Hanyang University Radiation Engineering Laboratory

Deformation of mesh-type ICRP reference computational phantoms in different statures and postures for individualized dose calculations

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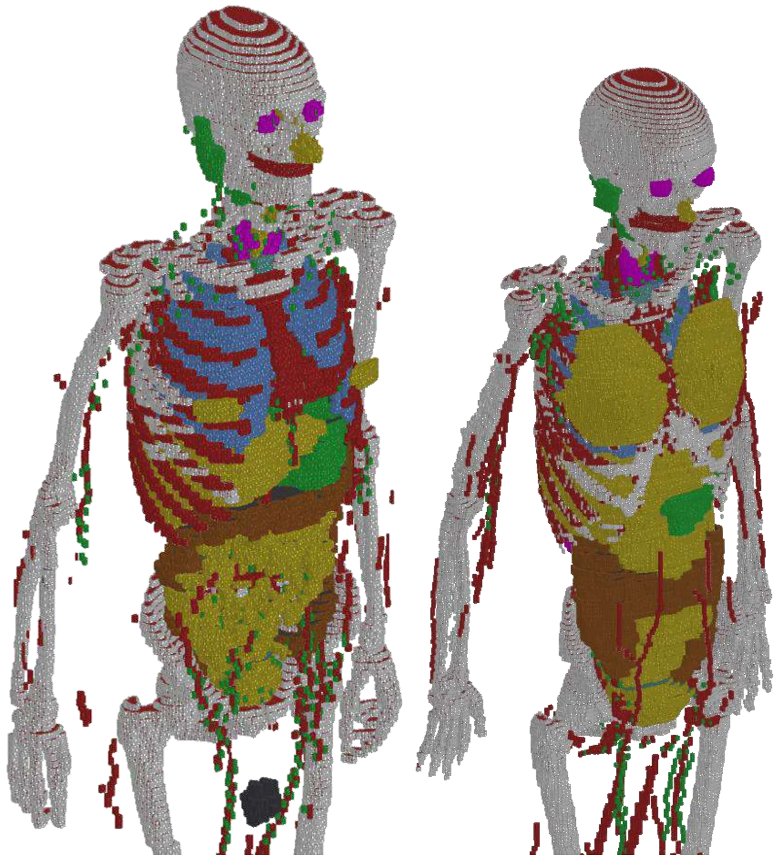
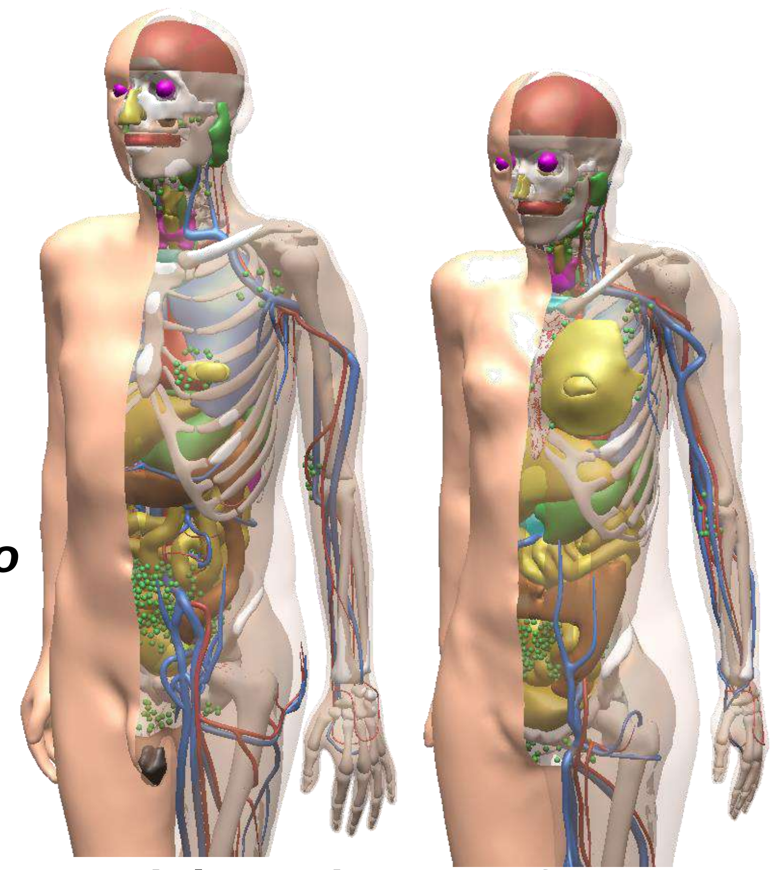
New Mesh-type ICRP Reference Phantoms (MRCP)



ICRP adult voxel-type reference phantoms

Conversion to mesh format



ICRP adult mesh-type reference phantoms

- One of substantial advantages is ***'high deformability,'*** which encourages us to deform the reference phantoms in different statures and postures.

Objective of the Present Study

Stature deformation

- The stature of mesh-type ICRP reference computational phantoms (MRCPs) were deformed to represent **the 10th and 90th percentiles of Caucasian population.**

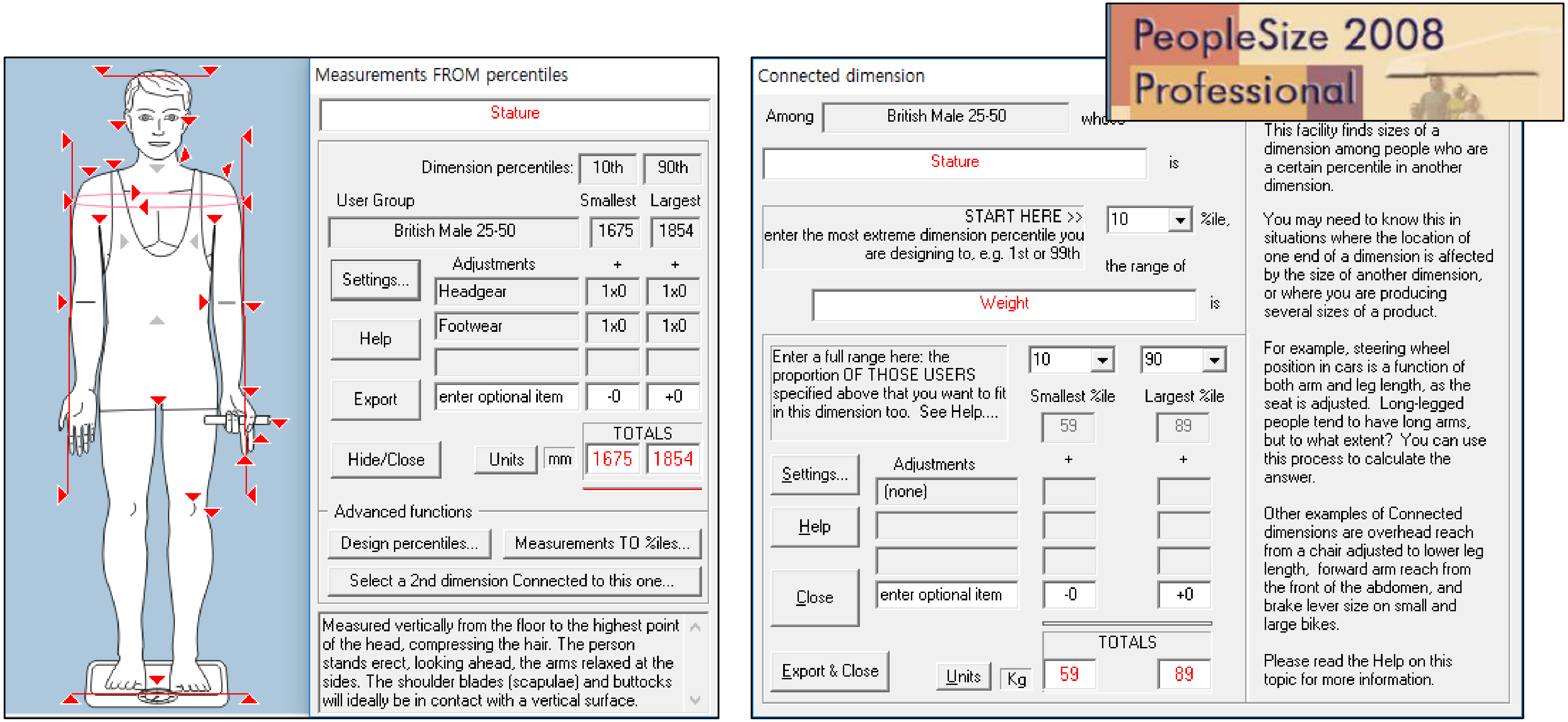
Posture deformation

- **A systematic procedure for realistic posture change** of mesh-type phantoms was developed based on ***'as-rigid-as-possible (ARAP) shape deformation'***.

- The developed method was used to **deform the ICRP adult male mesh-type reference computational phantom (MRCP)** following several postures of a real person via a motion capture device.

1. Phantom Deformation in Different Statures

10^{th} and 90^{th} percentile standing height and weight



- 10^{th} and 90^{th} percentile values for standing height and body weight for nine countries (i.e., Sweden, Netherlands, Germany, Belgium, Australia, USA, France, UK, and Italy) were extracted from the anthropometry program **PeopleSize**.

Determination of lean body mass

- **Lean Body Mass (LBM) equation (Deurenberg et al. 1991)**

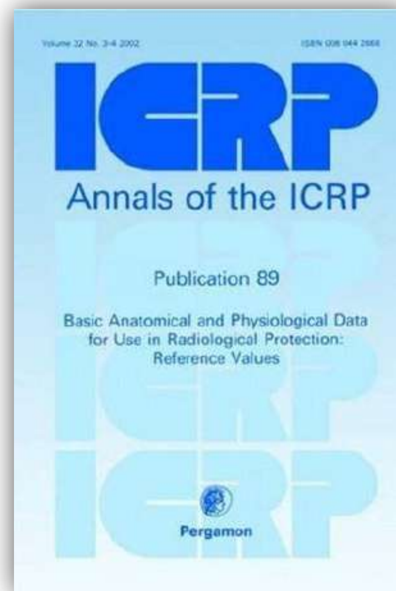
$$\boldsymbol{LBM = W - [\,W \times \frac{1.2 \times \left({}^{W}\!/_{H^2}\right) + 0.23 \times A - 10.8(if\ male) - 5.4}{100}]}$$

where LBM is Lean body mass (kg), H is height (cm), W is weight (kg), A is age (yr).

Deurenberg, Paul, Jan A. Weststrate, and Jaap C. Seidell. "Body mass index as a measure of body fatness: age-and sex-specific prediction formulas." British journal of nutrition 65.2 (1991): 105-114.

- **LBM** is defined as a mass subtracting fat mass from whole body mass, and has a **high correlation with the masses of most internal organs and tissues** (Bosy-Westphal et al. 2004).
- The differences between the LBM from the ICRP Publication 89 and the LBM calculated by LBM equation for reference body shape are 0.16% for male and 0.36% for female, respectively.

Determination of skin mass



1. **Surface area of the body(SA)** was first calculated by using the equation given in *ICRP publication 89*.

$$\boldsymbol{Suface\ area\ of\ the\ body\ (SA)}$$

$$= \mathbf{0.0235} \times \boldsymbol{H^{0.42246}} \times \boldsymbol{W^{0.51456}}$$

where SA is surface area (m^2), H is height (cm), W is weight (kg).

2. **Skin mass** was then calculated from reference skin mass given in *ICRP publication 89* by assuming that the skin mass is proportional to SA.

$$\boldsymbol{Skin\ mass_{target} = Skin\ mass_{ICRP-89} \times \frac{SA_{target}}{SA_{ICRP-89}}}$$

Determination of Anthropometric parameters

- Calf circumference
- Upper arm circumference
- Waist circumference
- Thigh circumference
- Buttock circumference
- Sagittal abdominal diameter

NHANES Continuous (1999 – 2014) & III (1988 – 1994)

National Center for Health Statistics

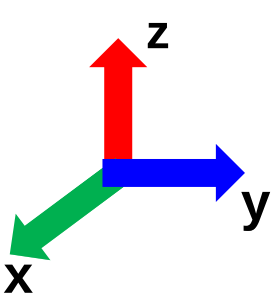
National Health and Nutrition Examination Survey

- Head breadth
- Head length

ANSUR II (2010 – 2012)

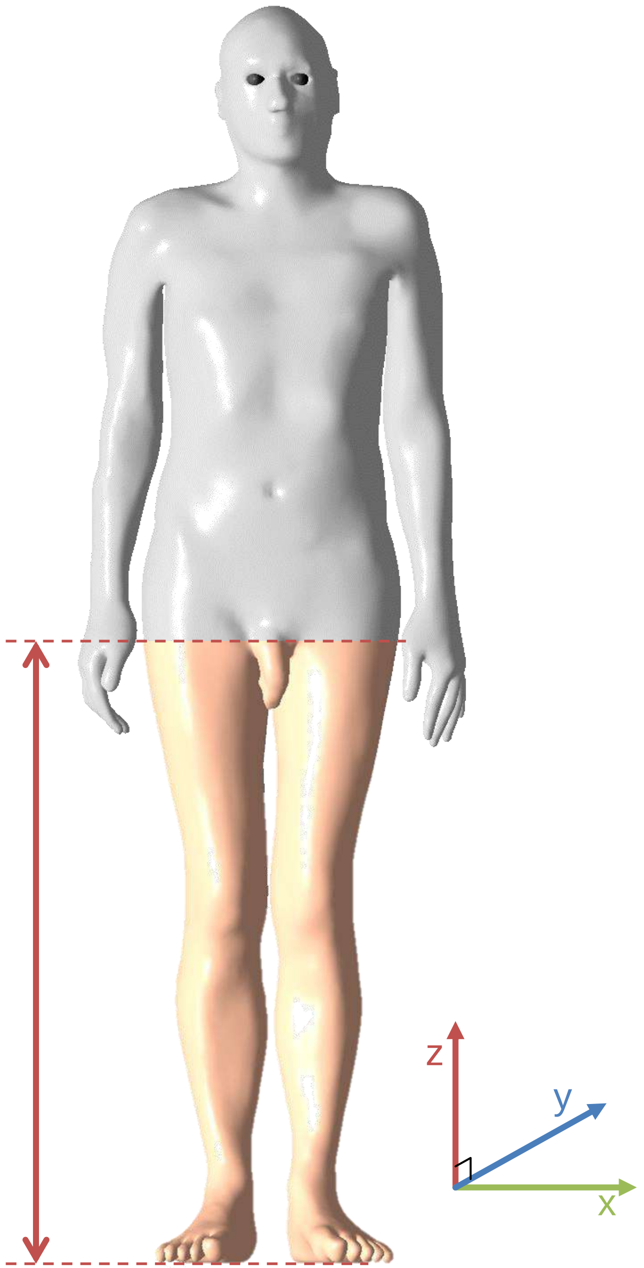
Adjustment of phantom height

1) Head height, torso length, and leg length are scaled in the **z direction**, respectively, to match the target standing height.



Adjustment of phantom height

1) Head height, torso length, and leg length are scaled in the **z direction**, respectively, to match the target standing height.



× the scaling factor for leg length

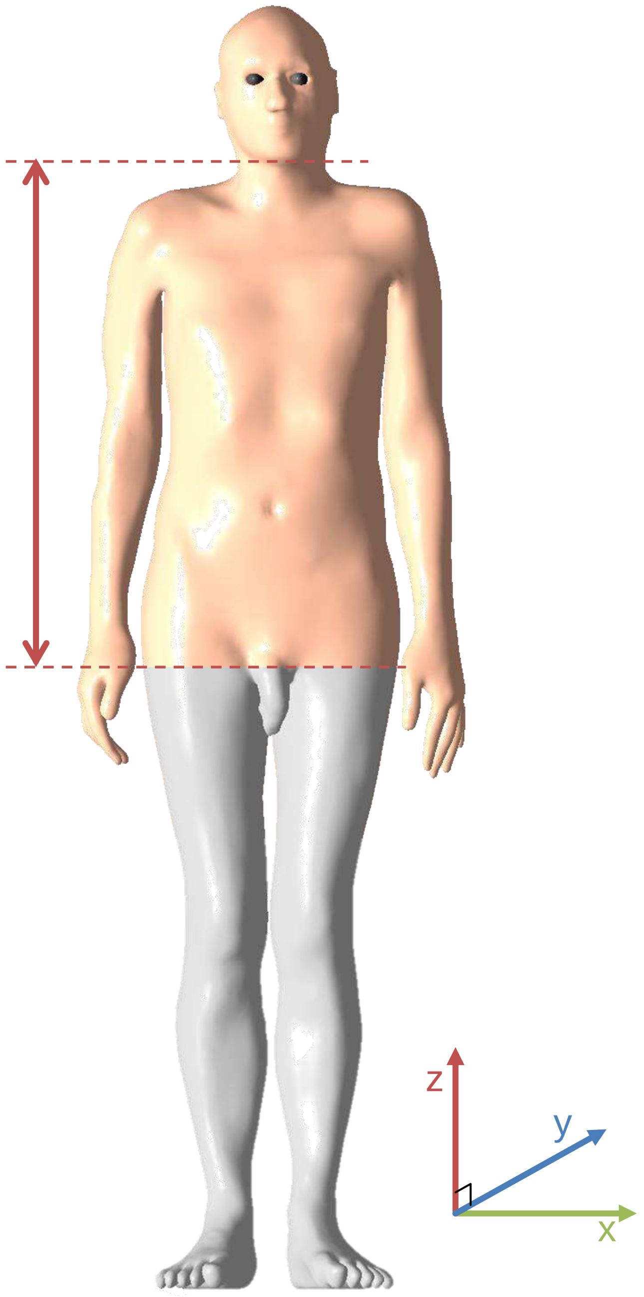
$$\left(= \frac{\boldsymbol{the\ target\ leg\ length}}{\boldsymbol{the\ leg\ length\ of\ adult\ male\ MRCP}}\right)$$

Adjustment of phantom height

1) Head height, torso length, and leg length are scaled in the **z direction**, respectively, to match the target standing height.

$\times$ **the scaling factor for torso length**

$$\left(= \frac{\textit{the target torso length}}{\textit{the torso length of adult male MRCP}}\right)$$



Adjustment of phantom height

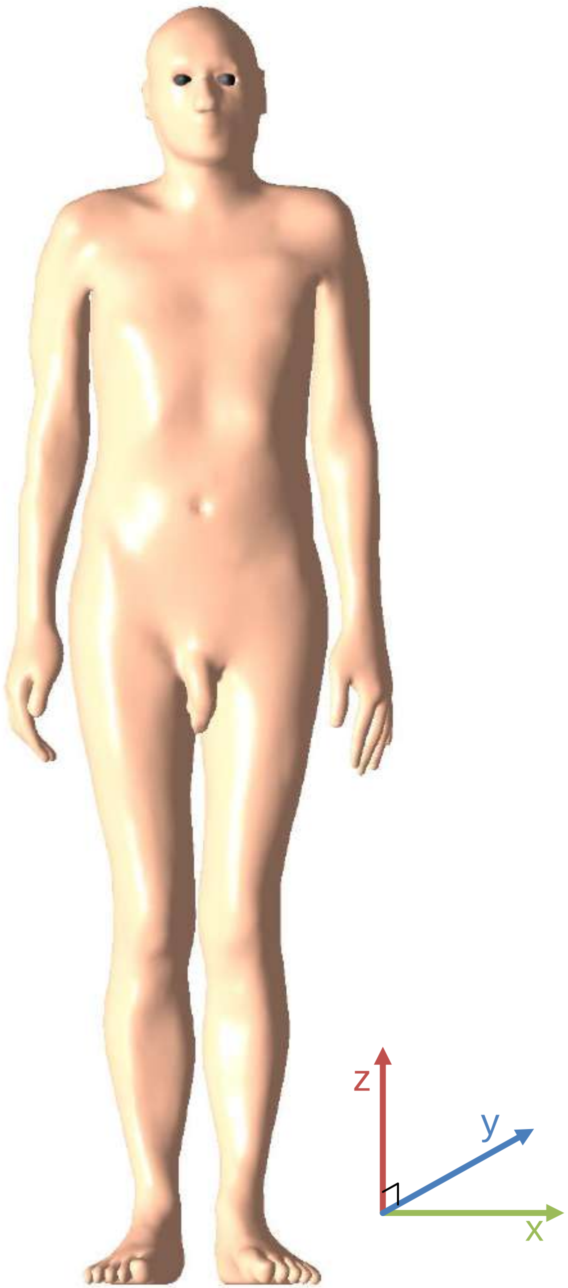
1) Head height, torso length, and leg length are scaled in the **z direction**, respectively, to match the target standing height.

× **the scaling factor for head height**

$$\left(= \frac{\textit{the head height at target standing height}}{\textit{the head height at adult male MRCP height}}\right)$$

Adjustment of phantom height

2) Torso and legs are scaled **in the x and y directions** by using ***<u>'Lean body mass (LBM).'</u>***

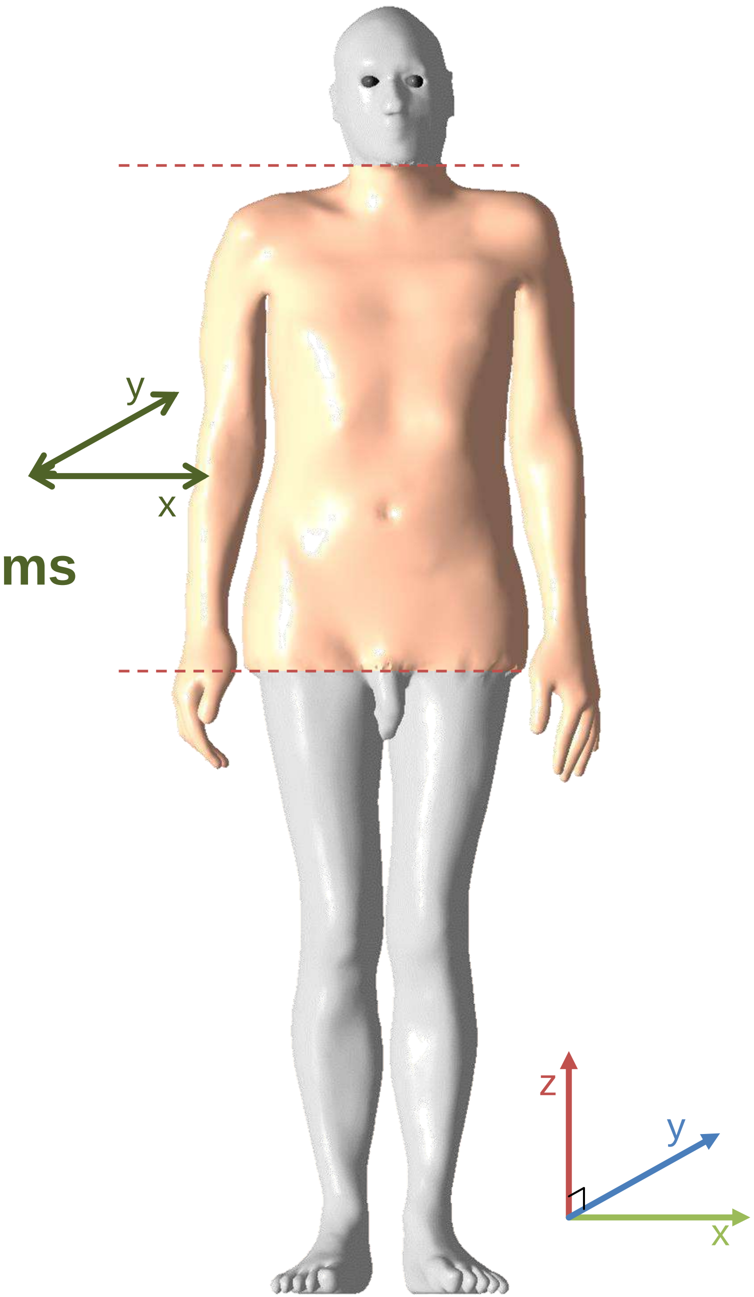


Adjustment of Organ/Tissue Masses

2) Torso and legs are scaled **in the x and y directions** by using ***<u>'Lean body mass (LBM).'</u>***

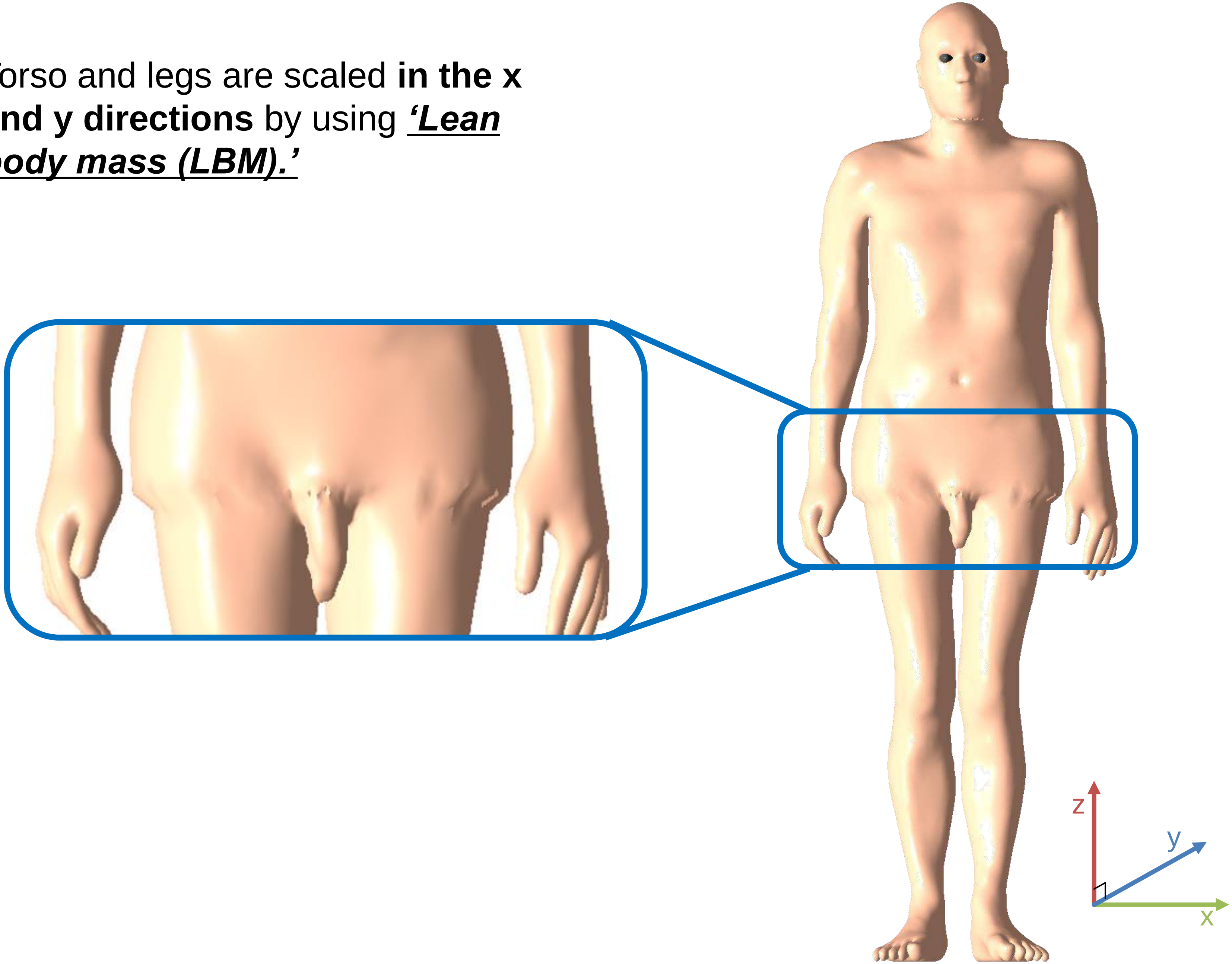
× the scaling factor of the torso and arms for LBM

$$\left(= \sqrt{\frac{LBM_{target} \,/\, LBM_{MRCP}}{the\ scaling\ factor\ for\ torso\ length}}\right)$$



Adjustment of phantom height

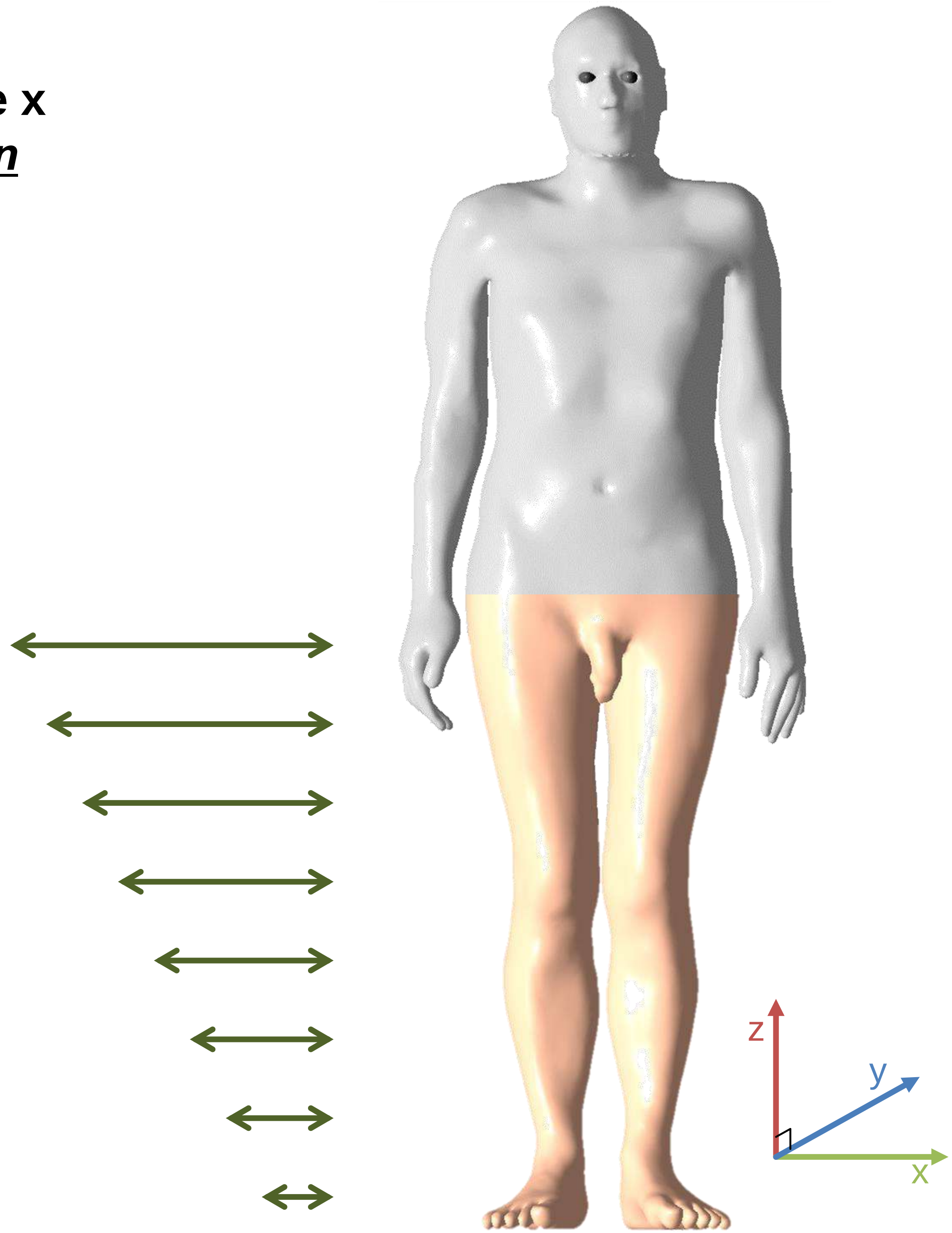
2) Torso and legs are scaled **in the x and y directions** by using ***<u>'Lean body mass (LBM).'</u>***



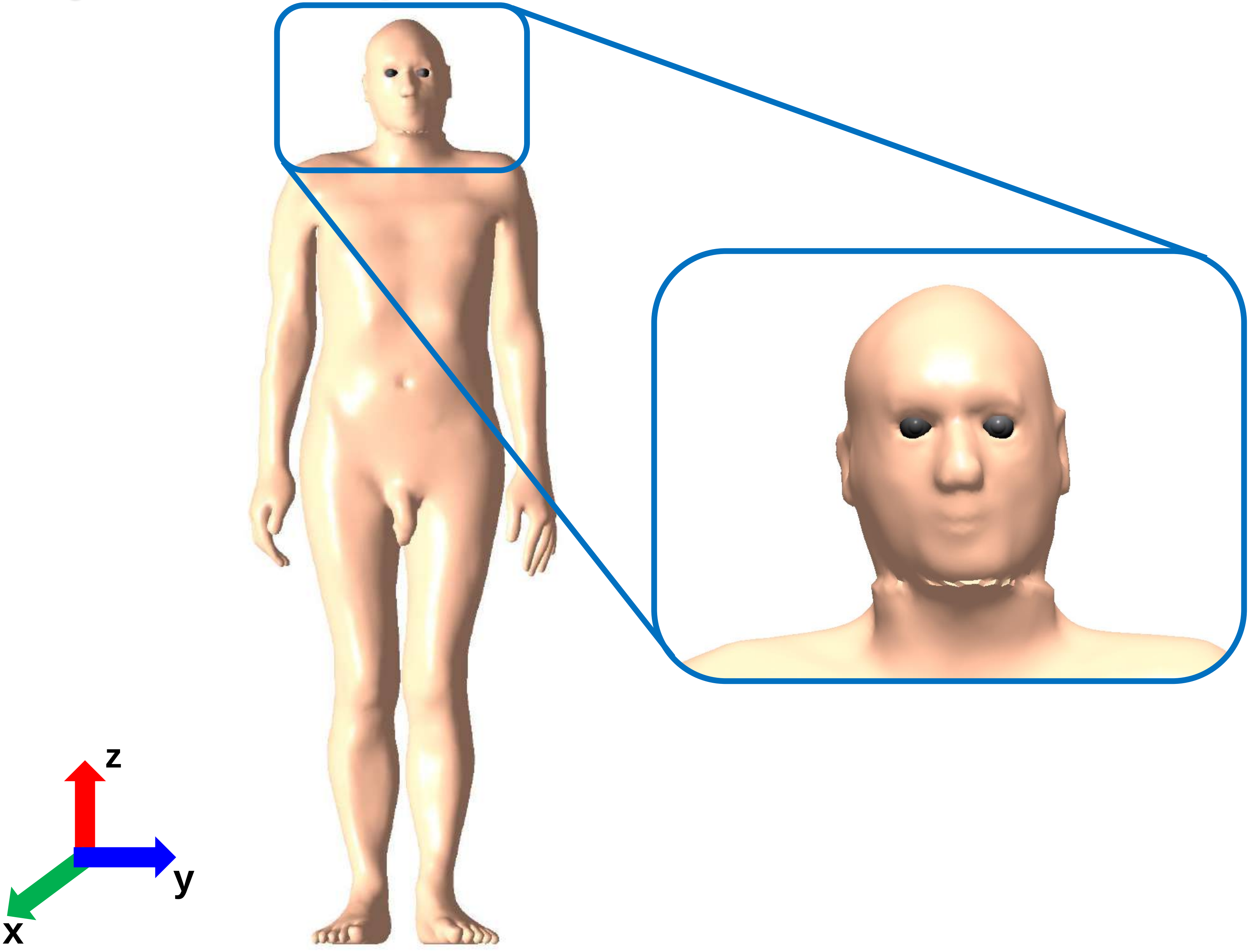
Adjustment of phantom height

2) Torso and legs are scaled **in the x and y directions** by using ***<u>'Lean body mass (LBM).'</u>***

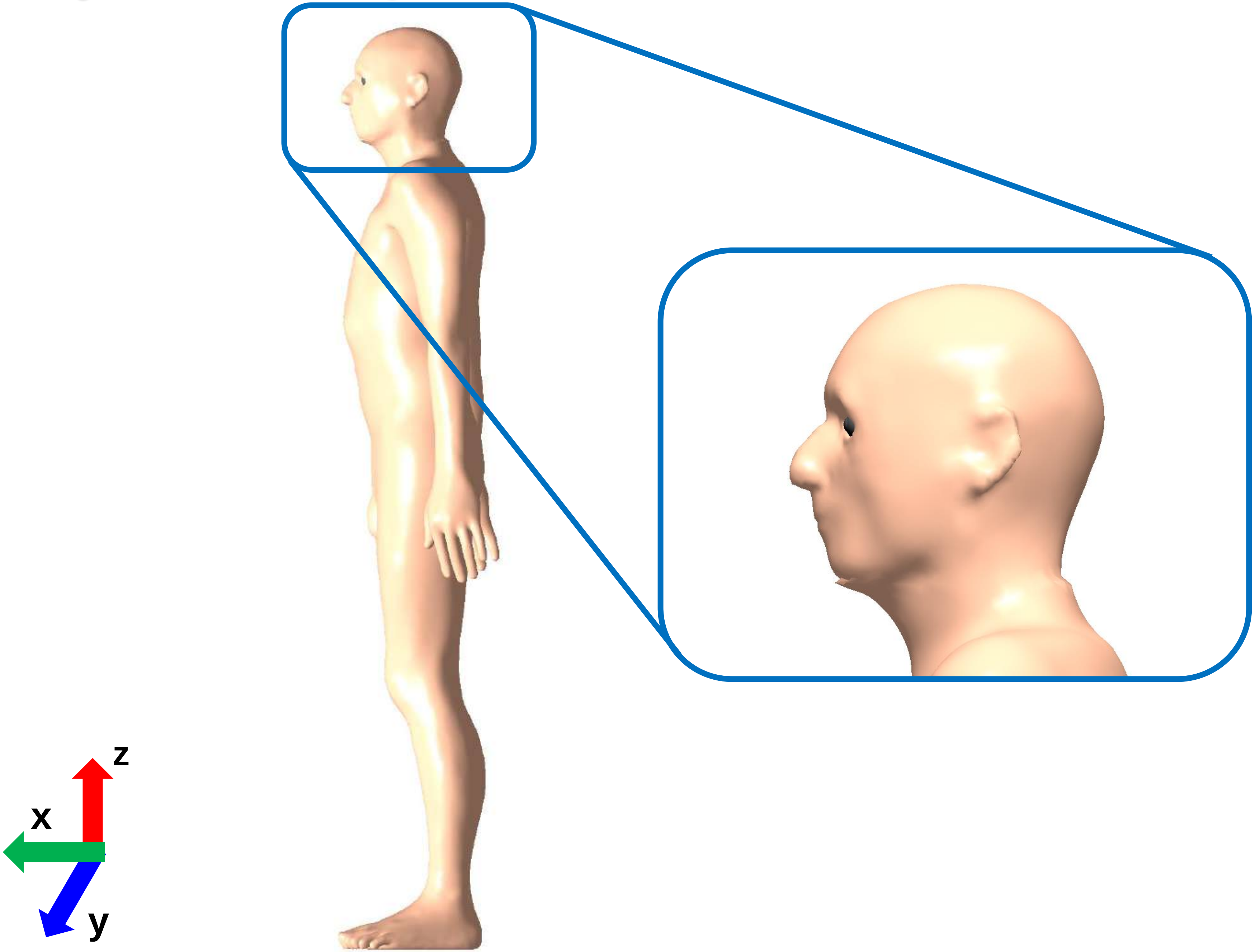
Dislocation problem was addressed by applying the scaling factor **<u>linearly</u>**



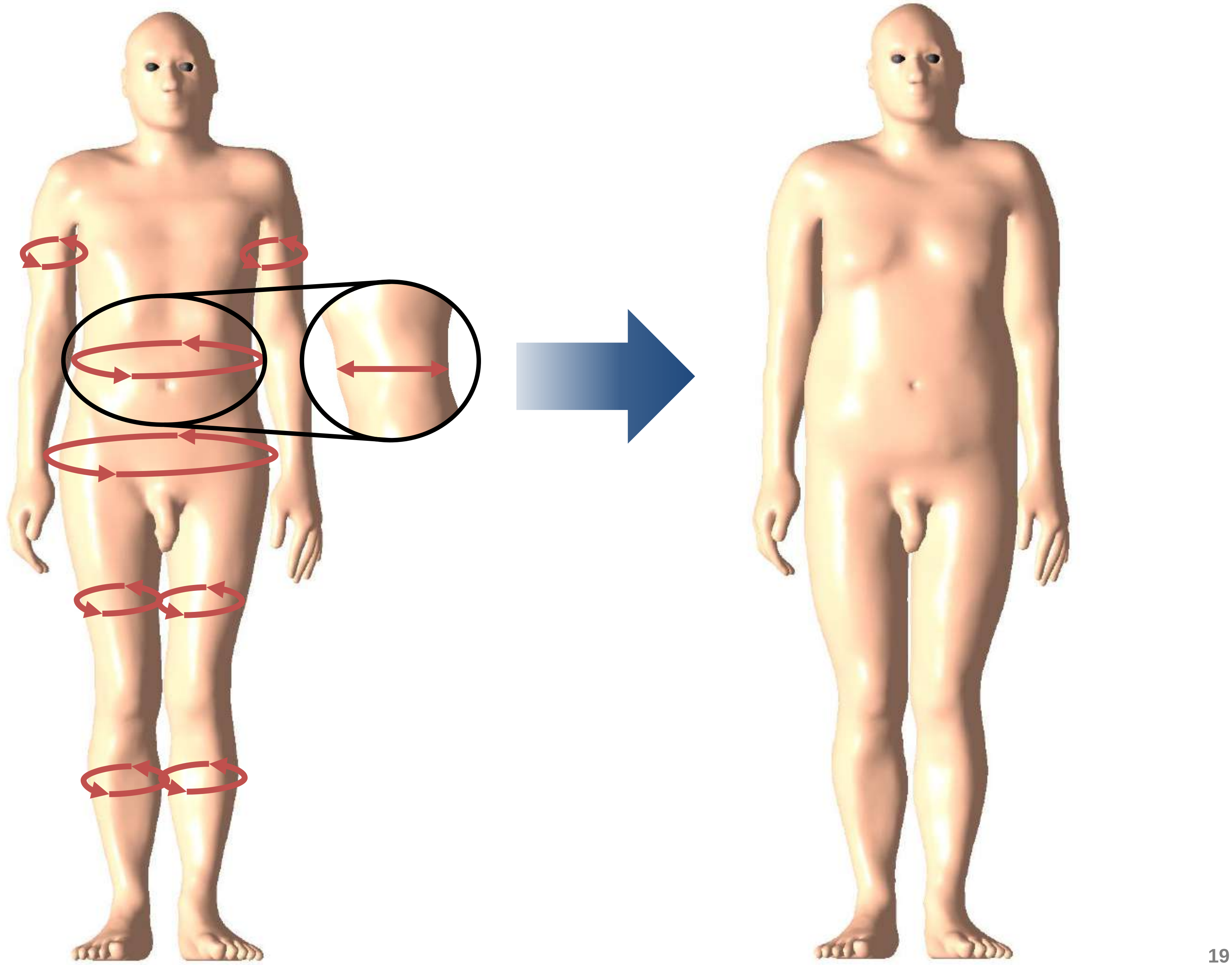
Adjustment of phantom head dimension



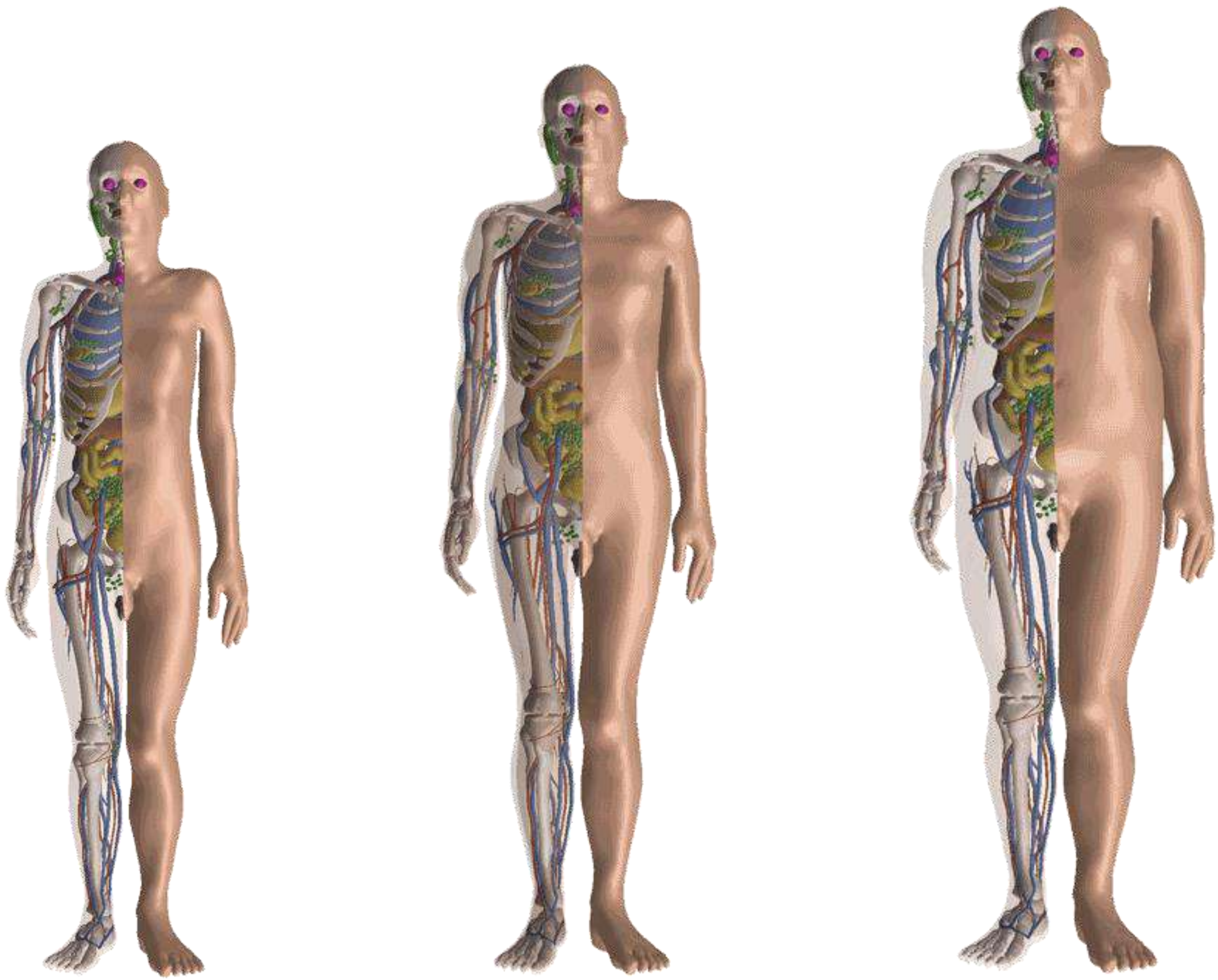
Adjustment of phantom head dimension



Adjustment of phantom weight

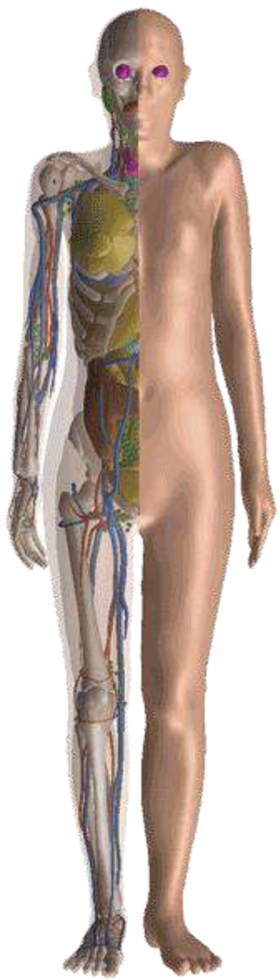


Male phantoms in different body shapes

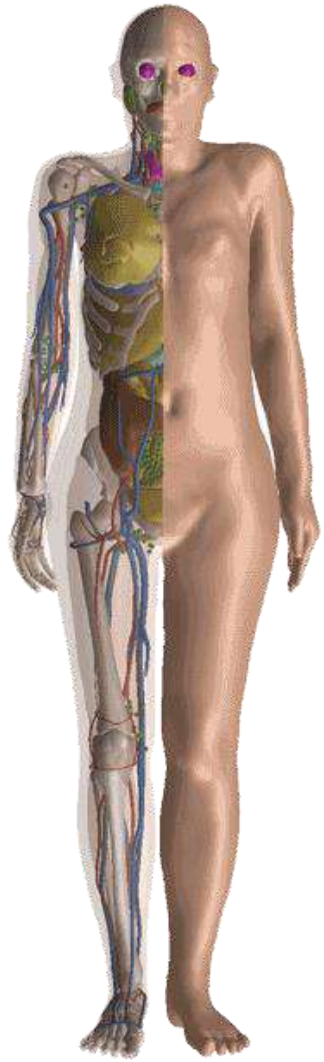


H10W10-AM **MRCP-AM** **H90W90-AM**

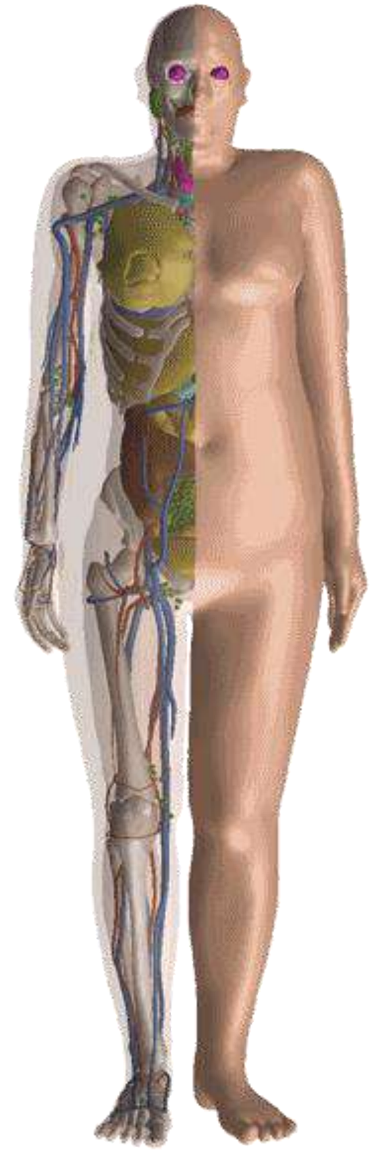
Female phantoms in different body shapes



H10W10-AF



MRCP-AF

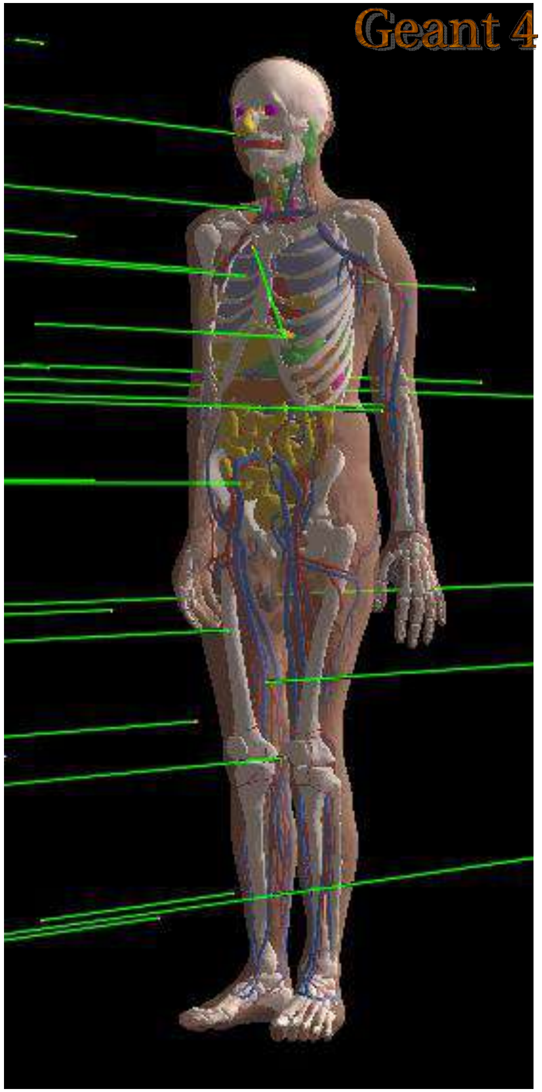


H90W90-AF

Dose Calculations with Geant4

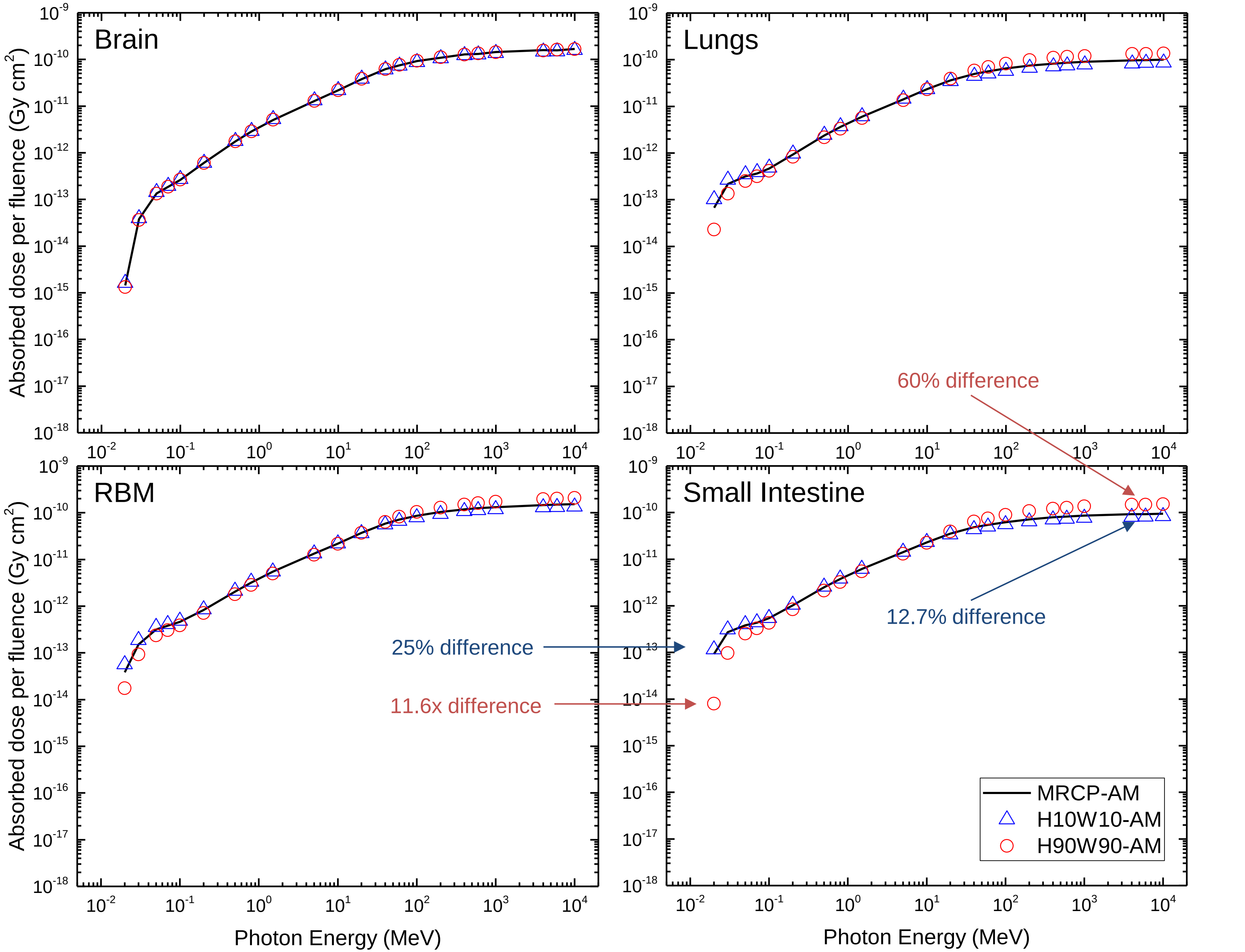
- **Calculated values**
  - ✓ Organ/tissue dose coefficients for photons
    : brain, lungs, RBM, small intestine

- **MC simulation conditions**
  - ✓ Geant4 version: 10.04
  - ✓ Physics library: *G4EmLivermorePhysics*
  - ✓ Secondary range cut: 1 µm
  - ✓ Relative errors: less than 3%
  - ✓ Photon energy: 15 keV – 10^4 MeV
  - ✓ Irradiation geometry: AP

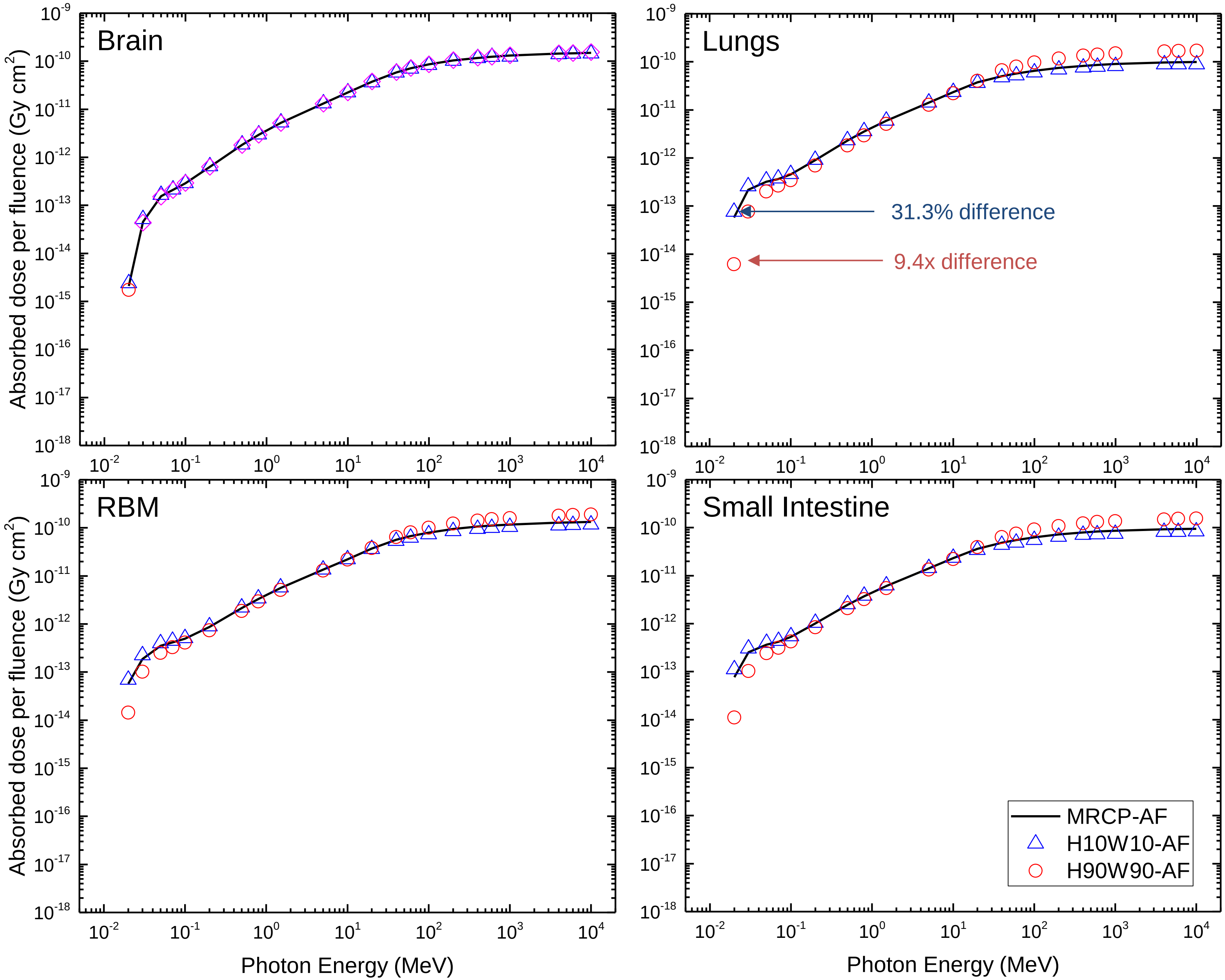


Mesh-type male phantom in Geant4 (direct implementation)

Male (10, 90%tile) - Photon beam in AP direction

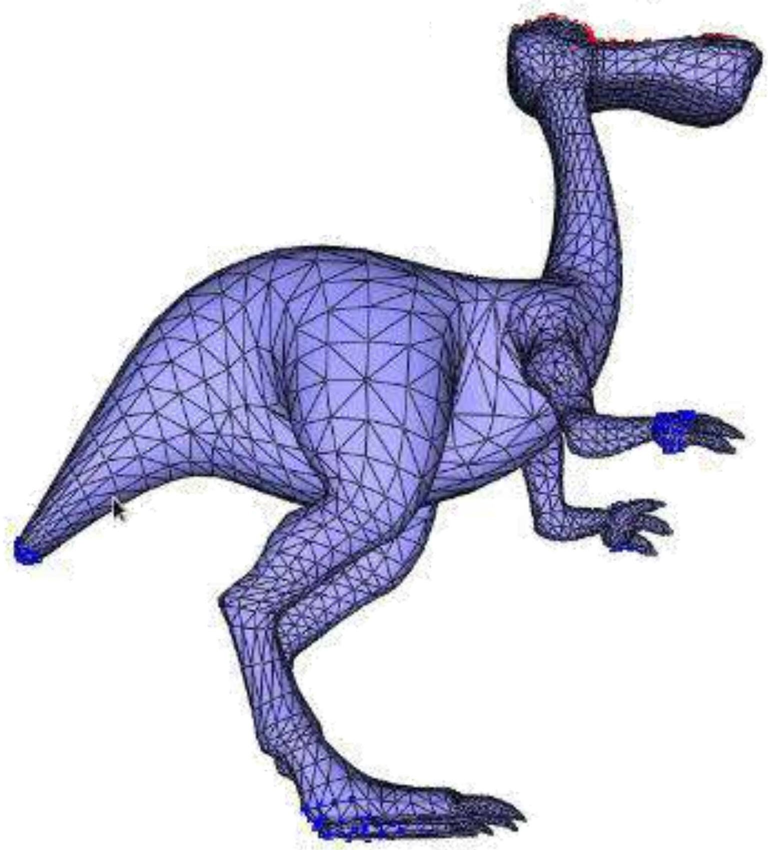


Female (10, 90%tile) - Photon beam in AP direction



2. Phantom Deformation in Different Postures

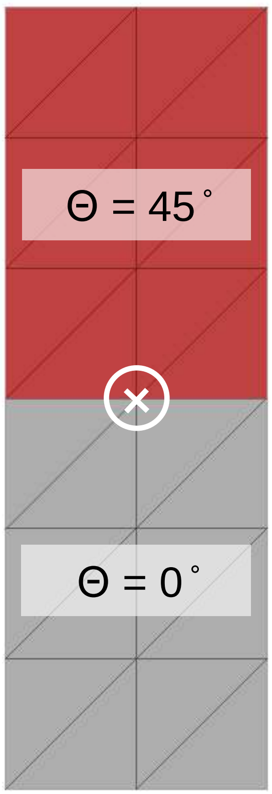
As-Rigid-As Possible (ARAP) Shape Deformation



CGAL doxygen (http://doc.cgal.org/latest/Surface_mesh_deformation/index.html#SModelingVideo_3)

Principle of ARAP Shape Deformation

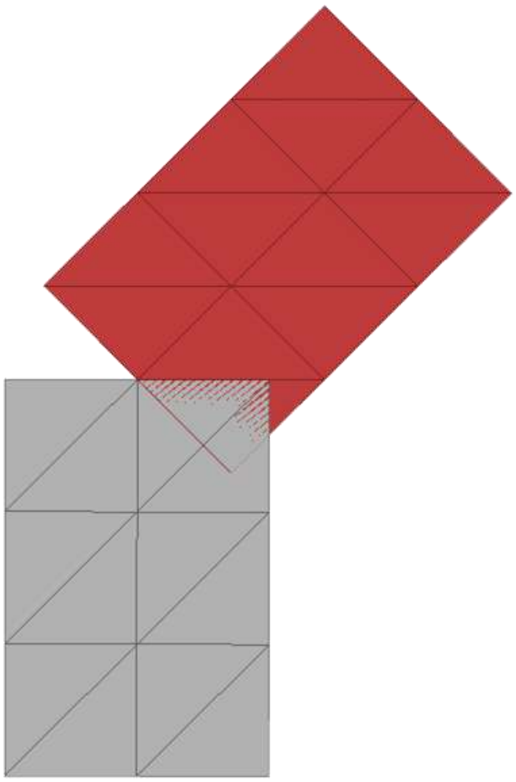
A



Rigid deformation

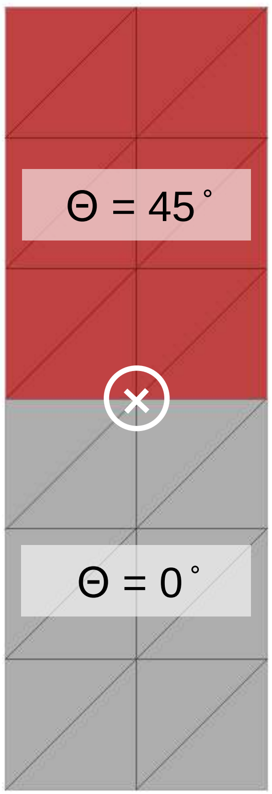
$$\sum_{i=1} \|A_i R_i - B_i\|^2 = \mathbf{0}$$

B



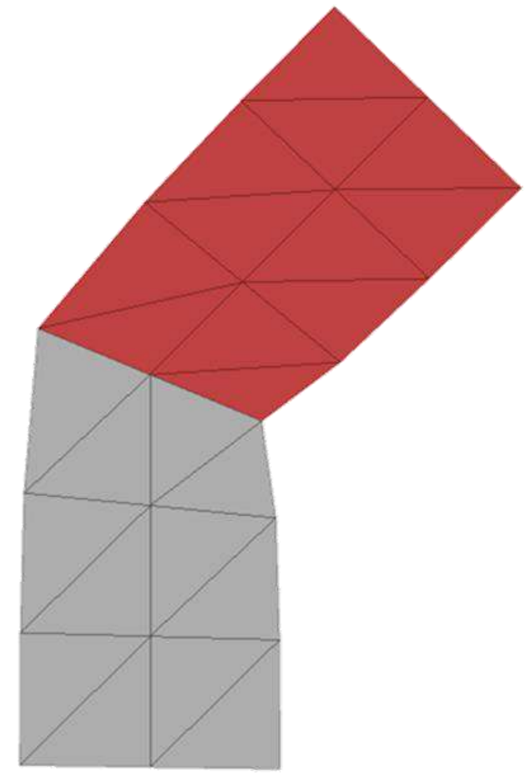
Principle of ARAP Shape Deformation

A



ARAP deformation

B



$$\sum_{i=1} \|A_i R_i - B_i\|^2 = \mathbf{E_{min}}\ (> \mathbf{0})$$

as similar as $A_i R_i$ (rigid deformation)

Overall Procedure of Posture Change

STEP 1

Segmentation of a mesh-type ph

STEP 2

Posture data

Assign rotation matr corresponding seg

STEP 3

A dedicated c++ program to minimize ARAP energy

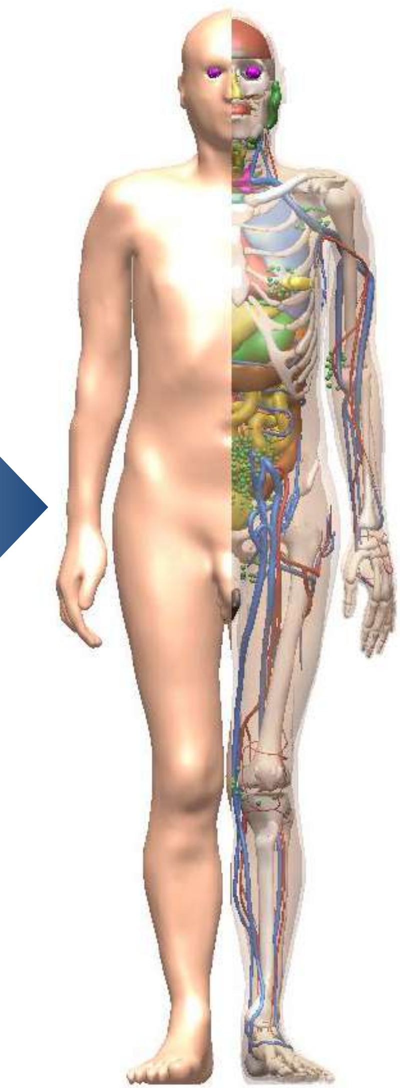
$$E = \sum_{i=1}^{n} w_i \| M_i -$$

E_{min}

Deformed phan

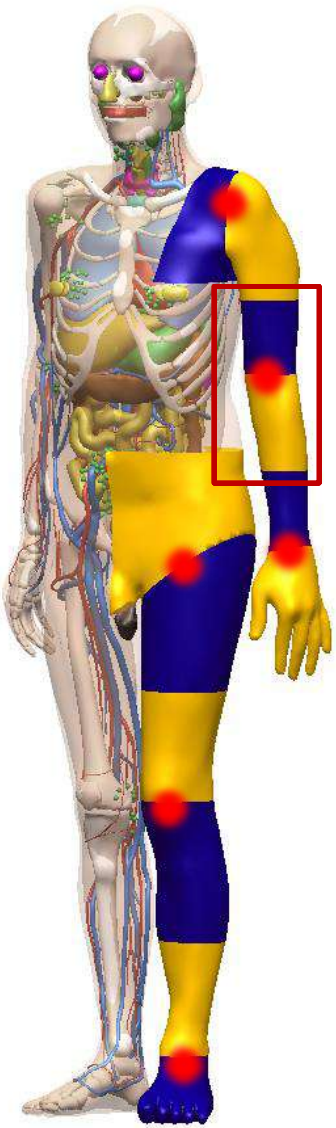
STEP 4

Modify the deformed phantom to el inherent defects



ICRP adult male mesh-type reference phantom

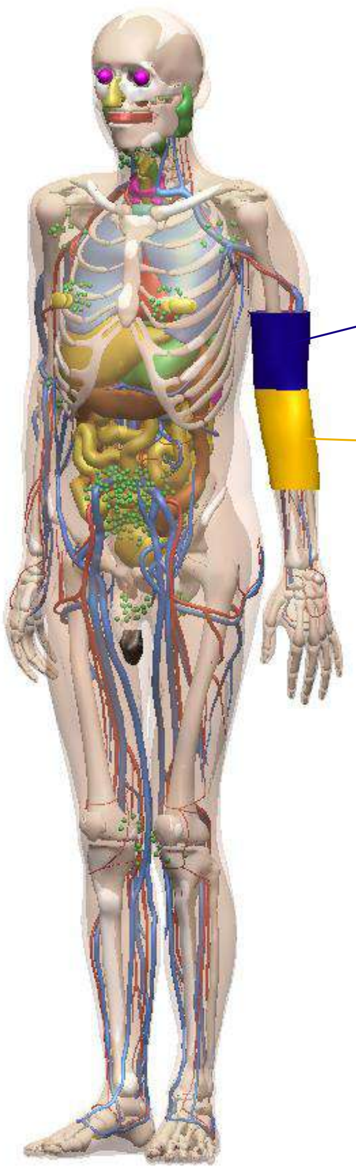
Step 1 – Phantom Segmentation



- The phantom was preferentially segmented into several groups according to main joints (●).
- The segmented groups were also divided into halves to reduce the computation time.

For the rotation, only two adjacent groups at a joint will be deformed.

Step 2 – Assigning Rotation Matrices

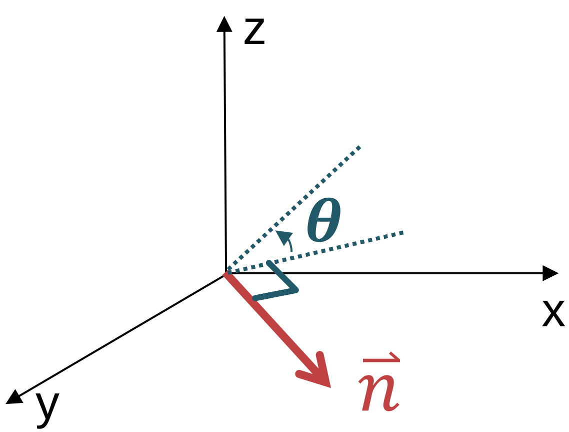


- A rotation matrix is assigned to each segmented group considering posture change.

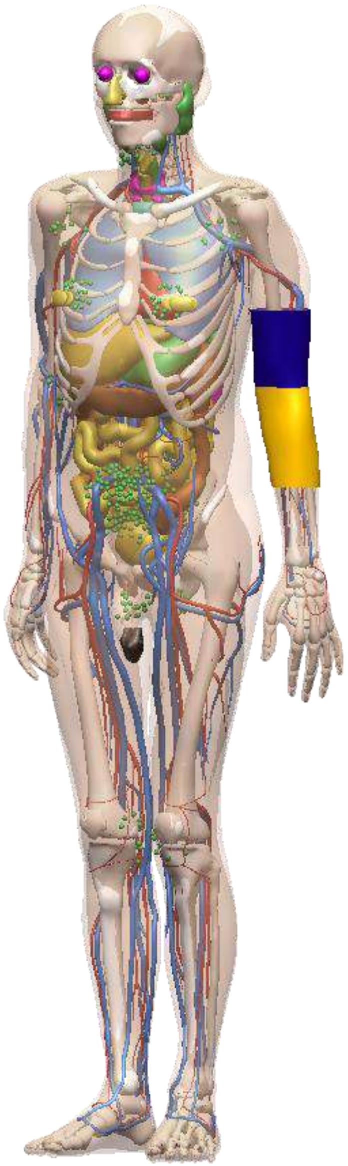
Unit matrix

Theta: 30 degree
Unit vector: (-1, 0, 0)

$$R = \begin{bmatrix} cos\theta + n_x^2(1 - cos\theta) & n_x n_y(1 - cos\theta) - n_z sin\theta & n_x n_z(1 - cos\theta) + n_y sin\theta \\ n_y n_x(1 - cos\theta) + n_z sin\theta & cos\theta + n_x^2(1 - cos\theta) & n_y n_z(1 - cos\theta) - n_x sin\theta \\ n_z n_x(1 - cos\theta) + n_y sin\theta & n_z n_y(1 - cos\theta) + n_x sin\theta & cos\theta + n_z^2(1 - cos\theta) \end{bmatrix}$$



Step 3 – Minimization of ARAP Energy



1. ARAP energy is set for the tetrahedrons of deforming tissues (e.g., muscle, residual soft tissue, blood vessels, and lymphatic nodes), assuming that bones are rigidly rotated and the other organs are not deformed.

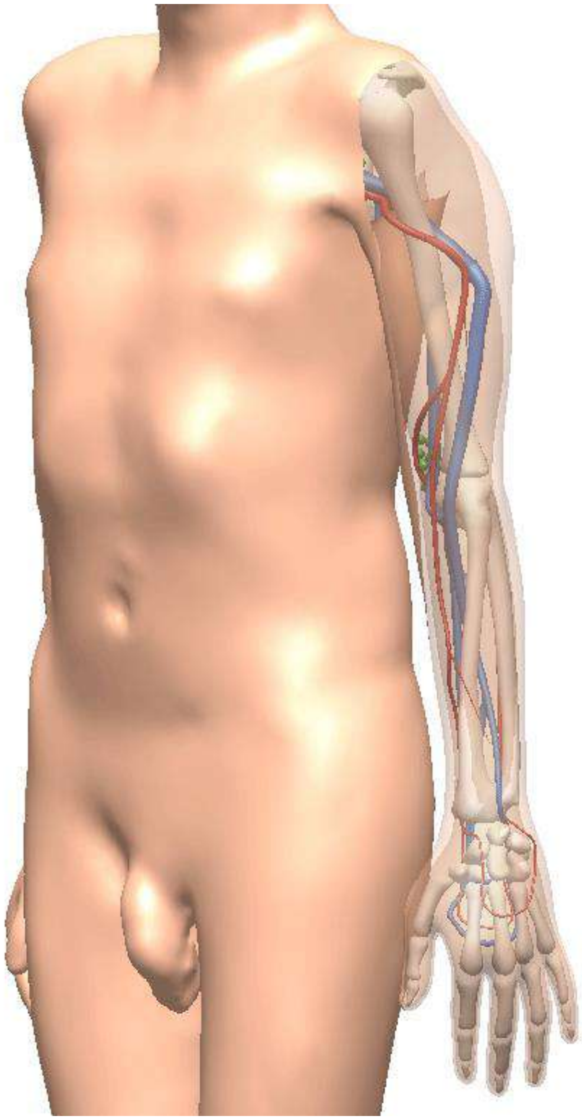
$$E = \sum_{i=1}^{n} w_i \|M_i - R\|_F^2$$

2. The ARAP energy is minimized to deform the mesh.
   ① This quadratic optimization problem can be easily transformed to a linear system.

   $$KX=d_x,\ KY=d_y,\ KZ=d_z$$

   ② The deformed mesh (i.e., X, Y, Z) that minimizes the ARAP energy can be obtained by using LeastSquaresConjugateGradient method provided in Eigen 3.3.90 library.

Phantom Deformation with ARAP Algorithm

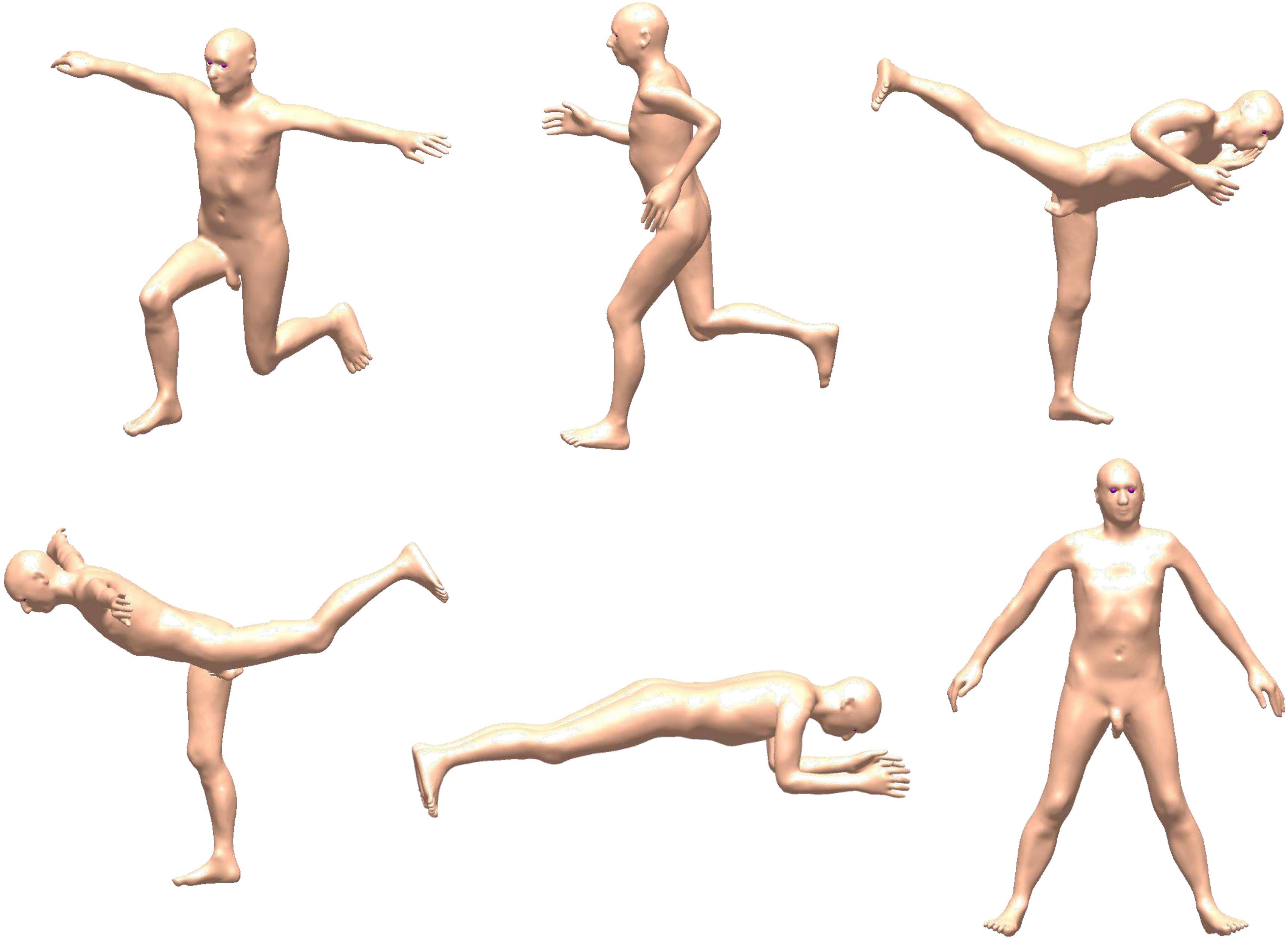


Step 4 – Phantom Refinement

- <u>Some overlapping problems</u> can be found, which are then refined as follows:

  - Overlapping regions were modified,
  - Skin layers were re-defined,
  - Lymph nodes were re-generated, and
  - Organs were adjusted for mass preservation.

Phantoms in Various Postures

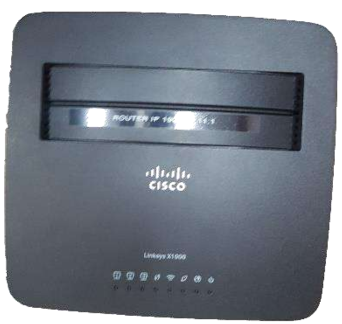


Motion Capture System

IGS-C200 Gyro Motion Capture System (Synertial)

Wireless MPU

Gyroscopic sensors

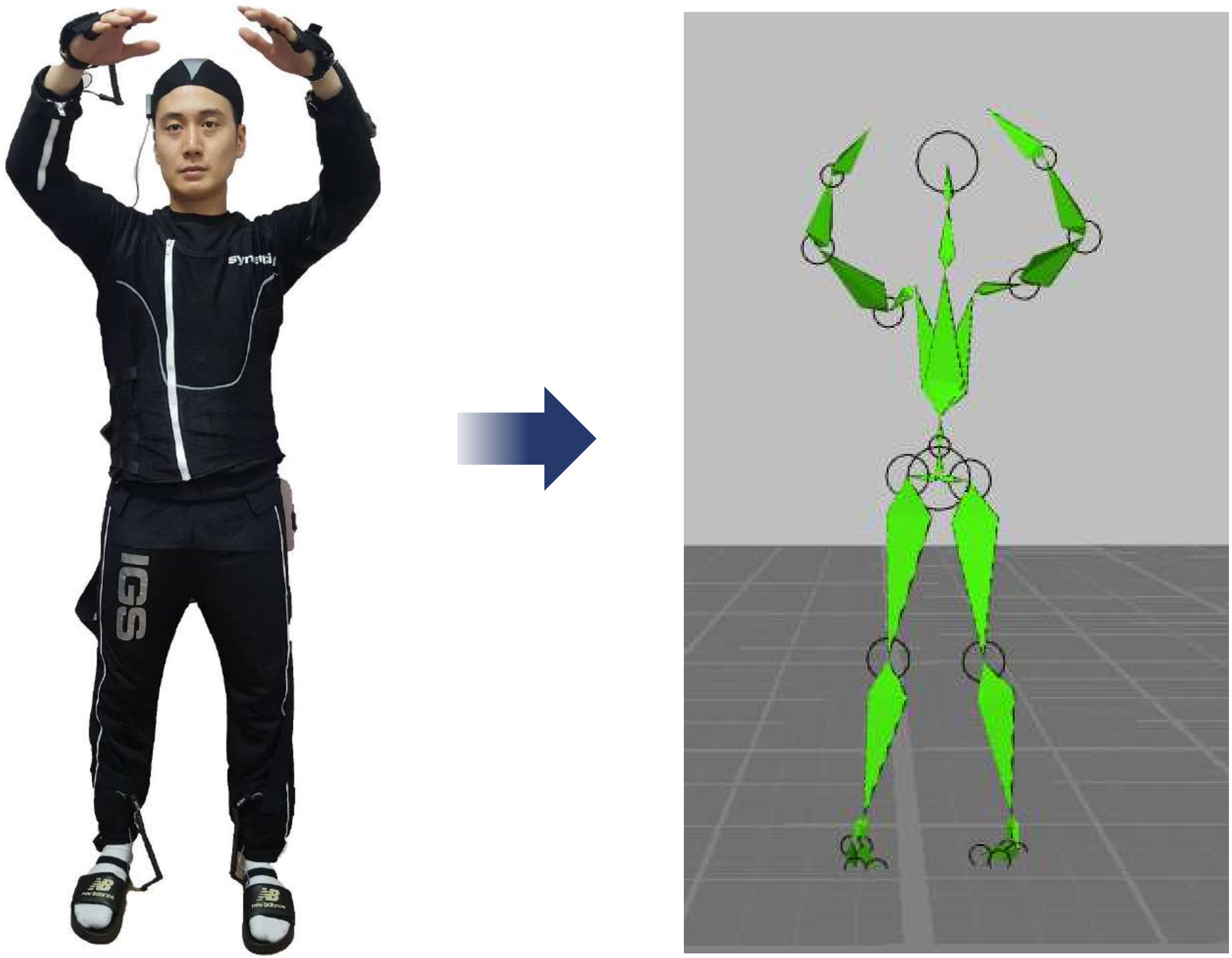


Router

Suit

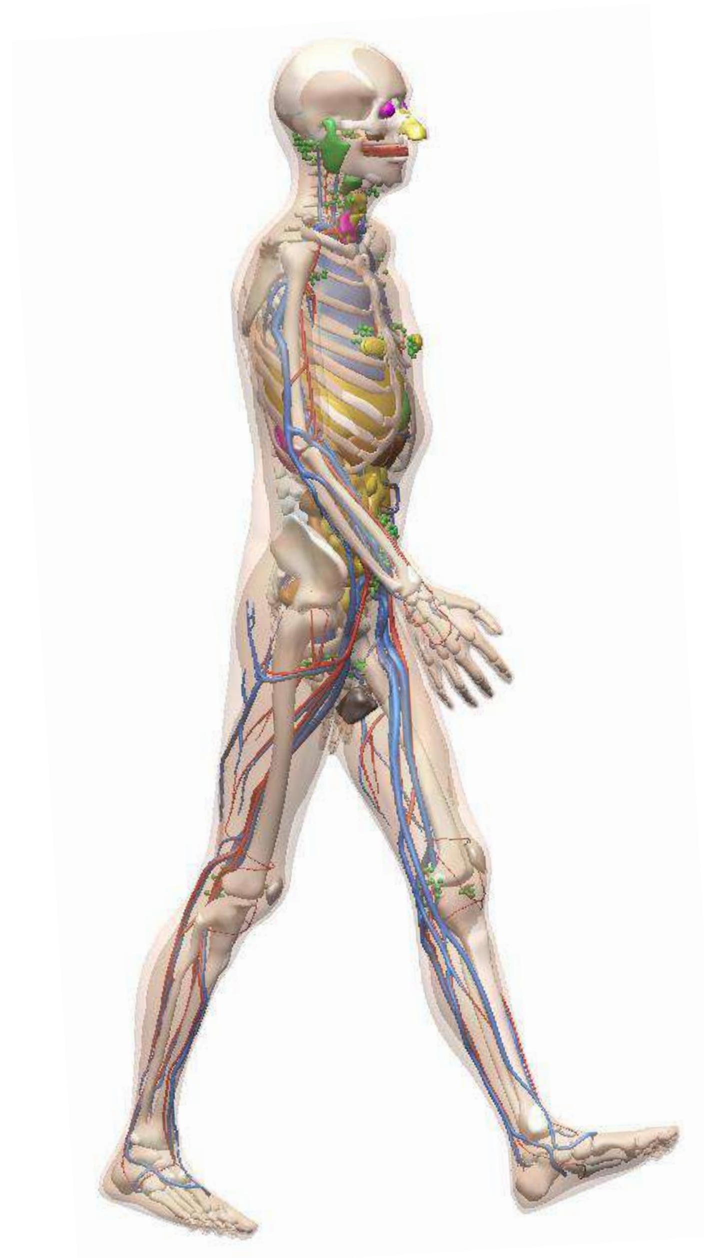
Battery

Posture Data Acquisition

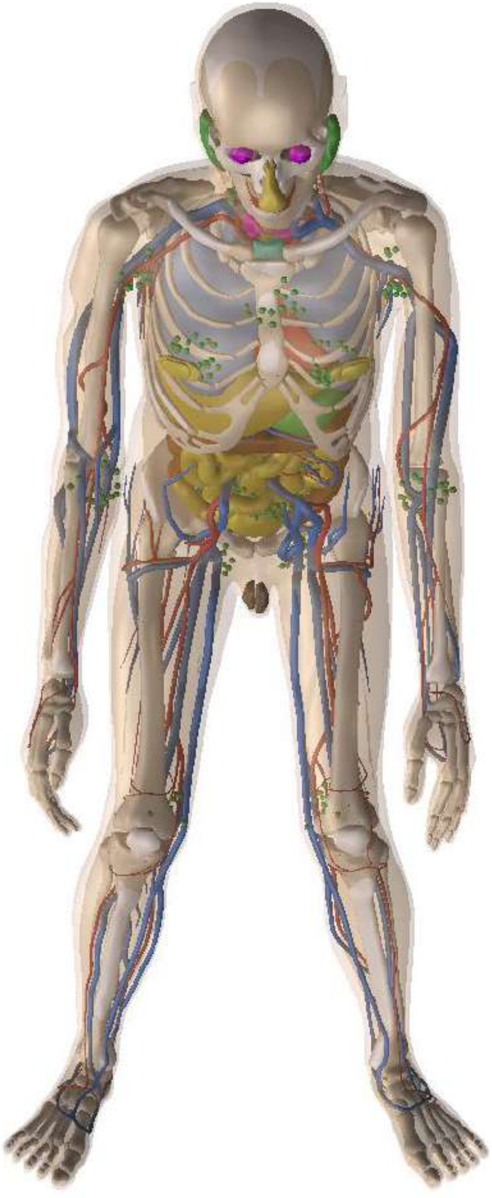


Sitting Posture

Walking Posture



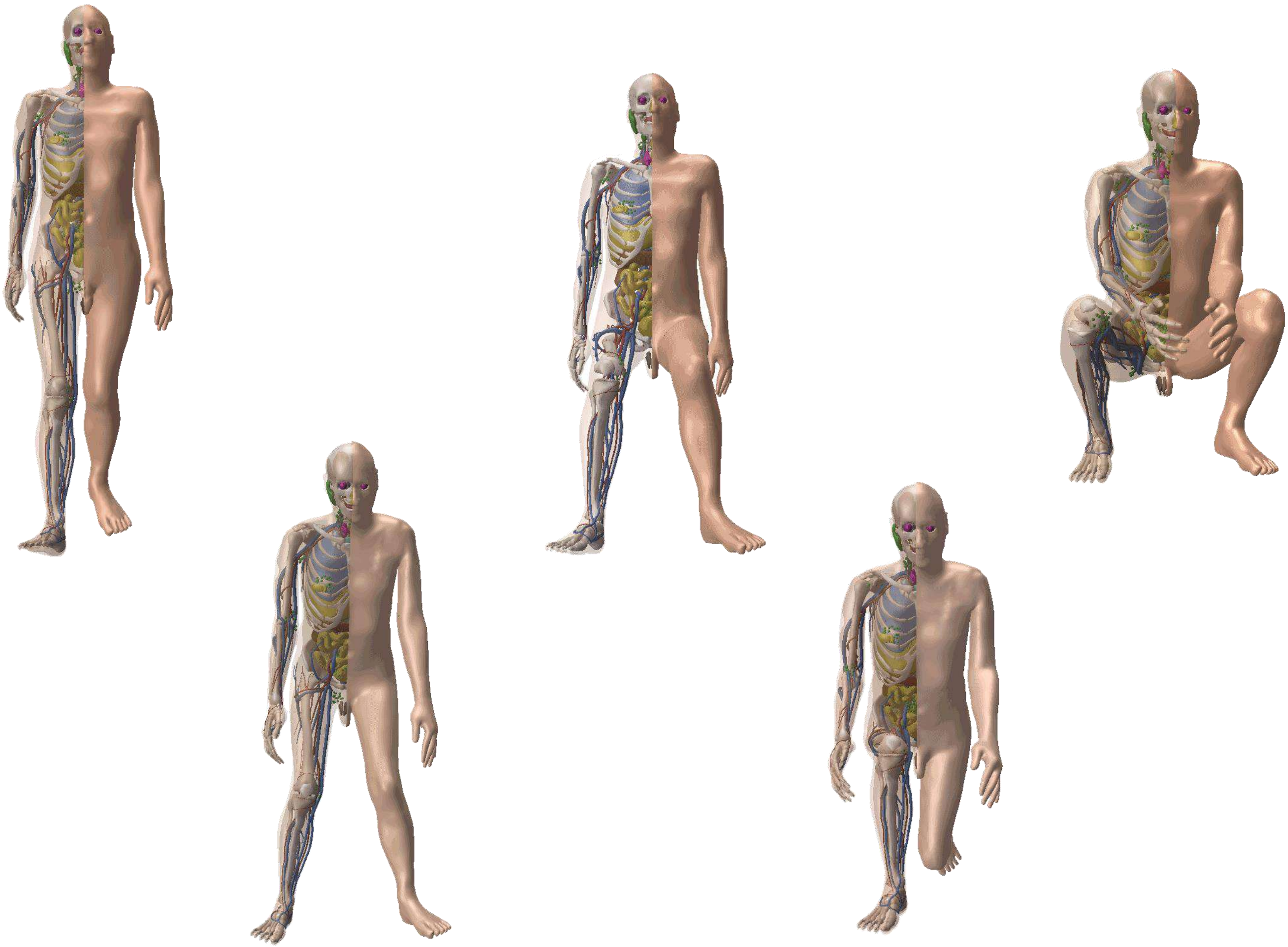
Bending Posture



Kneeling Posture

Squatting Posture

Phantoms deformed in different postures

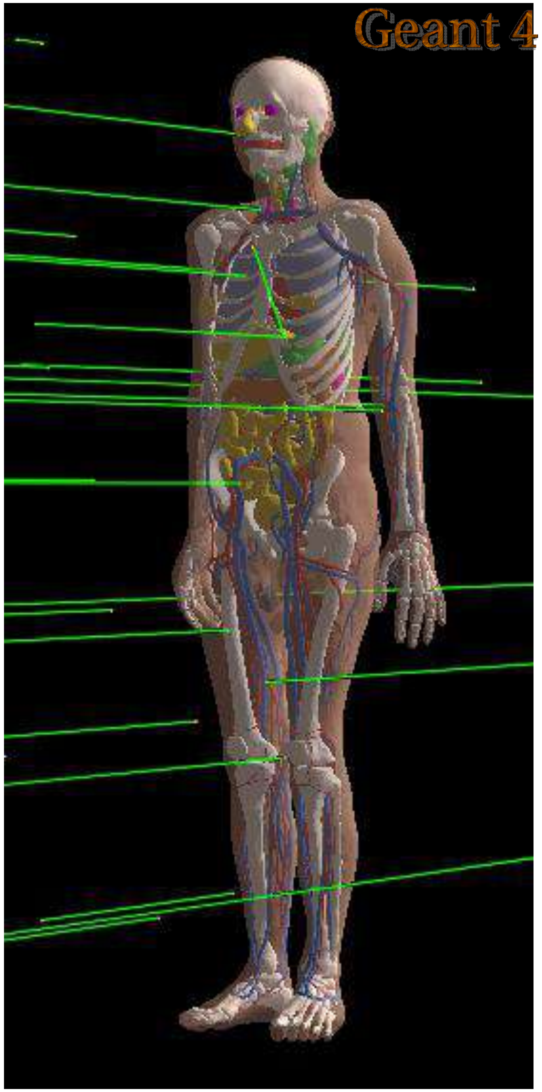


Dose Calculations with Geant4

- **Calculated values**
  - ✓ Organ/tissue dose coefficients for photons
  - ✓ w_T-weighted dose coefficients for photons

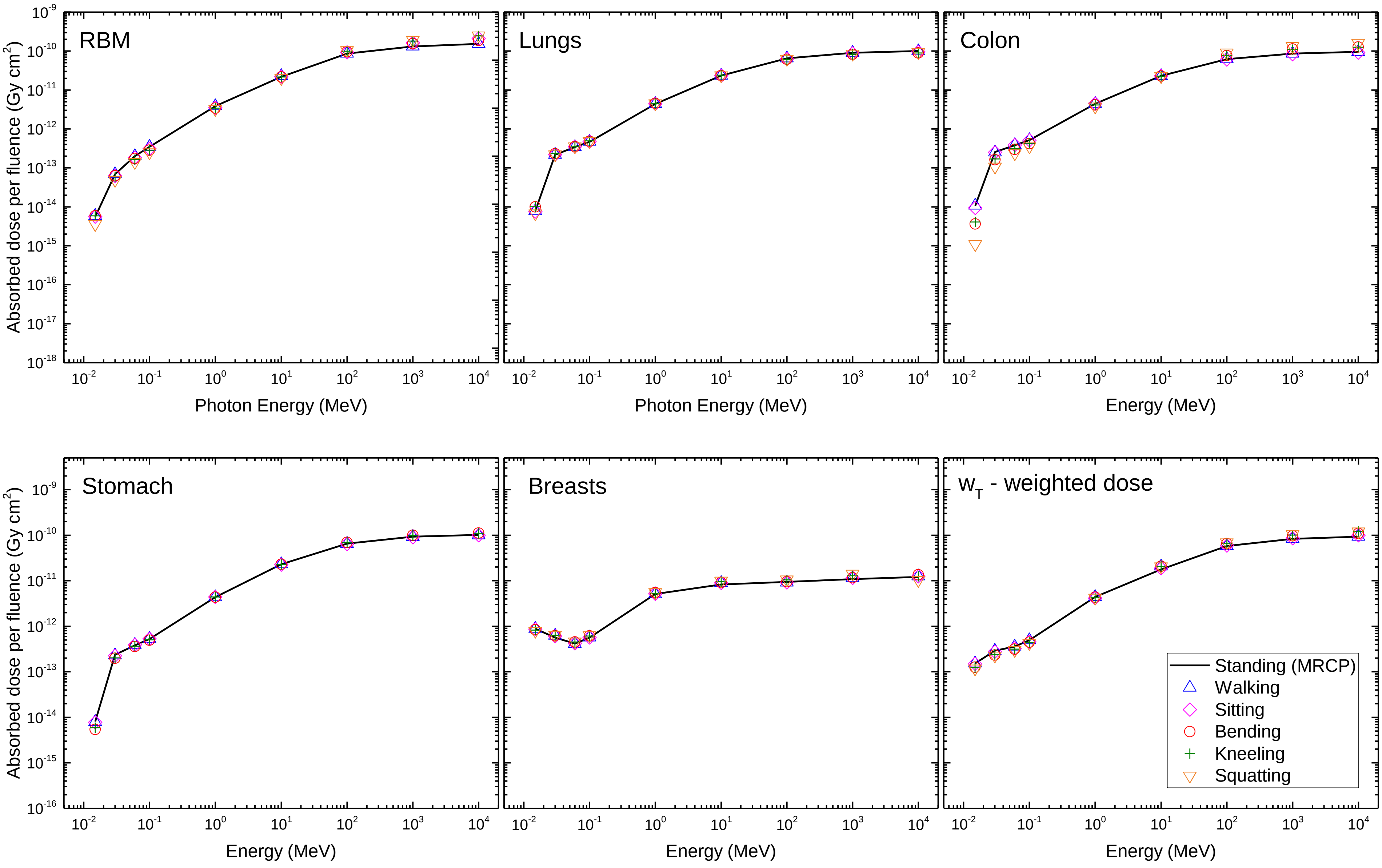
$$w_T\text{-weighted dose} = \sum_T w_T H_T = \sum_T w_T D_T$$

- **MC simulation conditions**
  - ✓ Geant4 version: 10.04
  - ✓ Physics library: *G4EmLivermorePhysics*
  - ✓ Secondary range cut: 1 µm
  - ✓ Relative errors: less than 3%
  - ✓ Photon energy: 15 keV – 10^4 MeV
  - ✓ Irradiation geometry: AP, RLAT

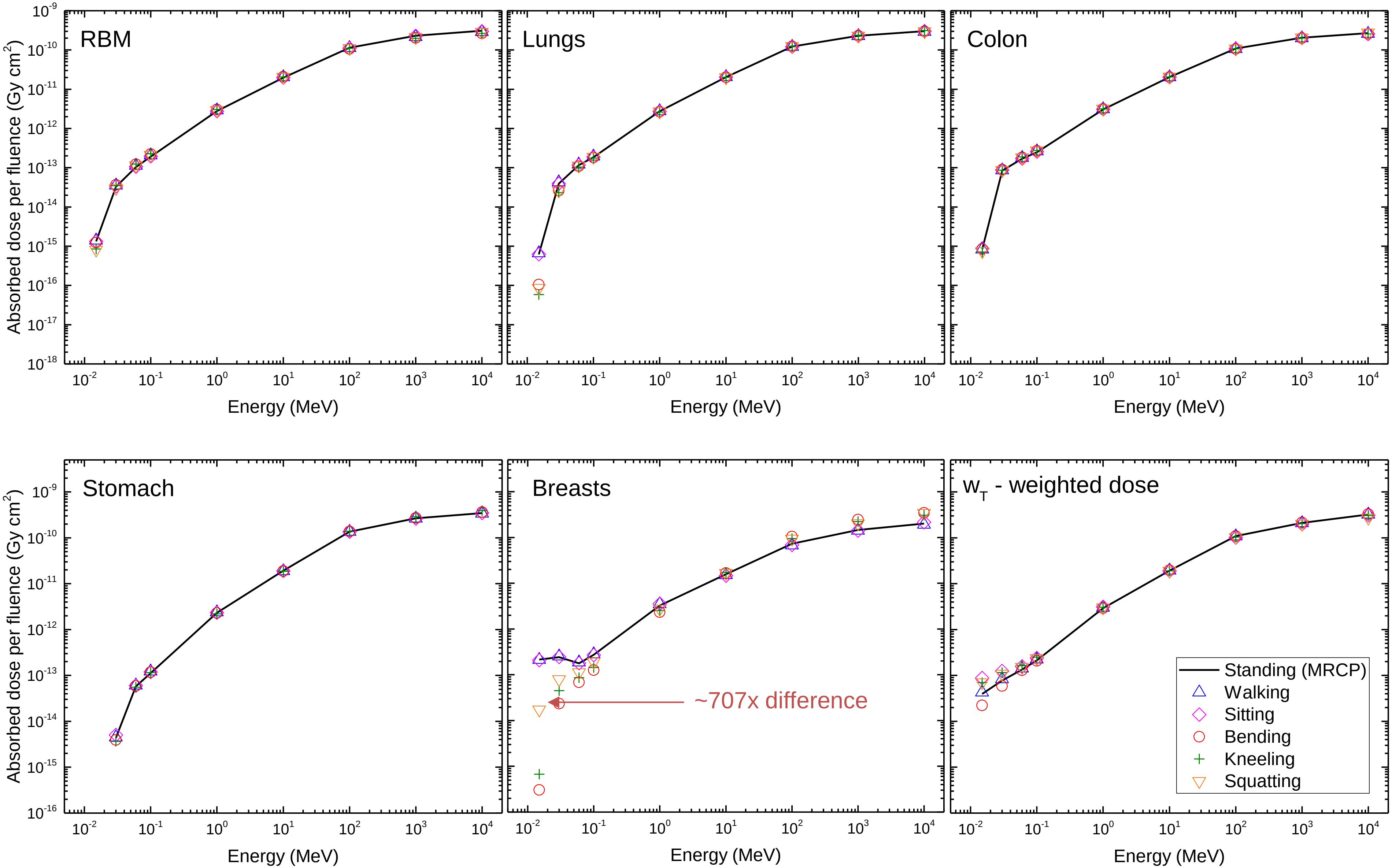


Mesh-type male phantom in Geant4 (direct implementation)

Photon beam in AP direction



Photon beam in RLAT direction



Summary

- In the present study, **the stature of the ICRP adult mesh-type reference computational phantom (MRCPs) were deformed** to represent 10th and 90th percentile of Caucasian population.

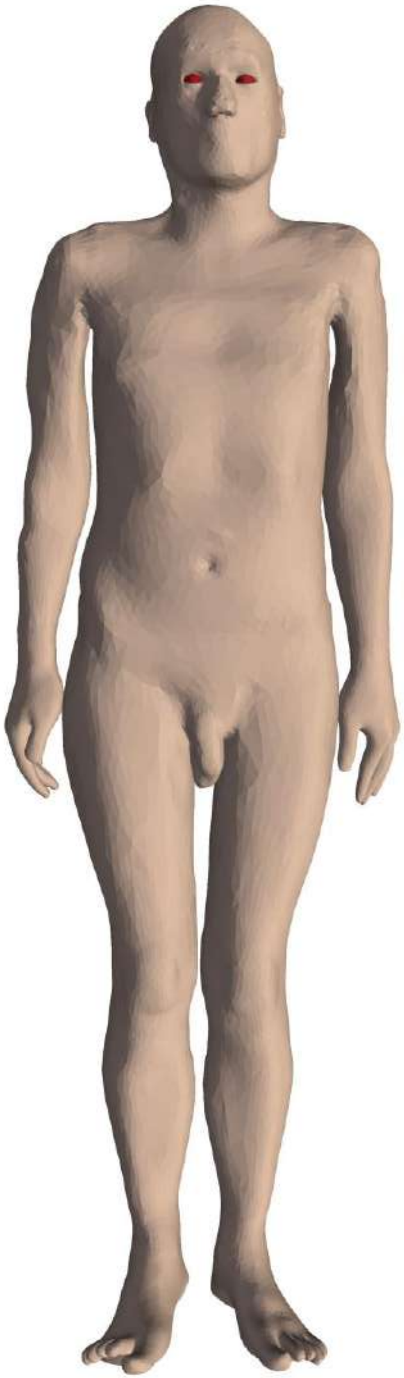
- The adult male MRCP in **several postures (i.e., walking, sitting, bending, kneeling, squatting)** were also constructed by using the motion capture device and newly developed methodology based on ARAP algorithm.

- Photon dose coefficients (DCs) in idealized irradiation geometries for the deformed phantoms were compared with those for the original standing MRCP; **significant dosimetric effects of stature/posture** were found.
  - ✓ ~12 times lower small intestine DCs were found for adult male in the 10%tile height and weight in AP at 15 keV.
  - ✓ ~707 times lower breast DCs were found in squatting phantom in RLAT at 15 keV.

Summary

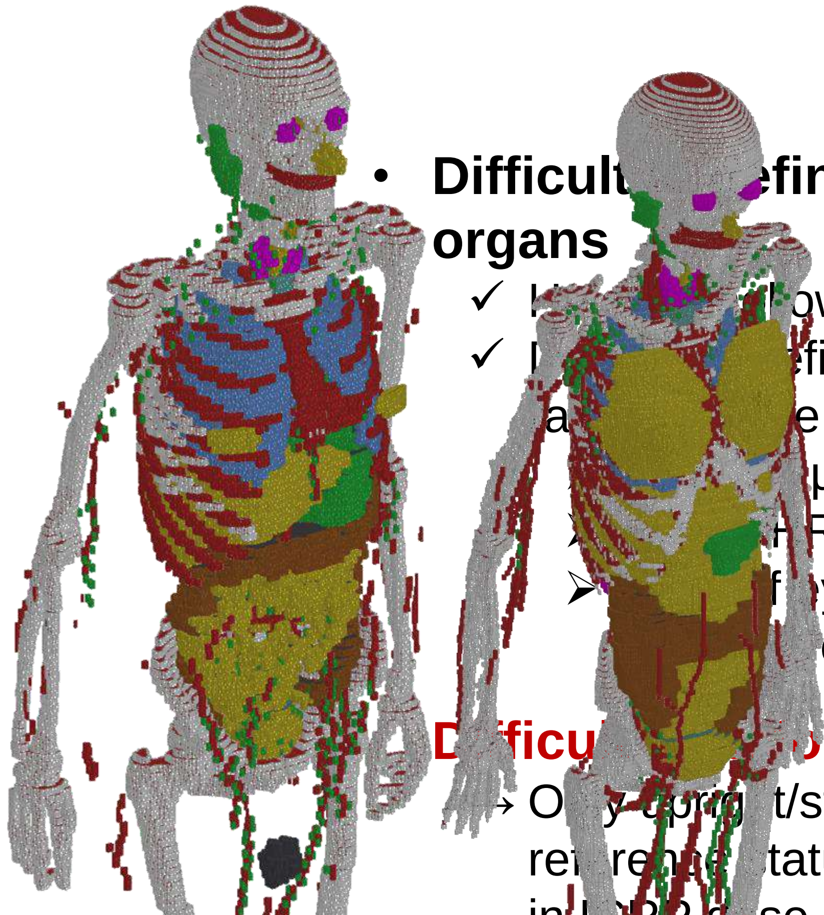
- The deformed phantoms developed in the present study are **currently used by ICRP Task Group 103** to calculate dose coefficients for industrial radiography sources for use in dose estimation of workers accidentally exposed by an industrial radiography source.

- The developed stature/posture deformation method **is semi-automatic**, involving manual refinement works, which makes it **exceedingly labor-intensive** to construct a large number of deformed phantoms (i.e., *phantom library or posture deformed phantoms for dynamic motions*). We will do a further study to improve **the deformation methods to be fully automatic in the future**.



Thank you!

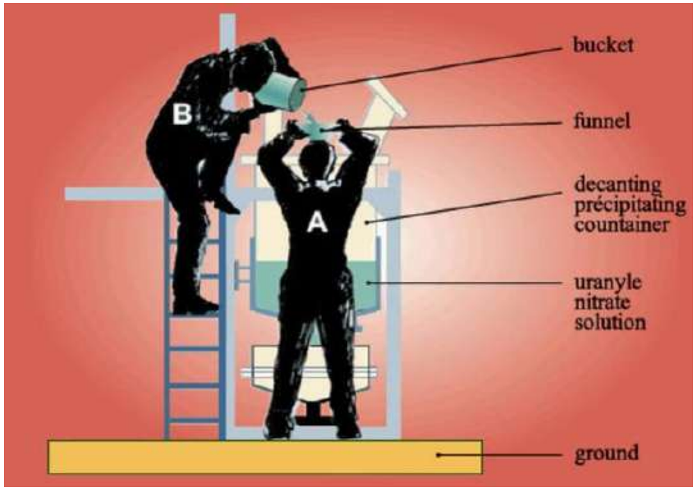
ICRP-110 Reference Phantoms



- **Difficult efine thin or small organs**
  - ✓ I ow organs
  - ✓ I efine micron-thick a e target regions
    - ➢ µm target layer
    - ➢ RTM: 8-40 µm target layer
    - ➢ f ye: averagely 400 µm er
- **Difficu orm the phantoms**
  - → O t/standing phantom with ref tature has been considered in ICRP dose calculations.

ICRP adult reference voxel phantoms (ICRP Publication 110)

Real Exposure Situations



Tokaimura nuclear accident

Computed tomography

A worker inspecting a pipe by industrial radiography testing

Pilots in flight

Overall Procedure of Stature Change

Mesh-type ICRP reference phantoms

Stature
deformation

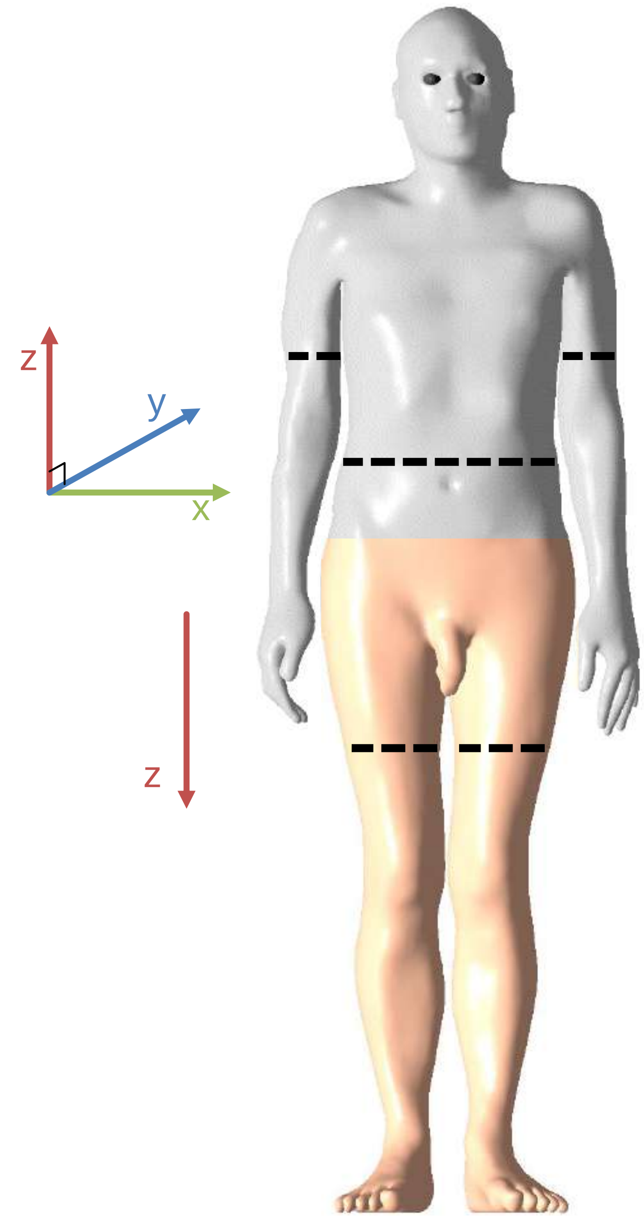
height / weight	10%tile	90%tile
10%tile	✓	
90%tile		✓

UF/NCI body-shape deformation methodology

1) Head, arms, and torso (including all of the internal organs and tissues) were scaled **<u>uniformly in the x, y, z direction</u>** to match the target **sitting height.**

2) Legs were then scaled **<u>only in the z direction</u>** to match the **leg length**.

3) Outer body surface was deformed to match 4 anthropometric parameters (waist, buttocks, upper arm, and thigh circumference) and target weight.



Overall Procedure of Stature Change

1) Head height, torso length, and leg length are scaled in the z direction, respectively, to match the target standing height.

2) Torso and legs are scaled **in the x and y directions** by using ***‘Lean body mass (LBM).’***

3) Head breadth and length are scaled **in the x and y direction**, respectively.

4) Outer body surface was deformed to match 4 anthropometric parameters (waist, buttocks, upper arm, thigh circumferences) and target weight, **but also 2 additional parameters (waist depth and calf circumference)**.