Development of Mesh-type Computational Phantoms for Reference Korean Adults

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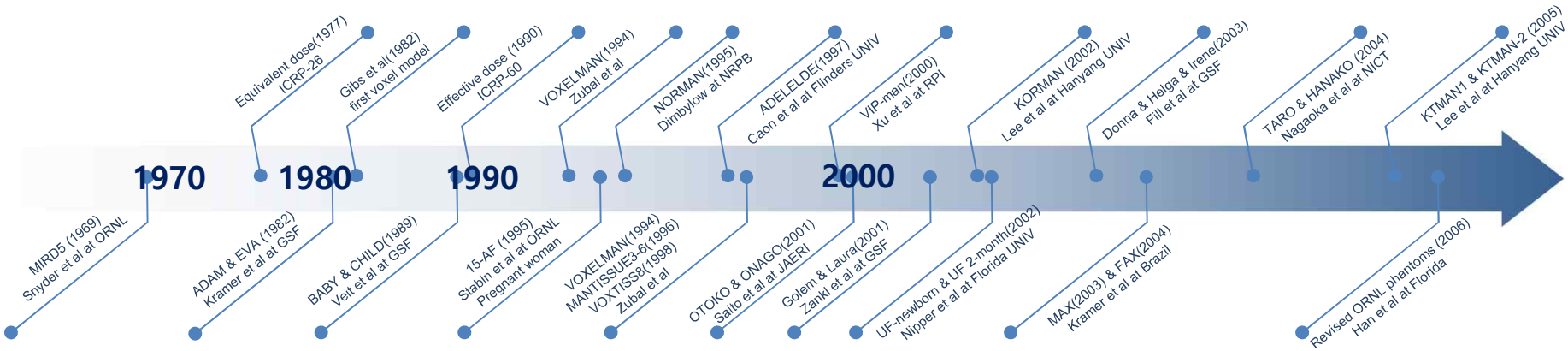
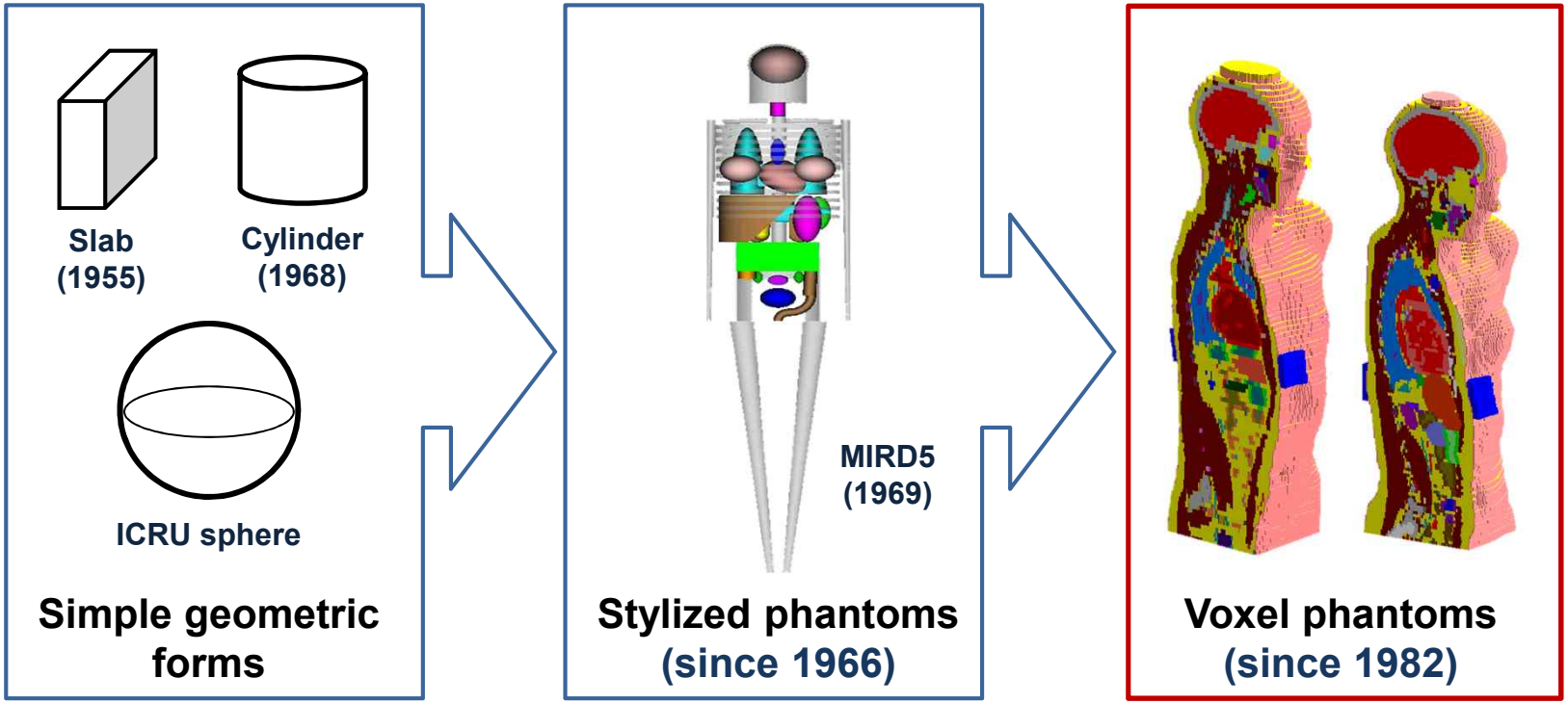
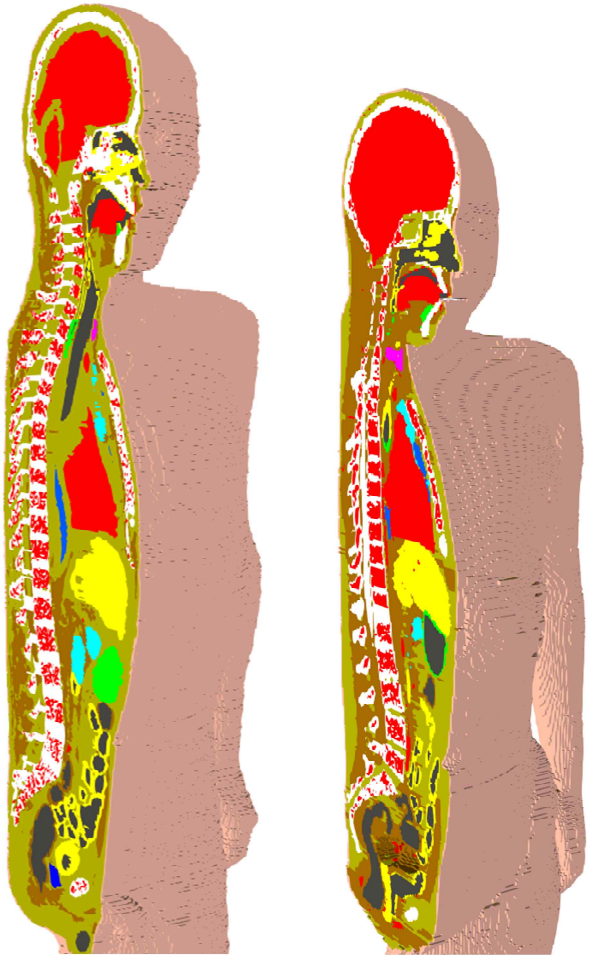
Computational Human Phantoms





Current Korean Reference Phantoms



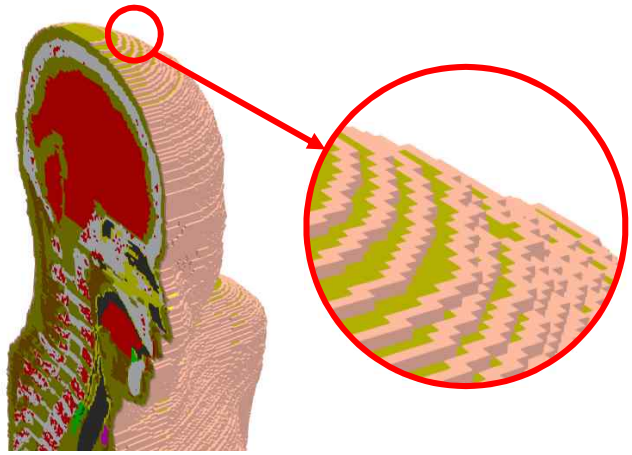
HDRK-Man[1] HDRK-Woman[2]

- **Voxel resolution:**
  - HDRK-Man: 1.981 × 1.981 × 2.0854 mm^3
  - HDRK-Woman: 2.0351 × 2.0351 × 2.0747 mm^3
- **Voxel array:**
  - HDRK-Man: 247 × 141 × 850
  - HDRK-Woman: 261 × 109 × 825
- **Number of organs/tissues**
  - HDRK-Man: 30
  - HDRK-Woman: 40
- **Dimensions were matched to the reference Korean data**

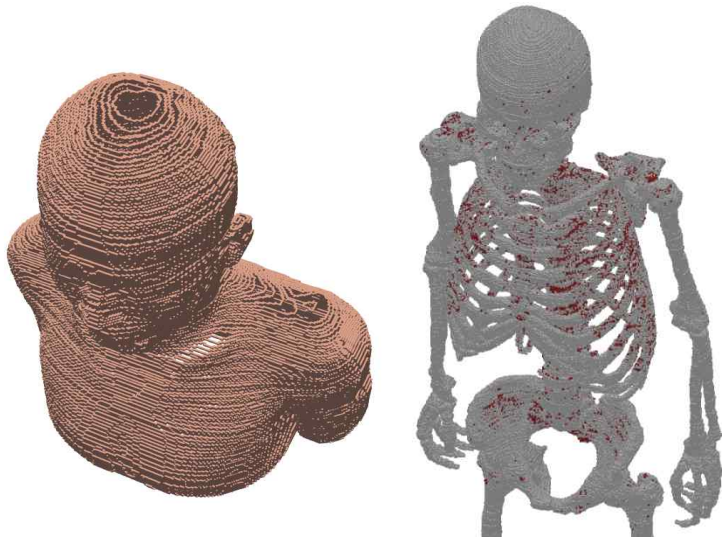
[1] C. H. Kim, S. H. Choi, J. H. Jeong, C. Lee and M. S. Chung, *Phys. Med. Biol.*, 53, 15, 2008.
[2] Y. S. Yeom, J. H. Jeong, G. H. Kim, M. C. Han, B. K. Ham, K. W. Cho and S. B. Hwang, *Phys. Med. Biol.*, 59, 14, 2014.

Limitation of Voxel Phantoms

- **Stair-stepped surfaces**
  - Anatomically unrealistic
- **Difficult to define thin or small organs**
  - Holes in the skin and hollow organs
  - Difficult to define micron-thick radiosensitive target regions
    - Skin: 50 μm target layer
    - HATM/HRTM: 8-40 μm target layer
- **Difficult to deform the phantoms**
  - Practically difficult to deform phantoms in various postures and body shapes

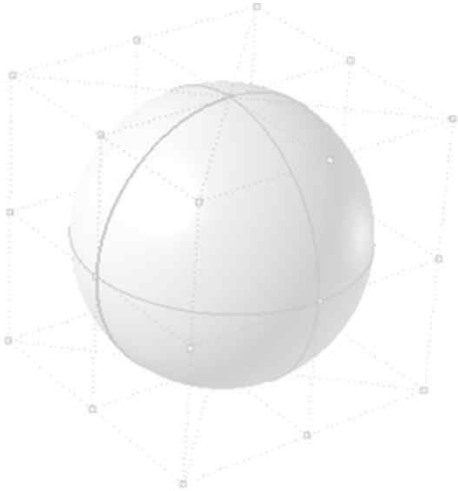


Stair-stepped surfaces



Holes in organs and tissues

Advantage of Surface Phantoms



NURBS
(Non-Uniform Rational B-spline Surface)

Polygon mesh

- **Smooth surfaces**
  - Anatomically realistic
- **Possible to define thin or small organs**
  - Possible to define micron-thick radiosensitive target regions
    - Skin: 50 μm target layer
    - HATM/HRTM: 8–40 μm target layer
- **Deformable**
  - Possible to change posture
  - Possible to change shape and size
  - Appropriate for 4D Monte Carlo simulation

Conversion of ICRP Reference Phantoms

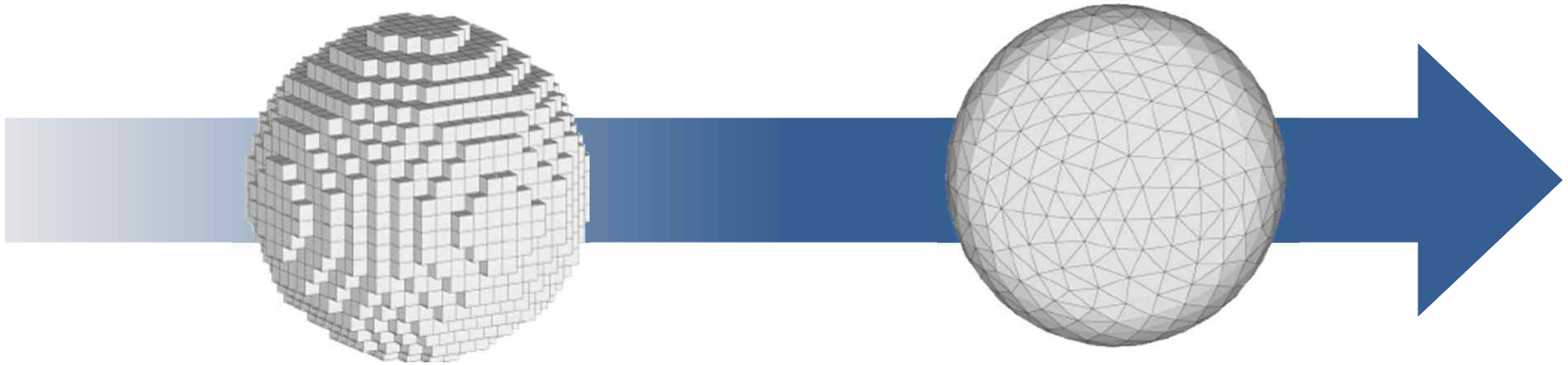
Voxel-type Reference Computational Phantoms

Mesh-type Reference Computational Phantoms[3]

[3] C.H. Kim, Y. S. Yeom, T. T. Nguyen, M. C. Han, C. Choi, H. Lee, H. Han, B. Shin, J-K Lee, H. S. Kim, M. Zankl, N. Petoussi-Henss, W. E. Bolch, C. Lee, B. S. Chung, R. Qiu and K. Eckerman, *ICRP 2017 Proceedings*, 2018.

Objectives of the Present Study

- **<u>To develop new mesh-type reference Korean phantoms (MRKPs) for adult male and female</u>** to address limitations of current voxel-type reference Korean adult phantoms



Voxel format **Mesh format**

New Korean Reference Data

- **New Korean reference data[4] (published in 2018)**
  - provide reference values of 133 anthropometric parameters, including standing height and total body mass
  - and provide reference values of 58 organ/tissue masses, including those required for effective dose calculation

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Korean Anatomical Reference Data for Adults for Use in Radiological Protection

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For radiological protection from exposure to ionizing radiation, in which a population-averaged dose evaluation is used, establishing a system of reference anatomical and physiological data for a specific population of interest is important. Some studies were done in the past to establish Korean reference data; however, the data provided the mass values only for a limited number of organs/tissues. In addition, the standing height and total body mass are based on ~ 20-year-old data. In the present study, a new set of Korean reference anatomical values was established for use in the radiological protection of Korean workers and members of the public. The established Korean reference data provide the masses of 58 organs/tissues, including those needed to calculate the effective dose, which were derived by collecting and analyzing various scientific reports in the literature and data. In addition, the data provide not only standing height and total body mass, but also 131 additional anthropometric parameters; these values were derived from the most recent Korean national survey project, 7th Size Korea. The characteristics of the data were also compared with several other population data, including the Asian and the International Commission on Radiological Protection (ICRP) reference data.

PACS numbers: 87.50.cm, 87.53.–j
Keywords: Radiological protection, Reference man, Korean, Organ/tissue data, Anthropometric data
DOI: 10.3938/jkps.72.183

I. INTRODUCTION

For radiological protection, evaluating the radiation dose of a worker or a member of the public exposed to external or internal radiation source is necessary. The dose evaluation is influenced by the anatomical and the physiological characteristics of the exposed individual; however, the individual dose evaluation is highly demanding. Thus, establishing a consistent regulation and practice on radiological protection is considered impractical. Therefore, the population-averaged dose evaluation has been used for radiological protection, so establishing a system of reference anatomical and physiological data for a specific population of interest is critical.

The International Commission on Radiological Protection (ICRP) published comprehensive reference anatomical and physiological values in 1975 via ICRP *Publication* 23 [1] and updated those values in 2002 via ICRP *Publication* 89 [2]. The ICRP reference data were established based mainly on anatomical and physiological data for Caucasians, particularly, those in Western Europe and North America. This Caucasian population, however, is only ~ 20% of the world population [3]; that is, strictly speaking, the ICRP reference data represent only ~ 20% of the world population. In 1998, the International Atomic Energy Agency (IAEA) published a report [4] to establish the Asian reference data based on anatomical and physiological data from nine Asian countries, which represent ~ 60% of the world population. This report found that the Asian reference masses for organs and tissues tended to be less than the ICRP reference values and concluded that each Asian country should undertake a specific research activity to establish national reference data [4].

Several attempts were made to establish Korean reference data for radiological protection [5–7]. In 1982 - 1983, Kim *et al.* [5,6] provided the mean mass values for six organs/tissues, which were derived from data for 1921 adults based on autopsies compiled by the National Institute of Scientific Investigation in Korea. These values were used by the IAEA to establish the Asian reference data [4]. In 2005, Park *et al.* [7] provided the

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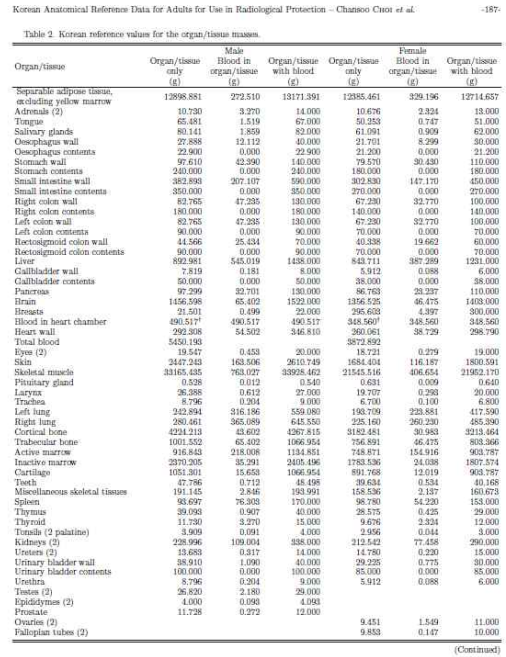


Table 2. Korean reference values for the organ/tissue masses.

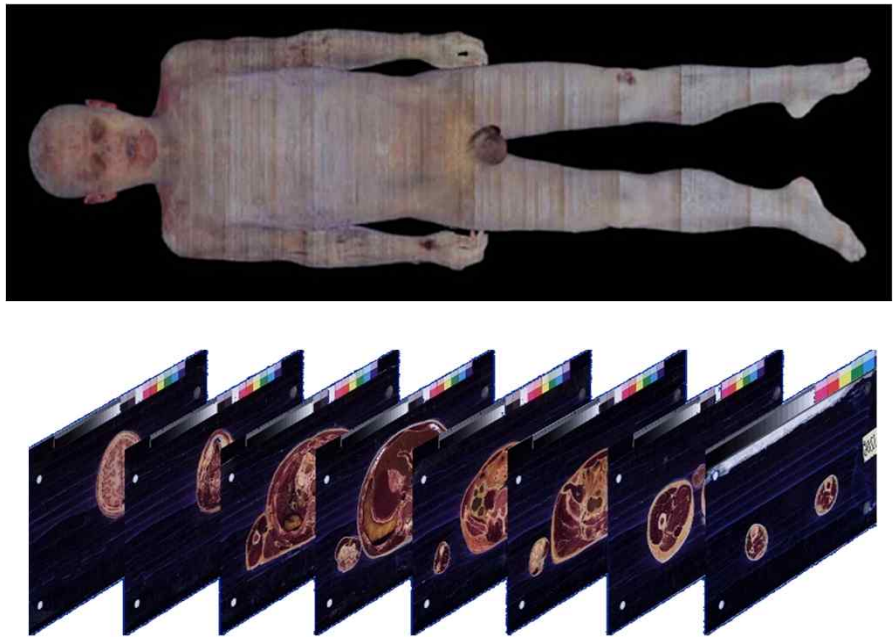
Organ/tissue	Male			Female		
	Organ/tissue only (g)	Blood in organ/tissue (g)	Organ/tissue with blood (g)	Organ/tissue only (g)	Blood in organ/tissue (g)	Organ/tissue with blood (g)
Separable adipose tissue, excluding yellow marrow	12898.881	272.510	13171.391	12385.461	329.196	12714.657
Adrenals (2)	10.730	3.270	14.000	10.676	2.324	13.000
Tongue	65.481	1.519	67.000	50.253	0.747	51.000
Salivary glands	80.141	1.859	82.000	61.091	0.909	62.000
Oesophagus wall	27.888	12.112	40.000	21.701	8.299	30.000
Oesophagus contents	22.900	0.000	22.900	21.200	0.000	21.200
Stomach wall	97.610	42.390	140.000	79.570	30.430	110.000
Stomach contents	240.000	0.000	240.000	180.000	0.000	180.000
Small intestine wall	382.893	207.107	590.000	302.830	147.170	450.000
Small intestine contents	350.000	0.000	350.000	270.000	0.000	270.000
Right colon wall	82.765	47.235	130.000	67.230	32.770	100.000
Right colon contents	180.000	0.000	180.000	140.000	0.000	140.000
Left colon wall	82.765	47.235	130.000	67.230	32.770	100.000
Left colon contents	90.000	0.000	90.000	70.000	0.000	70.000
Rectosigmoid colon wall	44.566	25.434	70.000	40.338	19.662	60.000
Rectosigmoid colon contents	90.000	0.000	90.000	70.000	0.000	70.000
Liver	892.981	545.019	1438.000	843.711	387.289	1231.000
Gallbladder wall	7.819	0.181	8.000	5.912	0.088	6.000
Gallbladder contents	50.000	0.000	50.000	38.000	0.000	38.000
Pancreas	97.299	32.701	130.000	86.763	23.237	110.000
Brain	1456.598	65.402	1522.000	1356.525	46.475	1403.000
Breasts	21.501	0.499	22.000	295.603	4.397	300.000
Blood in heart chamber	490.517†	490.517	490.517	348.560†	348.560	348.560
Heart wall	292.308	54.502	346.810	260.061	38.729	298.790
Total blood	5450.193			3872.892		
Eyes (2)	19.547	0.453	20.000	18.721	0.279	19.000
Skin	3447.243	163.506	2610.749	1684.404	116.187	1800.591
Skeletal muscle	33165.435	763.027	33928.462	21545.516	406.654	21952.170
Pituitary gland	0.528	0.012	0.540	0.631	0.009	0.640
Larynx	36.388	0.612	37.000	19.707	0.293	20.000
Trachea	8.796	0.204	9.000	6.700	0.100	6.800
Left lung	242.894	316.186	559.080	193.709	223.881	417.590
Right lung	280.661	365.089	645.550	225.160	260.230	485.390
Cortical bone	4224.213	43.602	4267.815	3182.481	30.983	3213.464
Trabecular bone	1001.552	65.402	1066.954	756.891	46.475	803.366
Active marrow	916.843	218.008	1134.851	748.871	154.916	903.787
Inactive marrow	2370.205	35.291	2405.496	1783.536	24.038	1807.574
Cartilage	1051.301	15.653	1066.954	891.768	12.019	903.787
Teeth	47.786	0.712	48.498	39.634	0.534	40.168
Miscellaneous skeletal tissues	191.145	2.846	193.991	158.536	2.137	160.673
Spleen	93.697	76.303	170.000	98.780	54.220	153.000
Thymus	39.093	0.907	40.000	28.575	0.425	29.000
Thyroid	11.730	3.270	15.000	9.676	2.324	12.000
Tonsils (2 palatine)	3.909	0.091	4.000	2.956	0.044	3.000
Kidneys (2)	228.996	109.004	338.000	212.542	77.458	290.000
Ureters (2)	13.683	0.317	14.000	14.780	0.220	15.000
Urinary bladder wall	38.910	1.090	40.000	29.225	0.775	30.000
Urinary bladder contents	100.000	0.000	100.000	85.000	0.000	85.000
Urethra	8.796	0.204	9.000	5.912	0.088	6.000
Testes (2)	26.820	2.180	29.000			
Epididymes (2)	4.000	0.093	4.093			
Prostate	11.728	0.272	12.000			
Ovaries (2)				9.451	1.549	11.000
Fallopian tubes (2)				9.853	0.147	10.000

(Continued)

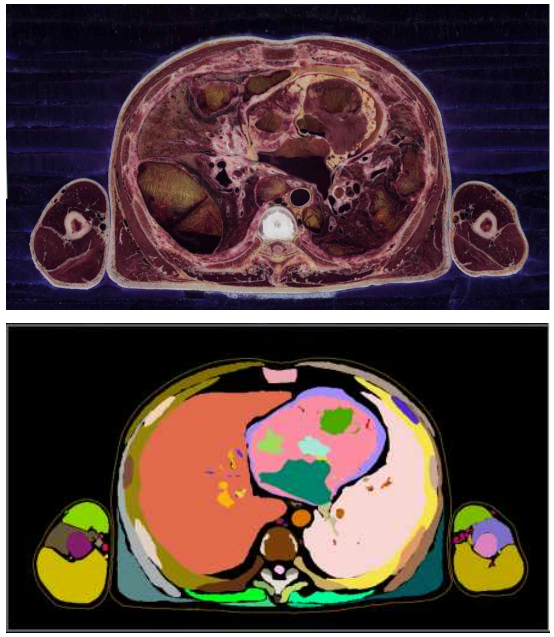
[4] C. Choi, Y. S. Yeom, T. T. Nguyen, H. Lee, H. Han, B. Shin, X. Zhang and C. H. Kim, *Jour. Kor. Phys. Soc.*, 72, 183, 2018.

Construction of General Organs

- **Visible Korean Human (VKH) serially sectioned images**
  - VKH images were obtained by Korea Institute of Science and Technology Information (KISTI) and Ajou University by serially sectioning cadavers of 33-year old Korean male and 26-year old Korean female at 0.2 mm intervals

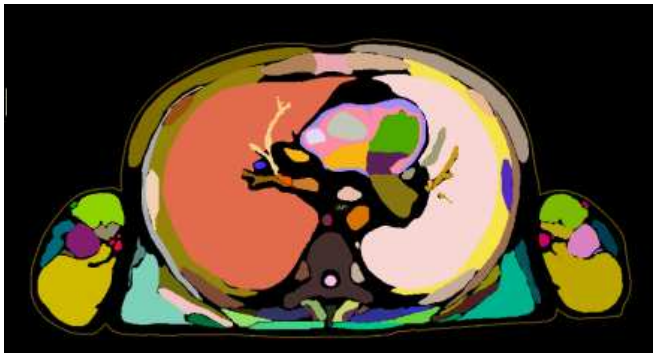


Korean male cadaver and VKH images



VKH image and organ-segmented image

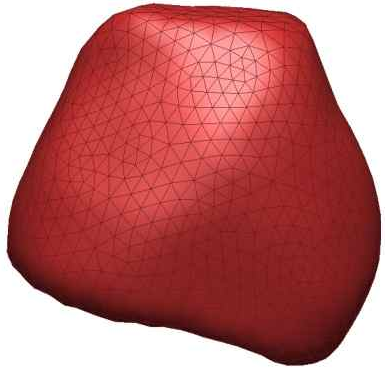
- **Conversion method 1**



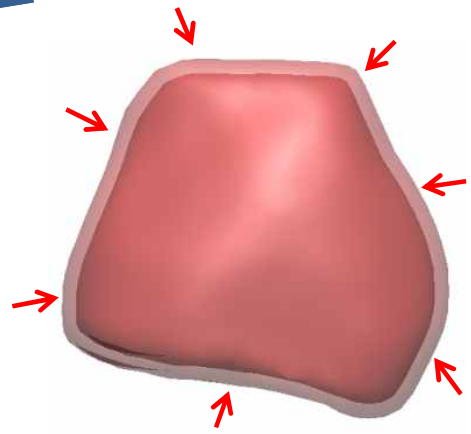
Conversion to primitive polygon-mesh model

Refinement work (fill holes, smooth, remesh…)

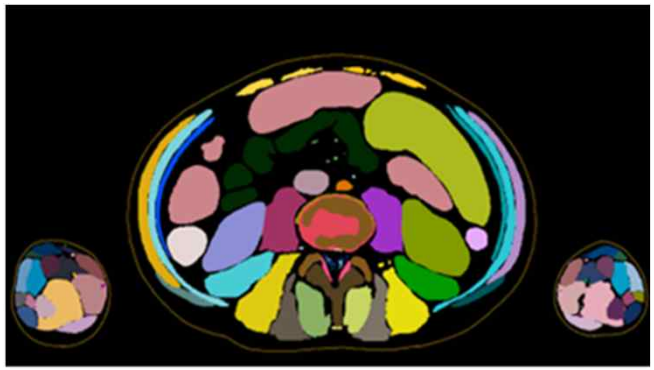
Decrease in number of facets and smoothing of surfaces



Adjustment of volumes

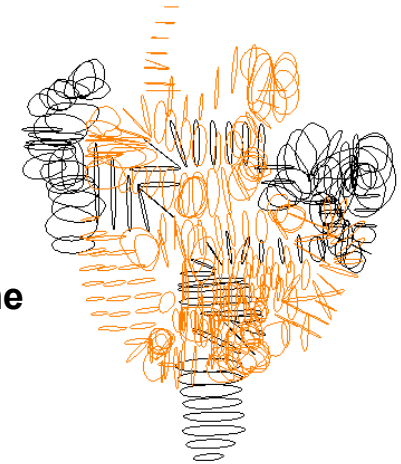


- **Conversion method 2**

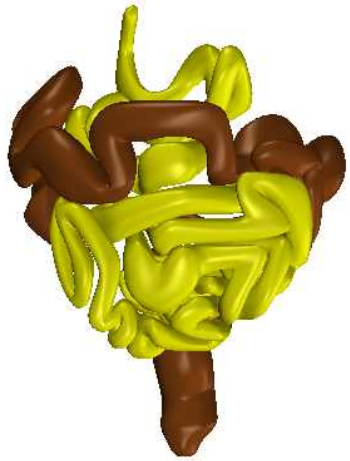


Conversion to primitive polygon-mesh model

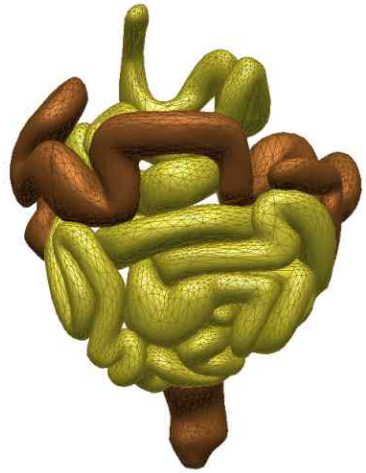
Generation of contours along the intestine tracks



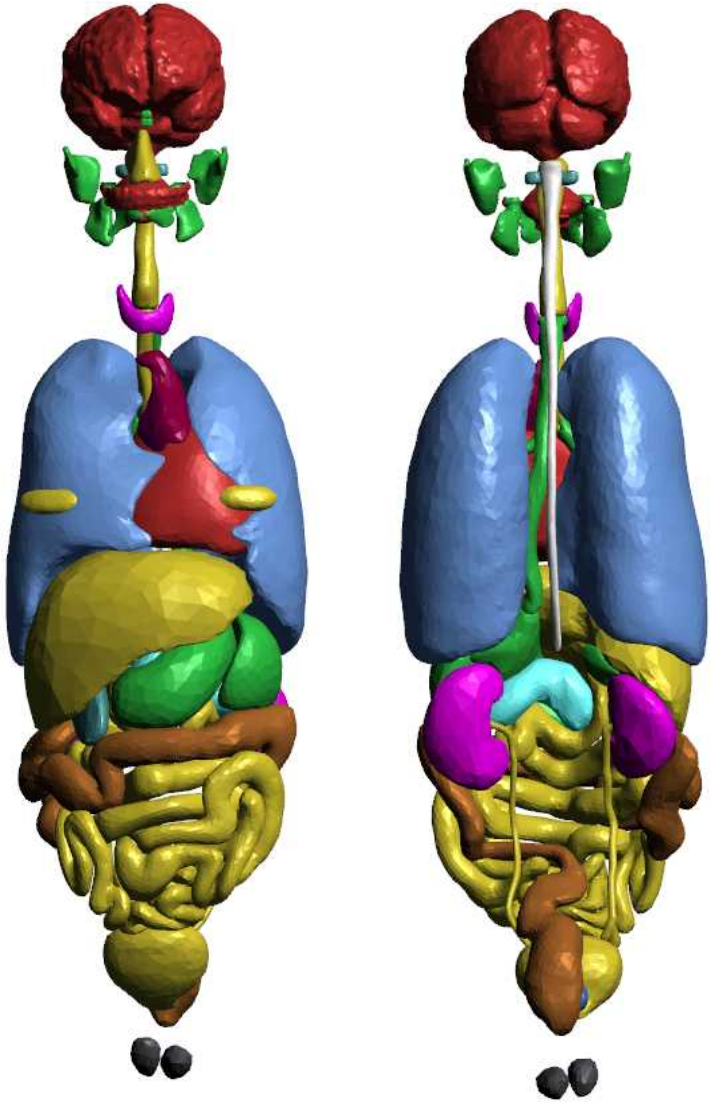
Conversion to NURBS model



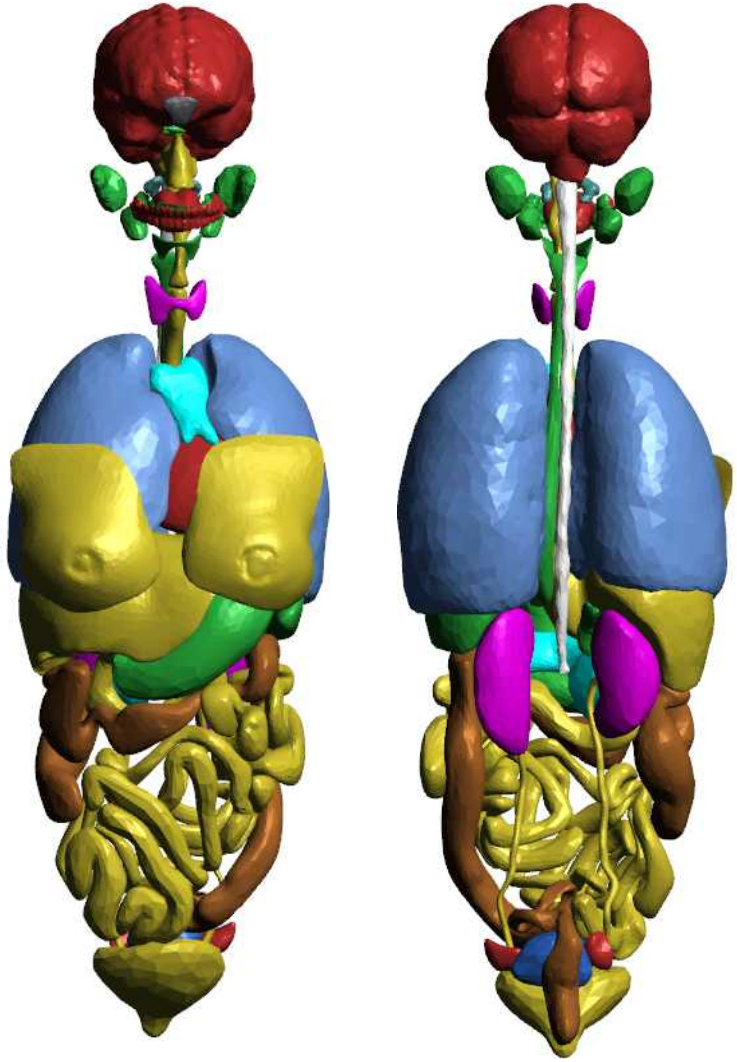
Reconversion to polygon-mesh model and adjustment work



General Organs



Adult male

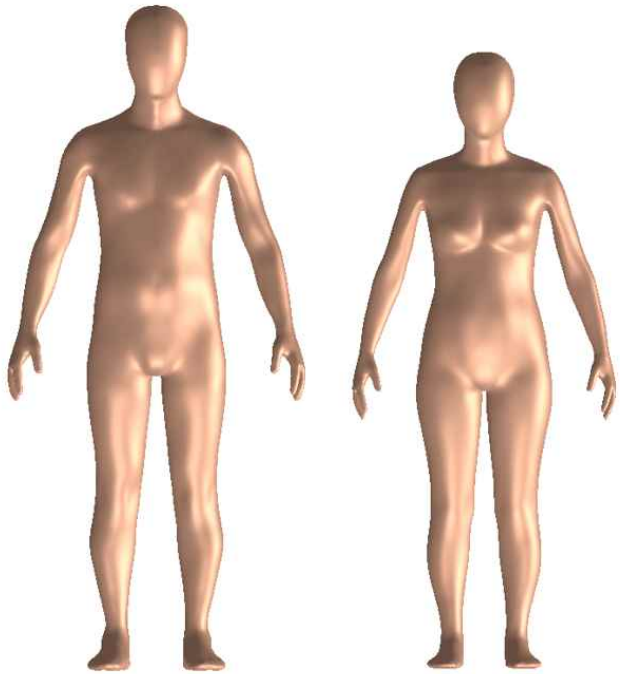


Adult female

Construction of Skin

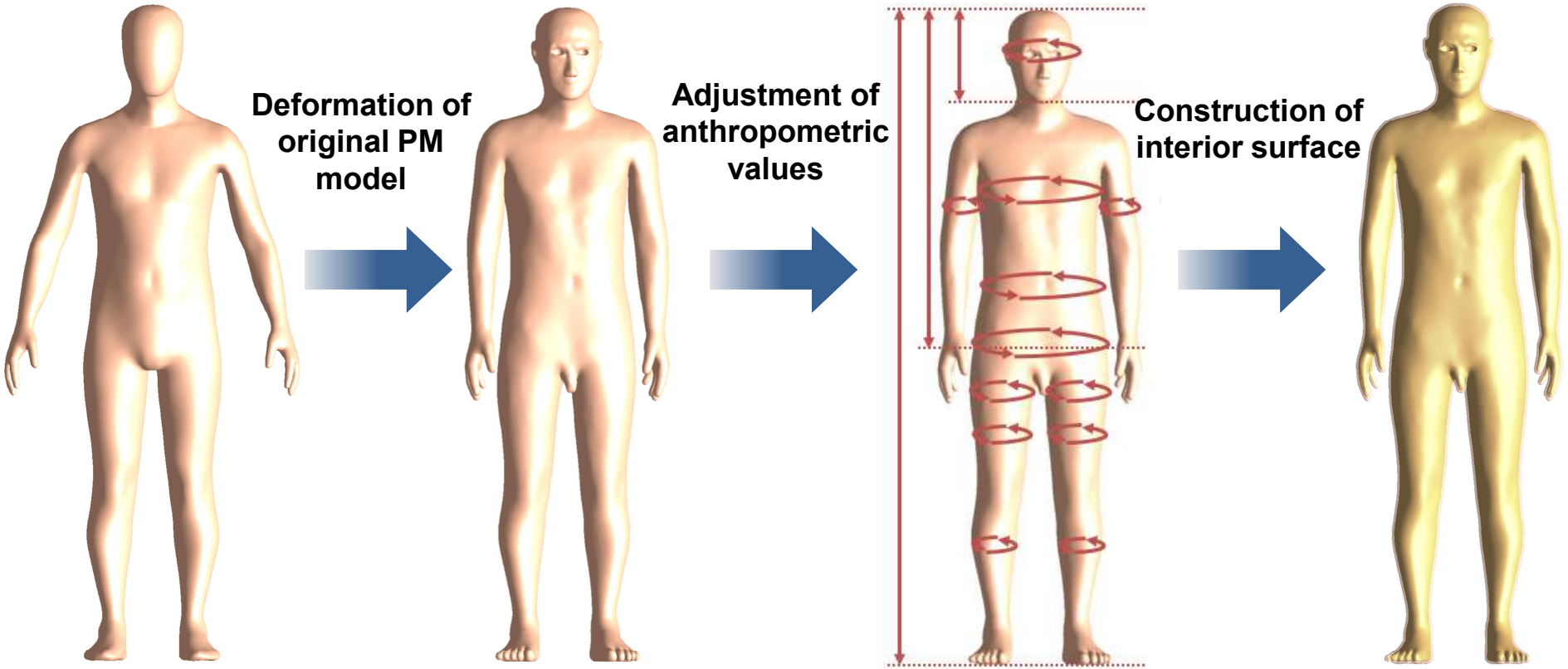
- **Standard body shape model of 30s in Korea**
  - KATS conducted the 3-D whole body scan on 405 Korean subjects in their 30s through the 6th National Anthropometric Survey in 2010, and constructed the standard body shape model of 30s in Korea

3-D whole body scanner (BL Scanner, Hamamatsu, Japan)

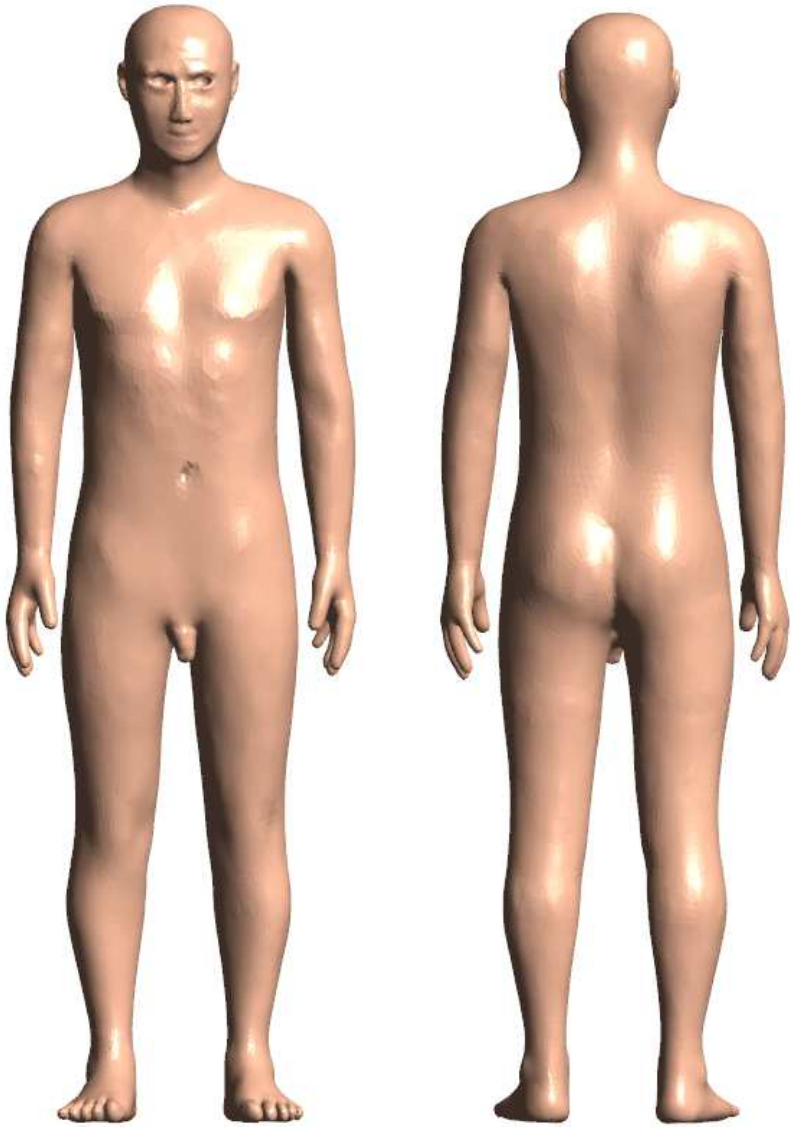


Standard body shape model of 30s in Korea

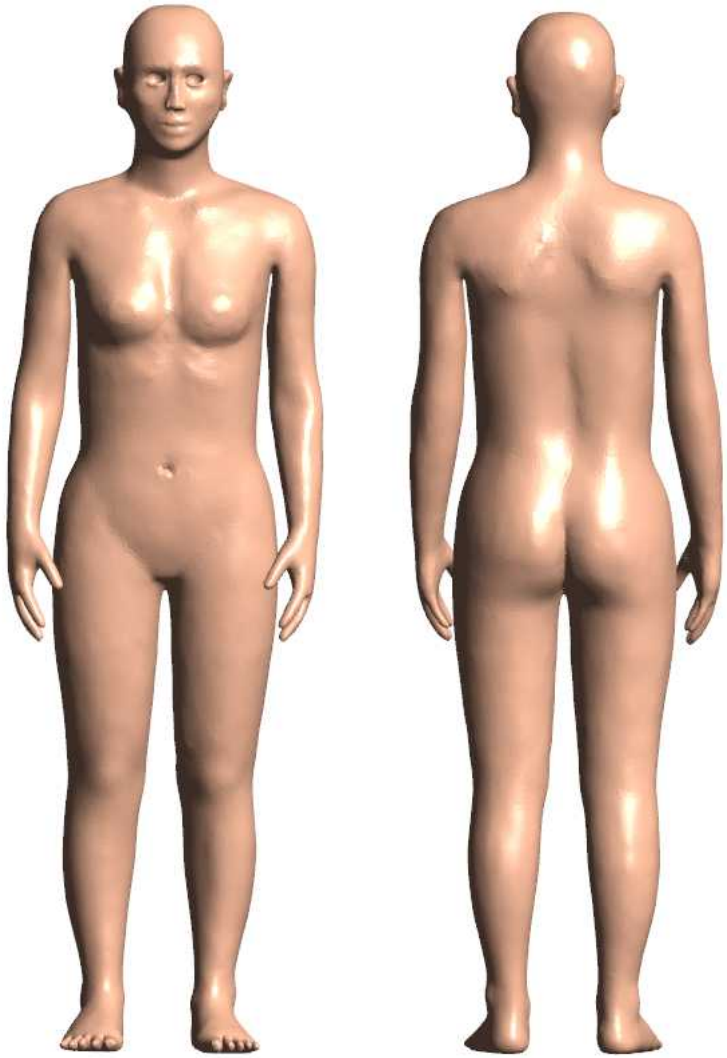
- **Construction method**



Skin



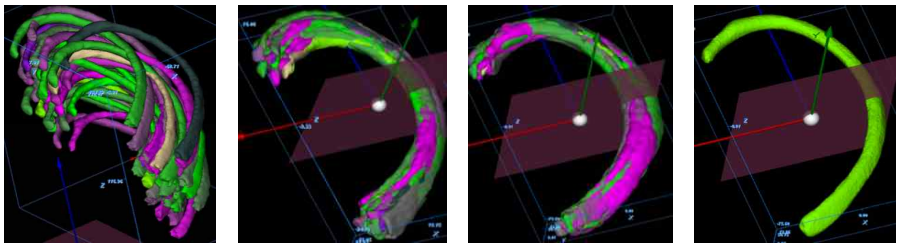
Adult male



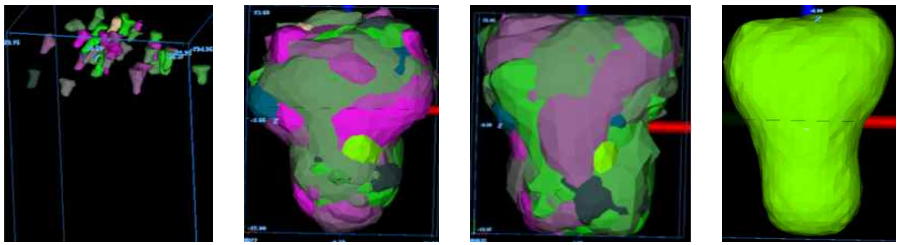
Adult female

Construction of Skeletal System

- **Korean averaged bone model**
  - KISTI and Catholic University constructed the Korean averaged bone model by averaging the CT data of skeleton of 106 Korean cadavers

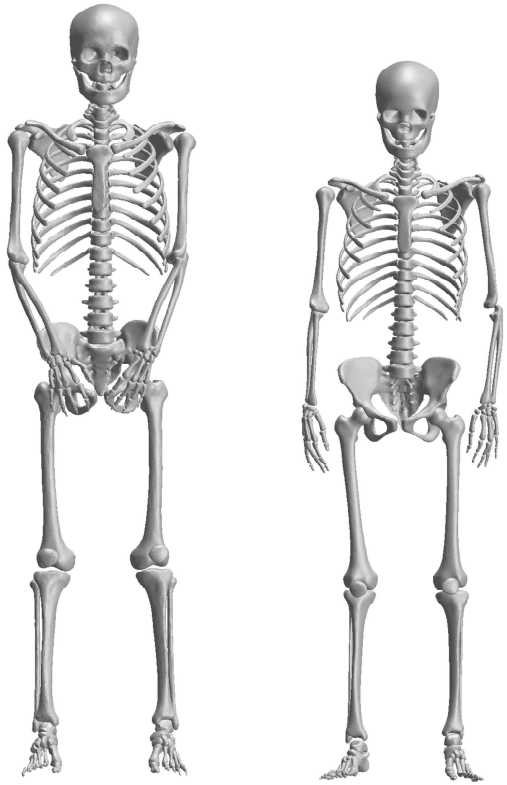


Ribs



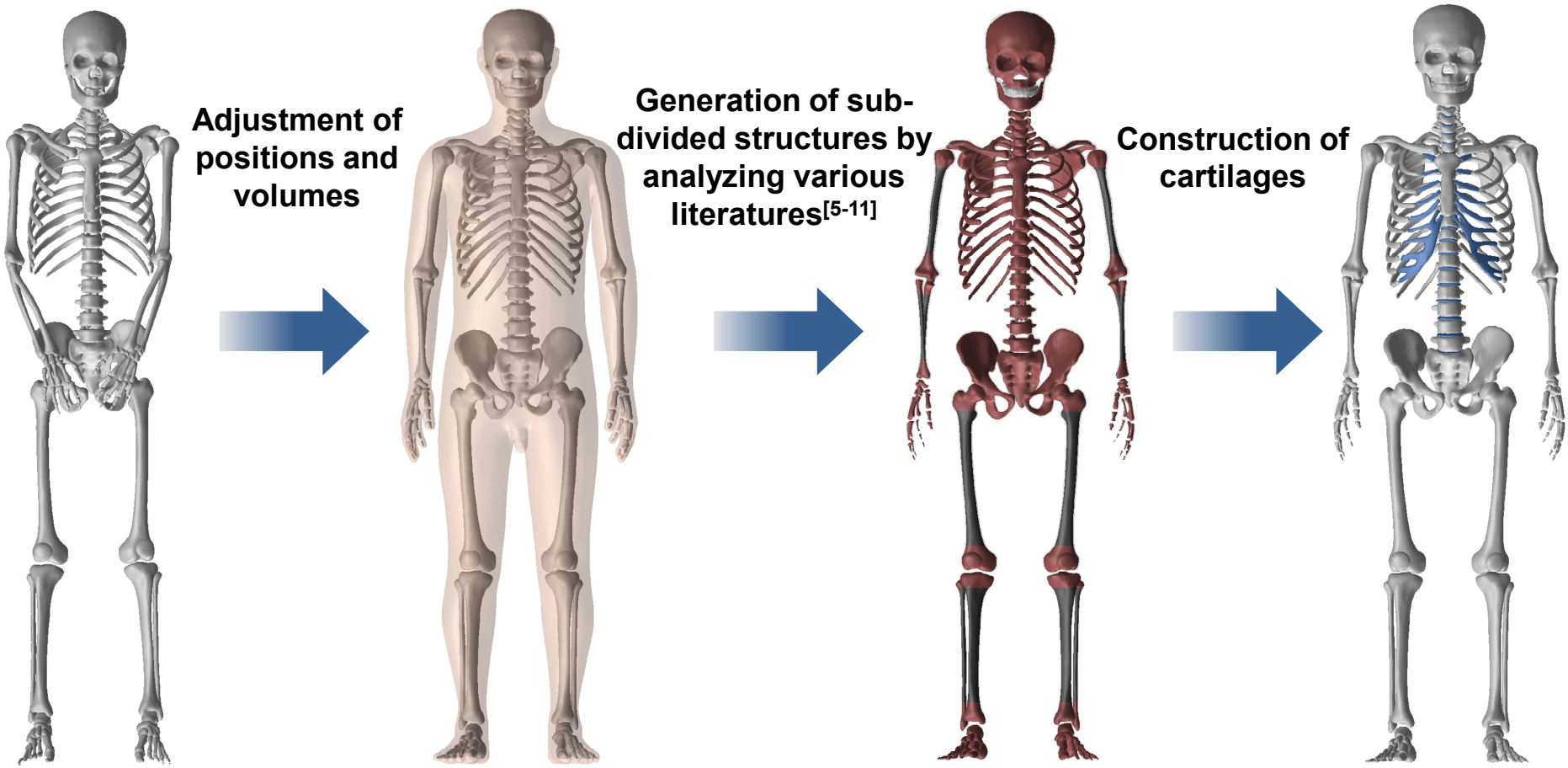
1st distal phalanx

Process of averaging skeletal data



Korean averaged bone model

- **Construction method**



[5] D. S. Kwak, U. Y. Lee, S. H. Han, K. N. Choi and T. J. Kim, *KSPE*. 85, 177, 2006.
[6] S. Gao, L. Ren, R. Qiu, Z. Wu and J. Li, *Radiat. Prot. Dosim.*, 175, 4, 2017.
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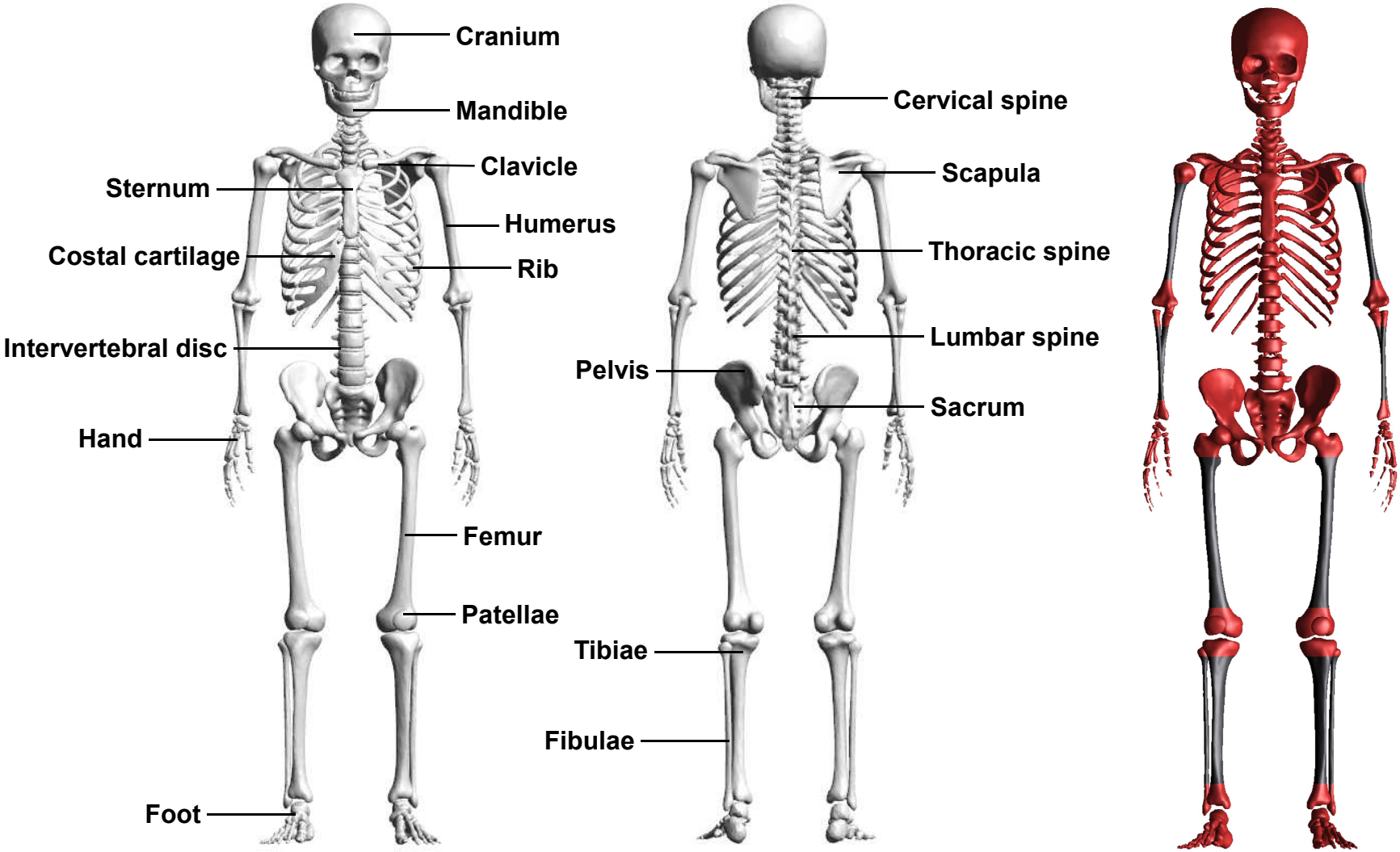
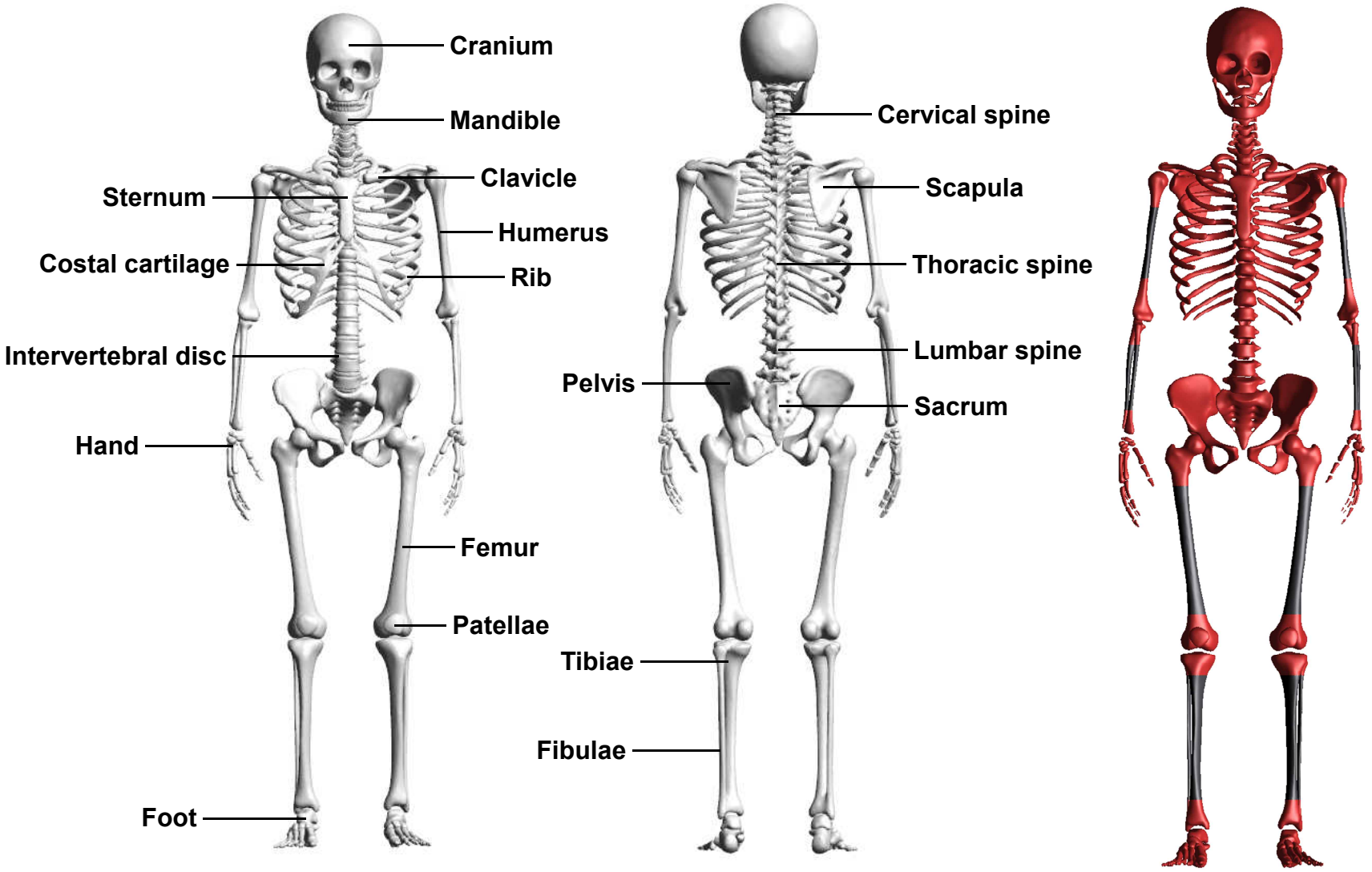
[9] M. Hough, P. Johnson, D. A. Rajon, D. Jokisch, C. Lee and W. E. Bolch, *Phys. Med. Biol.,* 56, 2309 (2001).
[10] S. E. O'Reilly, L. S. DeWeese, M. R. Maynard, D. A. Rajon, M. B. Wayson, E. L. Marshall and W. E. Bolch, *Phys. Med. Biol.,* 61, 8794, 2016.
[11] D. H. Pafundi. UF Dissertation, 2009.

Skeletal System of Adult Male

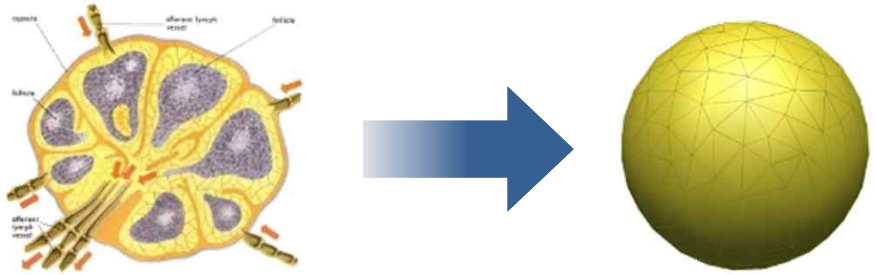


Skeletal System of Adult Female



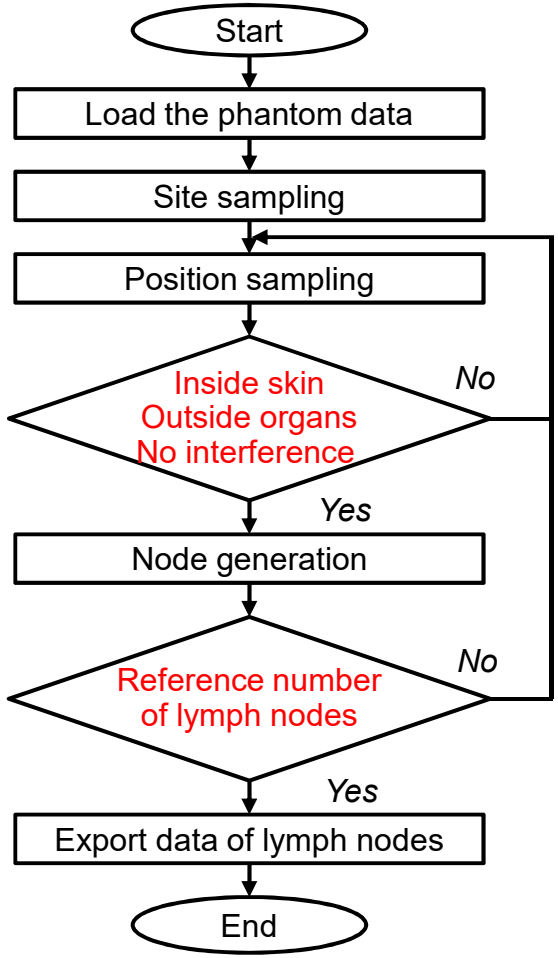
Construction of Lymphatic Nodes

- **Randomly generated, following the procedure[12] that was used for the construction of the ICRP pediatric phantoms**



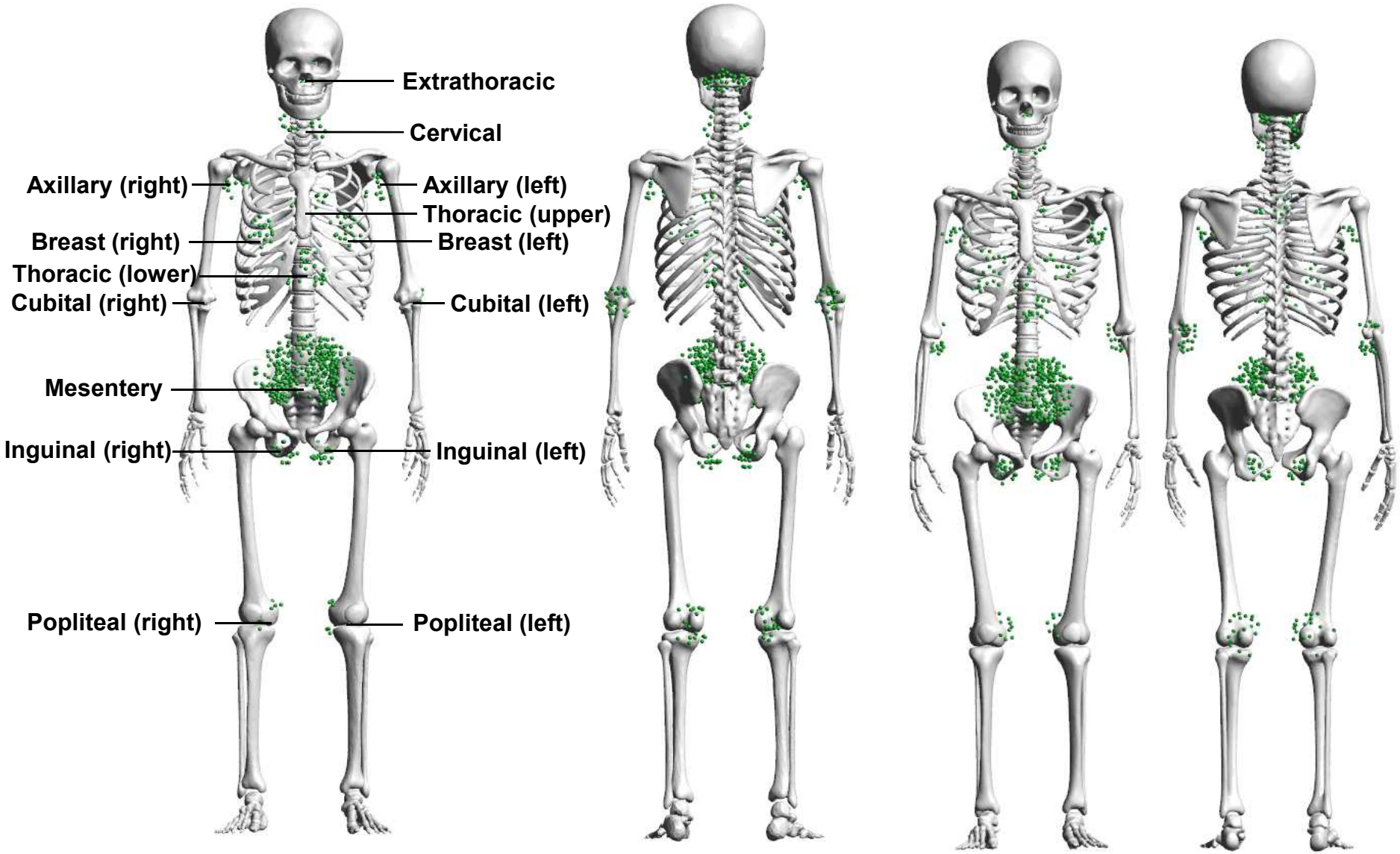
Korean reference data for lymphatic nodes

Site	Number of nodes	Number of nodes given in ICRP-89	Reference mass (g)	
			Male	Female
Extrathoracic	55		18.50	14.30
Cervical	19		6.39	4.94
Thoracic	55	50–60	7.74	5.98
Breast	38		12.78	9.88
Mesentery	350	200–500	18.50	14.30
Axiliary	23	8–37	12.78	9.88
Cubital	38		117.74	90.98
Inguinal	38		12.78	9.88
Popliteal	38		12.78	9.88
Total	654	600–700	220.0	170.0



[12] C. Lee, S. Lamart and B. E. Moroz, *Health physics*, 58, 5, 2013.

Lymphatic Nodes

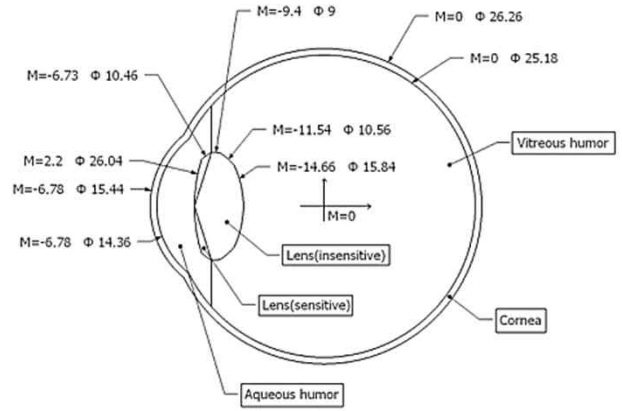


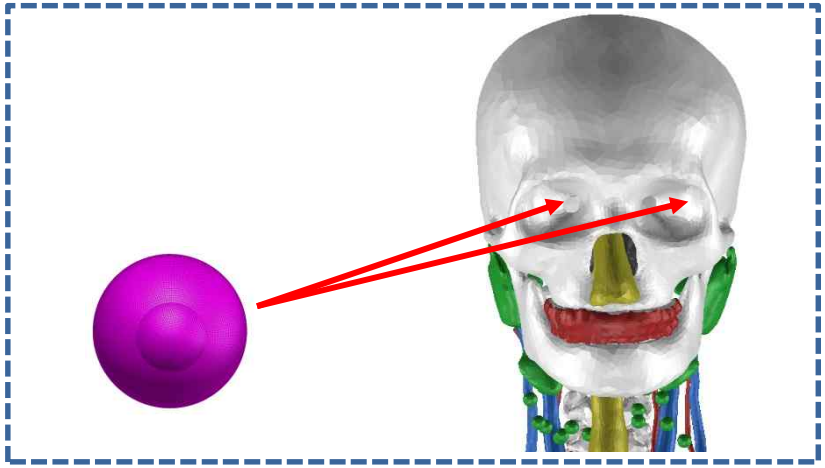
Adult male

Adult female

Incorporation of Eyes

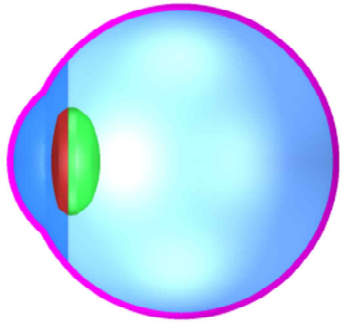
Korean stylized detailed eye model[13]



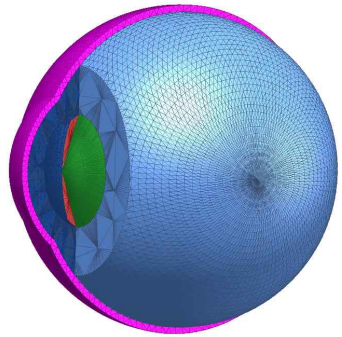


Construction of NURBS surface model

Incorporation into phantoms



Conversion to polygon-mesh model and refinement work

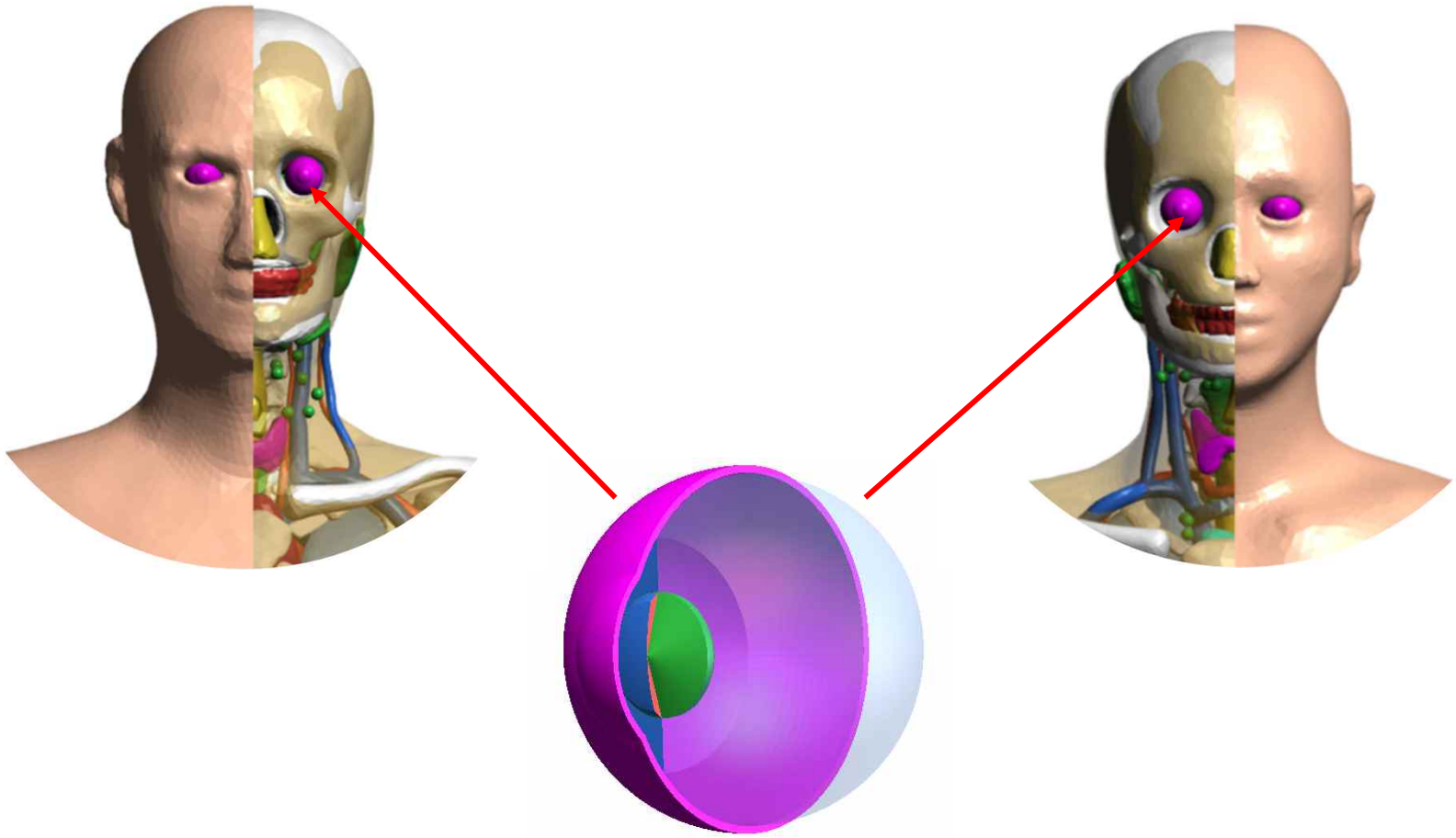


[13] X. Zhang, H. Han, Y. S. Yeom, T. T. Nguyen, C. Choi, H. Lee, B. Shin and C. H. Kim, *Proceeding of Korean Association for Radiation Protection Spring Meeting*, 172-173, 2018.

Eyes

Adult male

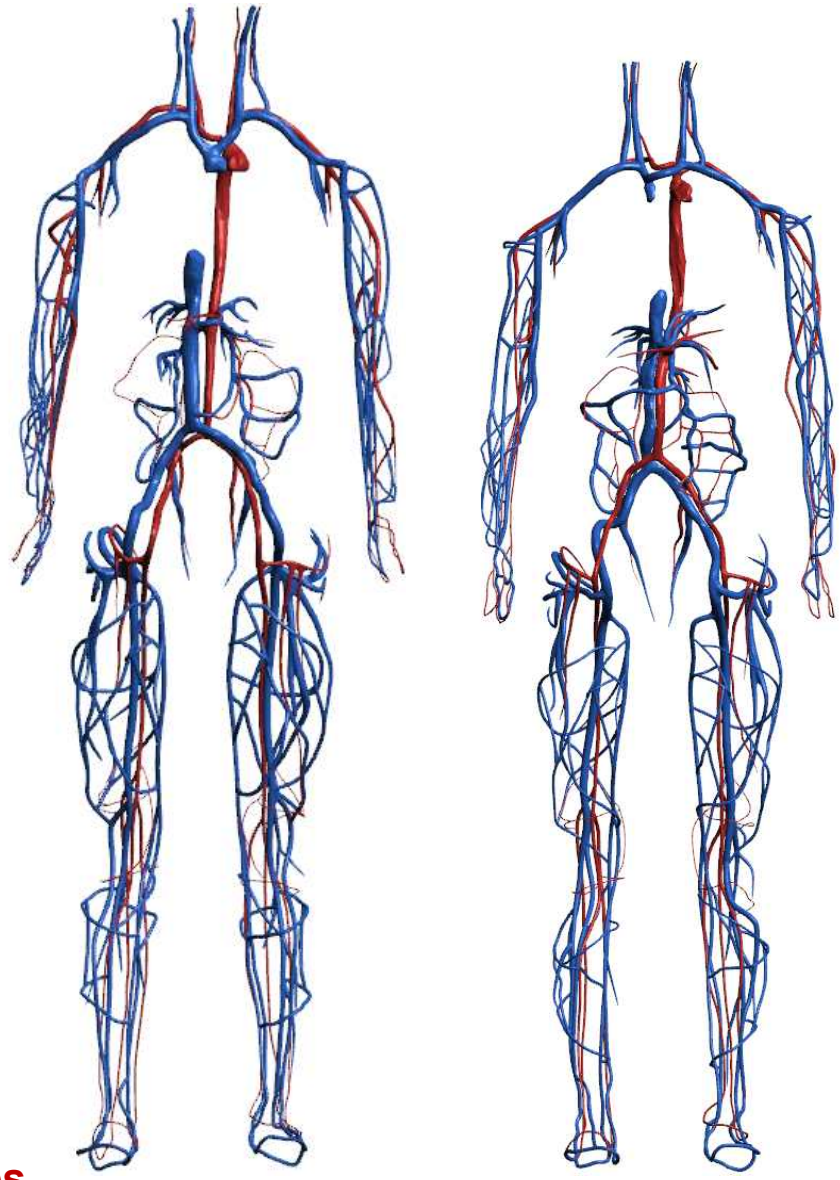
Adult female



Mesh-type Korean Eye Model

Blood in Large Arteries & Veins

- **Construction of blood in large arteries and veins**
  - Blood in large arteries and veins was modeled based on anatomy books and consultation with anatomists
  - Small arteries/veins and capillary vessel were not modeled, assuming that blood contained in these vessels is homogeneously distributed in organs/tissues



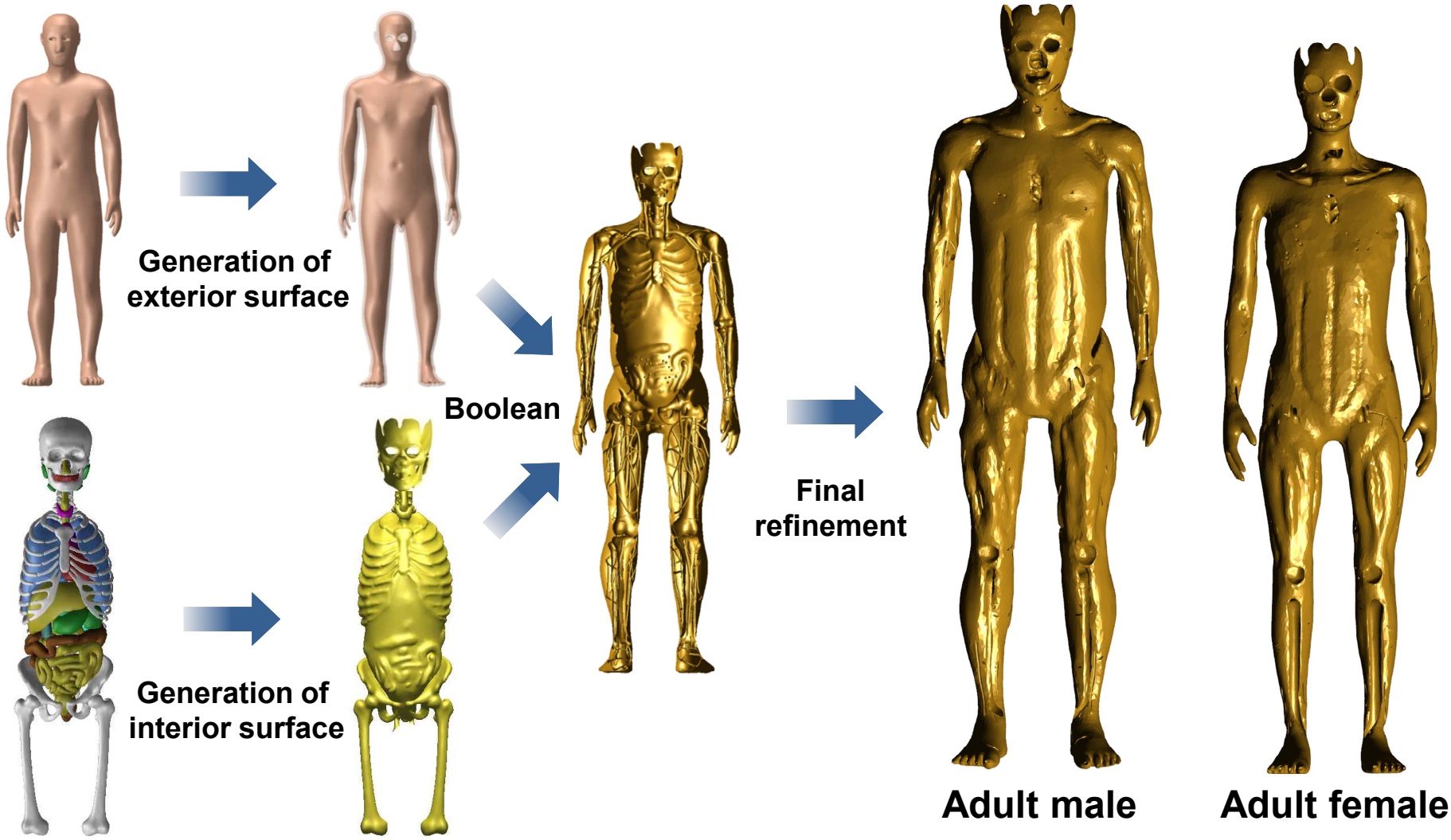
Red: arteries

Blue: veins

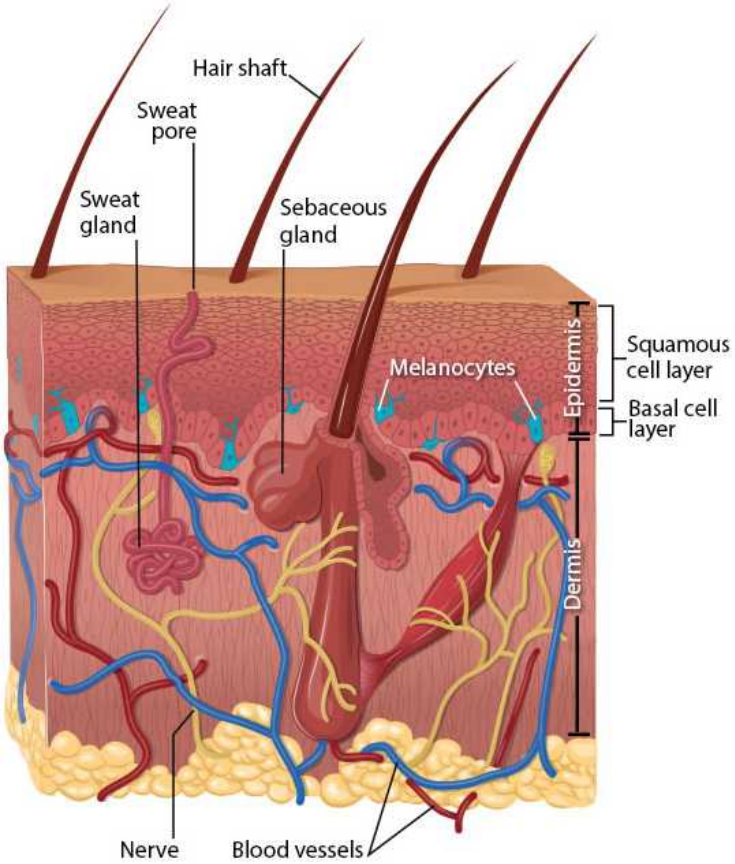
Adult male **Adult female**

Muscle

- **Manually constructed based on anatomy books and consultation with anatomists**

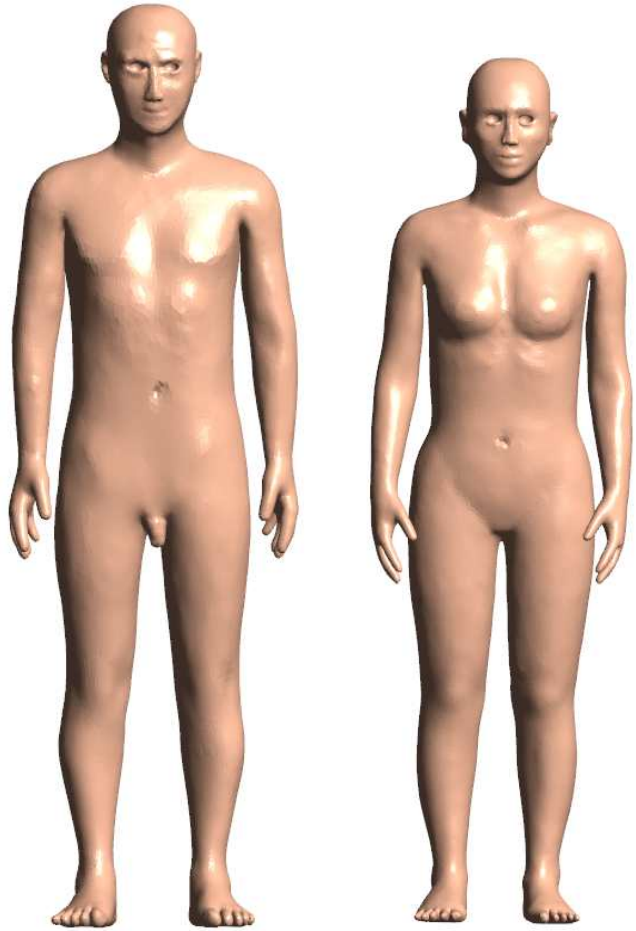


Inclusion of Skin Target Layer

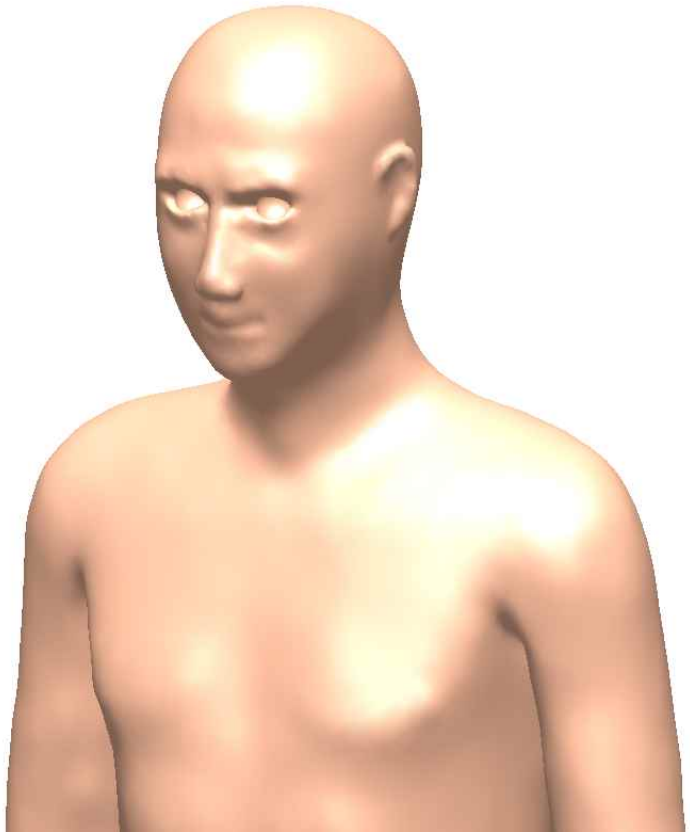


Basal cell layer in skin (50–100 μm)

Include

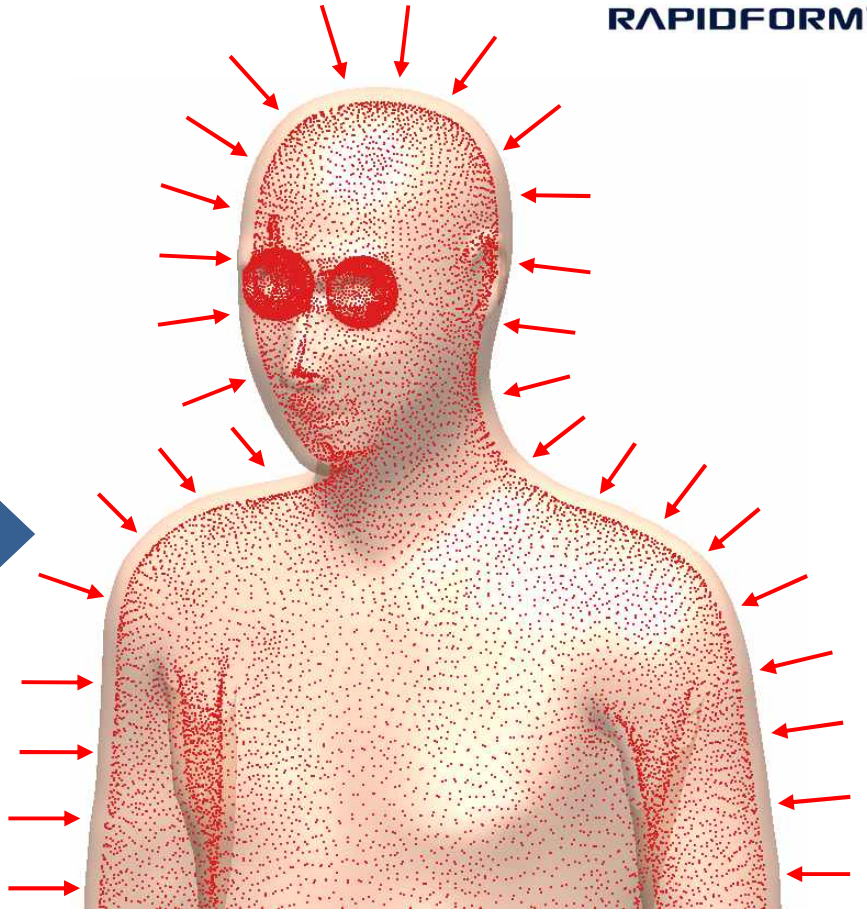


Skins of MRKPs

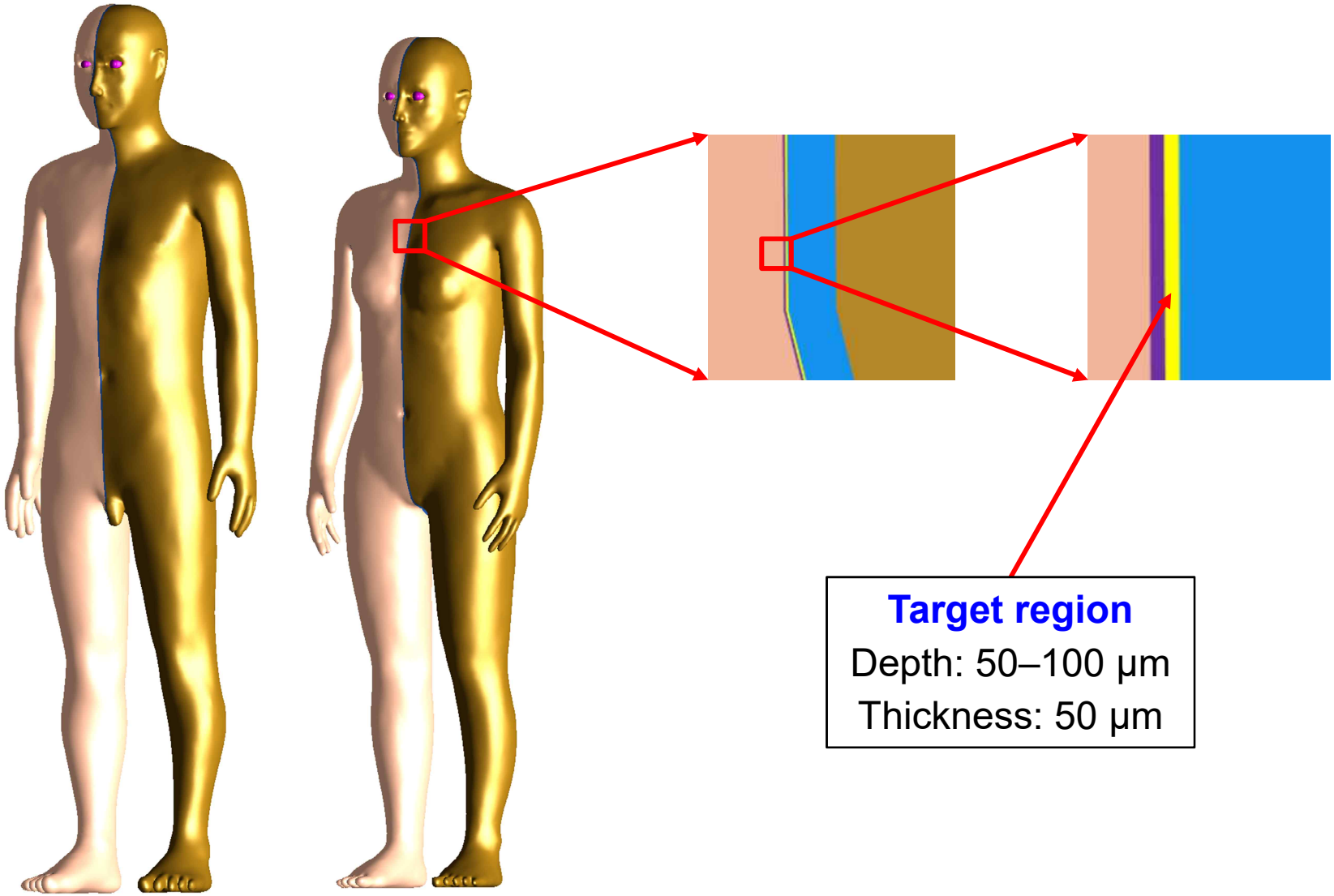


Outer skin surface

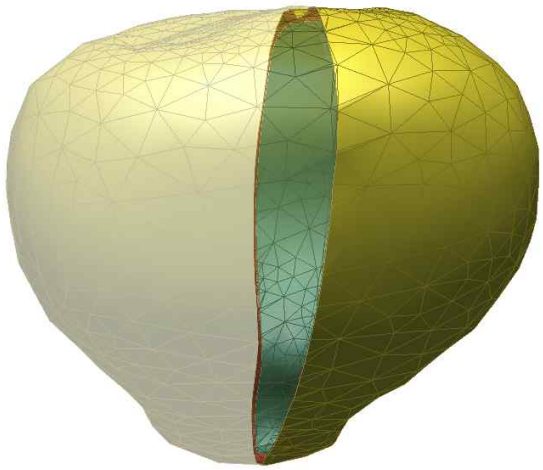
Offset



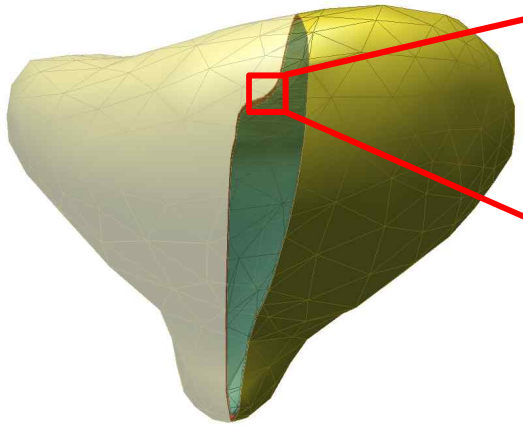
Target Layer in Skin



Target Layer in Urinary Bladder Wall



Adult male

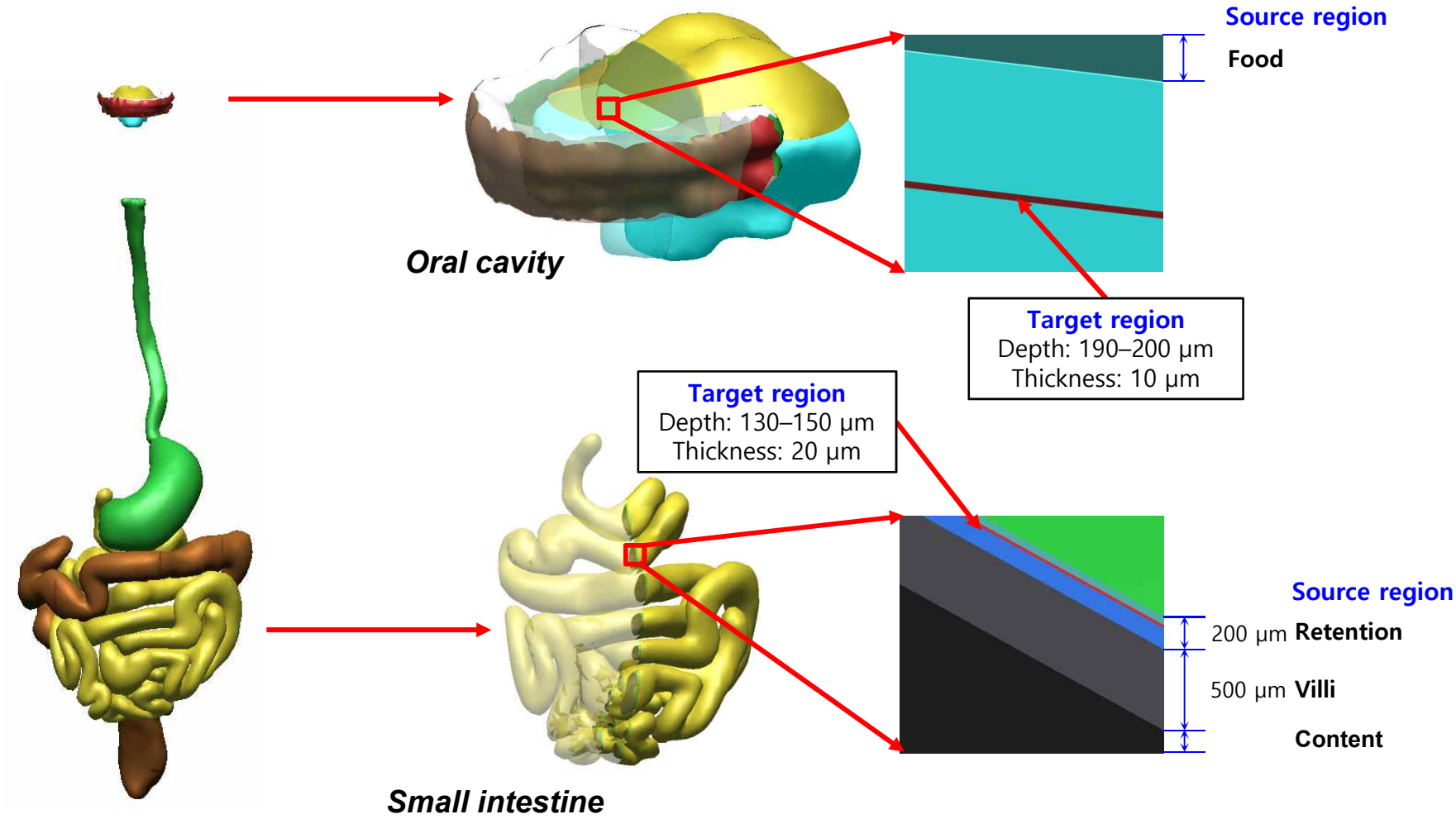


Adult female

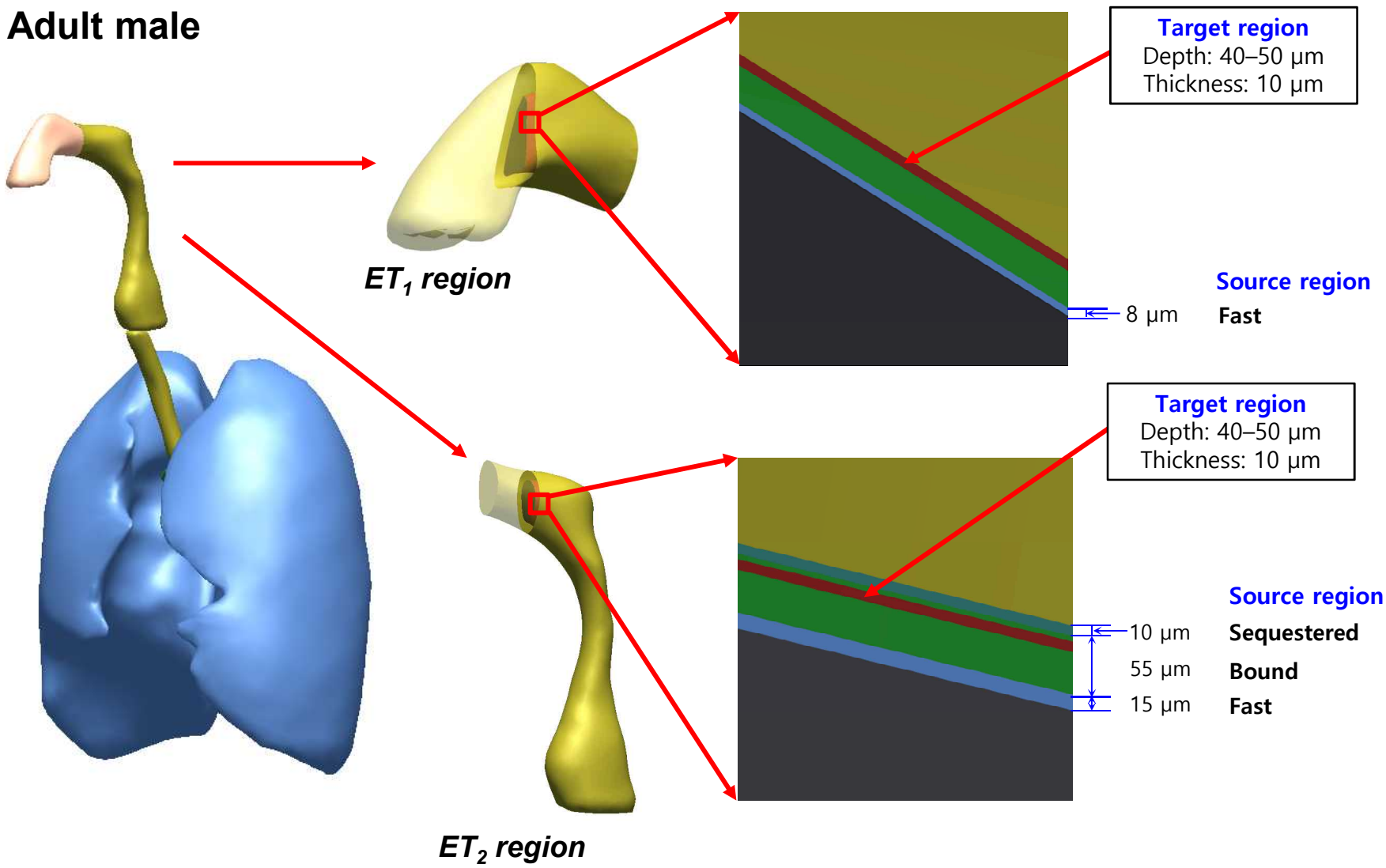
Target region
Depth: 69–185 μm
Thickness: 116 μm

Target and Source Regions in Alimentary Tract Organs

Adult male

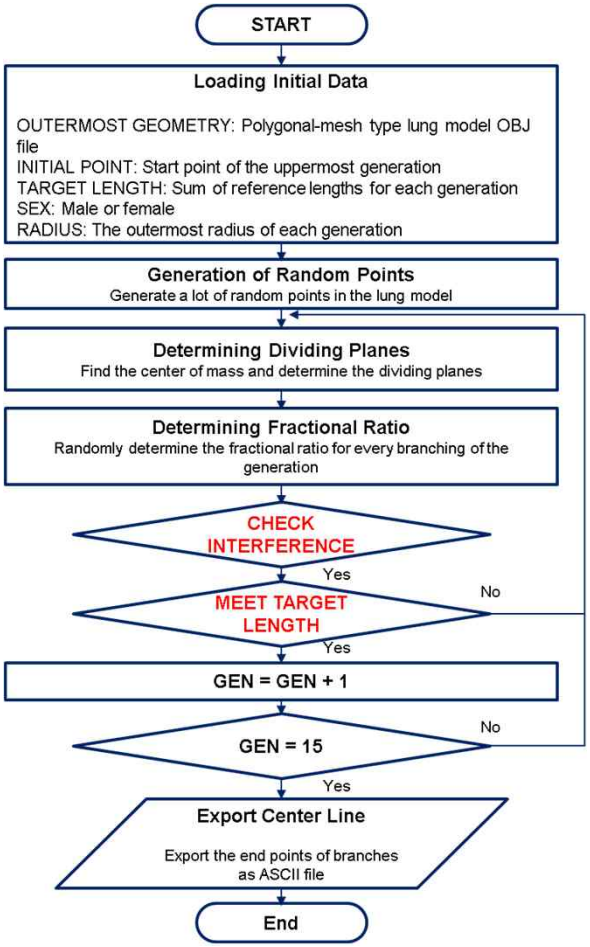


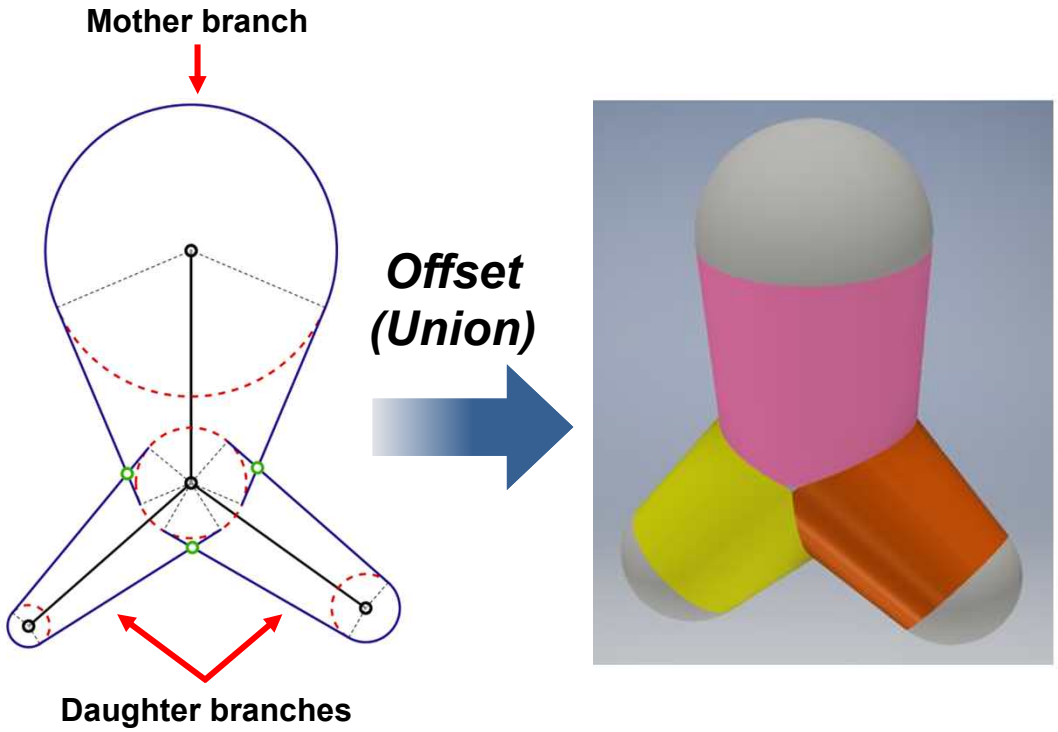
Target and Source Regions in Respiratory Tract Organs



Construction of Bronchi (BB) / Bronchioles (bb) Regions

- **Developed using the same modeling approach[14] used to generate the airway of ICRP mesh-type reference phantoms.**

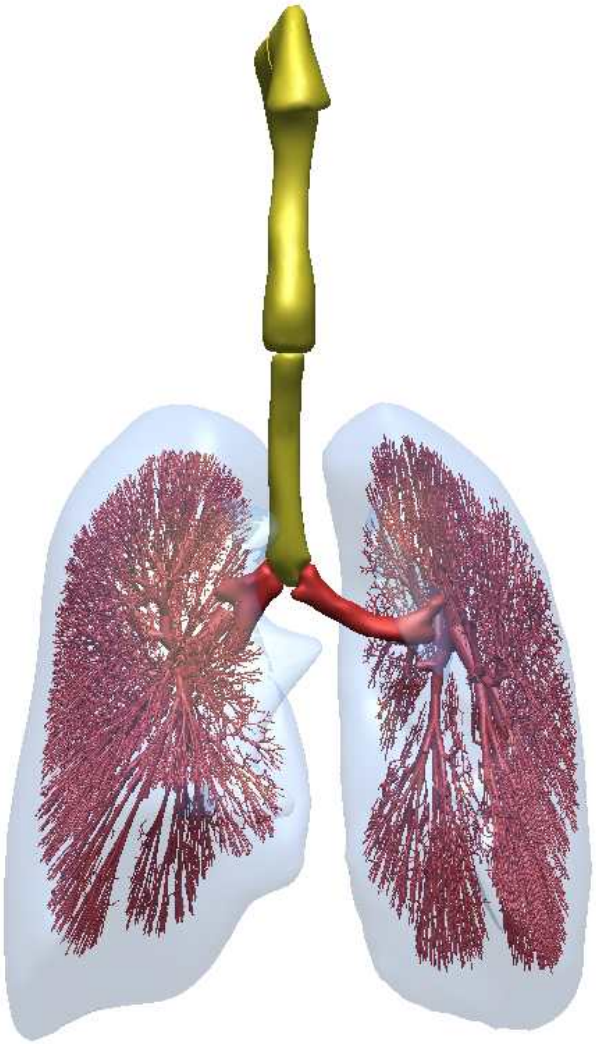




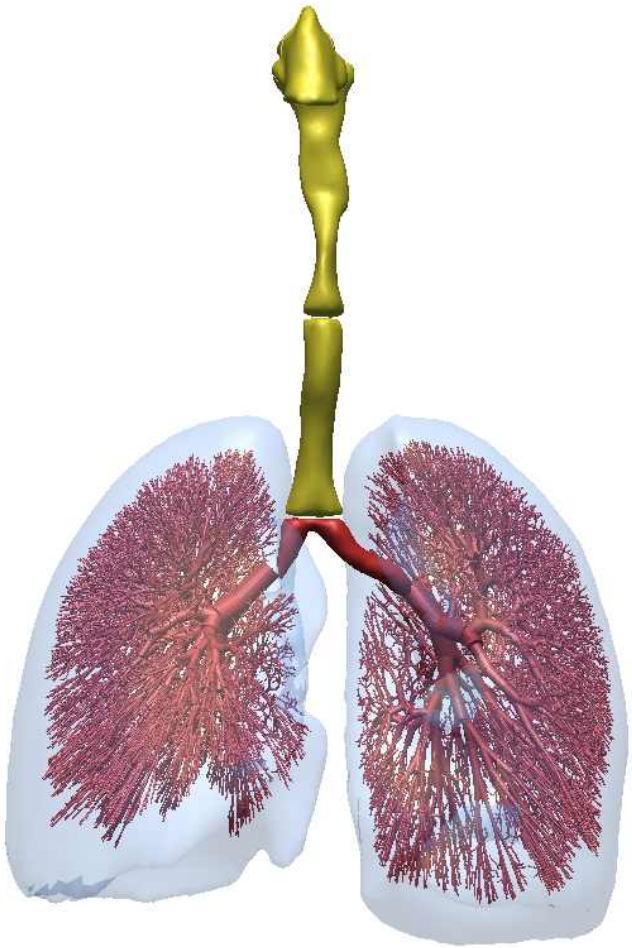
Inverted Y-shape model

[14] H. S. Kim, Y. S. Yeom, T. T. Nguyen, C. Choi, M. C. Han, J. K. Lee, C. H. Kim, M. Zankl, N Petoussi-Henss and W. E. Bolch, *Phys. Med. Biol.*, 62, 2132, 2017.

BB / bb Regions

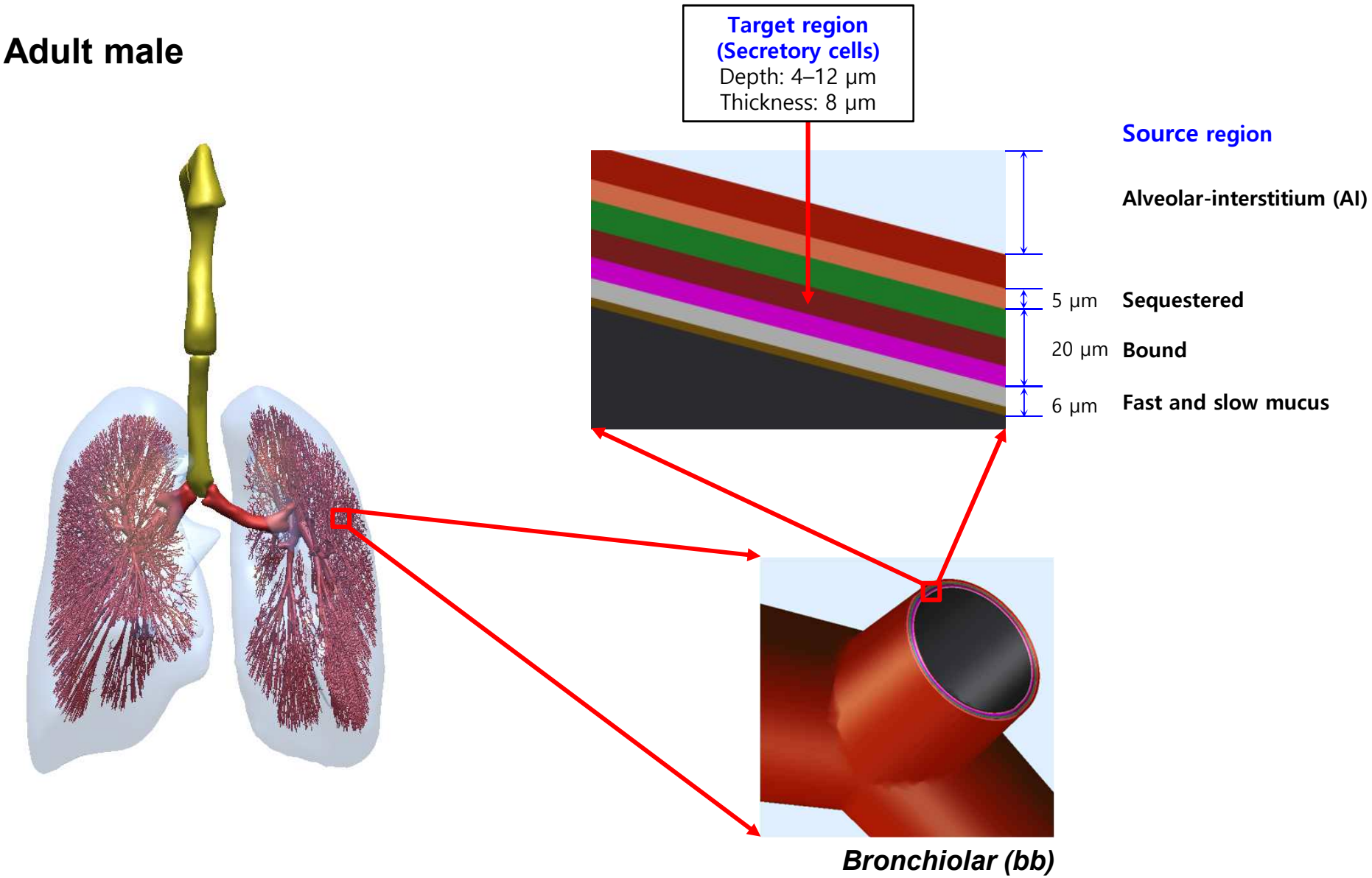


Adult male



Adult female

Target and Source Regions in BB and bb



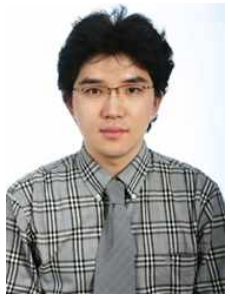
Review by Advisory Group of Anatomists

- **An advisory group of anatomists has thoroughly reviewed developed Korean reference phantoms**

Prof. Min Suk Chung
(Department of Anatomy, Ajou University School of Medicine)

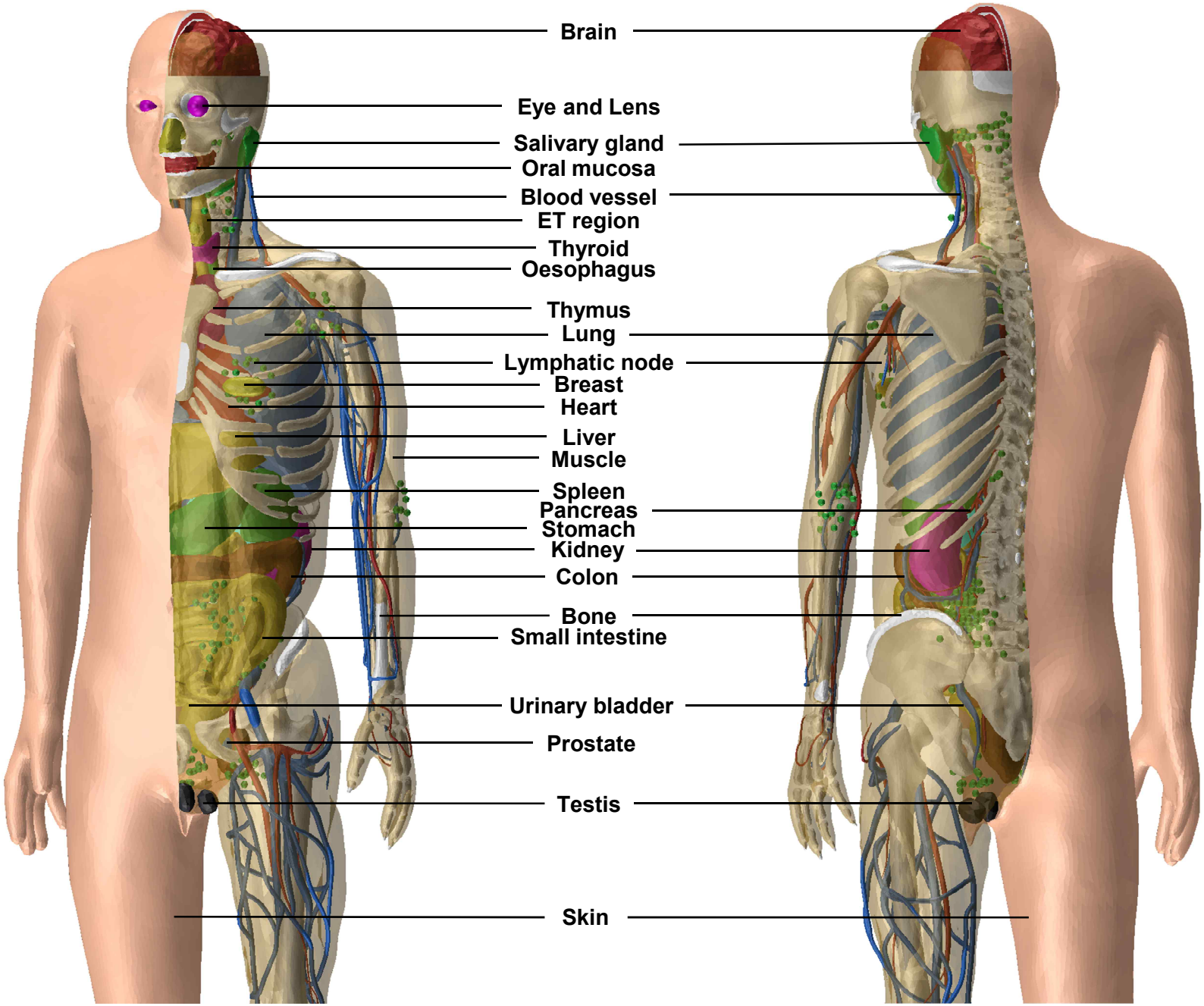
Prof. Jin Seo Park
(Department of Anatomy, Dongguk University College of Medicine)

Prof. Bong Chul Kim
(Department of Oral and Maxillofacial Surgery, Daejeon Dental Hospital, Wonkwang University College of Dentistry)

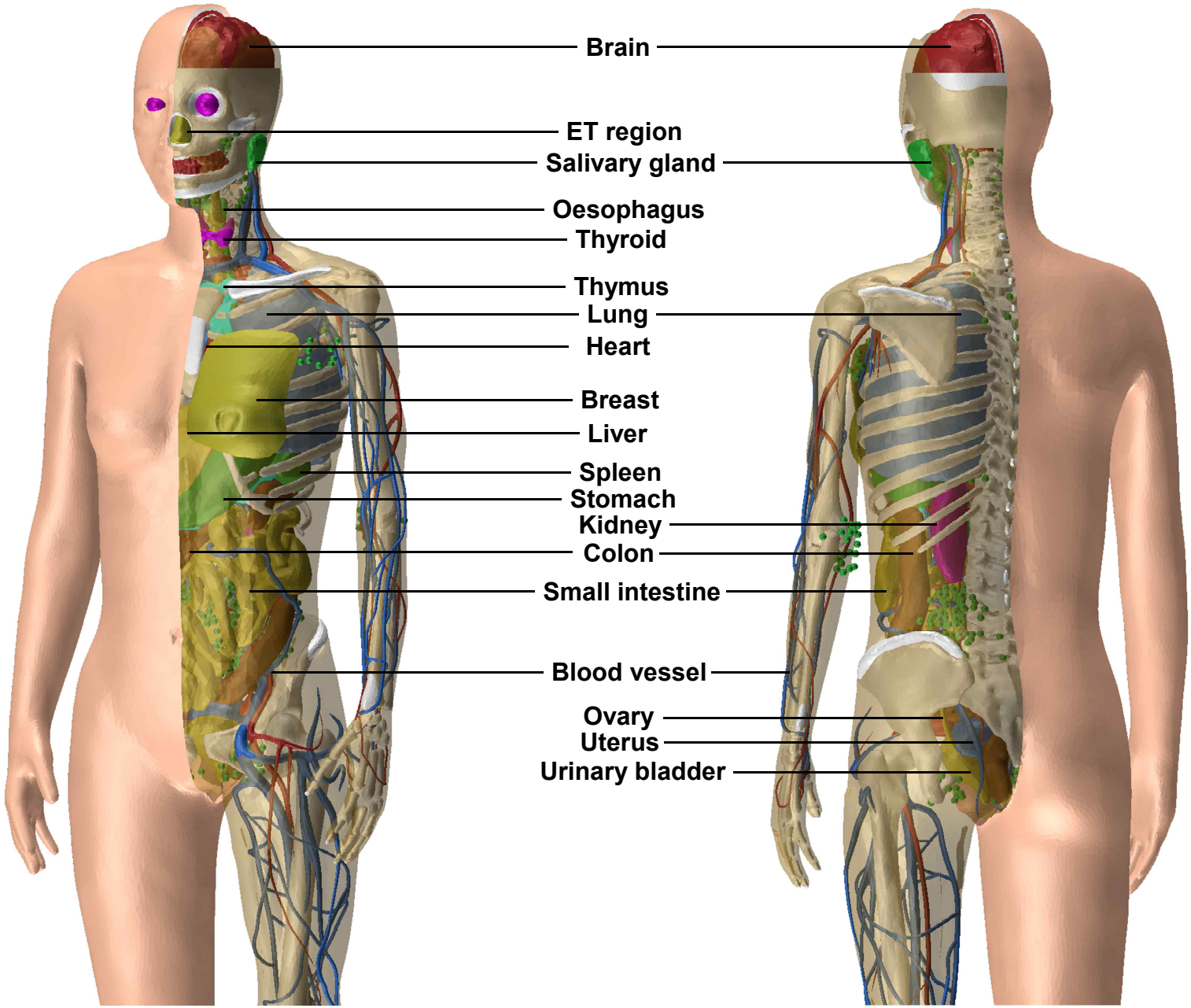


Prof. Hyo Seok Park
(Department of Anatomy, Daejeon University College of Oriental Medicine)

Korean Reference Adult Male Phantom

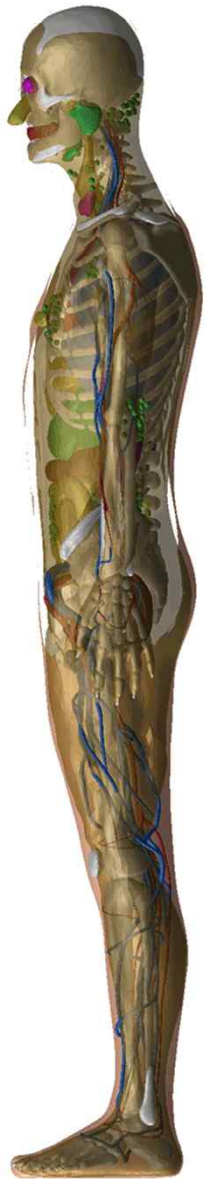


Korean Reference Adult Female Phantom



Rotational Views

Adult male

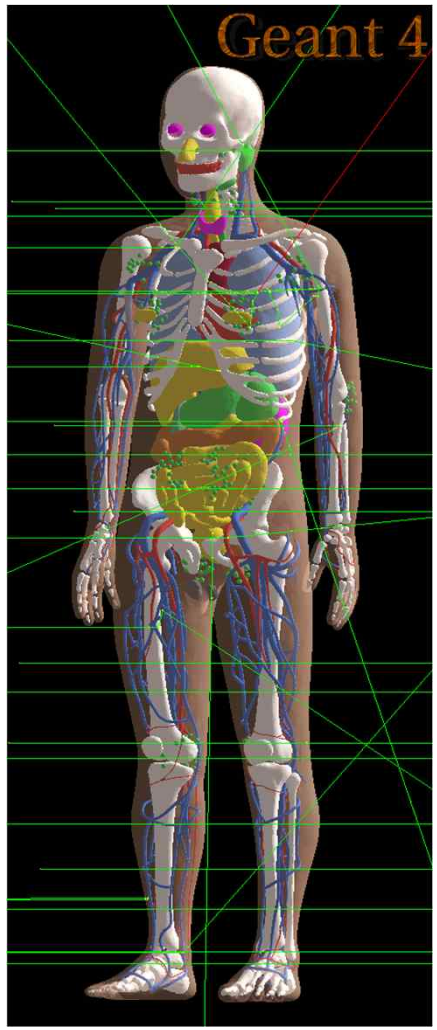


Adult female

Monte Carlo Dose Calculations with Geant4

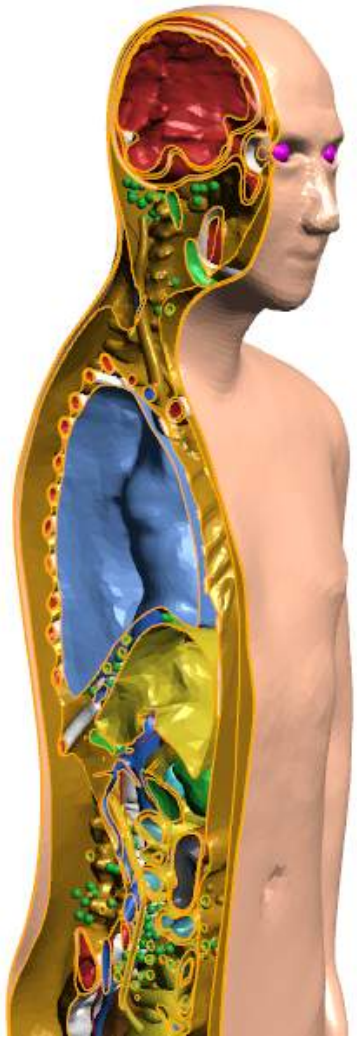
- **Calculated values**
  - ✓ Effective dose coefficients
    - Particle: photon, electron
    - Irradiation geometry: AP
    - Energy: 10 keV – 10^4 MeV
    - Relative error: less than 0.5%

- **Monte Carlo simulation conditions**
  - ✓ Geant4 version: 10.04
  - ✓ Physics library: *G4EmLivermorePhysics*
  - ✓ Secondary range cut: 1 μm



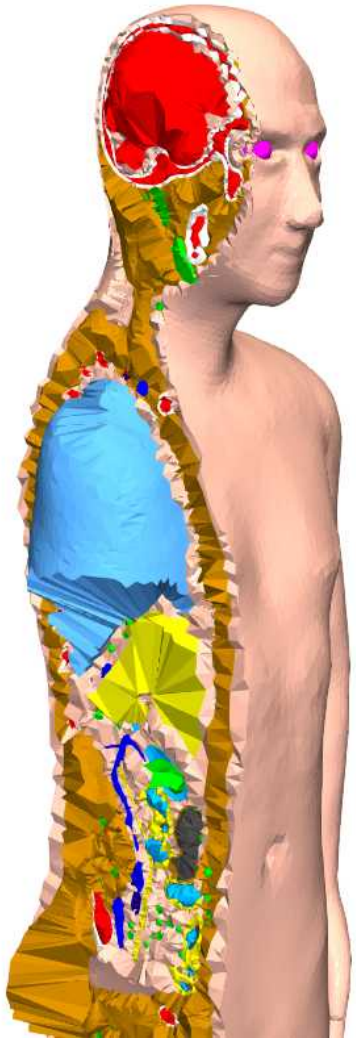
Male phantom in Geant4 (ver. 10.04)

Tetrahedralization of Korean Reference Phantoms



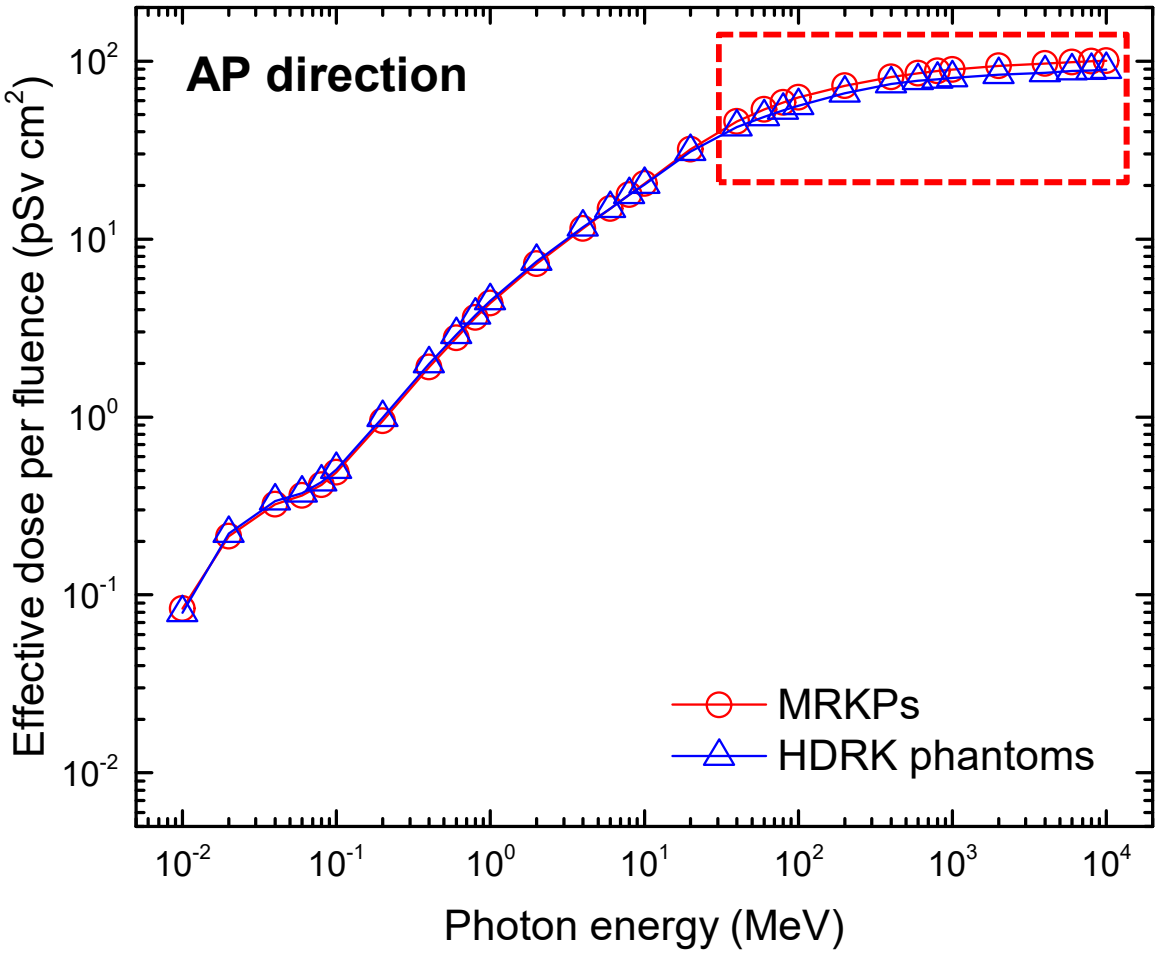
Polygonal-mesh-type Korean Reference Adult Male Phantom

Tetrahedralization



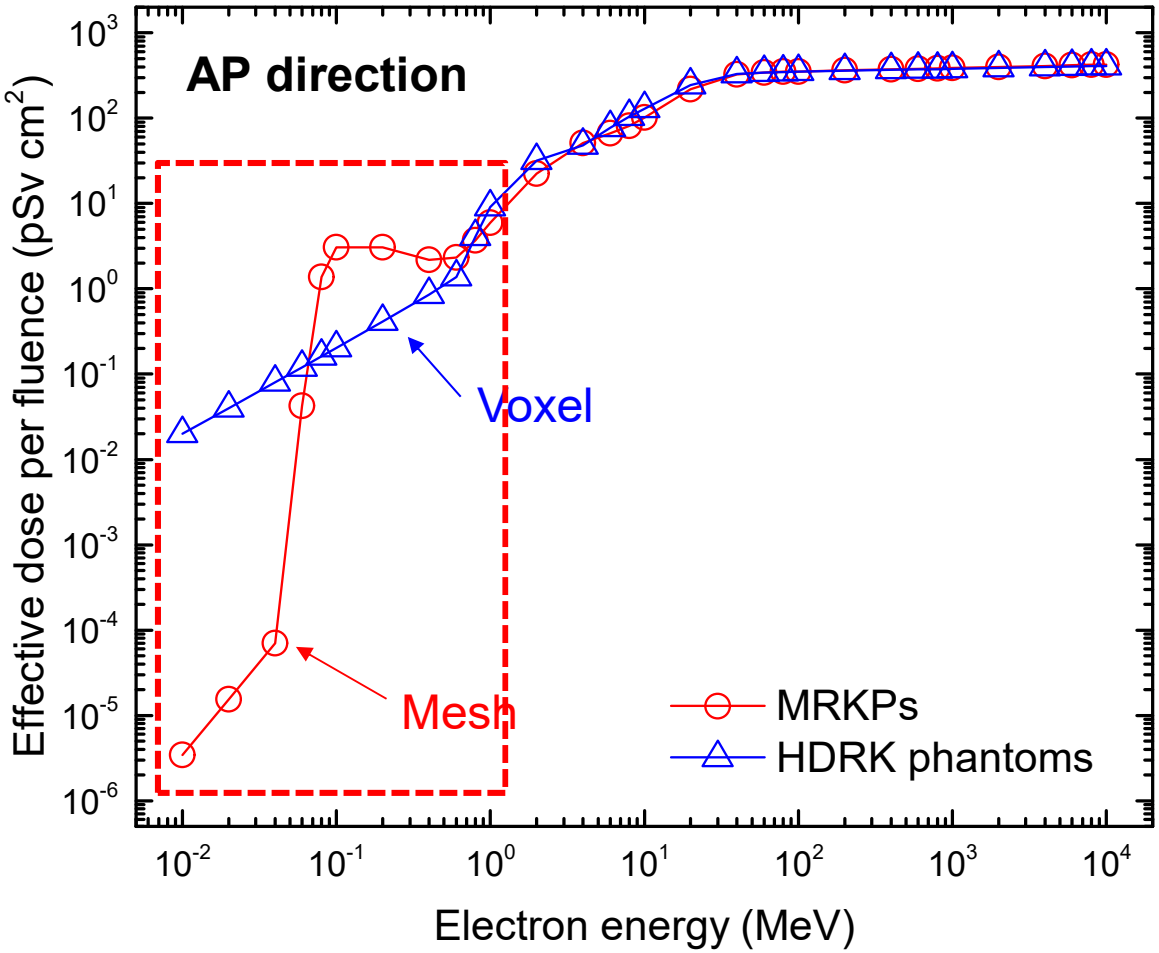
Tetrahedral-mesh-type Korean Reference Adult Male Phantom

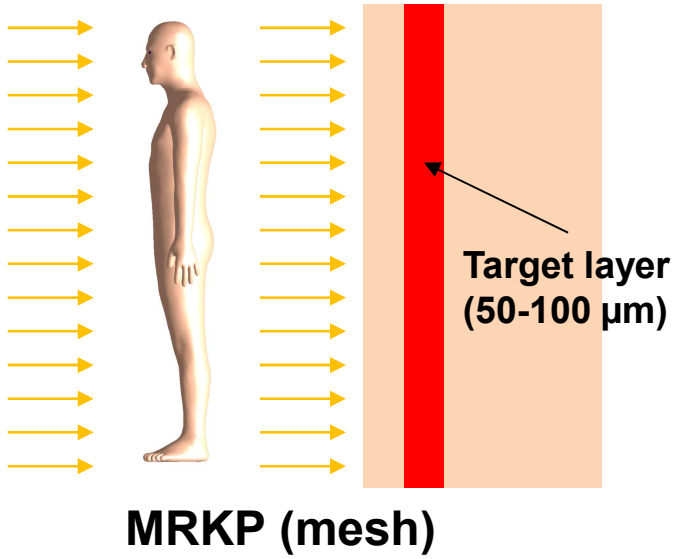
Effective Dose Coefficient for Photon Beam

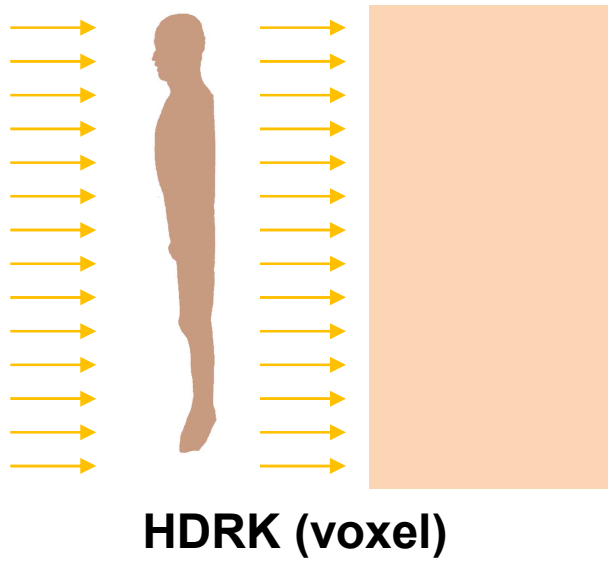


- **BMI of male**
  - **MRKP: 25.01 kg/m^2**
  - **HDRK: 23.26 kg/m^2**
- **BMI of female**
  - **MRKP: 22.55 kg/m^2**
  - **HDRK: 20.83 kg/m^2**

Effective Dose Coefficient for Electron Beam







Conclusion

- In the present study, **new Korean reference phantoms** were developed in a high quality mesh format to overcome the limitations of the previous voxel-type reference phantoms.
  - The developed phantoms are based on the **latest Korean reference** data for anthropometric parameters and organs/tissues data.
  - The developed phantoms faithfully represent the anatomical characteristics of Korean adults because most of organs are based on **information from high-quality 3-D models and images for Korean adults** provided by Korean governmental agencies.
  - The developed phantoms include all target and source regions required for effective dose calculation, even **micrometer-scale target and source regions** of the respiratory and alimentary tract organs, skin, urinary bladder, and eye lens.

- **Effective dose coefficients** of the developed phantoms were compared to those of the voxel-type reference Korean phantoms, i.e., HDRK phantoms.
  - Generally **similar dose values for photon** exposures.
  - Significantly **different dose values for electron** exposures.
- The new mesh phantoms are expected to provide **more accurate or correct dose values for Korean workers and the members of the public**, which can be valuable sources for the establishment of Korean radiation regulatory system.
- We plan to **establish the dataset of dose coefficients** for external and internal exposures for various particles using the developed phantoms.

Thank you!