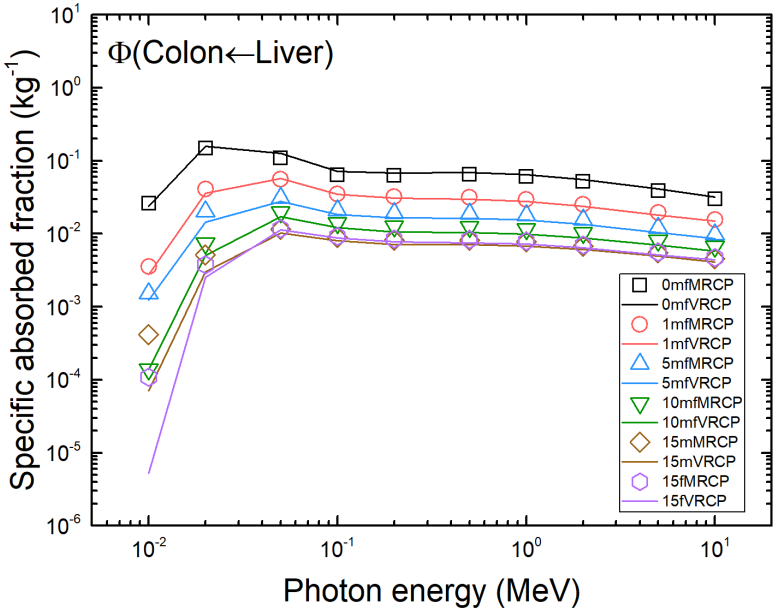
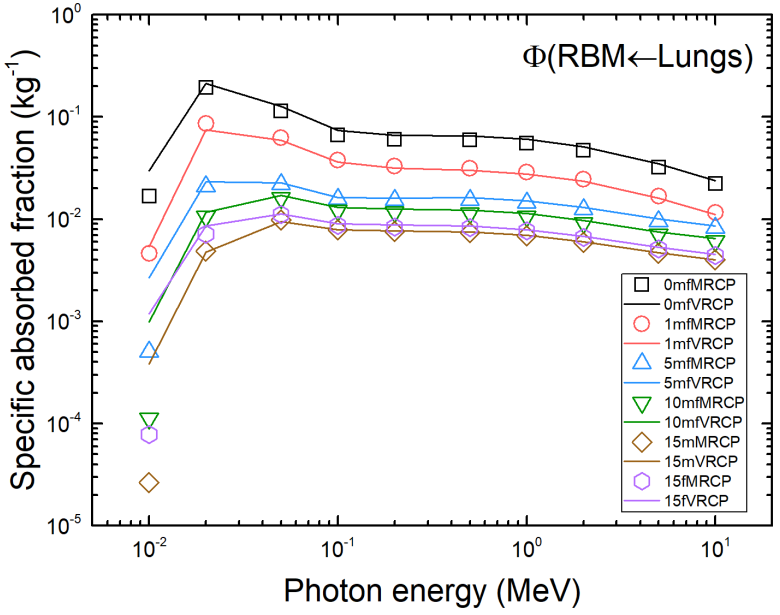
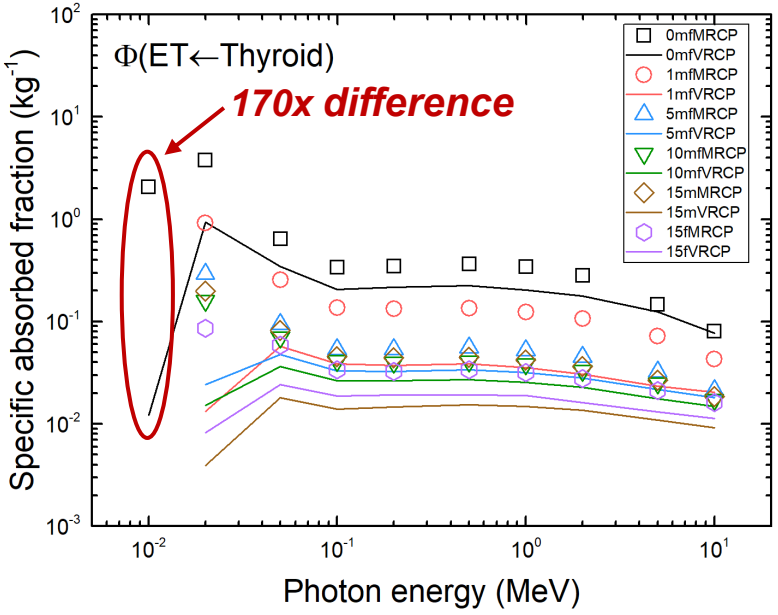
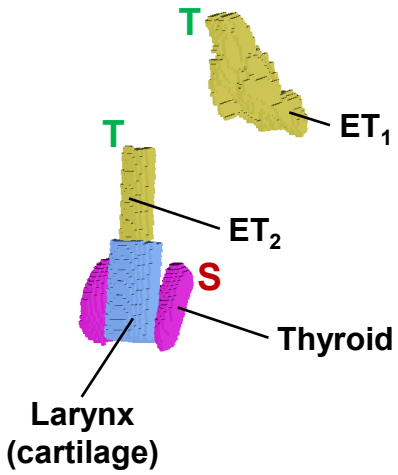
15-year M	1300.000	1709.440	**27%**
15-year F	1300.000	1628.278	**22%**

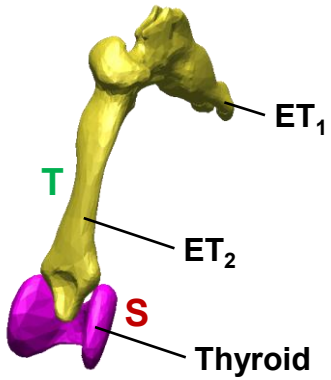
SAFs for Cross-fire Cases – Photons





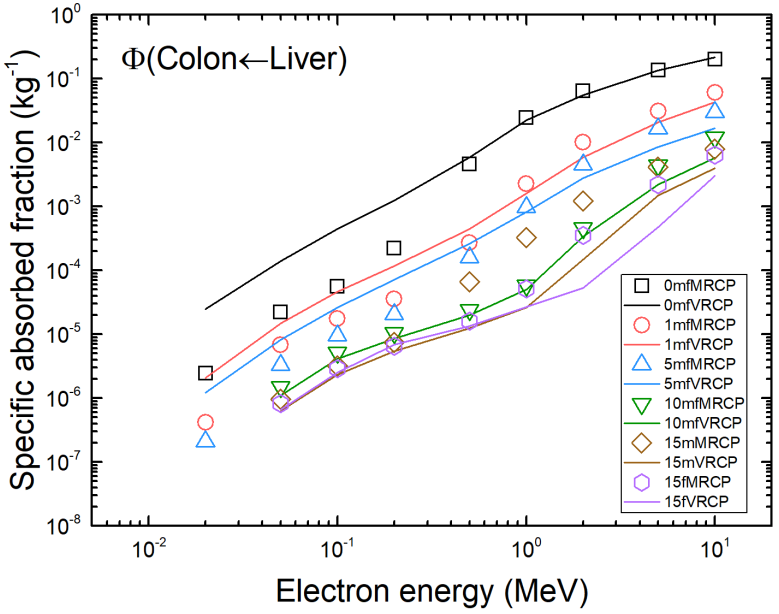


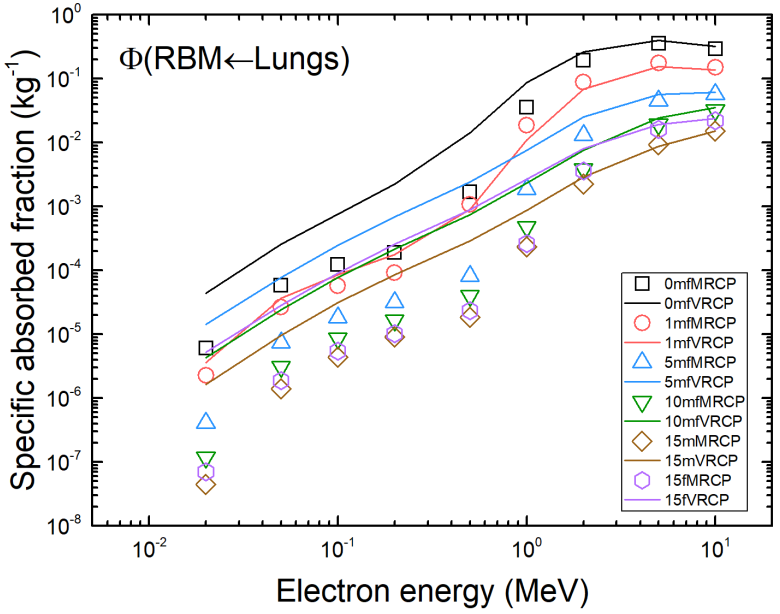


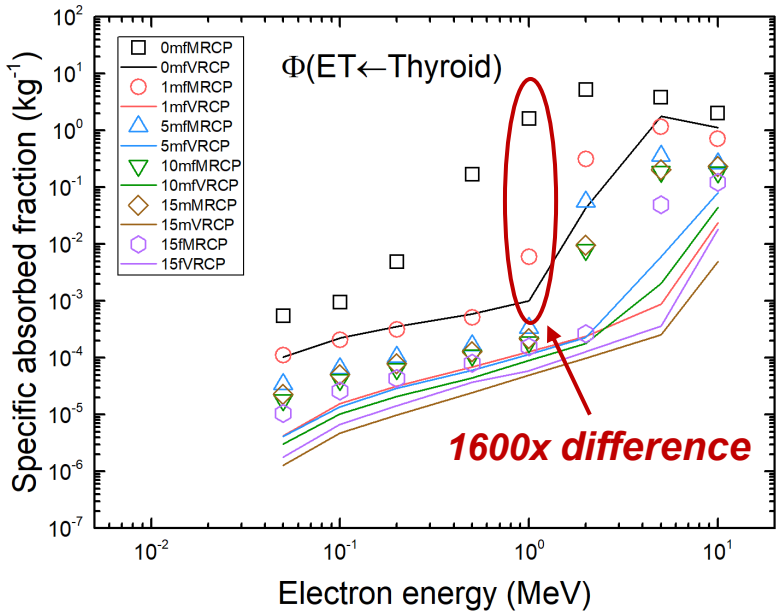


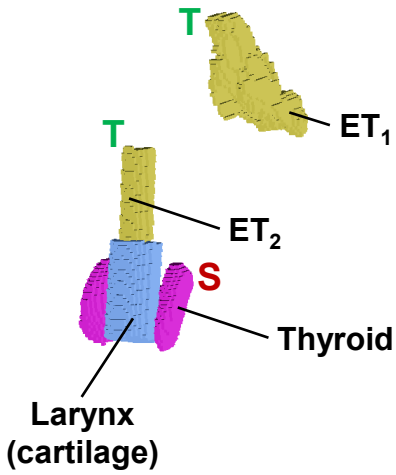
VRCPs **MRCPs**

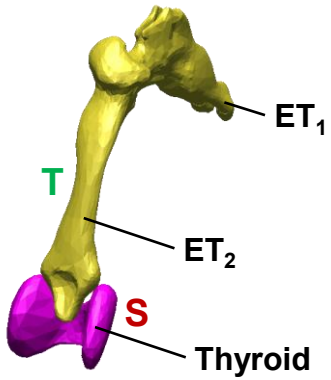
SAFs for Cross-fire Cases – Electrons





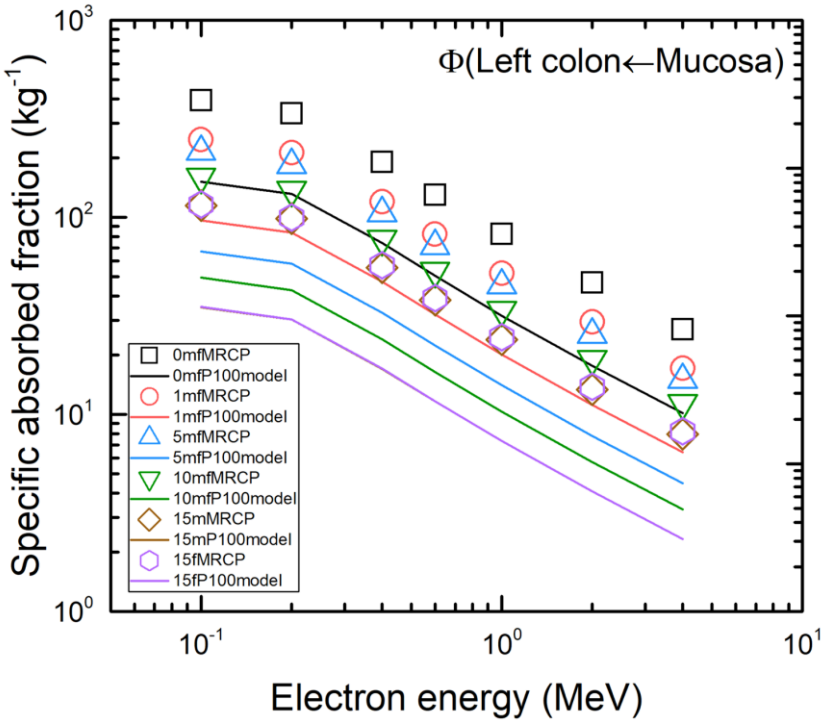


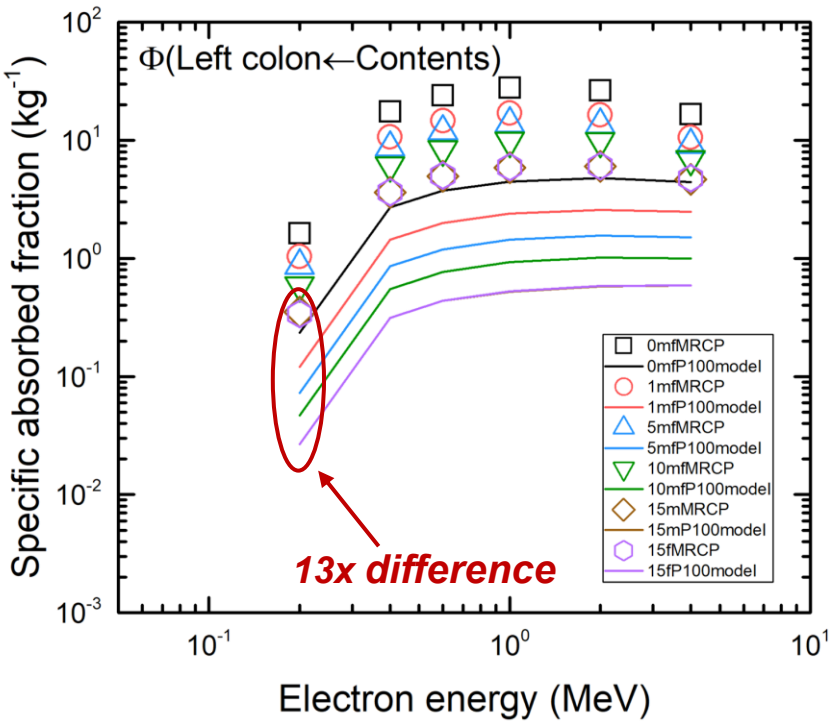


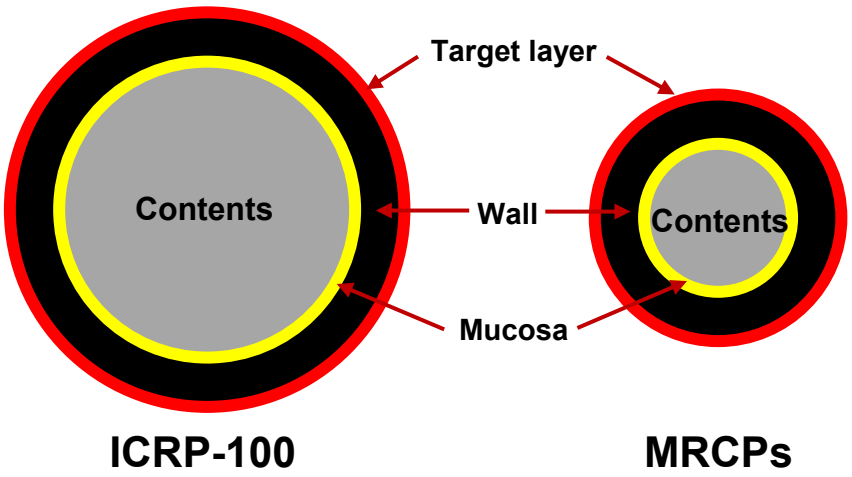


VRCPs **MRCPs**

SAFs for Alimentary Tract System – Electrons



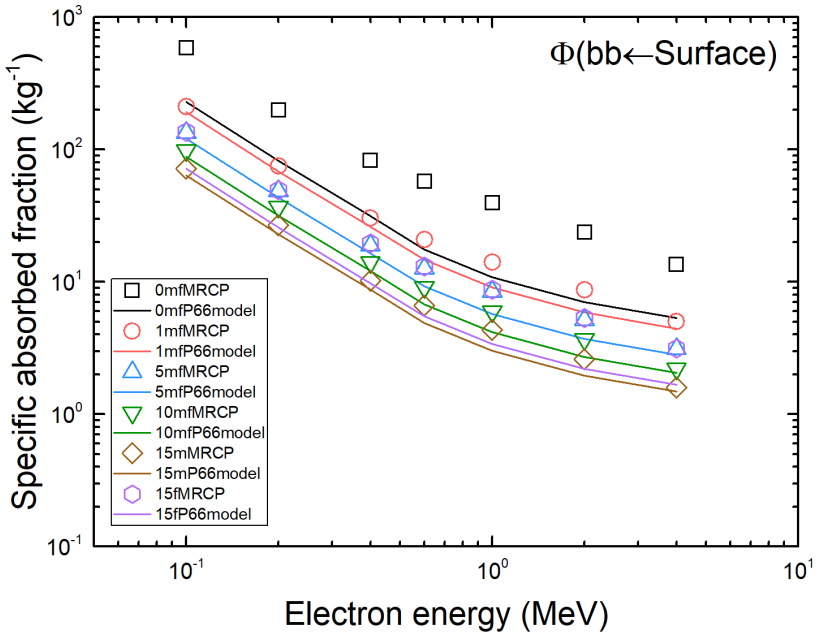


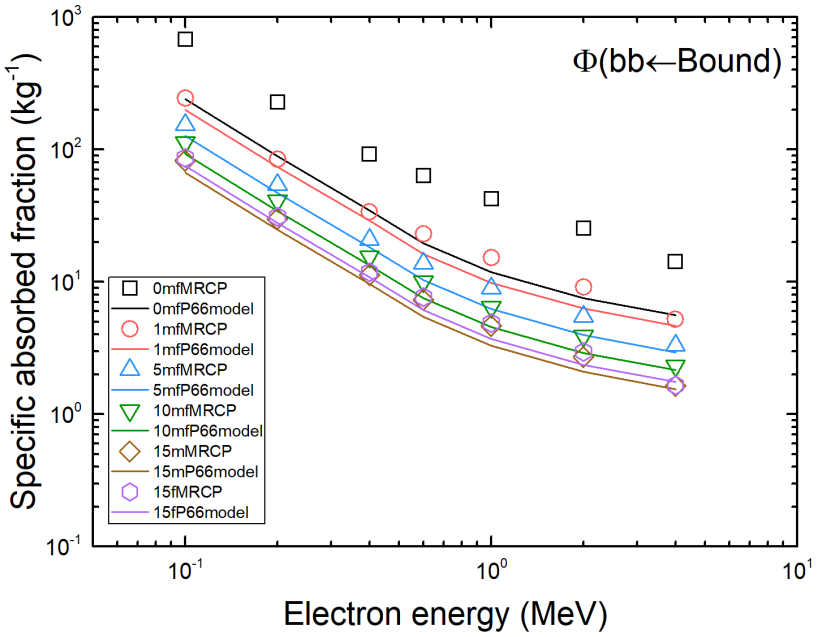


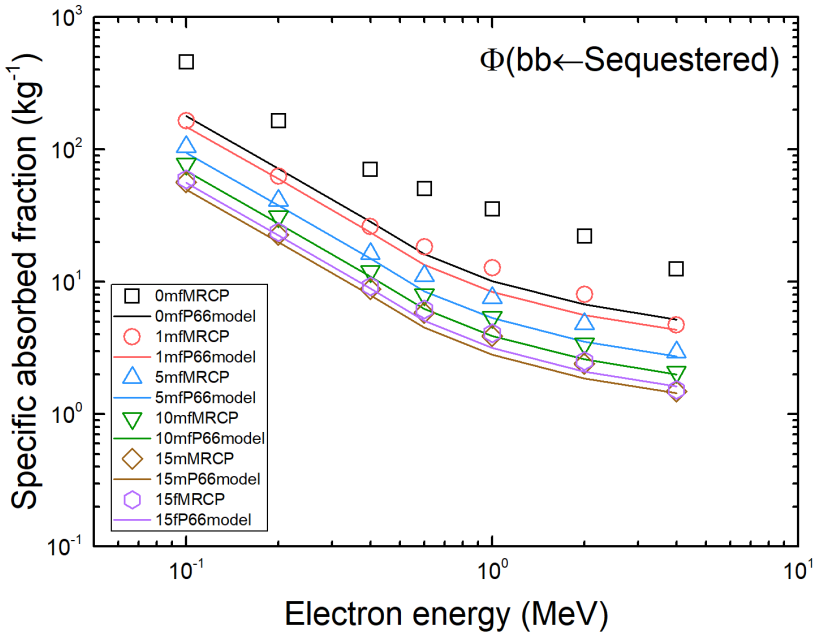
Example: 15-year male

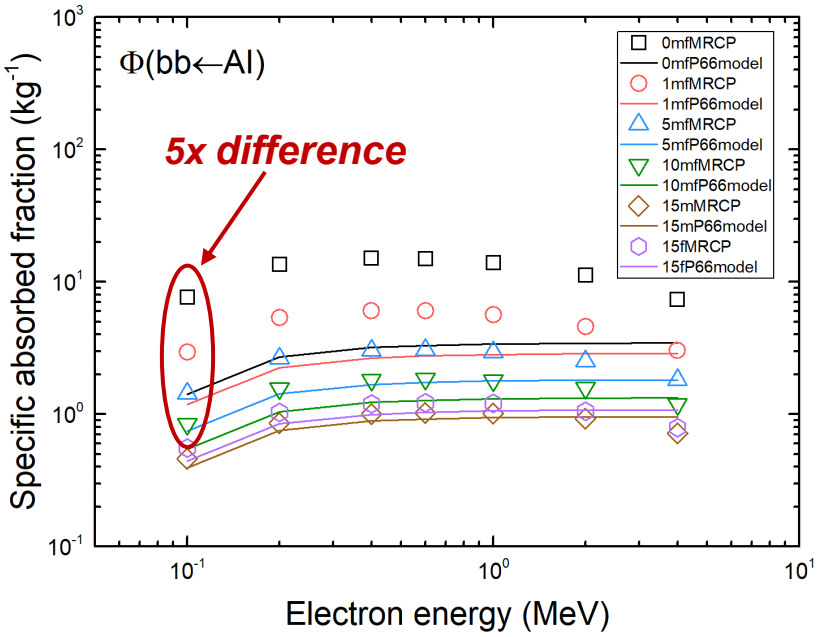
Leff colon	Stylized model (ICRP-100)	Paediatric MRCPs	ICRP-89 reference values
Target mass (g)	1.157	0.356	–
Content mass (g)	687.2	60.0	60.0

SAFs for Respiratory Tract Systems – Electrons





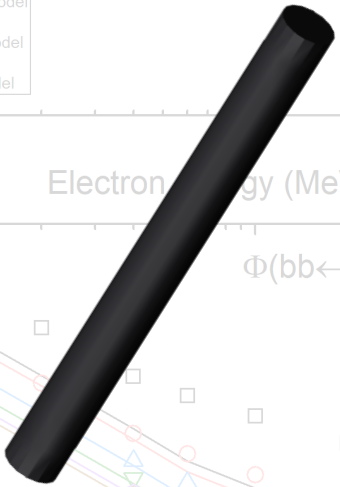




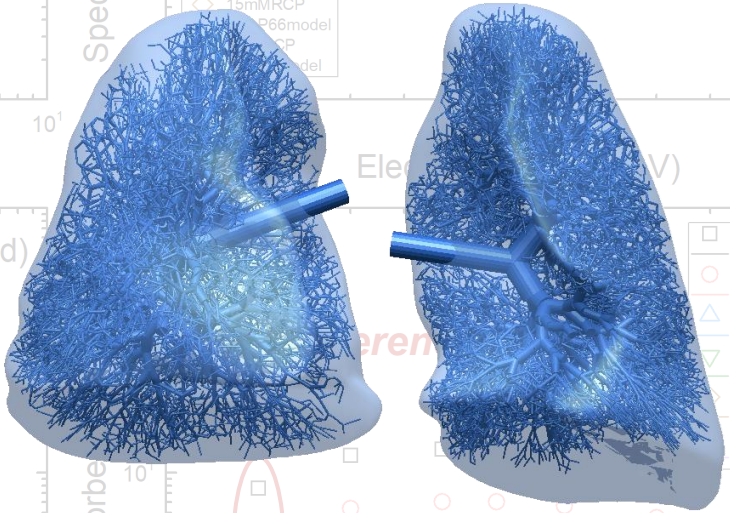
SAFs for Respiratory Tract Systems – Electrons

Example: newborn male

Left colon	Stylized model (ICRP-66)	Paediatric MRCPs
Target mass (g)	0.50 g	0.17 g



bb region (ICRP-66)



bb region (MRCPs)

Ⅶ. Summary

Summary

- This publication presents the development of the **new paediatric mesh-type reference computational phantoms (MRCPs)**, converted from the paediatric voxel-type reference computational phantoms (VRCPs) into a high-quality mesh format with substantial enhancements in anatomical detail.

- The developed paediatric MRCPs —
  - **faithfully preserve the original topology** of most organs of the paediatric VRCPs;
  - represent the skin and hollow organs with **continuous and fully-closed surfaces;**
  - include **detailed and/or more accurate models** for the eyes, teeth, colon, thyroid, skeletons, ET region, lymphatic nodes, blood in large vessels, muscle, and exterior body contour;
  - include **intra-organ blood content**; and
  - include **micron-thick thin target and source layers** in the skin, urinary bladder, and alimentary and respiratory tract organs.

- The paediatric MRCPs can be directly used in general-purpose Monte Carlo codes (i.e., Geant4, PHITS, and MCNP6) and provide **competitive computation speed compared to the paediatric VRCPs** except for the MCNP6.

- The paediatric MRCPs provide —
  - **similar dose values** with those from the paediatric VRCPs **for highly-penetrating radiations**, and
  - **more accurate and reliable dose values for weakly-penetrating radiations** (e.g., electrons and low energy photons).

- The paediatric MRCPs will be used in **all other future calculations of the ICRP radiological protection system** and will provide a resource for wider use in radiological protection applications.

Thank You!