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Adult Mesh-type Reference Computational Phantoms

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ADULT MESH-TYPE REFERENCE COMPUTATIONAL PHANTOMS

ICRP Publication XXX

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Abstract- Following the issuance of new radiological protection recommendations in *Publication 103* (ICRP, 2007), the Commission released, in *Publication 110* (ICRP, 2009), the adult male and female voxel-type reference computational phantoms to be used for the calculation of the reference dose coefficients for both external and internal exposures. While providing more anatomically realistic representations of internal anatomy than the older stylised phantoms, the voxel phantoms have their limitations, mainly due to voxel resolution, especially with respect to small tissue structures (e.g. lens of the eye) and very thin tissue layers (e.g. stem cell layers in the stomach wall mucosa and intestinal epithelium).

This report describes the construction of the adult mesh-type reference computational phantoms (MRCPs) that are the modelling counterparts of the *Publication 110* voxel-type reference computational phantoms. The MRCPs include all source and target regions needed for estimating effective dose, even the µm-thick target regions in the respiratory and alimentary tract, skin, and urinary bladder, thereby obviating the need for supplemental stylised models. The MRCPs can be directly implemented into Monte Carlo particle transport codes for dose calculations, i.e. without voxelisation, fully maintaining the advantages of the mesh geometry. Dose coefficients (DCs) of organ dose and effective dose and specific absorbed fractions (SAFs) calculated with the MRCPs for some external and internal exposures show that − while some differences were observed for small tissue structures and for weakly penetrating radiation − the MRCPs provide the same or very similar values as the previously published reference DCs and SAFs for most tissues and penetrating radiations; consequently, the DCs for effective dose, i.e. the fundamental protection quantity, were found not to be different. The DCs of *Publications 116* (ICRP, 2010) and the SAFs of *Publication 133* (ICRP, 2016) thus remain valid.

To demonstrate deformability of the MRCPs in this report, the phantoms were transformed to construct phantoms that represent the 10th and 90th percentiles of body height and weight for the Caucasian population. The constructed non-reference phantoms were then used to calculate DCs for industrial radiography sources near the body, which can be used to estimate organ doses of workers accidentally exposed by these sources, and which reflect the stature of the exposed worker. The MRCPs of this report were also transformed to phantoms that represent different postures (walking, sitting, bending, kneeling, and squatting), which were then used to evaluate variations in the DCs from the traditional up-right standing position.

Keywords: Phantoms; polygon mesh; tetrahedral mesh; dose coefficients; internal and external exposures

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PREFACE

The membership of Task Group 103 on Mesh-type Reference Computational Phantoms (MRCP) at the time of completion of this publication was:

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MAIN POINTS

- **This document presents mesh-type reference computational phantoms (MRCPs) representing the Reference Adult Male and Reference Adult Female, which are the counterparts of the voxel-type reference computational phantoms of *Publication 110* (ICRP, 2009) developed from segmented computed tomographic data of real persons.**
- **The adult MRCPs were constructed by converting the voxel-type *Publication 110* reference phantoms to a high-quality mesh format and adding those tissue layers that are considered to contain the cells at radiogenic cancer risk, which were below the image resolution of the voxel phantoms and could therefore not be represented previously.**
- **The MRCPs include all the source and target organs/tissues required for the calculation of effective dose, including the µm-thick target layers of the alimentary and respiratory tract organs, skin and urinary bladder, thereby obviating the need for supplemental stylised models (e.g. respiratory airways, alimentary tract organ walls and stem cell layers, lens of the eye and skin basal layer).**
- **The organ/tissue masses of the MRCPs are in agreement with *Publications 89* (ICRP, 2002) and are given as *in situ* values i.e. organ/tissue with blood content. Small differences exist between the organ/tissue masses of the voxel-type reference phantoms (given in Annex A of *Publication 110*) and those of the MRCPs described in this report, as the latter now include the in-situ blood content of each organ/tissue.**
- **To investigate the impact of the MRCPs, the dose coefficients (DCs) of organ dose and effective dose and specific absorbed fractions (SAFs) for some selected external and internal exposures were calculated and compared with the reference values of *Publications 116* and *133* (ICRP, 2010, 2016) calculated using the *Publication 110* phantoms and supplemental stylised models (ICRP, 1994a, 2006, 2016). While some differences in the DCs and SAFs were observed for small tissue structures and weakly penetrating radiations, the values of the effective dose, the quantity of most relevance in radiation protection, and the DCs and SAFs of most of the organs considered in the computation of the effective dose, were found not to be different. Therefore, the DCs of *Publications 116* (ICRP, 2010) and the SAFs of *Publication 133* (ICRP, 2016) remain valid.**
- **The MRCPs were modified to construct additional (standing) phantoms representing individuals of the 10th and 90th body height/weight percentile of Caucasian adult males and adult females. In addition, non-standing phantoms (i.e. with different postures of the reference size) were created. These modified phantoms were used to calculate DCs for exposures to industrial radiography sources, reflecting different statures or postures, which can be used to estimate the organ/tissue doses of a worker accidentally exposed to these radiation sources.**
- **The phantom data in the PM and TM formats, as well as examples of input files for the Monte Carlo codes (Geant4, MCNP6 and PHITS), are included in the supplementary electronic data that accompany the printed document.**

GLOSSARY

Absorbed dose, D

The absorbed dose is given by:

$$D = \frac{\mathrm{d}\bar{\varepsilon}}{\mathrm{d}m}$$

where $\mathrm{d}\bar{\varepsilon}$ is the mean energy imparted by ionising radiation to matter of mass dm. The SI unit of absorbed dose is joule per kilogramme (J kg^{-1}), and its special name is gray (Gy).

Absorbed fraction, AF, $\phi(r_\mathrm{T} \leftarrow r_\mathrm{S}, E_{\mathrm{R,i}})$

Fraction of energy $E_{R,i}$ of the i^{th} radiation of type R emitted within the source region r_S that is absorbed in the target region r_T. These target regions may be tissues (e.g. liver) or may be cell layers within organs (e.g. stem cells of the stomach wall) (see definitions for ‘Target region’ and ‘Target tissue’).

Active (bone) marrow

Active marrow is haematopoietically active and gets its red colour from the large numbers of erythrocytes (red blood cells) being produced. Active bone marrow serves as a target region for radiogenic risk of leukaemia.

Activity

The number of nuclear transformations of a radioactive material during an infinitesimal time interval, divided by its duration (s). The SI unit of activity is s^{-1} and its special name is becquerel (Bq).

Bone marrow [see also ‘Active (bone) marrow’ and ‘Inactive (bone) marrow’]

Bone marrow is a soft, highly cellular tissue that occupies the cylindrical cavities of long bones and the cavities defined by the bone trabeculae of the axial and appendicular skeleton. Total bone marrow consists of a sponge-like, reticular, connective tissue framework called ‘stroma’, myeloid (blood-cell-forming) tissue, fat cells (adipocytes), small accumulations of lymphatic tissue and numerous blood vessels and sinusoids. There are two types of bone marrow: active (red) and inactive (yellow), where these adjectives refer to the marrow’s potential for the production of blood cell elements (haematopoiesis).

Charged-particle equilibrium

Charged-particle equilibrium in a volume of interest means that the energies, numbers, and directions of the charged particles are constant throughout this volume. This is equivalent to saying that the distribution of charged-particle energy radiance does not vary within the volume. In particular, it follows that the sums of the energies (excluding rest energies) of the charged particles entering and leaving the volume are equal.

Cortical (bone) marrow

The marrow contained in the medullary cavities in the shafts of the long bones.

Cross section, σ

The cross section of a target entity, for a particular interaction produced by incident charged or uncharged particles of a given type and energy, is given by:

$$\sigma = \frac{N}{\Phi}$$

where N is the mean number of such interactions per target entity subjected to the particle fluence, Φ. The unit of cross section is m^2. A special unit often used for the cross section is the barn, where 1 barn (b) = 10^{-28} m^2. A full description of an interaction process requires, ‘inter alia’, knowledge of the distributions of cross sections in terms of energy and direction of all emergent particles from the interaction. Such distributions, sometimes called ‘differential cross sections’, are obtained by differentiations of r with respect to energy and solid angle.

Dose coefficient

A coefficient relates a dose quantity to a physical quantity, both for internal and external radiation exposure. For external exposure, the physical quantity ‘fluence’ or ‘air kerma’ is chosen. In internal dosimetry, a dose coefficient is defined as either the committed equivalent dose in tissue *T* per activity intake, $h_{\mathrm{T}}(50)$, or the committed effective dose per activity intake, *e*(50), where 50 is the dose-commitment period in years over which the dose is calculated. Note that elsewhere, the term ‘dose per intake coefficient’ is sometimes used for dose coefficient.

Dose equivalent, *H*

The product of *D* and *Q* at a point in tissue, where *D* is the absorbed dose and *Q* is the quality factor for the specific radiation at this point, thus:

$$H = DQ$$

The unit of dose equivalent is joule per kilogramme (J kg^{-1}), and its special name is sievert (Sv).

Dose–response function (DRF)

A particular function used in this publication to represent the absorbed dose in a target region per particle fluence in that region, derived using models of the microscopic structure of the target region geometry and the transport of the secondary ionising radiations in those regions.

Effective dose, *E*

The tissue-weighted sum of equivalent doses in all specified organs and tissues of the body, given by the expression:

$$\mathrm{E} = \sum_{\mathrm{T}} w_{\mathrm{T}} \sum_{\mathrm{R}} w_{\mathrm{R}} D_{\mathrm{T,R}} = \sum_{\mathrm{T}} w_{\mathrm{T}} H_{\mathrm{T}}$$

where H_{T} is the equivalent dose in an organ or tissue T, $D_{\mathrm{T,R}}$ is the mean absorbed dose in an organ or tissue T from radiation of type R, and w_{T} is the tissue weighting factor.

The sum is performed over organs and tissues considered to be sensitive to the induction of stochastic effects. The unit of effective dose is joule per kilogramme (J kg^{-1}), and its special name is sievert (Sv).

Endosteum (or endosteal layer)

A 50-μm-thick layer covering the surfaces of the bone trabeculae in regions of trabecular spongiosa and those of the cortical surfaces of the medullary cavities within the shafts of all long bones. It is assumed to be the target tissue for radiogenic bone cancer. This target region replaces that previously introduced in ICRP *Publications 26* and *30* (ICRP, 1977, 1979) – the bone surfaces – which had been defined as a single-cell layer, 10 μm in thickness, covering the surfaces of both the bone trabeculae and the Haversian canals of cortical bone.

Equivalent dose, H_{T}

The equivalent dose in an organ or tissue T is given by:

$$H_{\mathrm{T}} = \sum_{\mathrm{R}} w_{\mathrm{R}} D_{\mathrm{T,R}}$$

where $D_{\mathrm{T,R}}$ is the mean absorbed dose from radiation of type R in the specified organ or tissue T, and w_{R} is the radiation weighting factor. The unit of equivalent dose is joule per kilogramme (J kg^{-1}), and its special name is sievert (Sv).

Fluence, Φ

The quotient of dN by da, where dN is the number of particles incident on a sphere of cross-sectional area da, thus:

$$\Phi = \frac{\mathrm{d}N}{\mathrm{d}a}$$

The unit of fluence is m^{-2}.

Identification (ID) number

Number assigned unequivocally to each individually segmented organ/tissue.

Inactive (bone) marrow

In contrast to the active marrow, the inactive marrow is haematopoietically inactive, i.e. does not directly support haematopoiesis. It gets its yellow colour from fat cells, which occupy most of the space of the yellow bone marrow framework.

Intake, I

Activity that enters the body through the respiratory tract or the gastrointestinal tract or the skin.

– Acute intake

A single intake by inhalation or ingestion, taken to occur instantaneously.

– Chronic intake

An intake over a specified period of time.

LET

See 'Linear energy transfer'.

Linear energy transfer/unrestricted linear energy transfer, L or LET

The quotient of dE by dl, where dE is the mean energy lost by the charged particle due to electronic interactions in traversing a distance dl, thus:

$$L = \frac{\mathrm{d}E}{\mathrm{d}l}$$

The unit of linear energy transfer is joule per metre (J m^{-1}), often given in keV/µm.

Mean absorbed dose in an organ or tissue, D_T

The mean absorbed dose in a specified organ or tissue T, is given by:

$$D_\mathrm{T} = \frac{1}{m_\mathrm{T}} \int_{m_\mathrm{T}} D \,\mathrm{d}m$$

where m_T is the mass of the organ or tissue, and D is the absorbed dose in the mass element dm. The unit of mean absorbed dose is joule per kilogramme (J kg^{-1}), and its special name is gray (Gy). The mean absorbed dose in an organ is sometimes termed 'organ dose'.

Mesh phantom

Computational anthropomorphic phantom whose anatomy is represented by either the polygon mesh format or the tetrahedral mesh format.

NURBS

NURBS, Non-Uniform Rational B-Spline, represents 3D surface geometry by mathematical curves defined by four parameters: degree, control points, knots and an evaluation rule. NURBS-based models are widely used in computer-aided design (CAD), manufacturing (CAM) and engineering (CAE) and other various 3D modelling and animation applications.

Organ absorbed dose or organ dose

Short phrase for 'mean absorbed dose in an organ or tissue'.

Polygon mesh

Polygon mesh represents 3D surface geometry composed of polygonal facets (such as triangles), and is one of the geometry formats of a mesh phantom (see 'Mesh phantom').

Radiation weighting factor, w_R

A dimensionless factor by which the organ or tissue absorbed dose is multiplied to reflect the higher biological effectiveness of high-LET radiation compared with low-LET radiation. It is used to derive the equivalent dose from the absorbed dose averaged over a tissue or organ.

Red (bone) marrow

See 'Active (bone) marrow'.

Reference Male and Reference Female

Reference males and females are defined as either adults or children of ages 0, 1, 5, 10 and 15 years.

Reference Person

An idealised person for whom the equivalent doses to organs and tissues are calculated by averaging the corresponding organ doses in the Reference Male and Reference Female. The equivalent doses of Reference Person are used for the calculation of effective dose.

Reference phantom

The computational phantom of the human body (male or female voxel phantom based on medical imaging data), defined in *Publication 110* (ICRP, 2009), with the anatomical and physiological characteristics of the Reference Male and Reference Female defined in *Publication 89* (ICRP, 2002).

Reference value

Value of a quantity recommended by ICRP for use in dosimetric applications or biokinetic models. Reference values are fixed and specified with no uncertainty, independent of the fact that the basis of these values includes many uncertainties.

Sievert (Sv)

The special name for the SI unit of equivalent dose, effective dose and operational dose quantities. The unit is joule per kilogramme (J kg^{-1}).

Source

An entity for which radiological protection can be optimised as an integral whole, such as the x-ray equipment in a hospital, or the release of radioactive material from an installation. Sources of radiation, such as radiation generators and sealed radioactive materials, and, more generally, the cause of exposure to radiation or to radionuclides.

Source region, S_i

An anatomical region within the reference phantom body which contains the radionuclide following its intake. The region may be an organ, a tissue, the contents of the gastrointestinal tract or urinary bladder, or the surfaces of tissues as in the skeleton, the alimentary tract and the respiratory tract.

Specific absorbed fraction (*SAF*)

The fraction of energy of that emitted as a specified radiation type in a source region, S, that is absorbed per mass of target tissue, T (kg^{-1}).

Spongiosa

Term referring to the combined tissues of the bone trabeculae and marrow tissues (both active and inactive) located within cortical bone cortices across regions of the axial and appendicular skeleton. Spongiosa is one of three bone regions defined in the ICRP *Publication 110* reference phantoms (ICRP, 2009), the other two being cortical bone and medullary marrow of the long bone shafts. As the relative proportions of trabecular bone, active marrow and inactive marrow vary with skeletal site, the homogeneous elemental composition and mass density of spongiosa are not constant but varies with skeletal site [see Annex B of ICRP *Publication 110* (ICRP, 2009)].

Stem cell

Non-differentiated, pluripotent cell, capable of unlimited cell division.

Stochastic effects of radiation

Malignant disease and heritable effects for which the probability of an effect occurring, but not its severity, is regarded as a function of dose without threshold.

Target region, r_T

A tissue region of the body in which a radiation absorbed dose or equivalent dose is received.

Target tissue, T

Organ or tissue in the body for which tissue weighting factors are assigned in the effective dose (ICRP, 1991a, 2007). In many cases, each target tissue T corresponds to a single target region r_T. In the case of the extrathoracic region, lungs, colon and lymphatic nodes, however, a fractional weighting of more than one target region r_T defines the target tissue T (ICRP, 1991a, 2007).

Tetrahedral mesh

Tetrahedral mesh represents 3D geometry composed of tetrahedrons, which is one of the geometry formats of a mesh phantom (see 'Mesh phantom'). Tetrahedral mesh can be generated by subdividing polygon mesh (see 'Polygon mesh') with tetrahedrons.

Tissue reaction

Injury in populations of cells, characterised by a threshold dose and an increase in the severity of the reaction as the dose is increased further. Also termed 'deterministic effect'. In some cases, these effects are modifiable by postirradiation procedures including biological response modifiers.

Tissue weighting factor, w_T

The factor by which the equivalent dose in an organ or tissue T is weighted to represent the relative contribution of that organ or tissue to overall radiation detriment from stochastic effects (ICRP, 1991a, 2007). It is defined such that:

$$\sum_T w_T = 1.$$

Trabecular (bone) marrow

The marrow contained in the spongiosa regions of all bones.

Voxel phantom

Computational anthropomorphic phantom based on medical tomographic images or photographic images of a cadaver in which the anatomy is described by small three-dimensional volume elements (voxels) specifying the organ or tissue to which they belong.

Yellow (bone) marrow

See ‘Inactive (bone) marrow’.

1. INTRODUCTION

(1) Implementing a system of radiological protection requires the assessment of doses from radiation exposures of individuals, including workers and members of the general public. The protection quantities are used in the control of radiation exposures, to ensure that the occurrence of stochastic health effects is kept below acceptable levels and that tissue reactions are avoided.

(2) The effective dose (*E*), in units of sievert (Sv), is accepted internationally as the central radiological protection quantity, providing a risk-adjusted measure of dose delivered to the human body from both external and internal radiation sources. *E* has proved to be a valuable and robust quantity for use in the optimisation of protection, for the setting of control criteria (limits, constraints and reference levels), and for the demonstration of regulatory compliance. *E* is calculated for sex-averaged Reference Persons of specified ages, by estimating their organ absorbed doses and applying both radiation and tissue weighting factors (ICRP, 2007).

(3) Absorbed dose (*D*), in units of gray (Gy), averaged over a specified organ and tissue is the physical quantity from which *E* is calculated. Equivalent dose (*H*) to organs and tissues is obtained by multiplying the absorbed dose by radiation weighting factors (w_R) to account for the relative effectiveness of different radiation types in causing stochastic effects at low levels of exposure. Nominal stochastic risk coefficients and corresponding detriment values, to which *E* relates, are calculated as averages from sex-, age-, and population-specific values, to provide internationally applicable values for all workers (18–65y) and for the whole population (all ages). Tissue-weighting factors (w_T) used in the calculation of effective dose are a simplified representation of relative detriment values, relating to detriment for the whole population (sex, age and population averaged).

(4) The estimation of organ absorbed doses requires, among other tools, computational anatomical phantoms (or models). A computational anatomical phantom is a 3D computerised representation of the human anatomy, with definitions of both internal organs and outer body surfaces.

(5) Until the mid-2000s, the ICRP relied on the use of so-called stylised or mathematical models of organ anatomy, such as those developed at the Oak Ridge National Laboratory (ORNL) (Snyder et al., 1969, 1978; Cristy, 1980; Cristy and Eckerman, 1987) and by the Medical Internal Radiation Dose (MIRD) Committee of the Society of Nuclear Medicine. Body and organ surfaces are defined in these stylised phantoms using geometrical 3D surface equations such as spheres, cones, ellipsoids, and toroids. These models are generally hermaphrodites with both male and female sex organs included. As an improvement to these early stylised models, "Adam" and "Eva", separate male and female adult mathematical phantoms, were introduced (Kramer et al., 1982). Subsequently, four models representing the non-pregnant adult female and the pregnant female at 3 stages of pregnancy were developed by Stabin et al. (1995). All of the above phantoms were employed for the estimation of reference dose coefficients (DCs) and specific absorbed fractions (SAFs) issued by ICRP for internal and external exposures, as given in *Publications 30*, *53*, *56*, *60*, *61*, *66*, *67*, *68*, *69*, *71*, *72*, *74*, *80* and *100* (ICRP, 1979, 1988, 1990, 1991a, 1991b, 1994a, 1993, 1994b, 1995a, b, 1996a, b, 1998, 2006).

(6) The most recent recommendations by ICRP were published in 2007 in *Publication 103* (ICRP, 2007). In that document, the Commission includes the specifications of separate reference male and female anatomical models to be used together with radiation transport codes that simulate the radiation transport and energy deposition for the assessment of the mean

absorbed dose, D_T, in specified target organs or tissues T, from which equivalent doses and the effective dose can be successively calculated.

(7) Consequently, the Commission released new computational phantoms of ICRP reference adult male and reference adult female in *Publication 110* (ICRP, 2009). These reference computational phantoms are based on human computed tomographic data. They are consistent with the information given in *Publication 89* (ICRP, 2002) on the reference anatomical parameters for both the reference adult male and female.

(8) The reference computational phantoms (or models) were constructed by modifying the voxel models (Zankl and Wittmann, 2001; Zankl et al., 2005) of two individuals (Golem and Laura) whose body height and mass closely resembled the reference data. The organ masses of both phantoms were adjusted to the ICRP data without significantly altering their realistic anatomy. The phantoms contain all target regions relevant to the assessment of human exposure to ionising radiation for radiological protection purposes (ICRP, 2007), with the exception of certain very thin target tissues located within the alimentary and respiratory tracts. Each phantom is represented in the form of a 3D array of cuboidal voxels. Each voxel is a volume element, and the voxels are arranged in columns, rows, and slices. Each entry in the array identifies the organ or tissue to which the corresponding voxel belongs. The male reference computational phantom consists of approximately 1.95 million tissue voxels (excluding voxels representing the surrounding vacuum), each with a slice thickness (corresponding to the voxel height) of 8.0 mm and an in-plane resolution (i.e. voxel width and depth) of 2.137 mm, corresponding to a voxel volume of 36.54 mm^3. The number of slices is 220, resulting in a body height of 1.76 m; the body mass is 73 kg. The female reference computational phantom consists of approximately 3.89 million tissue voxels, each with a slice thickness of 4.84 mm and an in-plane resolution of 1.775 mm, corresponding to a voxel volume of 15.25 mm^3. The number of slices is 346, and the body height is 1.63 m; the body mass is 60 kg. The number of individually segmented structures is 136 in each phantom, to which 53 different tissue compositions have been assigned. The various tissue compositions reflect both the elemental composition of the tissue parenchyma (ICRU, 1992) and each organ's blood content (ICRP, 2002) (i.e. organ composition inclusive of blood).

(9) While providing more anatomically realistic representations of internal anatomy than the older stylised phantoms, voxel phantoms have their limitations mainly due to image resolution, especially with respect to small tissue structures (e.g. lens of the eye) and very thin tissue layers (e.g. stem cell layers in the stomach wall mucosa and intestinal epithelium). The in-plane resolution of modern CT scanners is generally 0.5 mm or better. However, the Z dimension of the phantom voxels corresponding to the image slice thickness can be a few to several mm for typical clinical protocols (Bolch et al., 2010). Images with higher in-plane resolution would be difficult to obtain, since significant absorbed doses would be given to the patient or volunteer.

(10) The voxel-based reference computational phantoms have been used to estimate the reference DCs for external radiation exposures of *Publication 116* (ICRP, 2010), the SAFs of *Publication 133* (ICRP, 2016) and for the series of reports on occupational intakes of radionuclides (ICRP, 2015, 2017a, b). Calculations for DCs due to ingestion and inhalation from members of the public are in progress. For these calculations, supplemental organ-specific stylised models were employed for estimating internal electron and alpha particle SAFs for thin tissue layers to replace those computed directly in the computational reference voxel phantoms. Similarly, for some selected external exposures, separate simulations were made to determine the absorbed dose to the eye lens and to local regions of the skin (ICRP, 2010).

(11) In order to overcome the limitations of the voxel-type ICRP reference phantoms related to their resolution, to avoid the use of supplementary phantoms, and to provide all-in-one anatomical computational phantoms, ICRP formed the Task Group 103 - Mesh-type Reference Computational Phantoms. The aim of this Task Group was to provide a new generation of ICRP reference computational phantoms, constructed by converting the voxel-type ICRP reference phantoms to a high-quality mesh format to include thin target and source regions, even the 8–40-µm-thick target layers of the alimentary and respiratory tract.

(12) It is noted that these mesh-type computational phantoms, represented by either polygon mesh (PM) or tetrahedral mesh (TM) geometry as necessary, are considered presently as the most advanced type of computational phantoms, in that they can be directly implemented into Monte Carlo codes, i.e. without the conventionally used 'voxelisation' process, thus fully maintaining the advantages of the mesh geometry in Monte Carlo dose calculations (Kim et al., 2011; Yeom et al., 2013, 2014; Han et al., 2015). Note that the tetrahedral mesh (TM) geometry is available in Geant4 and MCNP since 2013 and in PHITS since 2015.

(13) This report describes (1) the conversion of the voxelised ICRP adult reference computational phantoms to their mesh-format counterparts; (2) the simulation of several additional tissues such as target cell layers defined by ICRP for the respiratory and alimentary tract, urinary bladder, skin, eye and lymph nodes, and their inclusion in the phantoms; (3) investigates the impact of the newly developed phantoms for the determination of DCs within the ICRP system; and (4) discusses further applications.

(14) The new mesh-type ICRP reference phantoms preserve the original topology of the voxel-type ICRP reference phantoms, present substantial improvements in the anatomy of small tissues, and include all of the necessary source and target tissues defined by the Commission, thereby obviating the need for supplemental stylised models such as those defined for respiratory tract airways, the alimentary tract organ walls and stem cell layers, the lens of the eye and the skin basal layer. In the mesh phantoms, the skeletal target tissues (red bone marrow and endosteum) are not explicitly represented, but implicitly included in the spongiosa and medullary cavity in the same manner as provided in the *Publication 110* phantoms). Doses to these skeletal tissues can be estimated by using dedicated skeletal-dose-calculation methods (e.g. fluence-to-dose response functions) such as those given in Annex E and F of in *Publication 116* (ICRP, 2010).

(15) In general, it can be stated that the mesh-type reference phantoms provide effective dose DCs very similar to those of the voxel-type ICRP reference phantoms for penetrating radiations and, at the same time, more accurate DCs for weakly penetrating radiations.

(16) In addition to the greater anatomical accuracy of the mesh-type phantoms, they are deformable and, as such, can serve as a starting point to create phantoms of various statures and postures for use, for example, in retrospective emergency or accidental dose reconstruction calculations. These non-reference versions may be useful to calculate organ doses for purposes other than calculating effective dose. To demonstrate this feature, the MRCPs in this report were modified via various scaling/deforming procedures to construct (standing) phantoms which represent the 10^{th} and 90^{th} body height/weight percentiles of the adult male and female Caucasian populations. Furthermore, they were also used to create non-standing phantoms (i.e. with different postures of the reference size). The constructed phantoms were then used to calculate DCs for exposures to industrial radiography sources near the body, reflecting different statures or postures, which can be used to estimate the organ/tissue doses to workers accidentally exposed to these radionuclide sources.

(17) The new phantoms have applications beyond the calculation of reference DCs. For example, the deformation capability of the phantoms can facilitate the virtual calibration of whole body counters to account for the stature of radiation workers in efficiency calibration. The new phantoms are in mesh format and therefore can be directly used to produce physical phantoms, as necessary, with 3D printing technology. It is relatively easy to model detailed structures in the phantoms and, therefore, the new phantoms could find applications in medicine and other areas requiring sophisticated organ models. One of the aims of this report is to assist those who wish to implement the phantoms for their own applications; therefore, the detailed data on the phantoms in both polygonal mesh and tetrahedral mesh formats are provided in the supplementary electronic data that accompany the printed publication, together with some input examples of the Monte Carlo codes.

(18) Chapter 1 explains the main motives for the construction of the adult mesh-type reference computational phantoms. Chapter 2 focuses on those tissues of the reference computational phantoms of *Publication 110* for which the anatomical description has been significantly improved in the mesh-type formats. Chapter 3 describes the general procedure for the conversion of the *Publication 110* phantoms to the mesh format. Chapter 4 describes the adjustment of the converted MRCPs to the reference values for the mass, density and elemental composition of organs and tissues inclusive of blood content. Chapter 5 describes the inclusion of the thin target and source regions of the skin, alimentary tract system, respiratory tract system, and the urinary bladder in the MRCPs. Chapter 6 describes the general characteristics of the resulting mesh-type reference computational phantoms. Chapter 7 investigates the impact of the improved internal morphology of the MRCPs on the calculation of DCs for external and internal exposures. Finally, Chapter 8 describes an application to the calculation of DCs for industrial radiography exposures in order to demonstrate the capability of the MRCPs in calculation of DCs for accidental or emergency exposure scenarios.

(19) A detailed description of the MRCPs is given in Annexes A–F. Annex A presents a list of the individual organs/structures (identification list), together with the assigned media, densities and masses. Annex B presents a list of the phantom media and their elemental compositions. Annexes C and D list the source and target regions, respectively, together with their acronyms and identification numbers. Annex E provides depth distributions for selected organs from the front, back, left, right, top and bottom, along with the respective data of the *Publication 110* phantoms. Annex F provides chord-length distributions between selected pairs of source and target organs, along with the data of the *Publication 110* phantoms.

(20) Annex G presents selected transverse, sagittal, and coronal slice images of the mesh-type reference phantoms.

(21) In Annexes H and I, the DCs and SAFs calculated with the MRCPs for some selected idealised external and internal exposure cases are compared with the reference values of *Publications 116* and *133* (ICRP, 2010, 2016). Annex H shows comparisons of the organ and effective dose DCs, calculated for external exposure to photons, neutrons, electrons and helium ions, with the *Publication 116* values. Annex I compares the SAFs for photons and electrons with the *Publication 133* values.

(22) Annex J presents the DCs for industrial radiography sources calculated with the MRCPs as well as the stature-specific phantoms that were constructed by modifying the MRCPs.

(23) Annex K describes the contents of the supplementary electronic data that accompanies the printed publication including the detailed phantom data and the input examples of some Monte Carlo codes.

2. IMPROVEMENTS OF THE ADULT MESH-TYPE REFERENCE PHANTOMS OVER THE ADULT VOXEL-TYPE REFERENCE PHANTOMS

(24) The adult voxel-type reference computational phantoms described in *Publication 110* (ICRP, 2009) were adopted by ICRP and the International Commission on Radiation Units and Measurements (ICRU) as the phantoms for computation of the ICRP/ICRU reference dose coefficients (DCs) for radiological protection purposes. These computational phantoms are digital 3D representations of the human anatomy, constructed using computed tomographic (CT) images of real persons. The phantoms are consistent with the information given in *Publication 89* (ICRP, 2002) on the reference anatomical parameters of the Reference Adult Male and Reference Adult Female. The *Publication 110* phantoms are shown below in Fig. 2.1.

(25) While providing more anatomically realistic representations of internal anatomy than the older type of stylised phantoms, the adult voxel-type reference phantoms have limitations due to their voxel resolution, and hence some organs and tissues could not be explicitly represented or could not be adjusted to their reference mass due to their small dimensions or complex anatomic structure. This fact was already discussed in *Publication 110* (ICRP, 2009). In an attempt to address the limitations of the voxel-type reference phantoms related to the image resolution, further improvements in representing those organs and tissues were made in the adult mesh-type reference computational phantoms (MRCPs) described in the present publication. These improvements are summarised in the following paragraphs.

(26) The skin of the voxel-type reference phantoms is represented by a single voxel layer, considering only transverse directions, resulting in the skin being discontinuous between individual transverse slices, while at the same time the total skin mass of the phantoms is 13 % and 18 % higher than the reference values for the adult male and female, respectively. Through the discontinuous parts of the skin, radiation incident at non-zero angles of incidence relative to the transverse slices can directly reach internal organs or tissues (e.g. breasts, testes and salivary glands) without first penetrating the skin layer. This might lead to an overestimation of DCs for weakly penetrating radiations incident at angles that are not perpendicular to the body length axis. The mesh-type reference phantoms, in contrast, are fully wrapped by the skin whose total mass is in accordance with the reference value. Note that also other organs and tissues having thin tissue structures (such as gastrointestinal (GI) tract organs and cortical bone) are discontinuous in the voxel-type reference phantoms, an issue which is fully resolved within the mesh-type reference phantoms.

(27) The small intestine of the voxel-type reference phantoms, in addition to showing discontinuous parts, does not precisely represent its complex tubular structure. Therefore, high-quality small-intestine models were incorporated into the mesh-type reference phantoms, whereby models were generated by using a dedicated procedure based on a Monte Carlo sampling approach (Yeom et al., 2016a). Similarly, high-quality detailed models of the spine (cervical, thoracic and lumbar) and hand and foot bones were incorporated into the mesh-type reference phantoms (Yeom et al., 2016b).

(28) The lymphatic nodes of the voxel-type reference phantoms were manually drawn at locations specified in anatomical textbooks (Brash and Jamieson, 1943; Möller and Reif, 1993, 1997; GEO kompakt, 2005), because they could not be identified on the original CT images. Although the higher concentration at specific locations (e.g. groin, axillae, the hollows of the knees, crooks of the arms) described in the textbooks was correctly incorporated into the

Publication 110 phantoms, site-specific numbers of the lymphatic nodes presented in *Publication 89* (ICRP, 2002) were not considered. In the mesh-type reference phantoms, lymphatic nodes were regenerated by a modelling approach used for the UF/NCI family of phantoms (Lee et al., 2013) based on the lymphatic node data derived from the data of *Publications 23*, *66* and *89* (ICRP, 1975, 1994a, 2002) (see Chapter 3.4).

(29) The complex structure of the eye also could not be precisely represented in the voxel-type reference phantoms due to the image resolution. Therefore, the detailed eye model of Behrens et al. (2009) was adopted in *Publication 116* (ICRP, 2010), and the *Publication 116* lens DCs were calculated using either the voxel-type reference phantoms or the adopted eye model, depending on radiation type, energy, and irradiation geometry. In order to be able to compute the absorbed dose to the eye lens using only one anthropomorphic phantom for each sex, the detailed eye model of Behrens et al. (2009) was directly incorporated into the mesh-type reference phantoms (Nguyen et al., 2015).

(30) The Commission recommended that a range from 50–100 µm below the skin surface should be considered as an appropriate depth for the basal cell layer of most body regions of the skin (ICRP, 1977, 2010, 2015). The 50-µm-thick radiosensitive skin layer, however, cannot be represented in the voxel-type reference phantoms, due to their limited voxel resolution. The skin DCs of *Publication 116* (ICRP, 2010) for external exposures were thus calculated by averaging the absorbed dose over the entire skin of the phantoms. This approximation is acceptable for the calculation of effective doses for penetrating radiations, considering the small tissue weighting factor of the skin (w_T= 0.01). However, for weakly penetrating radiations, such as alpha and beta particles, this approximation leads to underestimations or overestimations in skin target cell layer doses. In the skin of the mesh-type reference phantoms, the 50-µm-thick radiosensitive target layer was defined explicitly.

(31) Similarly, the micrometre scales of radiosensitive tissues and source regions for radionuclide retention of the respiratory and alimentary tract systems, as described in *Publications 66* and *100* (ICRP, 1994a, 2006), could not be represented in the voxel-type reference phantoms. Separate stylised models, describing the respiratory and alimentary tract organs as mathematical shapes (e.g. a sphere or a right circular cylinder), were used for the calculation of specific absorbed fractions (SAFs) for charged particles (ICRP, 1994a, 2006, 2016). In the mesh-type reference phantoms, the micrometre-thick target and source regions in the alimentary and respiratory tract systems as described in *Publications 66* and *100* (ICRP, 1994a, 2006) were included (Kim et al., 2017). Realistic lung airway models that represent the bronchial (BB) and bronchiolar (bb) regions were also developed and incorporated into the mesh-type reference phantoms, whereas in the voxel-type reference phantoms the bronchi could not be followed down to more than the very first generations of airway branching. Furthermore, the bronchioles are too small to be represented in a voxel basis (ICRP, 2009).

(32) Previously, the organ and tissue masses of computational anthropomorphic phantoms (Lee et al., 2007; ICRP, 2009; Yeom et., 2013), were commonly adjusted to the reference values listed in Table 2.8 of *Publication 89* (ICRP, 2002). However, these masses correspond to the masses of organ/tissue parenchyma only, while the optimal phantom design would provide organ volumes consistent with both the organ parenchyma and included blood vasculature. In a living person, on the other hand, a large proportion of blood is distributed in small vessels and capillaries within the organs and tissues, thus increasing slightly the organ and tissue masses within the phantom body. In recognition of this circumstance, target tissue/organ masses inclusive of blood were used to calculate the self-irradiation SAFs of *Publication 133* (ICRP, 2016). To reflect this also in the new mesh-type reference phantoms,

the organ and tissue masses and tissue compositions of these phantoms were adjusted such as to include their organ blood content. The blood distribution among the organs and tissues was derived from the reference regional blood volume fractions given in *Publication 89* (ICRP, 2002) using an approach similar to that outlined in *Publication 133* (ICRP, 2016).

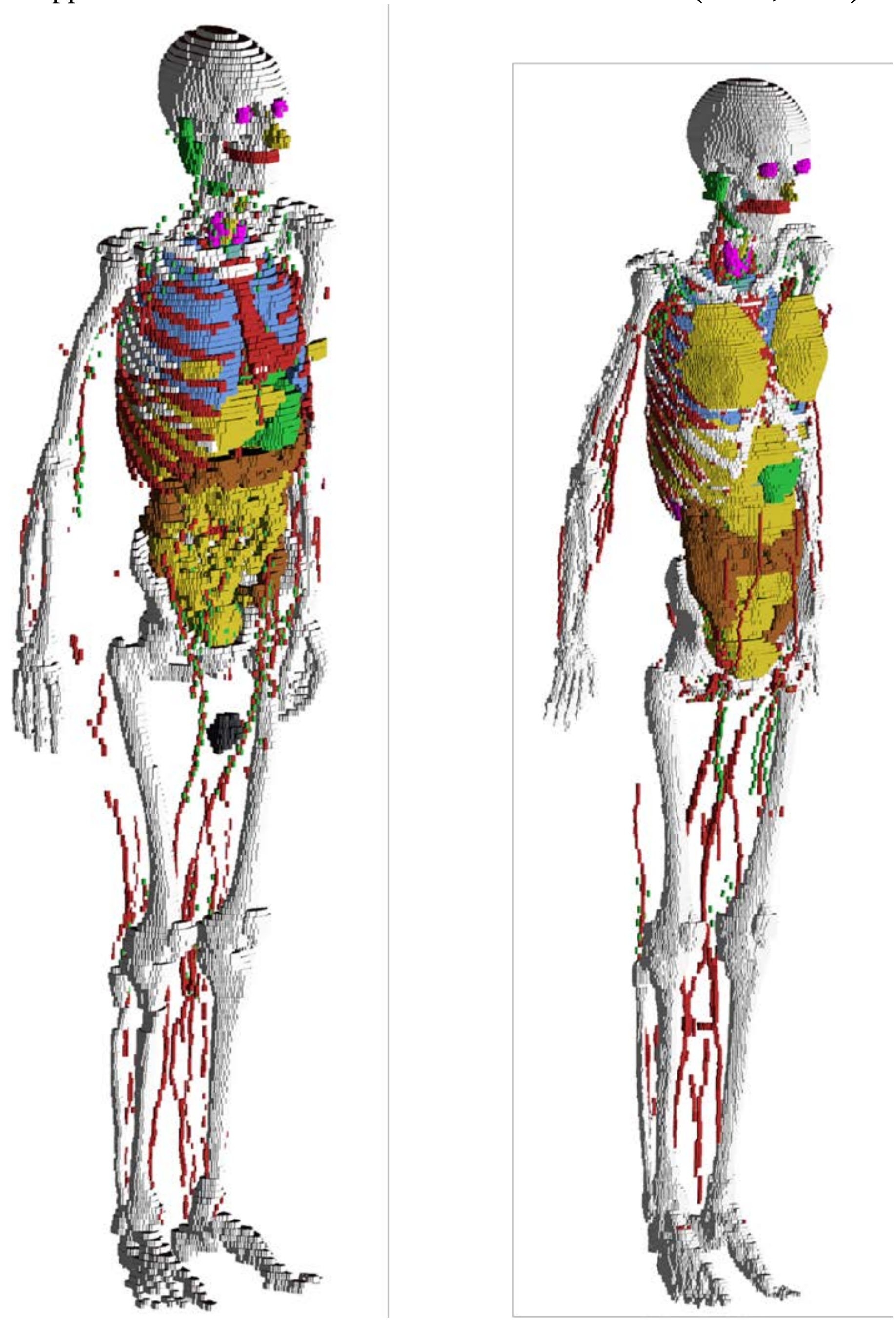


Fig. 2.1. The voxel-type reference phantoms of adult reference male (left) and adult reference female (right). The skin, muscle and adipose tissue are not displayed in this figure.

3. CONVERSION OF THE ADULT VOXEL-TYPE REFERENCE PHANTOMS TO MESH FORMAT

3.1. Simple organs and tissues

(33) Most of the organs and tissues in the mesh phantoms were constructed by directly converting the adult voxel-type reference phantoms to the polygon-mesh (PM) format via 3D surface rendering and subsequent refinement procedures. Figure 3.1 schematically describes the procedure. The voxel data of the phantoms were imported into *3D-DOCTOR*^{TM} (Able Software Corp., Lexington MA). The organs and tissues were then contoured using the *Interactive Segmentation* command of the software. The contoured lines were converted to primitive PM models using the *Surface Rendering* command. These primitive PM models, generally showing some stair-stepped surfaces with holes and defects, were refined into high-quality PM models by using the *Rapidform*^{TM} software (INUS Technology Inc., Korea). In order to minimise the distortion of the original shape during the refinement process, the number of facets was increased using the *Subdivide* command of *Rapidform*^{TM} software. The PM models were smoothened with the *Smooth* command and, at the same time, their holes and defects were eliminated using the *Fill Holes* and *Healing Wizard* commands. Subsequently, the number of polygonal facets was reduced to a reasonable number by repeatedly applying the *Decimate* command. Finally, the refined PM models were adjusted to match their target mass using the *Deform* command. Reference target organ masses (inclusive of blood content) are given in Annex A of this Report. For the organs and tissues including inner structures such as hollow organs, the refined PM models were replicated to produce separate models to define inner structures. The sizes of the inner-structure models were then reduced by adjusting their volumes to match the target mass using the *Offset* and *Deform* commands. For some complex organs such as the colon, the voxels were first converted to NURBS (Non Uniform Rational B-Spline) models and then to PM models.

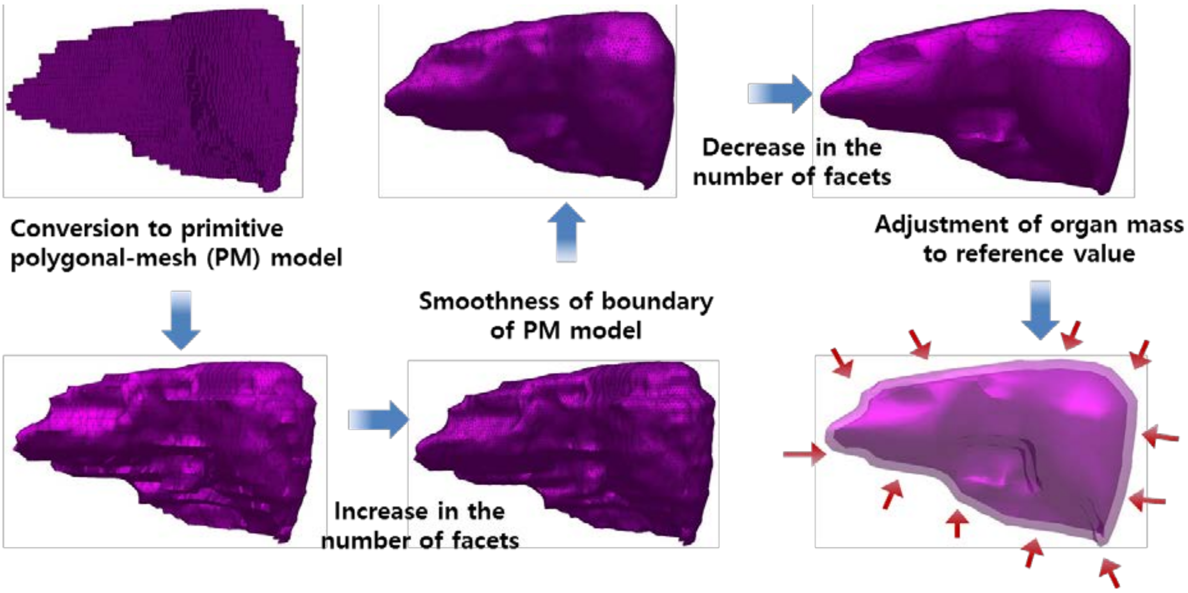


Fig. 3.1. Conversion procedure applied for most organs and tissues.

(34) Note that the reference value for the oesophageal contents is not given in *Publication 89* (ICRP, 2002); thus, the *Publication 110* phantoms do not include the oesophageal contents, which makes it impossible to calculate SAFs for the oesophagus for radiations emitted by ingested radioactive material during passage through the oesophagus. In the mesh phantoms, therefore, the oesophageal contents were added as part of the oesophagus, having the same volume as the *Publication 100* (ICRP, 2006) stylised models (male: 22.0 cm^3 and female: 20.4 cm^3). For this change, both the length and diameter of the original voxel-type oesophagus had to be increased by ~0.3 cm. Resultantly, the mass of the residual soft tissue (RST) was decreased in order to keep the body mass unchanged. The RST will be discussed in detail later in Section 4.3.

(35) During the inclusion of the oesophageal contents, it was found that in the *Publication 110* phantoms, the oesophagus contacts the thyroid for both the male and female phantoms and the thyroid contacts the thymus for the male phantom, which are anatomically incorrect. These organs were separated in the mesh phantoms.

(36) Due to the limited voxel resolution of the original voxel-type reference computational phantoms, it was impossible to properly segment the blood in the lungs of the *Publication 110* phantoms. Consequently, the blood mass (male: 150 g and female: 101 g) is significantly smaller than the reference value (male: 700 g and female: 530 g) and the unsegmented blood is implicitly included in the lung tissue (ICRP, 2009). In the PM model of the lungs, the segmented blood was included in the lung tissue by recalculating the density and elemental composition of the lung tissue. This approach slightly increased the lung density by 8.6% (male) and 7.3% (female). These changes will not significantly affect calculated absorbed doses to the lungs.

(37) During the conversion process, the PM models were adjusted to the voxel models, monitoring two indices which show the geometrical similarity between two given objects. The first index used in the process was the Dice index (DI), which simply represents the volume overlap fraction of two objects (Dice, 1945). For confirmation of successful adjustment, it was considered that the DI should be greater than 95% of the maximum achievable Dice index (MADI) for a given organ. Note that the MADI exists for a given organ due to the fundamental difference in the geometry format (i.e. voxel vs. PM), which was estimated by calculating the DI between the PM model under adjustment and its voxelised model with the same voxel resolution as the *Publication 110* phantoms. The second index is the centroid distance (CD), which is the distance between the centroids of the voxel model and the corresponding PM model. It was considered that the CD should be less than 0.5 mm for confirmation of a successful adjustment.

(38) The CD values were less than 0.5 mm for all organs and tissues which were directly converted from the *Publication 110* voxel models. The DI values were greater than the target DI (= 95% of MADI) for most of the organs and tissues, but there were some exceptions. For the oesophagus, for example, the DI value was less than the target DI, because the total volume of the oesophagus of the PM models was intentionally increased in order to include the oesophageal contents as discussed above. A few other organs and tissues also showed low DI values, because the finite voxel resolution resulted in disconnections of these organs in the *Publication 110* phantoms. For the PM models, the disconnected organ/tissue was first connected and then adjusted to maximise the DI value. After the completion of conversion, we also calculated an additional geometrical similarity index, the Hausdorff distance (HD) (Hausdorff, 1918), which is defined as follows:

$$\mathrm{HD} = \max(\bar{D}(A \cap B^c, B), \bar{D}(B \cap A^c, A)) \quad (1)$$

$$\bar{D}(A,B) = \frac{1}{N_a}\sum_{a\in A} D(a,B) \tag{2}$$

where a is a point within an object A and $D(a, B)$ is the minimum distance from point a to the other object B. It was found that the HD values are less than 2.5 mm for all organs and tissues, and for most cases less than 1.2 mm, which additionally indicates the high similarity of the PM models with the original voxel models.

3.2. Skeletal system

(39) Most of the bones (i.e. upper arm bones (humeri), lower arm bones (ulnae and radii), clavicles, upper leg bones (femora), lower leg bones (tibiae, fibulae and patellae), mandible, pelvis, scapulae, sternum, cranium and ribs) were produced by using the same conversion procedure employed for the single-region organs and tissues as demonstrated above for the liver. For the spine (cervical, thoracic and lumbar) which is a very complicated tissue structure, a set of existing high-quality PM models produced from serially sectioned color-photographic images of cadavers (Park et al., 2005) were taken and adjusted to the voxel models monitoring both the DI and CD. Similarly, for the hands and feet, a set of high-quality PM models produced from micro-CT data of cadavers (http://dk.kisti.re.kr) were adopted; these models were not adjusted to the voxel models but simply scaled to match the target masses and then placed at the ends of the arms and legs of the mesh phantoms. Note that the *Publication 110* female phantom, the feet are inclined (because the original subject was imaged under CT in a prone position). In the mesh-type phantom, the feet were reoriented in a flat, standing position such as found in the *Publication 110* male phantom.

(40) In the *Publication 110* phantoms, the cartilage was not fully segmented due mainly to low contrast in the original CT data. In the mesh-type phantoms, the costal cartilage and intervertebral disks were additionally modelled following the method used for the construction of the UF/NCI phantoms (Lee et al., 2010). To maintain the reference cartilage mass, the remaining cartilage was simply included in the residual soft tissue (RST), which is discussed later in Section 4.3. Strictly speaking, this approach is equally incorrect as the approach used in the *Publication 110* phantoms in which the non-segmented cartilage was included in the spongiosa regions. However, the present approach is dosimetrically more acceptable, considering that the density and effective atomic number of the cartilage are close to those of soft tissues and that the cartilage is neither a radiation-sensitive tissue nor a frequent source region for internal dosimetry; the exact location or distribution of remaining cartilage is thus not important from the dosimetric point of view.

(41) The sacrum of the *Publication 110* female phantom lacks cortical bone, again due to limitations with voxel resolution (ICRP, 2009); therefore, cortical bone was added to the sacrum of the female phantom, assuming the female cortical bone mass fraction is identical to that of the male. To maintain the total cortical bone mass unchanged, the cortical bone of the female lower leg bones was reduced considering that the cortical bone mass fraction of the female lower leg bones (= 19%) was significantly higher than that of the male lower leg bones (= 12%). More detailed information on the skeleton conversion can be found in Yeom et al. (2016b).

(42) Note that in the skeletal system, the micron-scale structure of the skeletal target tissues (i.e. active bone marrow and skeletal endosteum) are not modelled and, therefore, the dose to

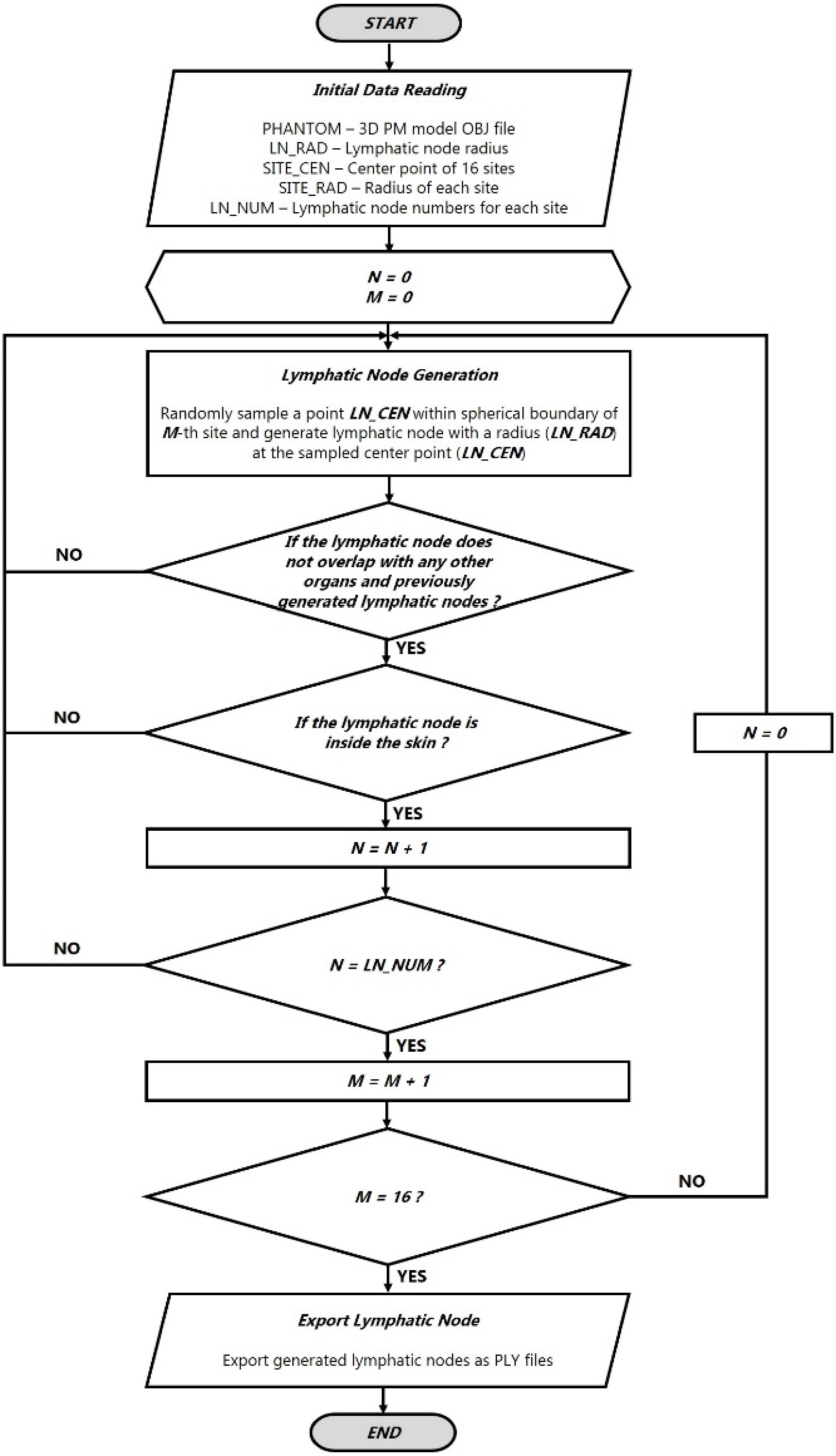
these skeletal tissues needs to be calculated by using fluence-to-dose response functions, such as those presented and described in Annexes D and E of *Publication 116* (ICRP, 2010).

3.3. Small intestine

(43) The small intestine was not precisely represented in the *Publication 110* phantoms (ICRP, 2009), mainly because its complex tubular structure was not clearly distinguishable in the original cross-sectional CT data and its modelling was limited due to the finite voxel resolution. Accordingly, a dedicated procedure and a computer program were used to generate the small-intestine models in the mesh phantoms (Yeom et al., 2016a). First, a surface frame, entirely enclosing the original small-intestine voxel model, was constructed using the alpha-shape algorithm (Edelsbrunner et al., 1983). Next, a dedicated computer program developed in C++ was used to generate a small-intestine passage line using a Monte Carlo sampling approach. Along with the passage line, a PM-format small-intestine model was generated, whose masses of the wall and contents were matched to the reference values given in *Publication 89* (ICRP, 2002). The aforementioned procedure was repeated to produce 1000 different small-intestine models, with the best model selected considering both its geometric and dosimetry similarity. More detailed information on the construction of the small-intestine model can be found in Yeom et al. (2016a).

3.4. Lymphatic nodes

(44) The lymphatic nodes of the *Publication 110* phantoms could not be directly converted to the PM format due to their complexity and distributed nature in the body. The lymphatic nodes in the PM format were therefore generated by using a similar modelling approach used to generate lymphatic nodes in the UF/NCI family phantoms (Lee et al., 2013) based on the lymphatic node data (see Table 3.1), which were derived from the data of *Publications 23*, *66* and *89* (ICRP, 1975, 1994a, 2002). Note that the derived lymphatic node data are consistent with the values adopted for the calculations of *Publication 133* (ICRP, 2016). For the generation of the lymphatic nodes, a dedicated computer program was developed following the procedure shown in Fig. 3.2. The program first loads the initial data: (1) the PM phantom data, (2) the single node PM data, (3) the nodal diameter, (4) the coordinates of the lymphatic nodal sites, (5) the diameters of the spherical clusters for the sites and (6) the site-specific nodal numbers. Then, the program randomly generates lymphatic nodes satisfying the following two criteria: (1) a node should be placed within the corresponding cluster sphere and (2) a node should overlap neither with other organs and tissues nor with the previously generated nodes. The procedure is repeated until the number of generated nodes reaches a predefined number.



781
782 Fig. 3.2. Flowchart of developed program to generate lymphatic nodes in the PM phantoms.

Table 3.1. Lymphatic nodal numbers and masses for the adult male and female derived from the data of *Publication 23*, *66* and *89* (ICRP, 1975, 1994a, 2002), along with reference nodal numbers given in *Publication 89* (ICRP, 2002).

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

3.5. Eyes

(45) The *Publication 110* phantoms (ICRP, 2009), due to their voxel sizes on the order of a few millimetres, do not properly represent the detailed structure of the eye. The lens DCs of *Publication 116* (ICRP, 2010) on idealised external radiation exposures were therefore calculated using either the *Publication 110* phantoms or the detailed stylised eye model developed by Behrens et al. (2009), depending on radiation type, energy and irradiation geometry. To avoid this situation, the detailed eye model of Behrens et al. (2009) was directly incorporated into the male and female mesh phantoms. First, using the geometrical information of the Behrens' detailed eye model, a NURBS-format eye model was produced and then converted to the PM format. Defects in the converted model were repaired by using the refinement functions of the *Rapidform*™ software (INUS Technology Inc., Korea). Finally, the PM eye model was placed in the mesh phantoms, matching the centroid of the eye of the *Publication 110* phantoms. More detailed information on the eye model can be found in Nguyen et al. (2015).

3.6. Blood in large vessels

(46) Only the blood in the large blood vessels is modelled in the *Publication 110* phantoms, again due to the limited resolution of the original CT image data (8 and 5 mm slice thicknesses for the male and female phantoms, respectively). Consequently, the mass of the segmented blood in the *Publication 110* phantoms (male: 371 g and female: 384 g) is significantly smaller than their corresponding reference values (male: 1344 g and female: 984 g). This issue was addressed in the mesh phantoms. For the mesh phantoms, first, the blood of the large blood vessels was converted to the PM format, whose mass was then matched to the reference value. For this step, the blood models of the *Publication 110* phantoms were first converted to primitive PM models using a surface rendering method in 3D-DOCTOR™ (Able Software Corp., Lexington MA). Then, the contour lines were carefully generated along the blood passages identified in the primitive PM models using the *Section* command of the *Rhinoceros* software (Robert McNeel & Associates, Seattle, Wash). The generated contour lines were then used to generate NURBS surfaces using the *Loft* command of the software. Finally, the NURBS

surfaces were converted to the PM format using the *Mesh* command. In the mesh phantoms, the remaining part of the blood in the smaller blood vessels was modelled manually with the NURBS modelling tools of the *Rhinoceros* software, referring to the high-quality 3D blood models provided by BioDigital (https://www.biodigital.com). The modelled NURBS surfaces were converted to the PM format and then the converted PM models were connected to the PM models of the blood in the large vessels by using the *Union* command of the *Rapidform*^{TM} software (INUS Technology Inc., Korea). Finally, the combined PM models were adjusted to match the reference values using the *Deform* command of the software. Figure 3.3 shows the developed blood PM models, along with the *Publication 110* blood voxel models. Note that the intra-organ vasculature is not modelled in the phantoms; that is, the blood in the large vessels stops at the surface of the organs and the blood within the organs is assumed to be homogeneously mixed with the parenchyma of the organs.

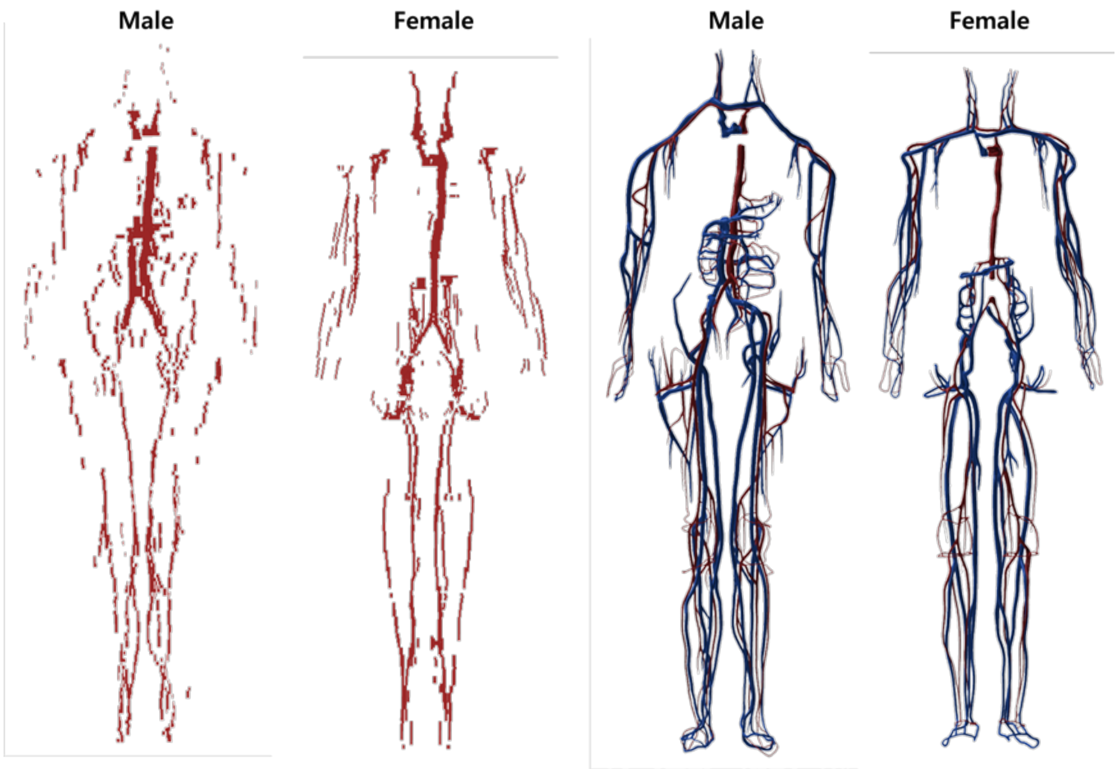


Fig. 3.3. Blood in large vessels of the *Publication 110* phantoms (left) and the MRCPs (right). In the MRCPs, the red colour indicates the blood in the large arteries and the blue colour indicates the blood in the large veins.

3.7. Muscle

(47) The muscle of the PM models was constructed after completion of all internal organs and tissues. Most of the muscle (i.e. trunk, arms and legs) were constructed by direct conversion and refinement, whereas the other complex parts (i.e. head, hands and feet) were constructed by a modelling approach. For the construction, a series of labour-intensive refinement work was involved to eliminate the defects and overlapping problems with the other organs and tissues by using the refinement tools of the *Rapidform*^{TM} software (INUS Technology Inc., Korea). In addition, the rear side of the muscle (back, hip and calf), which had been flattened

in the *Publication 110* phantoms due to the lying position of the individual original imaged under CT, was reshaped to produce the muscular shape present in a standing person.

4. INCLUSION OF BLOOD TO ORGANS AND TISSUES

(48) The organ/tissue masses of the mesh phantoms include their intra-organ blood content. This is not the case in the *Publication 110* phantoms, in which the organ/tissue masses are based on reference values listed in Table 2.8 of *Publication 89* (ICRP, 2002) which are the masses of organ/tissue parenchyma, i.e. not including blood content. Note that a large portion of blood situated in the small vessels and capillaries is distributed in the organs and tissues. For the mesh phantoms, therefore, the organ/tissue masses and compositions inclusive of the blood content for adult male and female were calculated based on the reference regional volume fractions given in *Publication 89* (ICRP, 2002) and, accordingly, the mesh phantoms were adjusted in volume to include the blood content in their organs and tissues. Note that *Publication 133* (ICRP, 2016) also considered the target masses inclusive of blood content for the calculation of SAFs for self-irradiation.

4.1. Calculation of mass, density, and elemental composition of organs and tissues inclusive of blood content

(49) Blood-content masses for all the organs and tissues listed in Table 2.8 of *Publication 89* (ICRP, 2002) were calculated by using the reference values of regional blood volume fractions given in Table 2.14 of *Publication 89* (ICRP, 2002), which is replicated in Table 4.1 below. There are organs and tissues whose reference blood fraction is explicitly given (i.e. fat, brain, stomach, oesophagus, small intestine, large intestine, right heart, left heart, coronary tissue, kidneys, liver, pulmonary, bronchial tissue, skeletal muscle, pancreas, active marrow, trabecular bone, cortical bone, other skeleton, skin, spleen, thyroid, lymph nodes, gonads, adrenals and urinary bladder). Their blood-content mass was simply calculated as the product of their reference blood fraction and the reference total body blood mass (adult male: 5600 g and adult female: 4100 g) given in *Publication 89* (ICRP, 2002).

(50) The reference blood fraction for the stomach and oesophagus is given as a single value, and thus not given separately as shown in Table 4.1; therefore, their blood mass was assigned in proportion to the organ mass under the assumption that the blood is uniformly distributed over these two organs. The same approach was used to calculate the blood mass of the inactive marrow, cartilage, teeth and miscellaneous skeletal tissue, which are grouped as ‘other skeleton’ in Table 4.1.

(51) In Table 2.8 of *Publication 89* (ICRP, 2002), there are organs and tissues whose blood fractions are not explicitly listed in Table 2.14 of *Publication 89* (ICRP, 2002), i.e. Table 4.1 (i.e. tongue, salivary glands, gall bladder wall, breasts, eyes, pituitary gland, larynx, trachea, thymus, tonsils, ureters, urethra, epididymis, prostate, fallopian tubes, uterus and ‘remaining 4%’ tissues), which are represented by the ‘all other tissues’ in Table 4.1. Note that the ‘remaining 4%’ tissues indicate all of the organs and tissues that are not explicitly listed in Table 2.8 of *Publication 89* (ICRP, 2002), which is about 4% of the body mass, mostly composed of separable connective tissues and certain lymphatic tissues. The blood mass of the ‘all other tissue’ (male: 107.5 g and female: 78.7 g) was distributed to these organs and tissues with proportion to their masses. For this calculation, the mass of the ‘remaining 4%’ tissues was reduced due to the extraction of the lymphatic nodes of which the mass (male: 178.4 g and female: 142.7 g) was adopted in *Publication 133* (ICRP, 2016), considering that the reference blood fraction for the lymphatic nodes is explicitly given as shown in Table 4.1. The reference

organ/tissue masses (exclusive of blood content) and the calculated blood content masses are given in Table 4.2.

Table 4.1. Reference values for regional blood volumes in adults given in *Publication 89* (ICRP, 2002).

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

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

Organ/tissue	Male		Female	
	Organ/tissue only (g)	Blood content (g)	Organ/tissue only (g)	Blood content (g)
Adipose tissue	14500	280.000	19000	348.500
Adrenals	14	3.360	13	2.460
Tongue	73	2.656	60	1.491
Salivary glands	85	3.093	70	1.739
Oesophagus, wall	40	11.789	35	8.200
Stomach, wall	150	44.211	140	32.800
Stomach, contents	250		230	
Small intestine, wall	650	212.800	600	155.800
Small intestine, contents	350		280	
Right colon, wall	150	49.946	145	36.331
Right colon, contents	150		160	
Left colon, wall	150	49.946	145	36.331
Left colon, contents	75		80	
Rectosigmoid, wall	70	23.308	70	17.539
Rectosigmoid, contents	75		80	
Liver	1800	560.000	1400	410.000
Gallbladder, wall	10	0.364	8	0.199
Gallbladder, contents	58		48	
Pancreas	140	33.600	120	24.600
Brain	1450	67.200	1300	49.200
Breasts, adipose	15	0.546	300	7.454
Breasts, glandular	10	0.364	200	4.969
Blood in heart chambers	510*	510.000	370*	370.000
Heart – tissue only	330	56.000	250	41.000
Total blood	5600	5600.000	4100	4100.000
Eyes	15	0.546	15	0.373
Skin	3300	168.000	2300	123.000
Muscle, skeletal	29000	784.000	17500	430.500
Pituitary gland	0.6	0.022	0.6	0.015
Larynx	28	1.019	19	0.472
Trachea	10	0.364	8	0.199
Blood in lung	700*	700.000	530*	530.000
Lung – tissue only	500		420	
Bone, cortical	4400	44.800	3200	32.800
Bone, trabecular	1100	67.200	800	49.200
Marrow, active	1170	224.000	900	164.000
Marrow, inactive	2480	36.261	1800	25.448
Cartilage	1100	16.084	900	12.724
Teeth	50	0.731	40	0.566
Skeletal miscellaneous	200	2.924	160	2.262
Spleen	150	78.400	130	57.400
Thymus	25	0.910	20	0.497
Thyroid	20	3.360	17	2.460
Tonsils	3	0.109	3	0.074
Kidneys	310	112.000	275	82.000
Ureters	16	0.582	15	0.373
Urinary bladder	50	1.120	40	0.820
Urethra	10	0.364	3	0.074
Testes	35	2.240		
Epididymes	4	0.145		
Prostate	17	0.619		

Ovaries			11	1.640
Fallopian tubes			2.1	0.052
Uterus			80	1.987
Lymphatic nodes	178.4†	11.200	142.7†	8.200
Blood, arteries		336.000		246.000
Blood, veins		1008.000		738.000
'Remaining 4%' tissues	2633.0‡	89.817	2364.6‡	40.251
Total body (kg)	73000		60000	

* The mass of blood in the heart chambers and lungs were included in the total blood and should not be included in the whole-body summation.
† The mass of the lymphatic nodes exclusive of blood content was adopted in *Publication 133* (ICRP, 2016).
‡ The mass of the 'remaining 4%' tissues was calculated by subtracting the total mass of all other organs and tissues from body mass.

(52) After the calculation of the blood masses, the densities and elemental compositions of the blood-inclusive organs and tissues were calculated by using the data in *Publication 89* (ICRP, 2002) and *Report 46* (ICRU, 1992), again under the assumption that the blood content is uniformly distributed over the organs and tissues. The density of the blood-inclusive liver, for example, was calculated by using the following equation:

$$\rho_{liver}^{with-blood} = \frac{m_{liver}^{ICRP89} + m_{blood-in-liver}}{\frac{m_{liver}^{ICRP89}}{\rho_{liver}^{ICRU46}} + \frac{m_{blood-in-liver}}{\rho_{blood}^{ICRU46}}} \quad (1)$$

where $\rho_{liver}^{with-blood}$ is the density of the blood-inclusive liver, ρ_{liver}^{ICRU46} is the density of the liver parenchyma as given in *Report 46* (ICRU, 1992), ρ_{blood}^{ICRU46} is the density of the blood, m_{liver}^{ICRP89} is the mass of the liver parenchyma as given in *Publication 89* (ICRP, 2002), and $m_{blood-in-liver}$ is the mass of the blood in the liver. Regarding the elemental composition, the mass percentage of hydrogen in the blood-inclusive liver, for example, was calculated by using the following equation:

$$(\%H)_{liver}^{with-blood} = \frac{(\%H)_{liver}^{ICRU46} m_{liver}^{ICRP89} + (\%H)_{blood}^{ICRU46} m_{blood-in-liver}}{m_{liver}^{ICRP89} + m_{blood-in-liver}} \quad (2)$$

where $(\%\mathrm{H})_{liver}^{with-blood}$ is the percentage by mass of hydrogen in the blood-inclusive liver, $(\%H)_{liver}^{ICRU46}$ is the percentage by mass of hydrogen in the liver parenchyma as given in *Report 46* (ICRU, 1992), and $(\%H)_{blood}^{ICRU46}$ is the percentage by mass of hydrogen in the blood. These calculation methods were used to calculate all of the densities and elemental compositions for the organs and tissues of the mesh phantoms. The calculated values of the density and elemental compositions are given in Table B.1 and Table B.2.

4.2. Phantom adjustment for blood inclusion

(53) The PM models for all organs and tissues were subsequently adjusted to increase their volumes to allow for the volumetric inclusion of their blood content. The adjustment was performed again using the *Rapidform^{TM}* software (INUS Technology Inc., Korea). Preferentially the volumes of the organs and tissues were increased to match the blood-inclusive reference masses by globally enlarging a PM surface in the normal direction of the

facets, which tends to maintain the centroid and original shape of the models. Among the increased organs and tissues, some overlaps were detected and the overlapping regions of the larger organs and tissues were preferentially eliminated rather than the smaller organs and tissues, in order to minimise the distortion of the organ/tissue shapes. The organs and tissues with decreased volumes were then manually adjusted to increase their volumes to match the reference masses, while at the same time monitoring the DI and CD to minimise the deformation of the organ shape from the original shape.

(54) If there was insufficient space for the increase of the organ/tissue volumes, the organs and tissues were moved slightly to secure space. For example, the volume of the liver was increased significantly, i.e. more than 30% for both the male and the female, resulting in significant overlap problems with the adjacent organs and tissues, especially for the female mesh phantom. The lungs and ribs, therefore, had to be moved outward in the lateral direction by ~2 mm and ~4 mm for the male and female, respectively, after which the liver and adjacent organs and tissues were again adjusted to match the reference masses without overlapping regions.

(55) Figures 4.1–4.2 compare the internal organs and tissues of the mesh phantoms before and after inclusion of blood content for male and female, respectively. It can be seen that in general, the inclusion of the blood content does not significantly change the topology of the phantoms. For detailed investigation to quantify geometric dissimilarity produced by the blood inclusion, three similarity indices (DI, CD and HD) were evaluated between the organs and tissues of the phantoms before and after their volumetric adjustment.

(56) It was found that the CD and HD values were less than ~2 mm for most of the organs and tissues. The DI values were greater than 0.95 for most of the organs and tissues. On the other hand, there are some organs and tissues that were significantly changed due to the blood inclusion. For the liver and kidney, for example, the CD and HD values ranged from 3.4 mm to 5.4 mm, and the DI values were within the range of 0.83–0.87; these differences are due to the fact that their mass was significantly increased by the blood inclusion. In addition, some organs and tissues (such as ribs and spleen), located near the liver or kidneys, were significantly changed because they were moved to secure space for blood inclusion.

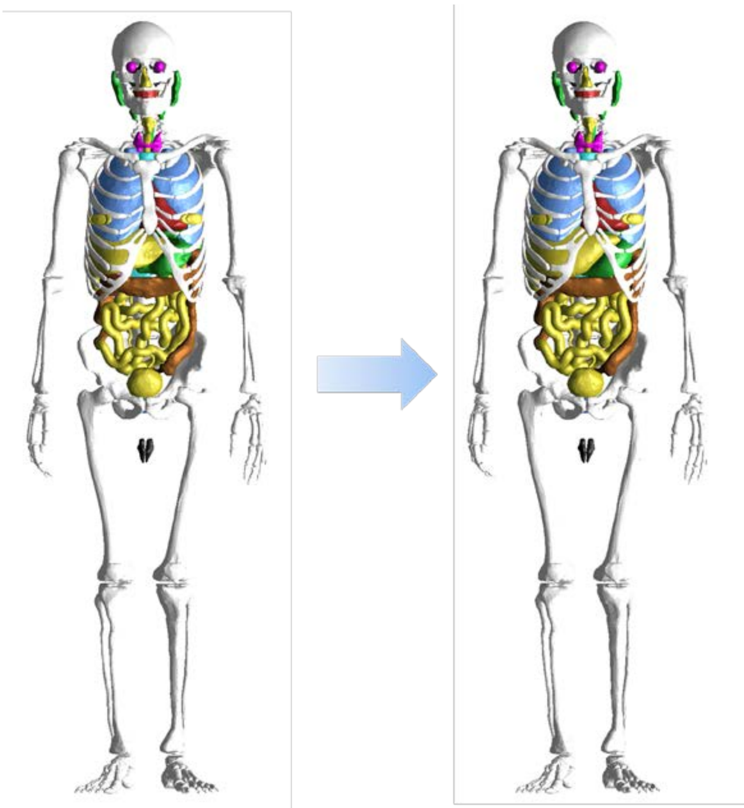


Fig. 4.1. Male phantom before (left) and after (right) adjustment for inclusion of blood content into organs and tissues.

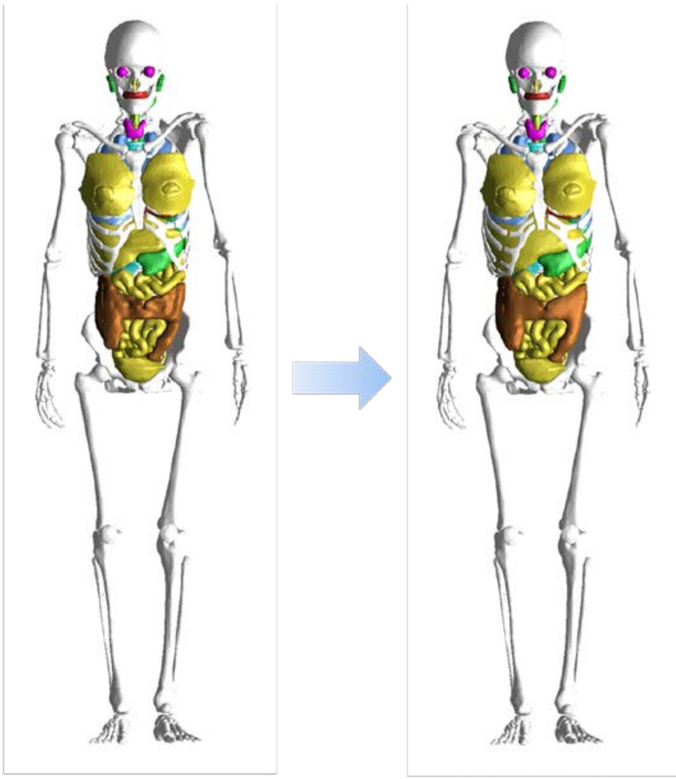


Fig. 4.2. Female phantom before (left) and after (right) adjustment for inclusion of blood content into organs and tissues.

4.3. Definition of residual soft tissue (RST)

(57) Although most of the organs and tissues in Table 4.2 are defined in the mesh phantoms, several organs and tissues (i.e. adipose tissue, larynx, urethra, epididymis and fallopian tubes) are not included explicitly in the phantom anatomical structure. In contrast, several organs and tissues of the phantoms (i.e. main bronchi (= generation 1), spinal cord, urine, oesophageal contents, extrathoracic (ET) and inner air) are not listed in the table, but they can be considered as a part of the 'remaining 4%' tissues in Table 4.2. In addition, the mesh phantoms include only costal and intervertebral cartilages, the total masses of which are significantly smaller than the reference values.

(58) Despite these inconsistencies, the phantom mass should be consistent with the reference total body mass (male: 73 kg and female: 60 kg). This agreement was reached by defining an imaginary tissue, called 'residual soft tissue (RST) ', in the mesh phantoms. The RST implicitly includes all of the reference organs and tissues that are not explicitly defined in the phantoms: adipose tissue, larynx, cartilage (excluding costal and intervertebral cartilages defined in the phantoms), urethra, epididymis, fallopian tubes, 'remaining 4%' tissue (excluding the organs and tissues defined in the phantoms but not listed in the reference values).

(59) This approach has been generally used in the field of phantom development to match the phantom body mass to the reference body mass (ICRP, 2009; Lee et al., 2010; Kim et al., 2011; Yeom et al., 2013). In *Publication 133* (ICRP, 2016), a similar approach was also used to establish the source organ/tissue masses (see Table A.3 of *Publication 133*) for the purpose of use in the latest biokinetic models of the OIR *Publication* series (ICRP, 2015, 2017a, b). The established source organs/tissues do not include some reference organs/tissues, but the total mass of the source organs/tissues was matched to the reference body mass simply by increasing the adipose tissue mass. The increased adipose tissue plays the same role as the RST defined in the mesh phantoms.

5. INCLUSION OF THIN TARGET AND SOURCE REGIONS

5.1. Skin

(60) The cells at risk in the skin are assumed to be in the tissue layer 50 µm to 100 µm below the skin surfaces (ICRP, 1977, 2010, 2015). However, the *Publication 110* phantoms, due to their voxel resolution, do not have this thin target layer and consequently cannot be used for skin dose calculation for weakly penetrating radiations (ICRP, 2010). In the mesh phantoms, the 50-µm-thick target layer was explicitly defined within the volume defining the total skin.

(61) For this, first, the exterior surface of the skin was imported into the *Rapidform*^{TM} software (INUS Technology Inc., Korea) and then replicated to two additional surfaces. The sizes of the two surfaces were reduced to define the target layer within the skin at a depth of 50 µm and 100 µm from the exterior skin surface, respectively, using the *Offset* command of the software. Note that the *Offset* command shrinks or enlarges a PM surface in the normal direction of the facets in the model, which allows the creation of surfaces to define the tens-of-micrometre-thick layer at a specific depth. Figure 5.1 shows the skin of the mesh phantoms including the 50-µm-thick target layer.

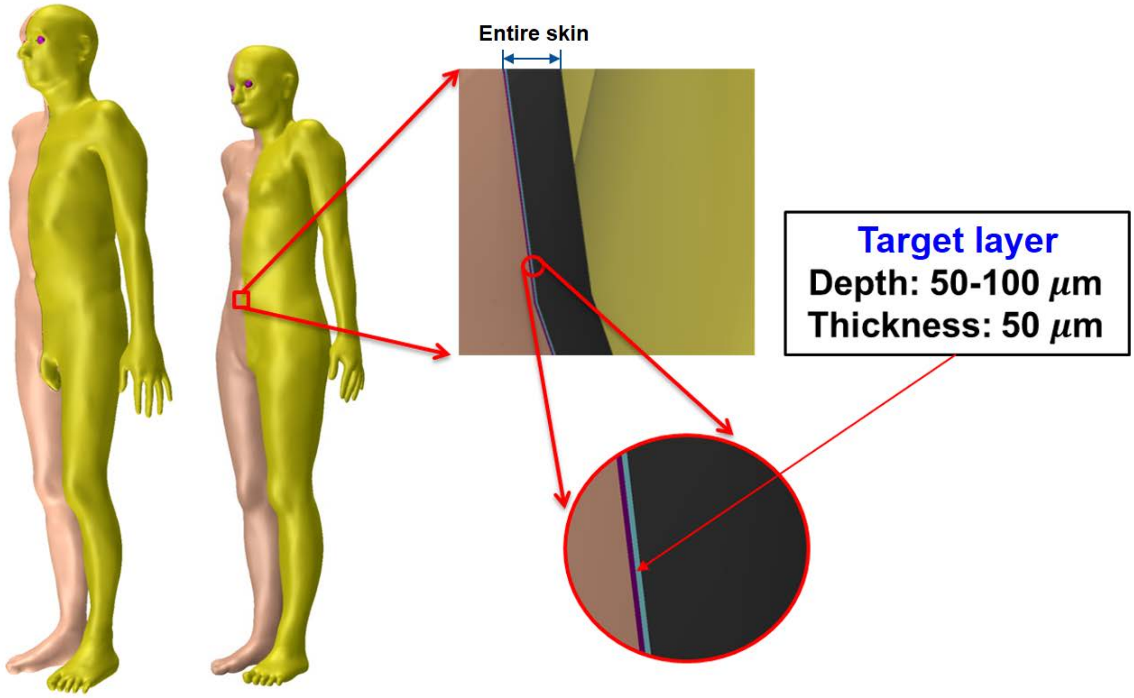


Fig. 5.1. Skin of the mesh phantoms including the 50-µm-thick target layer: dead layer (purple colour), target layer (sky blue colour) and dermis layer (black colour).

5.2. Alimentary tract system

(62) The target regions (stem cell layers) and source regions (mucosal layers) of the alimentary tract organs (i.e. oral cavity, oesophagus, stomach, small intestine and large intestine) were defined in the mesh phantoms according to the depth and thickness data for the target and source regions given in *Publication 100* (ICRP, 2006). For all organs except the oral cavity,

the thin target and source regions were simply defined using the *Offset* command of the *Rapidform*^{TM} software (INUS Technology Inc., Korea) following the same method as used for the skin. Figure 5.2 shows, as an example, the stomach of the male phantom including the target and source regions.

(63) In the oral cavity, two source regions were defined: source in food and source retained on the surface of the teeth. The food source volume (= 20 cm^3) should be placed on the tongue, but in the *Publication 110* phantoms, there was no sufficient space to define the food source region; therefore, the tongue was divided into two parts, i.e. upper and lower parts, and the upper part was considered to be the food source region for the purpose of SAF calculation. The teeth-retained radionuclides were defined by adding a 10-µm layer on the surface of the teeth. The target layer in the oral mucosa was defined in three parts: tongue, roof of mouth and lip and cheek. More detailed information on the alimentary tract system can be found in Kim et al. (2017).

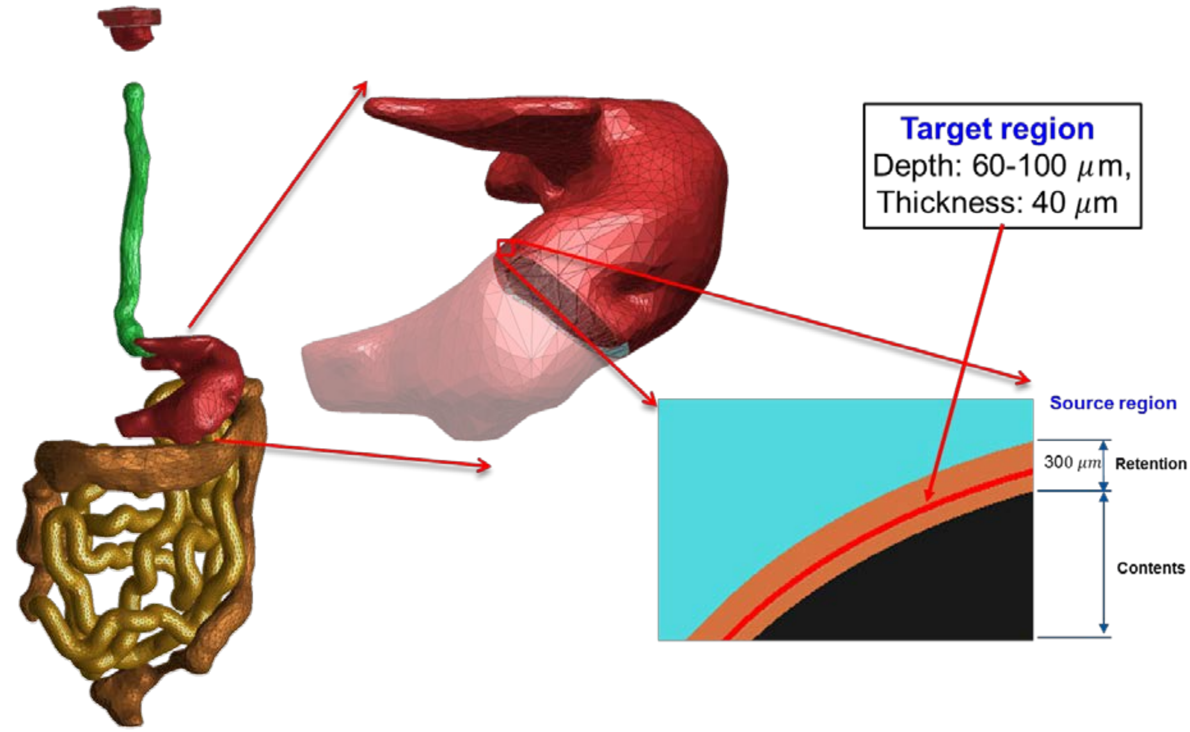


Fig. 5.2. Alimentary tract organs (left) of the male mesh phantom and the enlarged view (right) of the stomach including the target and source regions.

5.3. Respiratory tract system

(64) The target and source regions of the respiratory tract organs were defined in the mesh phantoms following the morphometric data given in *Publication 66* (ICRP, 1994a). The respiratory tract organs are composed of the extrathoracic regions (i.e. ET_1 and ET_2), bronchi (BB), bronchiole (bb) and alveoli-interstitial (AI). The AI was not defined separately but simply assumed to be homogeneously distributed within the lung tissue, except for the BB and bb regions in the MRCPs, considering the statement of *Publication 66* (ICRP, 1994a): *'(313) In the AI region, the interalveolar septa and the walls of blood and lymphatic capillaries are sufficiently thin to ensure that sensitive target cells are distributed homogenously throughout*

the tissue mass. Therefore, it can be assumed that the average dose received by the target cells is the same as that received by the whole tissue mass'.

(65) For the ET_1 and ET_2 regions, they were directly converted from the *Publication 110* voxel models to a PM format, with their target and source regions defined using the *Offset* command of the *Rapidform*^{TM} software (INUS Technology Inc., Korea) following the same method applied for the skin and alimentary tract organs. The same method was also applied to the main bronchi (generation 1) that were directly converted from the *Publication 110* voxel models to the PM format. Figure 5.3 shows the ET_2 region of the male phantom, as an example, including both its *Publication 66* source and target regions.

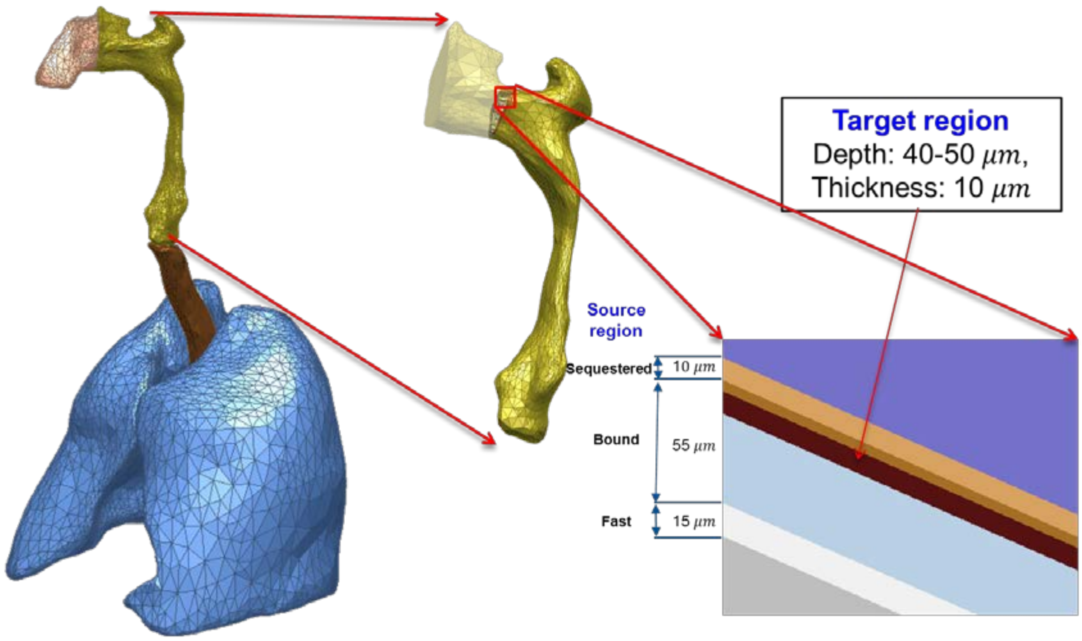


Fig. 5.3. Respiratory tract organs (left) of the male mesh phantom and the enlarged view (right) of the ET_2 including the target and source regions.

(66) The other generations (i.e. airway generations 2–8) of the bronchi (BB) and all subsequent generations of the bronchioles (bb) (i.e. airway generations 9–15) could not be converted from the *Publication 110* voxel models; therefore, these airways were modelled using a dedicated computer program developed by Kim et al. (2017). The developed computer program generated branch-centre lines within the left and right lungs of the mesh phantoms based on a branching generation algorithm (Tawhai et al., 2000), following the diameter and length for each airway generation as given in *Publication 66* (ICRP, 1994a). The branch-centre lines were used to construct airway models in the constructive solid geometry (CSG) format, whose models are based on an inverted Y-shape represented as a union geometry of spheres and truncated cones. The spheres, the diameters of which correspond to the branch diameters, are located at the ends of the branch-centre lines and the truncated cones are located so as to be tangent to the mother and daughter spheres. The use of the inverted Y-shape model makes it possible to not only precisely connect the surfaces of the neighbouring branches but also to define the micrometre-thick source and target layers simply by changing the sphere diameters (i.e. branch diameters) (Lázaro, 2011).

(67) Note that the CSG-format airway models needed to be converted to the PM format for incorporation into the mesh phantoms. For this step, however, a large number of polygonal facets, eventually tetrahedrons, would be necessary to properly represent the airways, requiring

a very large memory allocation (> ~50 GB), which is, at least at the present time, impractical. Therefore, a different approach was used for the airways; that is, the MRCPs were overlaid with the CSG lung airways in the Geant4 code (Agostinelli et al., 2003) by using the *G4VUserParalleWorld* class, which is used for implementation of hierarchically overlapping multiple geometries called 'parallel geometries' (Apostolakis et al., 2008). This overlaying approach is currently available only in Geant4, but enables us to perform dose calculation for the detailed CSG lung airways with minimal additional memory usage.

(68) Figure 5.4 shows the airway model produced in the lungs of the male phantom along with the original voxel model of the *Publication 110* male phantom. The airway models of the mesh phantoms represent a complex tree structure, at the same time representing the thin target and source layers. The total lengths of the airway branches for each generation of the lung tree are in good agreement with their reference values; that is, the discrepancies are less than 10% for all generations. More detailed information on the respiratory tract system can be found in Kim et al. (2017).

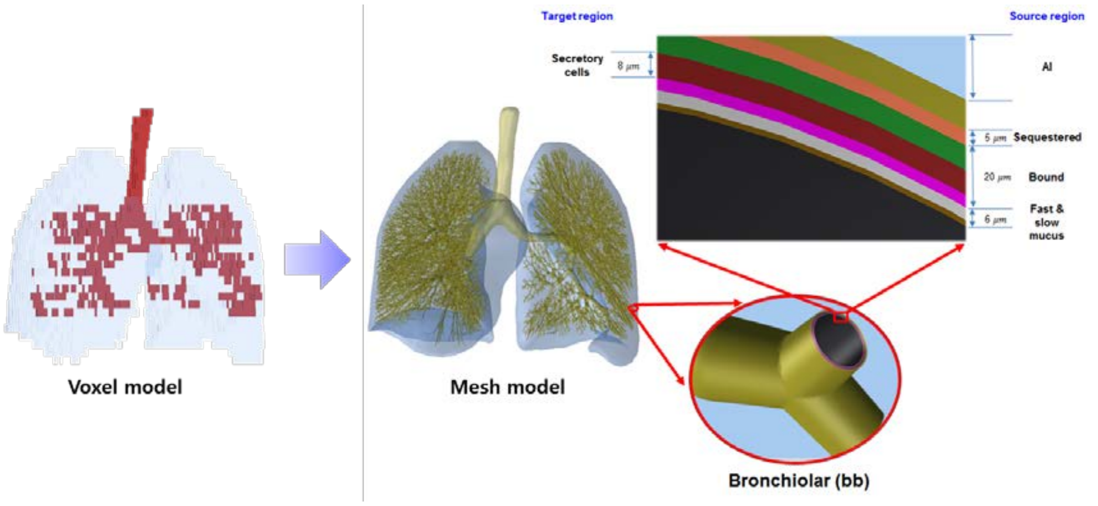


Fig. 5.4. Lung voxel model (left) and lung mesh model (right) for the male phantom (Kim et al., 2017).

5.4. Urinary bladder

(69) The target layer of the urinary bladder was also defined in the mesh phantoms. In the urinary bladder, the basal cells of the epithelium are believed to be the relevant target cells at radiogenic risk (Colin et al., 2009), but doses have previously been calculated to the whole wall of the bladder (ICRP, 2016). Eckerman and Veinot (2018) derived the depth and thickness of the basal cell layer of the urinary bladder as 118 µm and 75 µm, respectively, for the adult male and 116 µm and 69 µm, respectively, for the adult female, assuming a constant and reference urine volume of 200 cm^3 for both phantoms. In the mesh phantoms, these values were adopted to define the target layer in the urinary bladder, again by using the *Offset* command of the *Rapidform*^{TM} software (INUS Technology Inc., Korea). Figure 5.5 shows the urinary bladder of the male mesh phantom including the target layer.

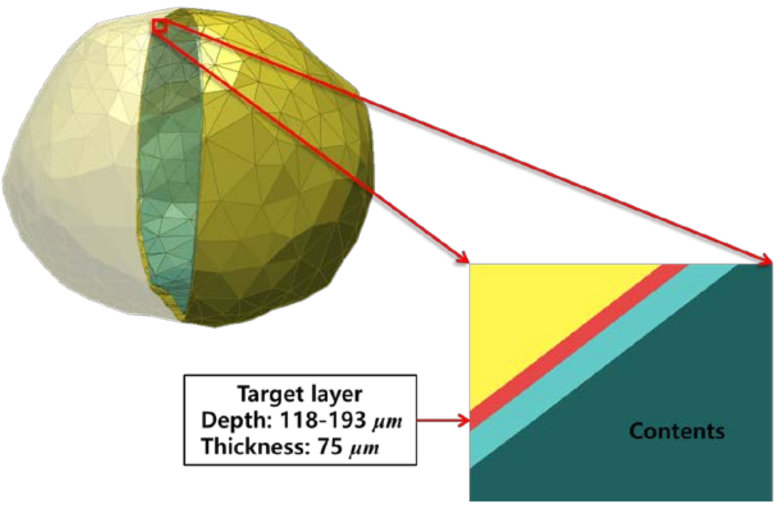


Fig. 5.5. Urinary bladder of the male mesh phantom including the target layer (red).

6. DESCRIPTION OF THE ADULT MESH-TYPE REFERENCE PHANTOMS

6.1. General phantom characteristics

(70) Figures 6.1 and 6.2 show the adult male and female mesh-type reference computational phantoms (MRCPs), respectively. The height and weight of the MRCPs are in accordance with the reference values (male: 176 cm and 73 kg; female: 163 cm and 60 kg). The male phantom is composed of 2.5 million triangular facets in the polygon mesh (PM) format and 8.2 million tetrahedrons in the tetrahedral mesh (TM) format. The female phantom is composed of 2.6 million triangular facets in the PM format and 8.6 million tetrahedrons in the TM format. Note that the TM-version MRCPs were directly converted from the PM-version MRCPs by using the TetGen code (Si, 2015). The MRCPs include all the radiosensitive organs and tissues relevant to dose assessment for ionising radiation exposure for radiological protection purposes. Note that the micron-scale structure of the active bone marrow and skeletal endosteum are not modelled in the MRCPs and, therefore, the calculation of the doses to these skeletal tissues should involve fluence-to-dose response functions, such as those presented in *Publication 116* (ICRP, 2010). The MRCPs include the tens-of-micrometre source and target regions of the eye lens, skin, alimentary tract organs, respiratory tract organs and urinary bladder. The lung airway models (representing the various branches of both the bronchi and bronchioles) produced in the CSG format are incorporated into the MRCPs using the Geant4 code (Agostinelli et al., 2003) via the parallel-geometry technique (Apostolakis et al., 2008).

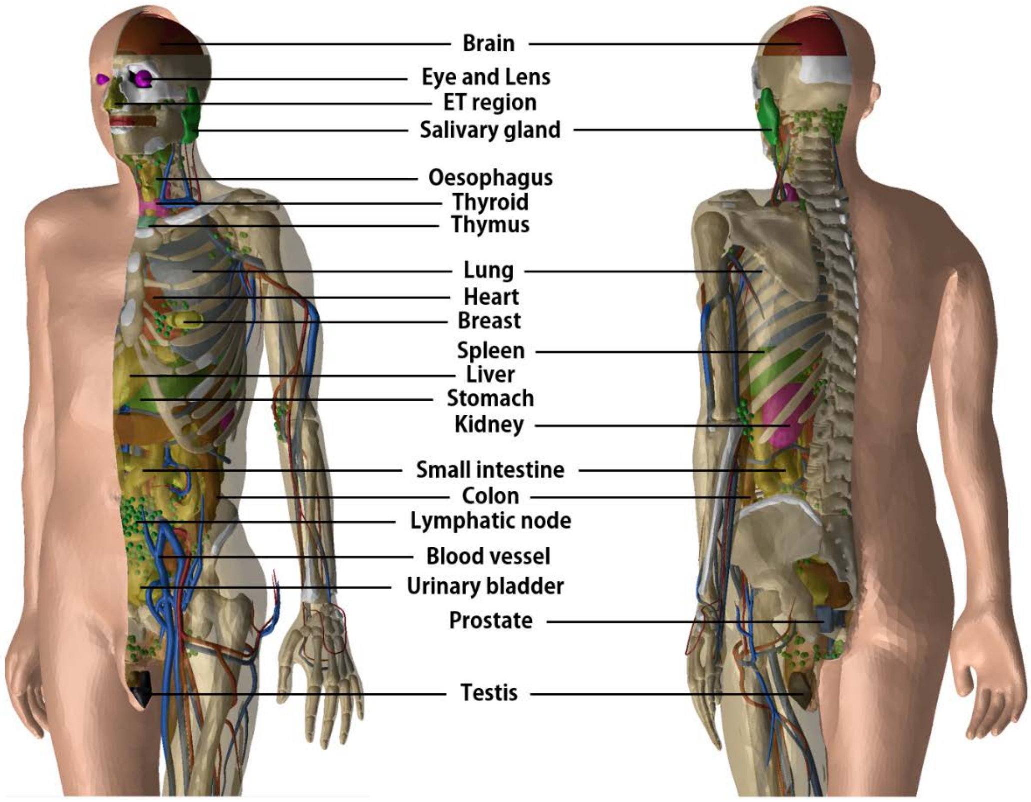


Fig. 6.1. Mesh-type ICRP adult male reference phantom.

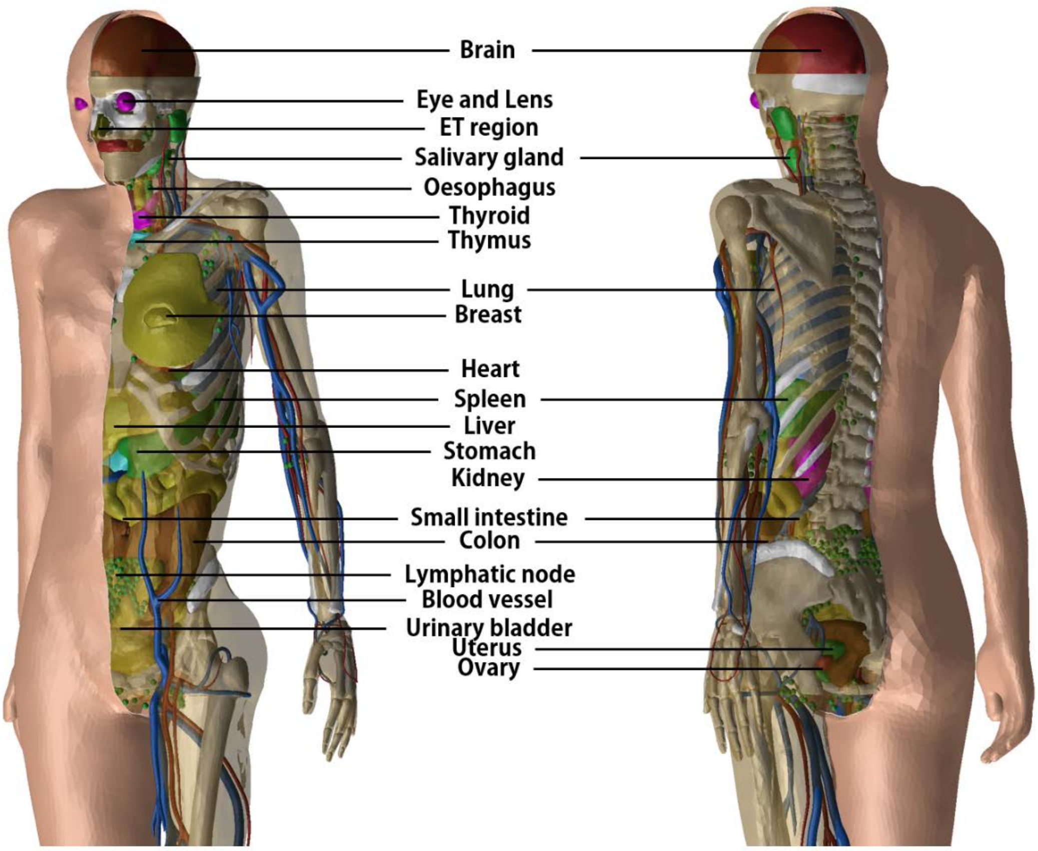


Fig. 6.2. Mesh-type ICRP adult female reference phantom.

(71) The masses of the organs and tissues of the MRCPs match the reference values inclusive of blood content (see Table 4.2) within 0.1% deviation. Table A.1 provides the numerical information of the MRCPs including the organ ID numbers, medium, densities and masses for each organ and tissue. Table B.1 and Table B.2 provide the elemental composition for each medium for the male and female, respectively. Table C.1 provides the list of source regions, their acronyms and corresponding organ ID numbers in the phantoms. Table D.1 provides the list of target regions, their acronyms and corresponding organ ID numbers in the phantoms.

(72) For the alimentary and respiratory tract organs, the dose values of the thin target regions, due to the tiny volumes, tend to have relatively larger statistical uncertainties when compared to other organs. For external exposures to penetrating radiation (such as photons and neutrons), the spatial gradients of the absorbed dose are very small, and thus the absorbed dose averaged over the thin target region tends to be close to the absorbed dose averaged over the entire region of the organ. Therefore, for these exposure cases, it is recommended that one use the entire region of the organ, not the thin target region, for dose calculation so as to save computation time.

(73) On the other hand, the target region of the skin and eye lens should be used in dose calculation for all external exposure cases, considering that there will be significant dose differences between the target region and the entire region even for penetrating uncharged particles (such as photons and neutrons), because charged-particle equilibrium (CPE) is not well established in these superficial organs. For the skin dose calculation, computation time is no longer a problem assuming the entire skin is exposed to the incident radiation field. For the lens dose calculation, computation time can be significantly reduced by assuming that only the head of the phantoms is exposed to radiation.

(74) The thin target regions of the alimentary and respiratory tract systems and the urinary bladder should be used in dose calculation for the internal exposure cases when subregions of these organs (e.g. contents) are considered as source regions. For these calculations, computation time is no longer an issue considering the layered geometries of the source and target regions.

(75) For cross-fire irradiation (e.g. stomach ← liver), it is recommended that one use the entire region of the organ, not just the thin target region, for dose calculation, as once again, dose gradients are small, and there will be savings in computation time. For electron cross-fire irradiation, there could be significant dose discrepancies, depending on the electron energy and organ topology, in which case it is recommended to use the thin target region.

(76) The MRCPs have addressed the geometrical limitations of the *Publication 110* phantoms due to the limited voxel resolution and the nature of voxel geometry. Figure 6.3 shows some internal organs and tissues of the mesh-type male phantom alongside with those of the *Publication 110* male phantom. It can be seen that the voxel models show stair-stepped surfaces, whereas the mesh models show smooth surfaces in their 3D viewing. In addition, the discontinuous structure of the hollow organs of the *Publication 110* phantoms is fully addressed in the MRCPs. Figure 6.4 shows the mesh-type female phantom and the *Publication 110* female phantom viewed in the superior-inferior direction. It can be seen that the *Publication 110* phantoms are not fully enclosed by the skin, showing many holes and several radiosensitive organs and tissues (such as breasts and muscle) directly exposed to the air. On the other hand, the MRCPs are fully enclosed by the skin without any holes; this improvement will prevent significant overestimates in DCs for these organs and tissues for specific situations of external exposure to weakly penetrating radiation. Similarly, the spongiosa and medullary cavity of the *Publication 110* phantoms are not fully enclosed by the cortical bone; this limitation is also addressed in the MRCPs, as shown in Fig. 6.5.

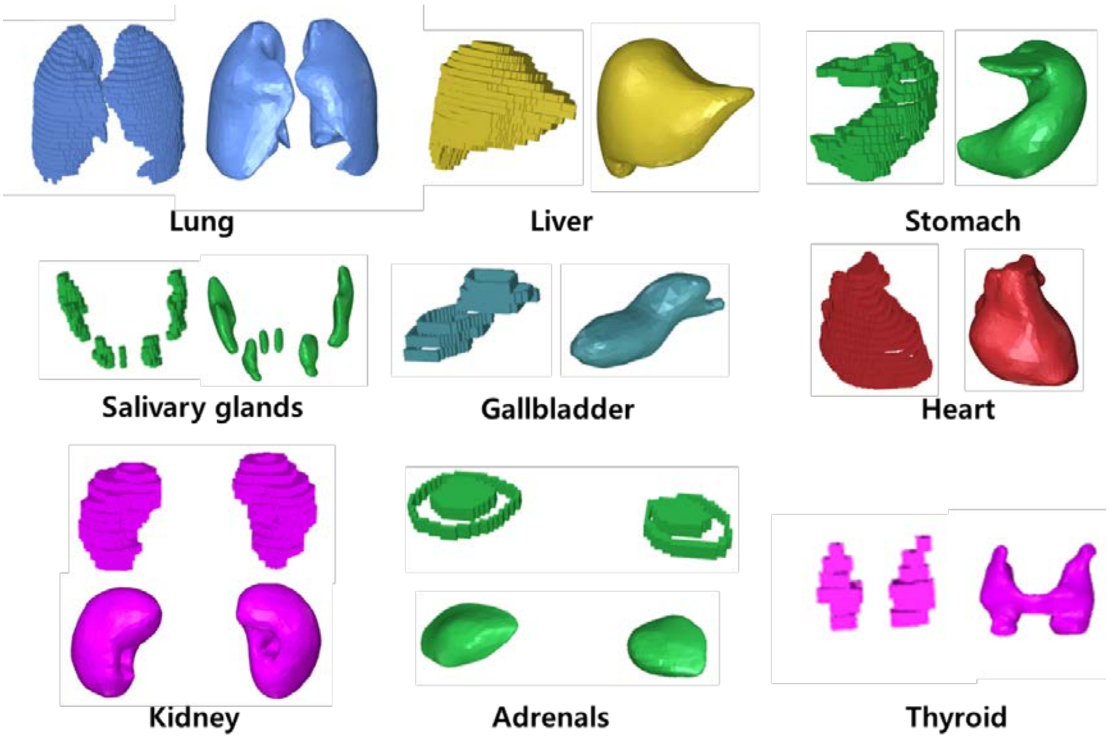


Fig. 6.3. Comparison of organs and tissues of the mesh-type male phantom with those of the *Publication 110* male phantom.

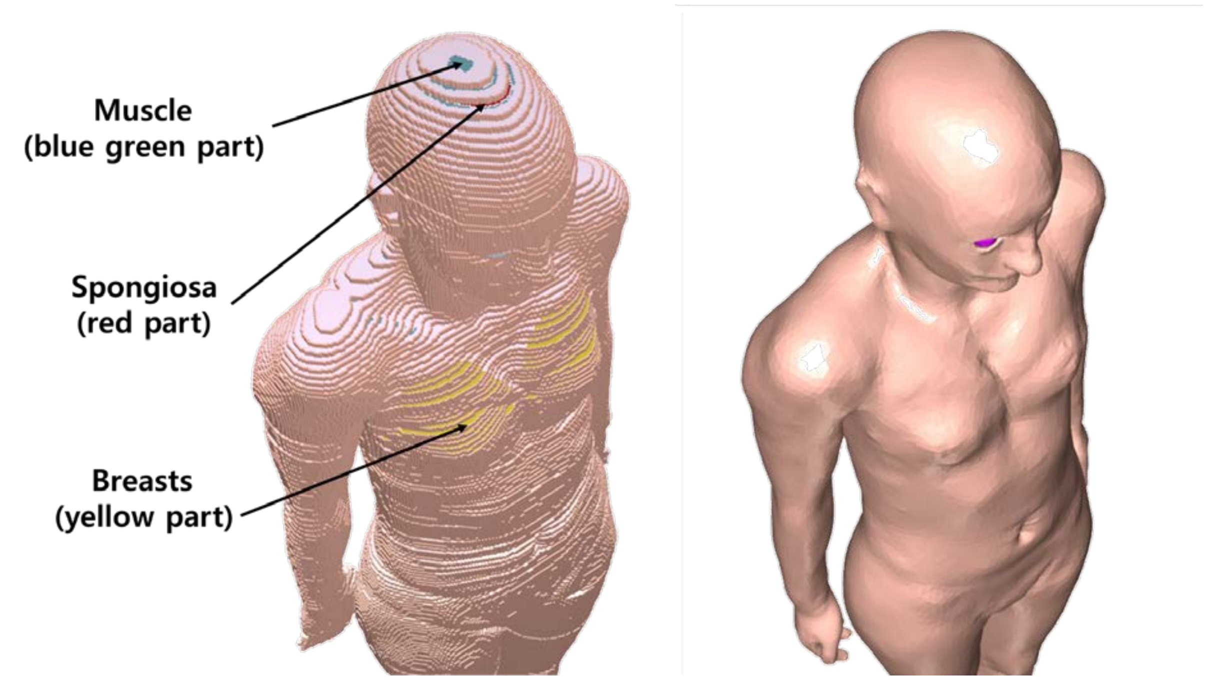


Fig. 6.4. ICRP-110 female phantom (left) and mesh-type female phantom (right); muscle (blue green part), spongiosa (red part) and breasts (yellow part) in ICRP-110 female phantom.

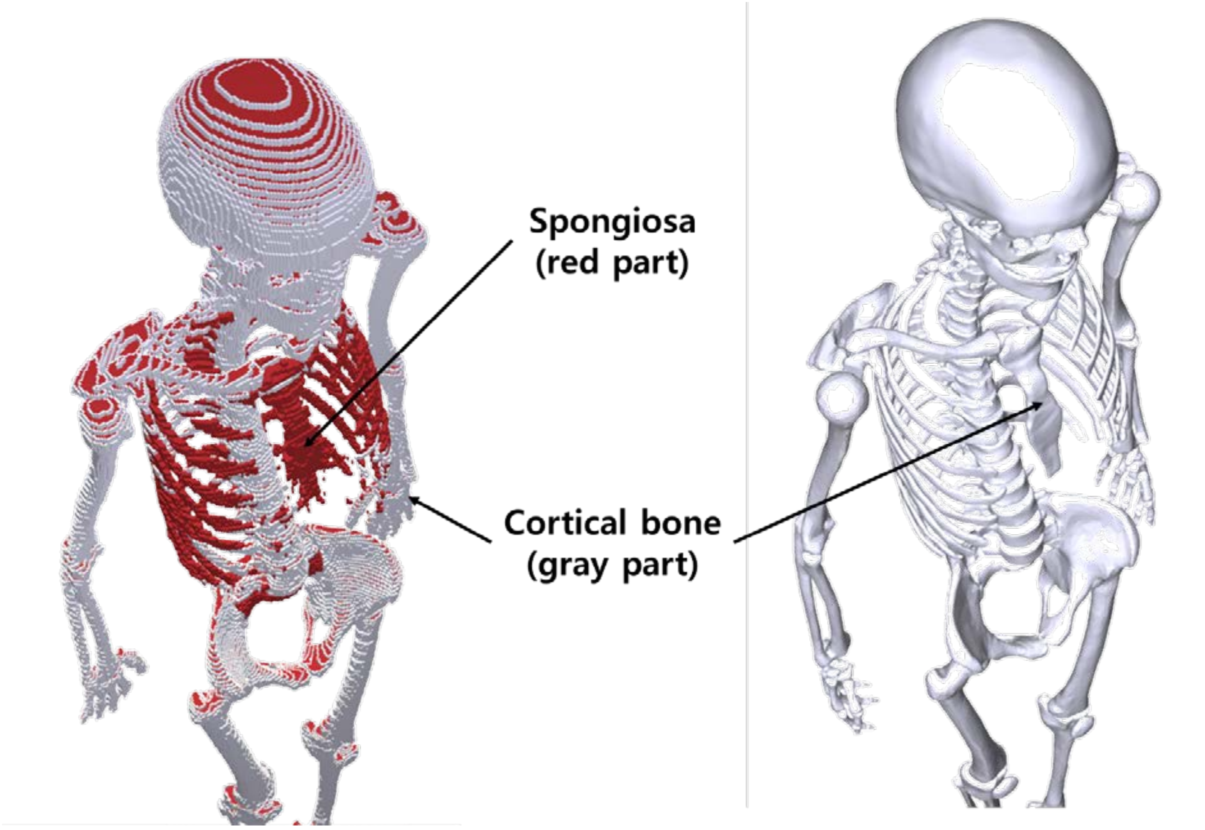


Fig. 6.5. Skeletal system of *Publication 110* female phantom (left) and mesh-type female phantom (right); spongiosa (red part) and cortical bone (gray part). The mesh phantom shows only cortical bone (gray part), which fully encloses inner structures (spongiosa and also medullary cavity).

6.2. Geometric similarity comparison with the adult voxel-type reference phantoms

(77) In order to determine the geometric similarity between the MRCPs and the adult voxel-type reference phantoms, the Dice Index (DI), Centroid Distance (CD) and Hausdorff Distance (HD) for the organs and tissues between these phantoms were evaluated as shown in Table 6.1. It can be seen that for most of the organs and tissues, the DI values were greater than 0.95, and that the CD and HD values were less than 2 mm. These results demonstrate good geometrical similarity between the MRCPs and the *Publication 110* phantoms in general.

(78) There were, however, relatively large dissimilarities for some organs and tissues. For example, the female hand bone showed the largest dissimilarity; the DI, CD and HD values were 0.13, 27.8 mm and 15.6 mm, respectively. Such large dissimilarities are due mainly to two reasons: (1) the organs and tissues such as spine, hands, feet and small intestine could not be directly converted from the voxel models, and therefore were constructed with modelling approaches, and (2) the organs and tissues such as ribs, liver, spleen and kidneys were more significantly adjusted to include the blood content, even though these organs were mostly constructed by using the direct conversion method.

(79) The organ depth distributions (ODDs) and the chord length distributions (CLDs) of the MRCPs were also compared with those of the *Publication 110* phantoms, as shown in Annexes E and F. The ODDs represent the organ depth below the body surface, which mainly influences external dose calculation, and the CLDs represent the distance between the target and source organs/tissues, which mainly influences internal dose calculation. The comparison results showed that the ODDs and CLDs of the MRCPs were generally in good agreement with those of the *Publication 110* phantoms for most of the organs and tissues, even though the MRCPs were adjusted for the blood inclusion.

(80) The results of the geometric similarity comparison indicate that overall, the MRCPs faithfully preserve the original shape and location of the organs and tissues in the *Publication 110* phantoms, and that therefore, they can be expected to provide similar dose values for penetrating radiation in both external and internal exposures.

Table 6.1. Dice index (DI), centroid distance (CD) and Hausdorff distance (HD) comparing the adult mesh-type reference phantoms (MRCPs) and the adult voxel-type reference phantoms.

Organs	Male			Female		
	DI	CD (mm)	HD (mm)	DI	CD (mm)	HD (mm)
Humeri	0.88	0.8	1.5	0.92	0.6	0.7
Ulnae and radii	0.89	0.5	0.8	0.90	0.7	0.9
Wrists and hand bones	0.24	17.8	12.7	0.13	27.8	15.6
Clavicles	0.83	0.4	0.8	0.84	1.1	0.8
Cranium	0.76	3.3	1.6	0.83	1.6	1.0
Femora	0.89	0.4	1.8	0.94	1.1	0.9
Tibiae, fibulae and patellae	0.90	0.5	1.1	0.91	0.4	1.1
Ankles and foot bones	0.56	8.0	4.3	0.32	4.1	11.8
Mandible	0.85	0.5	0.9	0.84	1.4	2.0
Pelvis	0.89	0.3	1.0	0.93	0.4	0.6
Ribs	0.56	4.9	2.0	0.32	2.1	2.7
Scapulae	0.82	1.4	1.0	0.86	0.4	0.7
Cervical spine	0.57	4.2	2.8	0.60	4.5	2.0
Thoracic spine	0.67	6.6	2.6	0.70	6.0	2.5

Lumbar spine	0.70	5.1	2.0	0.63	9.3	2.5
Sacrum	0.86	1.3	1.0	0.80	0.8	1.0
Sternum	0.79	5.1	1.3	0.31	9.3	5.9
Teeth	0.92	0.8	0.3	0.87	1.2	0.5
Tongue	0.90	1.3	1.1	0.94	0.9	0.6
Oesophagus	0.68	1.8	1.3	0.67	4.3	1.5
Stomach	0.87	4.5	2.0	0.92	2.7	1.3
Small intestine	0.40	23.3	6.2	0.55	15.3	6.8
Large intestine	0.82	1.2	1.6	0.87	1.9	1.5
Salivary glands	0.87	0.4	0.9	0.91	0.9	0.6
Tonsils	0.92	0.3	0.4	0.82	0.4	0.6
Liver	0.85	5.0	4.1	0.86	4.1	3.7
Gall bladder	0.84	2.5	1.6	0.91	0.4	0.7
Pancreas	0.83	5.2	2.3	0.85	6.6	2.4
Heart	0.94	1.5	1.1	0.93	2.2	1.7
Kidneys	0.81	5.4	2.8	0.84	5.3	3.3
Ureters	0.61	0.6	1.1	0.73	0.7	0.8
Urinary bladder	0.94	0.5	1.1	0.95	0.6	0.8
Gonads	0.87	0.2	0.6	0.86	0.2	0.7
Prostate / uterus	0.90	0.5	0.8	0.90	0.4	0.9
Adrenals	0.46	1.0	2.0	0.83	0.6	0.9
Breasts	0.83	0.5	0.7	0.91	0.4	0.6
Brain	0.96	0.9	1.0	0.97	0.4	3.8
Pituitary glands	0.81	0.5	0.5	0.73	0.3	0.6
Spinal cord	0.86	0.9	0.5	0.84	0.4	0.5
Spleen	0.78	4.8	2.6	0.80	4.3	2.3
Thymus	0.88	0.2	0.8	0.77	2.0	1.3
Thyroid	0.77	2.0	1.1	0.88	0.6	0.6
ET	0.76	0.5	1.3	0.76	0.5	1.1
Trachea	0.87	0.5	0.9	0.85	2.3	1.0
Lungs	0.90	3.0	3.8	0.90	1.6	2.7

6.3. Compatibility with Monte Carlo codes

6.3.1. Monte Carlo codes

(81) Most of the major general-purpose Monte Carlo simulation codes such as Geant4, MCNP6, PHITS and FLUKA can now directly implement polygon mesh (PM) or tetrahedral mesh (TM) geometries. The Geant4 code implements both PM and TM geometries by using the *G4TessellatedSolid* class and *G4Tet* class, respectively (Agostinelli et al., 2003). The MCNP6 code, as a merger of the MCNP5 and MCNPX versions, provides a new feature for implementation of unstructured mesh geometries including TM geometries. Note that since the version 1.1 beta of the MCNP6, the unstructured mesh geometry can support the transport of most particles available in the MCNP6 code (Goorley et al., 2013), whereas in the previous version (i.e. ver. 1.0), the transport of only neutrons and gammas was supported (Martz et al., 2014). The PHITS code, since version 2.82, provides a new feature for implementation of TM geometries (Sato et al., 2013). The FLUKA code can implement the PM geometry via FluDAG (http://svalinn.github.io/DAGMC/index.html).

6.3.2. Computation time and memory usage

(82) Computation time was measured for Geant4 (ver. 10.02), MCNP6 (ver. 2.0 prerelease) and PHITS (ver. 2.92) coupled with the female phantom of the TM format. The estimation was performed on a single core of the Intel® Xeon® CPU X5660 (@ 2.80 GHz and 128 GB memory). First, the estimated initialisation times for all Monte Carlo codes were found to be a few minutes, which are negligible compared to the total computation time, on the order of a day, which is a typical value for dose calculations. (Furuta el al., 2017).

(83) Run time was also measured with a single core of the same server computer to achieve 2% of relative error in effective dose for the left-lateral (LLAT) irradiation geometry of particle beams; photons and electrons (10 keV–10 GeV) and neutrons (10^{-9} MeV–20 MeV). For Geant4, the physics library of the *G4EmLivermorePhysics* was used to transport photons and electrons. To transport neutrons, the physics models and cross-sections of the *NeutronHPThermalScattering*, *NeutronHPElastic*, *ParticleHPInelastic*, *Neutron-HPCapture* and *NeutronHPFission* were used. A secondary cut value of 1 µm was applied to photons and electrons. For the PHITS code, the physics library of *AcelibJ40* was used to transport photons, electrons and neutrons. For the MCNP6 code, the physics libraries of MCPLIB84, EL03 and ENDF70 were used to transport photons, electrons and neutrons, respectively. Considering that a secondary cut value of 1 µm was used for the Geant4 calculations, the equivalent energy cut values were used in the PHITS and MCNP6 codes. The ‘implicit capture’ variance reduction technique was turned off for both PHITS and MCNP6 codes.

(84) The Geant4 result showed that for photons, the measured run times were within the range of 1–30 minutes for all of the considered energies. For electrons, the run times were less than 1 hour for energies higher than 0.06 MeV, but for the lower energies (≤ 0.06), the run times were much longer, i.e. 20–60 hours. These long run times are due to the facts that these low-energy electrons cannot penetrate the skin dead layer and that only the secondary photons, produced from electron interactions, contribute to skin dose, and eventually effective dose. For neutrons, the run times were within the range of 2–30 hours for all of the considered energies.

(85) The run times of the PHITS code for photons and electrons were generally much longer, i.e. 3–20 times when compared to the Geant4 code. Similarly, the run times of the MCNP6 code were also longer, i.e. 6–30 times than those of the Geant4 code. For neutrons, the run times of the PHITS code were shorter by 2–8 times than those of the Geant4 code, whereas those of the MCNP6 were 3–4 times longer than those of the Geant4 code.

(86) Memory usage was also measured for the three Monte Carlo codes. The Geant4 required ~10.6 GB, which is slightly smaller than that, ~13.7 GB, of MCNP6. PHITS, when compared to Geant4 and MCNP6, required much smaller memory, i.e. ~1.2 GB, which is due to the fact that PHITS, in contrast to other codes, uses dynamic allocation for most of the memory needed for implementing the MRCP. In general, considering memory usage, all of the above Monte Carlo codes can run the MRCPs in a personal computer equipped with 64 GB at maximum.

7. DOSIMETRIC IMPACT OF THE ADULT MESH-TYPE REFERENCE PHANTOMS

(87) In order to investigate the impact of the improved representation of the organs and tissues in the adult mesh-type reference computational phantoms (MRCPs) on dose coefficient (DC) calculations, DCs of organ dose and effective dose and specific absorbed fractions (SAFs) were calculated for some selected external and internal exposure cases using the MRCPs. The calculated values were then compared with the values provided in *Publications 116* and *133* (ICRP, 2010, 2016) which were calculated by using the *Publication 110* phantoms (ICRP, 2009) and the stylised models adopted in the previous *Publications* (ICRP, 1994a, 2006, 2016).

(88) In Annex H, the DCs of the MRCPs for external exposure to photons, neutrons, electrons and helium ions are compared with the *Publication 116* values. For photons, with some exceptions at very low energies, the DCs of the MRCPs were found to be very close to the *Publication 116* values for both organ dose and effective dose. For neutrons, the organ DCs of the MRCPs show some differences from the *Publication 116* values, but are very close to the values calculated using the *Publication 110* phantoms and the Geant4 code that was the same code used in the calculation of the MRCP DCs. This result indicates that the differences from the *Publication 116* values are not mainly due to the difference in phantom geometry or material composition, but just to the difference in Monte Carlo codes and cross-section data / physics models used in the calculations. Note that for neutrons, the *Publication 116* values were calculated using four Monte Carlo codes (MCNPX, PHITS, FLUKA and Geant4) and then the final reference values of the dose coefficients were taken as averaged values following an extensive smoothing process (ICRP, 2010).

(89) For charged particles (i.e. electrons and alphas) in Annex H, the DCs of the MRCPs for some organs (e.g. RBM, breasts and skin) showed large differences from the *Publication 116* values, which are mainly due to the improved representation of the thin tissues (e.g. cortical bone and skin) in the MRCPs over the voxel-type *Publication 110* phantoms (see Chapter 2). Large differences were also found in effective dose DCs for electrons (< 1 MeV) and helium ions (< 10 MeV/u); these differences are mainly caused by the differences of the skin DCs due to the consideration of the 50-µm-thick skin target layer in the MRCPs. Note that in real situations of electron exposures, polyenergetic electrons are generally encountered, for which the differences in effective doses are much less significant. For example, the difference in effective dose between the MRCPs and the *Publication 110* phantoms resulting from the isotropic (ISO) irradiation of beta radiations (^{14}C, ^{186}Re, ^{32}P, ^{90}Sr/^{90}Y and ^{106}Rh) are less than 2 times, except for ^{14}C for which the difference is ~4 times. Note that ^{14}C emits very low energy electrons (0.15 MeV maximum) and thus is generally not of concern for external exposures. In real situations of helium ion exposures, short-range alpha exposures are mostly encountered, which are practically unimportant for radiation protection purposes.

(90) In Annex I, the specific absorbed fractions (SAFs) of the MRCPs for photons and electrons are compared with the *Publication 133* values for selected source organs/tissues (= cortical bone, liver, lungs and thyroid). For photons, with some exceptions, the SAFs of the MRCPs were found to be very close to the *Publication 133* values. One exception was the RBM as a target, where the SAFs of the MRCPs were much smaller than the *Publication 133* values at low energies. These differences are due mainly to the fact that in the MRCPs, the spongiosa is fully enclosed by the cortical bone, whereas this is not the case for the *Publication 110* phantoms (see Fig. 6.5). In contrast, for the colon ← cortical bone case, the SAFs of the MRCPs were found to be greater than the *Publication 133* values, which is again due mainly to the difference of the distribution of the cortical bone; that is, in the *Publication 110* phantoms,

the cortical bone does not fully enclose the spongiosa and is not uniformly distributed, especially in the ribs, where the cortical bone is rarely distributed in the regions that are very close to the colon.

(91) For electrons in Annex I, the SAFs of the MRCPs were found to be very close to the *Publication 133* values for all of the self-irradiation cases. However, large differences were found for most cross-fire irradiation cases, which is due mainly to the different geometry formats of the phantoms (smooth surface of the MRCPs vs. stair-stepped surface of the *Publication 110* phantoms). The significances of these differences on the effective dose will be dependent on the biokinetics or chemical form of ingested or inhaled radionuclide.

(92) In Nguyen et al. (2015), the lens DCs of the MRCPs for external exposure to photons and electrons were compared with the *Publication 116* values that were produced with both the *Publication 110* voxel phantoms and the mathematical eye model of Behrens et al. (2009). The comparison was complicated because different phantoms were used for different cases in *Publication 116*. For photons, the lens DCs of the MRCPs were not found to be much different from the *Publication 116* values for all of the irradiation geometries, except for the PA geometry and low energies (< 0.1 MeV), in which cases the lens DCs of the MRCPs were smaller than the *Publication 116* values. These differences are not very important in practice, and are due mainly to the differences in head structure and composition between the MRCPs and the mathematical head phantom (incorporating the eye model) used to produce the *Publication 116* values (ICRP 2010). For electrons, generally the lens DCs of the MRCPs were found to be very close to the *Publication 116* values at the energies ≥ 2 MeV, but at the lower energies (< 2 MeV), relatively large differences were found. The largest differences were once again found in the PA geometry, which result is due to the differences in head structure and composition between the MRCPs and the *Publication 110* phantoms used to produce the *Publication 116* values (ICRP 2010). For the AP irradiation geometry, which is the most important irradiation geometry in radiation protection, the differences were much smaller, and significant differences were observed only at very low energies (< 0.7 MeV), where primary electrons cannot reach to the lens and thus very low energy secondary photons are the only contribution to lens dose. More detailed discussions on the comparison of the lens DCs can be found in Nguyen et al. (2015).

(93) In Kim et al. (2017), the electron SAFs of the MRCPs for the alimentary and respiratory tract systems were compared with the *Publication 133* values that were calculated using the supplementary stylised models (ICRP, 1994a, 2006, 2016). Generally, a good agreement was observed for the oral mucosa, oesophagus and bronchi (BB) region. In contrast, for the stomach, small intestine, large intestine, extrathoracic (ET) region and bronchiole (bb) region, relatively large differences were observed due mainly to the anatomical differences of these organs as described by the MRCPs and the stylised models. With some exceptions (stomach and bronchioles (bb) for the alveolar-interstitial region as a source), the MRCPs tend to overestimate SAFs when compared to the *Publication 133* values; the maximum difference was about 16 times for the large intestine for the contents as a source. More detailed discussions on the comparison of the SAFs for the alimentary and respiratory tract systems can be found in Kim et al. (2017).

(94) The male MRCP was used to calculate the SAFs for alphas and electrons for the urinary bladder wall ← urinary bladder content case, and then the calculated values were compared with the values which were calculated using a stylised model for the male (Eckerman and Veinot, 2018). Note that the values of the MRCP were not compared with the values in *Publication 133* because these values were calculated for the entire wall of the urinary bladder, not for the radiosensitive basal layer of the wall. The MRCP values were found to be slightly

less than the values of the stylised model, the differences being less than a few percent, which is mainly due to the slight difference (~ 6%) in the target mass between the MRCP urinary bladder model and the idealised spherical stylised model used in Eckerman and Veniot (2018).

8. APPLICATION: CALCULATION OF DOSE COEFFICIENTS FOR INDUSTRIAL RADIOGRAPHY SOURCES

(95) Accidents involving industrial radiography sources could result in very high radiation doses to workers, causing serious injuries and even death (IAEA, 2011). In addition, members of the public could be accidentally exposed if industrial radiography sources are not properly controlled or regulated. According to the IAEA (1998), industrial radiography accounts for approximately half of all reported accidents for nuclear-related industries, in both developed and developing countries. Radiation accidents could result in high radiation doses inducing acute radiation syndrome (ARS), which can be classified into hematopoietic (3–5 Gy), gastrointestinal (5–15 Gy) and cerebrovascular (> 15 Gy) syndromes (ICRP, 2007). In order to effectively treat patients (i.e. exposed individuals) with ARS, it is necessary to perform medical triage accurately and quickly, whereby those patients who will develop symptoms are separately identified from those who do not require medical intervention (Gougelet et al., 2010). Individual radiation doses can be estimated using various dosimetry techniques based on biological, physical or computational approaches. However, all of the existing dosimetry techniques have limitations, and thus none of them can be used as a stand-alone tool in a satisfactory manner for most radiation accident scenarios (Ainsbury et al., 2011). For example, biological and physical dosimetry techniques generally require several days for sample collection and analysis. Moreover, these techniques are impractical for use in a large-scale accident involving a multitude of exposed individuals (Gougelet et al., 2010; Rea et al., 2010; Swartz et al., 2014; Kulka et al., 2017) and are generally limited to estimating the whole-body dose, without information on organ/tissue specific doses or their dose distribution (Ainsbury et al., 2011). Note that the knowledge of the whole-body dose may not be sufficient, especially in partial-body or localised exposures (Ainsbury et al., 2011; Lu et al., 2017). Organ/tissue doses or dose distributions can be estimated using computational dosimetry techniques (e.g. Monte Carlo simulations with computational human phantoms), if reliable information on the accident scenario is available, including the source geometry and duration of exposure (Lu et al., 2017), which are often unclear immediately following accidental irradiation situations (Clairand et al., 2006; Ainsbury et al., 2011). Due to the fact that no single technique fully meets the criteria of an ideal dosimeter for use in accidental situations, an integrated approach using multiple dosimetry techniques is considered to be the best strategy (Ainsbury et al., 2011; Sullivan et al., 2013; Ainsbury et al., 2017). Doses calculated with computational anthropomorphic phantoms can be used as one of the dose estimators, particularly as an ‘initial, rapid estimator’.

(96) For dose estimation of individuals exposed to such high doses, consideration of the reference person may be insufficient, particularly when the body size of the individual involved in the accident is significantly different from that of the phantom representing the reference person. In such cases, the dose could be better approximated by using DCs calculated with a non-reference computational phantom whose body size is close to that of the actual person. To demonstrate this approach, non-reference adult male and female phantoms, representing the 10^{th} and 90^{th} percentiles of the Caucasian population, were developed in this report. The 10^{th} percentile phantoms, which represent small persons, were constructed by decreasing the size of the MRCPs to the 10^{th} percentile standing height and the 10^{th} percentile body mass (male: 1.672 m and 55.9 kg and female: 1.549 m and 44.2 kg). Similarly, the 90^{th} percentile phantoms, which represent large persons, were constructed by increasing the size of the MRCPs to the 90^{th} percentile standing height and the 90^{th} percentile body mass (male: 1.858 m and 108.4 kg and female: 1.717 m and 94.1 kg). Figure 8.1 shows the 10^{th} and 90^{th} percentile phantoms,

along with the MRCPs. The height and mass values were derived from the PeopleSize 2008 Professional data (http://www.openerg.com). The torso, arms, and legs were scaled considering the lean body mass (LBM) (Deurenberg et al., 1991; Pieterman et al., 2002). The head was scaled separately, using the PeopleSize 2008 Professional data and the US Army Anthropometric Survey (ANSUR II) data (Gordon et al., 2014). More detailed information on scaling can be found in Lee et al. (2018). The internal organs and tissues of the phantoms were modified via the scaling/deforming procedures as described by Lee et al. (2018).

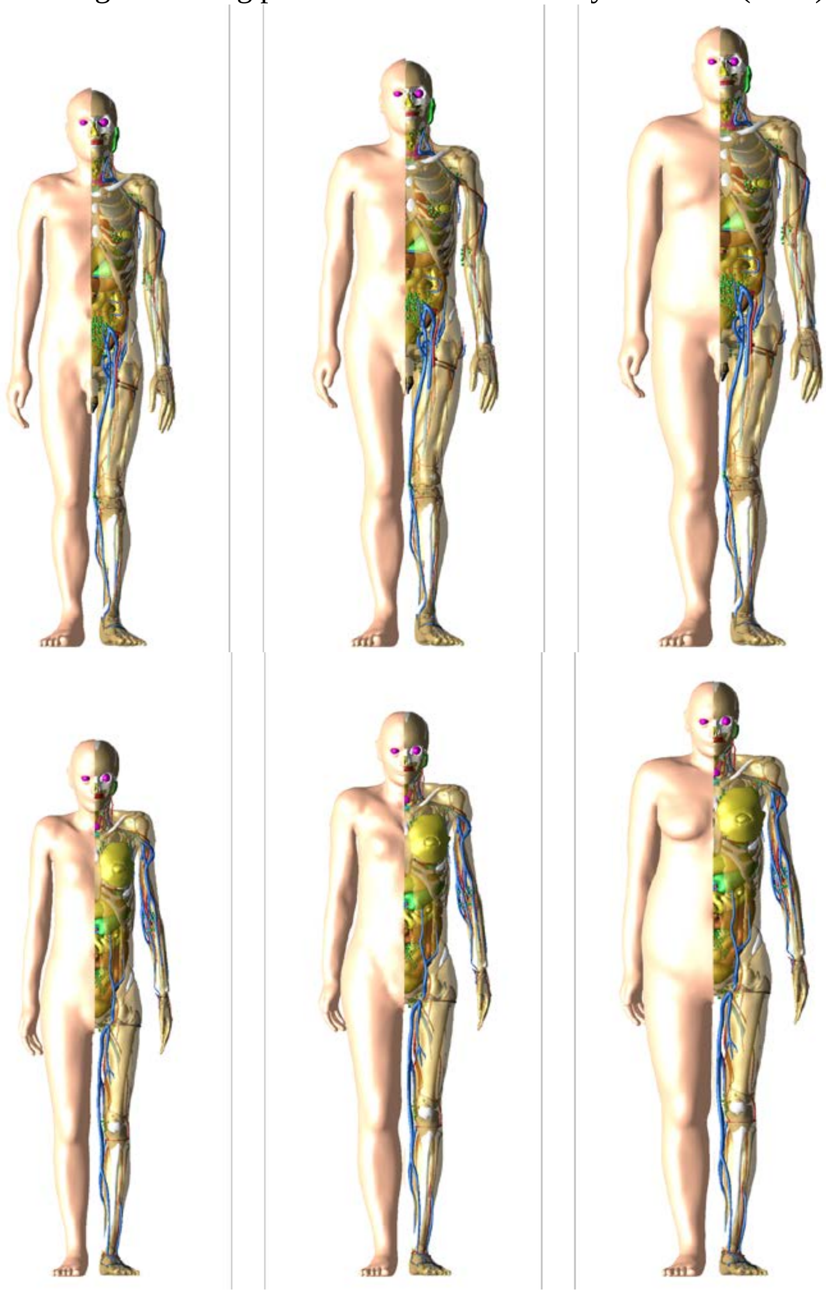


Fig. 8.1. Computational phantoms: 10th percentile phantom (left), MRCP (middle) and 90th percentile.

(97) In order to evaluate accidental exposures from industrial radiography sources, dose coefficients (DCs) were calculated using the adult MRCPs as well as the 10th and 90th percentile phantoms, implemented into the Geant4 Monte Carlo code (ver. 10.02) (Agostinelli et al., 2003). The most commonly used industrial radiography sources, i.e. ^{192}Ir, ^{137}Cs/^{137m}Ba and

^{60}Co, were simulated as point sources placed near each of the mesh-type phantoms. ^{192}Ir emits gamma rays with energies up to 0.820 MeV and a mean energy of 0.377 MeV, ^{137}Cs emits 0.662 MeV gamma rays, and ^{60}Co emits 1.33 and 1.17 MeV gamma rays. The point sources were assumed to be located at three different distances (0.005, 0.1 and 0.3 m) in four directions (anterior, posterior, right lateral and left lateral) at five levels (ground, middle thigh and lower, middle and upper torso) (see Fig. 8.2). In addition, three longer distances (1, 1.5 and 3 m) were modelled in the four directions at the lower torso level. The source distance used in the calculations is the distance from the surface of the phantom, except for the anterior and posterior directions at the ground and middle thigh levels, for which the distance is calculated from the centre of the imaginary segment tangent to the surfaces of the left and right legs at the given level.

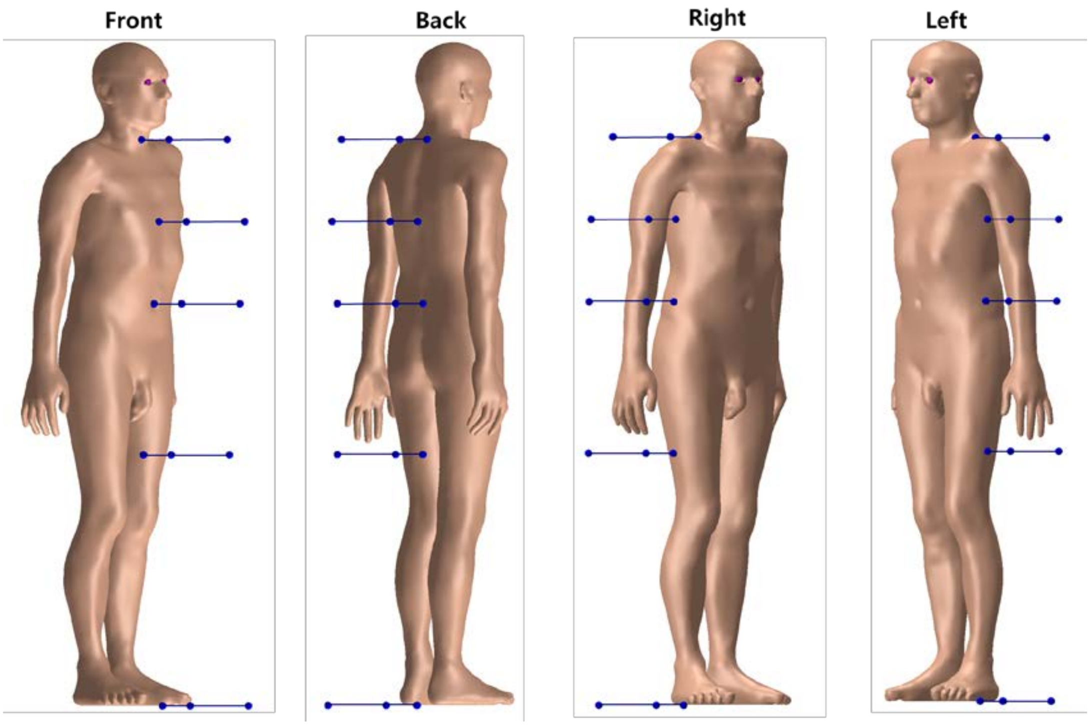


Fig. 8.2. Source locations at three distances (0.005, 0.1 and 0.3 m) at five levels (ground, middle thigh and lower, middle and upper torso) in four directions (anterior, posterior, right lateral and left lateral).

(98) In order to consider the doses of those organs/tissues that might manifest acute radiation syndrome, the doses for red bone marrow (RBM), brain, lungs, small and large intestine were calculate as organ/tissue-averaged absorbed dose per source disintegration (Gy s^{-1} Bq^{-1}). The RBM DCs were calculated by using the fluence-to-absorbed dose response functions (DRF) reported in Annex D of *Publication 116* (ICRP, 2010). In addition, the DCs of effective dose (effective dose per source disintegration) were calculated and could be used for the dosimetry of individuals who are exposed at lower doses related to stochastic effects. Effective doses cannot be calculated using non-reference phantoms (i.e., 10th and 90th percentile phantoms) and, therefore, in this report, the DCs of effective doses were calculated using only the MRCPs. The statistical errors of the calculated values were less than 5% for all cases. A complete set of the DCs calculated with the MRCPs and the 10th and 90th percentile phantoms are given in Annex J.

(99) Furthermore, the influence of different postures during exposure was investigated by calculating DCs using a set of non-standing phantoms (walking, sitting, bending, kneeling and squatting postures) that were constructed by modifying the MRCPs. For this purpose, the DCs were calculated for the lowest-energy source (i.e. ^{192}Ir) located 1 m from the phantom surface in the four directions of the lower-torso level. The calculated DCs of the non-standing phantoms were then compared with those of the standing MRCPs. The results of this limited investigation showed that the influence of different postures on the DC is not very large: generally less than 30%. It was, therefore, decided not to calculate the DCs of the non-standing phantoms.

(100) Note that the DCs in this report were calculated assuming point sources, not considering the source geometry. The user can consider the self-shielding effect of the source by applying, to the values in Annex J, the source self-shielding factors which were calculated for different thicknesses of radioactive material and capsule wall. The calculated values are given in Annex J.

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

Table A.1. List of organ ID, medium, density and mass of each organ/tissue in TM-version phantoms.

Organ ID	Organ/tissue	Medium	Density (g/cm^3)		Mass (g)	
			Male	Female	Male	Female
100	Adrenal, left	1	1.036	1.035	8.683	6.817
200	Adrenal, right	1	1.036	1.035	8.683	8.649
300	ET_1, 0 ~ 8 μm	2	1.031	1.031	0.022	0.009
301	ET_1, 8 ~ 40 μm	2	1.031	1.031	0.090	0.035
302	ET_1, 40 ~ 50 μm	2	1.031	1.031	0.028	0.011
303	ET_1, 50 μm ~ surface	2	1.031	1.031	11.291	4.375
400	ET_2, -15 ~ 0 μm	52	1.000	1.000	0.141	0.104
401	ET_2, 0 ~ 40 μm	2	1.031	1.031	0.390	0.288
402	ET_2, 40 ~ 50 μm	2	1.031	1.031	0.098	0.072
403	ET_2, 50 ~ 55 μm	2	1.031	1.031	0.049	0.036
404	ET_2, 55 ~ 65 μm	2	1.031	1.031	0.098	0.072
405	ET_2, 65 μm ~ surface	2	1.031	1.031	28.808	14.180
500	Oral mucosa, tongue	3	1.050	1.050	0.086	0.066
501	Oral mucosa, mouth floor	3	1.050	1.050	0.023	0.016
600	Oral mucosa, lips and cheeks	3	1.050	1.050	0.023	0.019
700	Trachea	2	1.031	1.031	10.364	8.201
800	$BB_1^\dagger$, -11 ~ -6 μm	52	1.000	1.000	0.025	0.010
801	$BB_1^\dagger$, -6 ~ 0 μm	2	1.031	1.031	0.031	0.013
802	$BB_1^\dagger$, 0 ~ 10 μm	2	1.031	1.031	0.052	0.021
803	$BB_1^\dagger$, 10 ~ 35 μm	2	1.031	1.031	0.130	0.053
804	$BB_1^\dagger$, 35 ~ 40 μm	2	1.031	1.031	0.026	0.011
805	$BB_1^\dagger$, 40 ~ 50 μm	2	1.031	1.031	0.052	0.021
806	$BB_1^\dagger$, 50 ~ 60 μm	2	1.031	1.031	0.052	0.021
807	$BB_1^\dagger$, 60 ~ 70 μm	2	1.031	1.031	0.053	0.021
808	$BB_1^\dagger$, 70 μm ~ surface	2	1.031	1.031	2.777	1.179
900	Blood in large arteries, head	4	1.060	1.060	1.504	1.908
910	Blood in large veins, head	4	1.060	1.060	6.935	3.007
1000	Blood in large arteries, trunk	4	1.060	1.060	193.183	117.872
1010	Blood in large veins, trunk	4	1.060	1.060	444.040	239.807
1100	Blood in large arteries, arms	4	1.060	1.060	32.467	46.314
1110	Blood in large veins, arms	4	1.060	1.060	167.306	139.583
1200	Blood in large arteries, legs	4	1.060	1.060	108.846	79.906
1210	Blood in large veins, legs	4	1.060	1.060	389.719	355.601
1300	Humeri, upper, cortical	5	1.904	1.904	159.456	113.682
1400	Humeri, upper, spongiosa	7	1.233	1.185	145.689	107.717
1500	Humeri, upper, medullary cavity	6	0.981	0.981	34.244	20.516
1600	Humeri, lower, cortical	5	1.904	1.904	106.461	103.295
1700	Humeri, lower, spongiosa	8	1.109	1.117	50.890	50.264
1800	Humeri, lower, medullary cavity	6	0.981	0.981	37.397	20.493
1900	Ulnae and radii, cortical	5	1.904	1.904	273.498	156.708
2000	Ulnae and radii, spongiosa	8	1.109	1.117	154.981	86.883
2100	Ulnae and radii, medullary cavity	6	0.981	0.981	22.996	34.068
2200	Wrists and hand bones, cortical	5	1.904	1.904	181.529	105.132
2300	Wrists and hand bones, spongiosa	8	1.109	1.117	118.927	69.360
2400	Clavicles, cortical	5	1.904	1.904	48.252	32.825
2500	Clavicles, spongiosa	9	1.157	1.192	45.057	38.798
2600	Cranium, cortical	5	1.904	1.904	568.469	407.670
2700	Cranium, spongiosa	10	1.165	1.252	382.073	391.311
2800	Femora, upper, cortical	5	1.904	1.904	253.548	244.126
2900	Femora, upper, spongiosa	11	1.125	1.046	413.232	232.804
3000	Femora, upper, medullary cavity	6	0.981	0.981	26.045	39.516
3100	Femora, lower, cortical	5	1.904	1.904	307.761	240.929
3200	Femora, lower, spongiosa	8	1.109	1.117	373.652	166.334
3300	Femora, lower, medullary cavity	6	0.981	0.981	82.179	56.762
3400	Tibiae, cortical	5	1.904	1.904	536.651	544.845
3500	Tibiae, spongiosa	8	1.109	1.117	621.408	558.529
3600	Tibiae, medullary cavity	6	0.981	0.981	79.815	88.883
3700	Ankles and foot, cortical	5	1.904	1.904	234.882	173.476
3800	Ankles and foot, spongiosa	8	1.109	1.117	432.615	257.451
3900	Mandible, cortical	5	1.904	1.904	76.877	45.394
4000	Mandible, spongiosa	12	1.271	1.189	56.287	33.479
4100	Pelvis, cortical	5	1.904	1.904	402.595	262.460
4200	Pelvis, spongiosa	13	1.121	1.105	619.672	455.599
4300	Ribs, cortical	5	1.904	1.904	368.797	164.514

4400	Ribs, spongiosa	14	1.170	1.087	457.351	277.325
4500	Scapulae, cortical	5	1.904	1.904	223.333	121.664
4600	Scapulae, spongiosa	15	1.201	1.125	156.670	96.730
4700	Cervical spine, cortical	5	1.904	1.904	103.943	71.596
4800	Cervical spine, spongiosa	16	1.049	1.129	78.915	75.601
4900	Thoracic spine, cortical	5	1.904	1.904	289.440	205.828
5000	Thoracic spine, spongiosa	17	1.070	1.080	345.222	271.915
5100	Lumbar spine, cortical	5	1.904	1.904	188.047	156.175
5200	Lumbar spine, spongiosa	18	1.108	1.165	291.584	264.976
5300	Sacrum, cortical	5	1.904	1.904	110.320	80.240
5400	Sacrum, spongiosa	19	1.033	1.052	192.224	154.840
5500	Sternum, cortical	5	1.904	1.904	9.991	1.685
5600	Sternum, spongiosa	20	1.041	1.073	61.420	51.347
5700	Cartilage, costal	21	1.099	1.099	56.331	41.959
5800	Cartilage, discs	21	1.099	1.099	82.063	69.351
6100	Brain	22	1.041	1.041	1517.390	1349.568
6200	Breast, left, adipose tissue	23	0.953	0.952	7.769	153.663
6300	Breast, left, glandular tissue	24	1.021	1.021	5.180	102.491
6400	Breast, right, adipose tissue	23	0.953	0.952	7.769	153.663
6500	Breast, right, glandular tissue	24	1.021	1.021	5.180	102.491
6600	Eye lens, sensitive, left	25	1.060	1.060	0.039	0.039
6601	Eye lens, insensitive, left	25	1.060	1.060	0.189	0.189
6700	Cornea, left	26	1.100	1.087	1.113	1.100
6701	Aqueous, left	27	1.025	1.014	0.308	0.304
6702	Vitreous, left	28	1.031	1.019	6.122	6.051
6800	Eye lens, sensitive, right	25	1.060	1.060	0.039	0.039
6801	Eye lens, insensitive, right	25	1.060	1.060	0.189	0.189
6900	Cornea, right	26	1.100	1.087	1.113	1.100
6901	Aqueous, right	27	1.025	1.014	0.308	0.304
6902	Vitreous, right	28	1.031	1.019	6.122	6.051
7000	Gall bladder wall	2	1.031	1.031	10.364	8.201
7100	Gall bladder contents	29	1.030	1.030	58.000	48.000
7200	Stomach wall, 0 ~ 60 µm	30	1.037	1.036	1.784	1.561
7201	Stomach wall, 60 ~ 100 µm	30	1.037	1.036	1.193	1.044
7202	Stomach wall, 100 ~ 300 µm	30	1.037	1.036	6.008	5.256
7203	Stomach wall, 300 µm ~ surface	30	1.037	1.036	185.286	165.012
7300	Stomach contents	33	1.040	1.040	250.000	230.000
7400	Small intestine wall, 0 ~ 130 µm	31	1.037	1.036	14.547	12.341
7401	Small intestine wall, 130 ~ 150 µm	31	1.037	1.036	2.264	1.922
7402	Small intestine wall, 150 ~ 200 µm	31	1.037	1.036	5.692	4.831
7403	Small intestine wall, 200 µm ~ surface	31	1.037	1.036	840.096	736.674
7500	Small intestine contents, -500 ~ 0 µm	33	1.040	1.040	53.337	45.227
7501	Small intestine contents, centre ~ -500 µm	33	1.040	1.040	296.663	234.773
7600	Ascending colon wall, 0 ~ 280 µm	32	1.037	1.036	3.071	4.451
7601	Ascending colon wall, 280 ~ 300 µm	32	1.037	1.036	0.223	0.322
7602	Ascending colon wall, 300 µm ~ surface	32	1.037	1.036	116.634	107.784
7700	Ascending colon contents	33	1.040	1.040	55.000	100.007
7800	Transverse colon wall, right, 0 ~ 280 µm	32	1.037	1.036	3.993	3.680
7801	Transverse colon wall, right, 280 ~ 300 µm	32	1.037	1.036	0.289	0.266
7802	Transverse colon wall, right, 300 µm ~ surface	32	1.037	1.036	75.671	64.847
7900	Transverse colon contents, right	33	1.040	1.040	95.000	59.995
8000	Transverse colon wall, left, 0 ~ 280 µm	32	1.037	1.036	2.824	2.196
8001	Transverse colon wall, left, 280 ~ 300 µm	32	1.037	1.036	0.205	0.160
8002	Transverse colon wall, left, 300 µm ~ surface	32	1.037	1.036	76.924	66.428
8100	Transverse colon contents, left	33	1.040	1.040	40.000	30.005
8200	Descending colon wall, 0 ~ 280 µm	32	1.037	1.036	2.779	3.021
8201	Descending colon wall, 280 ~ 300 µm	32	1.037	1.036	0.203	0.220
8202	Descending colon wall, 300 µm ~ surface	32	1.037	1.036	116.946	109.320
8300	Descending colon contents	33	1.040	1.040	35.000	50.003
8400	Sigmoid colon wall, 0 ~ 280 µm	32	1.037	1.036	4.451	4.222
8401	Sigmoid colon wall, 280 ~ 300 µm	32	1.037	1.036	0.324	0.306
8402	Sigmoid colon wall, 300 µm ~ surface	32	1.037	1.036	48.527	51.761
8500	Sigmoid colon contents	33	1.040	1.040	75.000	79.993
8600	Rectum wall	32	1.037	1.036	39.976	31.268
8700	Heart wall	34	1.051	1.051	385.839	290.890
8800	Blood in heart chamber	4	1.060	1.060	510.000	370.000
8900	Kidney, left, cortex	35	1.053	1.052	162.338	149.091
9000	Kidney, left, medulla	35	1.053	1.052	38.359	37.441
9100	Kidney, left, pelvis	35	1.053	1.052	7.652	7.494
9200	Kidney, right, cortex	35	1.053	1.052	166.542	125.147
9300	Kidney, right, medulla	35	1.053	1.052	39.362	31.440
9400	Kidney, right, pelvis	35	1.053	1.052	7.892	6.292
9500	Liver	36	1.060	1.060	2360.000	1810.000

9700	Lung (AI), left	37	0.415	0.413	545.877	427.256
9900	Lung (AI), right	37	0.415	0.413	652.861	522.518
10000	Lymphatic nodes, ET	38	1.032	1.032	15.949	12.695
10100	Lymphatic nodes, thoracic	38	1.032	1.032	15.949	12.695
10200	Lymphatic nodes, head	38	1.032	1.032	5.510	4.385
10300	Lymphatic nodes, trunk	38	1.032	1.032	130.203	103.641
10400	Lymphatic nodes, arms	38	1.032	1.032	11.019	8.771
10500	Lymphatic nodes, legs	38	1.032	1.032	11.019	8.771
10600	Muscle, head	39	1.050	1.050	1200.827	445.022
10700	Muscle, trunk	39	1.050	1.050	14841.796	8324.736
10800	Muscle, arms	39	1.050	1.050	2843.360	1479.783
10900	Muscle, legs	39	1.050	1.050	10890.597	7676.898
11000	Oesophagus wall, 0 ~ 190 µm	40	1.037	1.036	1.919	1.871
11001	Oesophagus wall, 190 ~ 200 µm	40	1.037	1.036	0.103	0.101
11002	Oesophagus wall, 200 µm ~ surface	40	1.037	1.036	49.783	41.247
11003	Oesophagus contents	33	1.040	1.040	22.870	21.240
11100	Ovary, left	41		1.051		6.318
11200	Ovary, right	41		1.051		6.318
11300	Pancreas	42	1.044	1.043	173.631	144.552
11400	Pituitary gland	2	1.031	1.031	0.622	0.615
11500	Prostate	43	1.031		17.618	
11600	RST, head	44	0.939	0.946	975.621	844.542
11700	RST, trunk	44	0.939	0.946	11176.903	11513.384
11800	RST, arms	44	0.939	0.946	1549.842	2171.515
11900	RST, legs	44	0.939	0.946	4510.159	7795.947
12000	Salivary glands, left	2	1.031	1.031	44.045	35.880
12100	Salivary glands, right	2	1.031	1.031	44.045	35.880
12200	Skin, head, insensitive	45	1.089	1.088	259.230	155.582
12201	Skin, head, sensitive, 50 ~ 100 µm	45	1.089	1.088	8.470	6.325
12300	Skin, trunk, insensitive	45	1.089	1.088	1271.128	871.564
12301	Skin, trunk, sensitive, 50 ~ 100 µm	45	1.089	1.088	38.418	32.368
12400	Skin, arms, insensitive	45	1.089	1.088	575.708	380.941
12401	Skin, arms, sensitive, 50 ~ 100 µm	45	1.089	1.088	18.843	15.599
12500	Skin, legs, insensitive	45	1.089	1.088	1259.982	924.625
12501	Skin, legs, sensitive, 50 ~ 100 µm	45	1.089	1.088	37.790	35.025
12600	Spinal cord	2	1.031	1.031	37.952	19.098
12700	Spleen	46	1.060	1.060	228.400	187.400
12800	Teeth	47	2.688	2.690	50.727	40.562
12801	Teeth, retention region	33	1.040	1.040	0.043	0.036
12900	Testis, left	41	1.041		18.617	
13000	Testis, right	41	1.041		18.617	
13100	Thymus	2	1.031	1.031	25.909	20.503
13200	Thyroid	48	1.051	1.051	23.351	19.455
13300	Tongue, upper (food)	3	1.050	1.050	20.993	20.995
13301	Tongue, lower	3	1.050	1.050	54.552	40.415
13400	Tonsils	2	1.031	1.031	3.109	3.075
13500	Ureter, left	2	1.031	1.031	8.809	7.689
13600	Ureter, right	2	1.031	1.031	7.773	7.689
13700	Urinary bladder wall, insensitive	49	1.040	1.040	49.028	38.546
13701	Urinary bladder wall, sensitive, 75/69‡ ~ 193/185‡ µm	49	1.040	1.040	2.071	2.259
13800	Urinary bladder contents	50	1.040	1.040	200.000	200.000
13900	Uterus	43		1.021		81.993
14000	Air inside body	51	0.001	0.001	0.140	0.036

† Only the main bronchi (BB_1) was defined in the TM-version phantoms. The other generations of the bronchi (BB) and all generations of the bronchioles (bb) were modelled in CSG format (see Chapter 5.3).

‡ Male/female.

Table A.2. List of organ ID, medium, density and mass of each organ/tissue in PM-version phantoms.

Organ ID	Organ/tissue	Medium	Density (g/cm^3)		Mass (g)	
			Male	Female	Male	Female
100	Adrenal, left	1	1.036	1.035	8.683	6.817
200	Adrenal, right	1	1.036	1.035	8.683	8.649
300	ET_1, 8 µm	2	1.031	1.031	0.022	0.009
301	ET_1, 40 µm	2	1.031	1.031	0.090	0.035
302	ET_1, 50 µm	2	1.031	1.031	0.028	0.011
303	ET_1, surface	2	1.031	1.031	11.291	4.375
400	ET_2, 0 µm	52	1.000	1.000	0.141	0.104
401	ET_2, 40 µm	2	1.031	1.031	0.390	0.288
402	ET_2, 50 µm	2	1.031	1.031	0.098	0.072
403	ET_2, 55 µm	2	1.031	1.031	0.049	0.036
404	ET_2, 65 µm	2	1.031	1.031	0.098	0.072
405	ET_2, surface	2	1.031	1.031	28.808	14.180
500	Oral mucosa, tongue	3	1.050	1.050	0.086	0.066
501	Oral mucosa, mouth floor	3	1.050	1.050	0.023	0.016
600	Oral mucosa, lips and cheeks	3	1.050	1.050	0.023	0.019
700	Trachea	2	1.031	1.031	10.364	8.201
800	BB_1†, -6 µm	52	1.000	1.000	0.025	0.010
801	BB_1†, 0 µm	2	1.031	1.031	0.031	0.013
802	BB_1†, 10 µm	2	1.031	1.031	0.052	0.021
803	BB_1†, 35 µm	2	1.031	1.031	0.130	0.053
804	BB_1†, 40 µm	2	1.031	1.031	0.026	0.011
805	BB_1†, 50 µm	2	1.031	1.031	0.052	0.021
806	BB_1†, 60 µm	2	1.031	1.031	0.052	0.021
807	BB_1†, 70 µm	2	1.031	1.031	0.053	0.021
808	BB_1†, surface	2	1.031	1.031	2.777	1.179
900	Blood in large arteries	4	1.060	1.060	336.000	246.000
910	Blood in large veins	4	1.060	1.060	1008.000	737.998
1300	Humeri, cortical	5	1.904	1.904	265.917	216.977
1400	Humeri, upper, spongiosa	7	1.233	1.185	145.689	107.717
1700	Humeri, lower, spongiosa	8	1.109	1.117	50.890	50.264
1800	Humeri, medullary cavity	6	0.981	0.981	71.641	41.009
1900	Ulnae and radii, cortical	5	1.904	1.904	273.498	156.708
2000	Ulnae and radii, spongiosa	8	1.109	1.117	154.981	86.883
2100	Ulnae and radii, medullary cavity	6	0.981	0.981	22.996	34.068
2200	Wrists and hand bones, cortical	5	1.904	1.904	181.529	105.132
2300	Wrists and hand bones, spongiosa	8	1.109	1.117	118.927	69.360
2400	Clavicles, cortical	5	1.904	1.904	48.252	32.825
2500	Clavicles, spongiosa	9	1.157	1.192	45.057	38.798
2600	Cranium, cortical	5	1.904	1.904	568.469	407.670
2700	Cranium, spongiosa	10	1.165	1.252	382.073	391.311
2800	Femora, cortical	5	1.904	1.904	561.309	485.055
2900	Femora, upper, spongiosa	11	1.125	1.046	413.232	232.804
3200	Femora, lower, spongiosa	8	1.109	1.117	373.652	166.334
3300	Femora, medullary cavity	6	0.981	0.981	108.224	96.278
3400	Tibiae, cortical	5	1.904	1.904	536.651	544.845
3500	Tibiae, spongiosa	8	1.109	1.117	621.408	558.529
3600	Tibiae, medullary cavity	6	0.981	0.981	79.815	88.883
3700	Ankles and foot, cortical	5	1.904	1.904	234.882	173.476
3800	Ankles and foot, spongiosa	8	1.109	1.117	432.615	257.451
3900	Mandible, cortical	5	1.904	1.904	76.877	45.394
4000	Mandible, spongiosa	12	1.271	1.189	56.287	33.479
4100	Pelvis, cortical	5	1.904	1.904	402.595	262.460
4200	Pelvis, spongiosa	13	1.121	1.105	619.672	455.599
4300	Ribs, cortical	5	1.904	1.904	368.797	164.514
4400	Ribs, spongiosa	14	1.170	1.087	457.351	277.325
4500	Scapulae, cortical	5	1.904	1.904	223.333	121.664
4600	Scapulae, spongiosa	15	1.201	1.125	156.670	96.730
4700	Cervical spine, cortical	5	1.904	1.904	103.943	71.596
4800	Cervical spine, spongiosa	16	1.049	1.129	78.915	75.601
4900	Thoracic spine, cortical	5	1.904	1.904	289.440	205.828
5000	Thoracic spine, spongiosa	17	1.070	1.080	345.222	271.915
5100	Lumbar spine, cortical	5	1.904	1.904	188.047	156.175
5200	Lumbar spine, spongiosa	18	1.108	1.165	291.584	264.976
5300	Sacrum, cortical	5	1.904	1.904	110.320	80.240
5400	Sacrum, spongiosa	19	1.033	1.052	192.224	154.840
5500	Sternum, cortical	5	1.904	1.904	9.991	1.685
5600	Sternum, spongiosa	20	1.041	1.073	61.420	51.347
5700	Cartilage, costal	21	1.099	1.099	56.331	41.959
5800	Cartilage, discs	21	1.099	1.099	82.063	69.351

6100	Brain	22	1.041	1.041	1517.390	1349.568
6200	Breast, left, adipose tissue	23	0.953	0.952	7.769	153.663
6300	Breast, left, glandular tissue	24	1.021	1.021	5.180	102.491
6400	Breast, right, adipose tissue	23	0.953	0.952	7.769	153.663
6500	Breast, right, glandular tissue	24	1.021	1.021	5.180	102.491
6600	Eye lens, sensitive, left	25	1.060	1.060	0.039	0.039
6601	Eye lens, insensitive, left	25	1.060	1.060	0.189	0.189
6700	Cornea, left	26	1.100	1.087	1.113	1.100
6701	Aqueous, left	27	1.025	1.014	0.308	0.304
6702	Vitreous, left	28	1.031	1.019	6.122	6.051
6800	Eye lens, sensitive, right	25	1.060	1.060	0.039	0.039
6801	Eye lens, insensitive, right	25	1.060	1.060	0.189	0.189
6900	Cornea, right	26	1.100	1.087	1.113	1.100
6901	Aqueous, right	27	1.025	1.014	0.308	0.304
6902	Vitreous, right	28	1.031	1.019	6.122	6.051
7000	Gall bladder wall	2	1.031	1.031	10.364	8.201
7100	Gall bladder contents	29	1.030	1.030	58.000	48.000
7200	Stomach wall, 60 µm	30	1.037	1.036	1.784	1.561
7201	Stomach wall, 100 µm	30	1.037	1.036	1.193	1.044
7202	Stomach wall, 300 µm	30	1.037	1.036	6.008	5.256
7203	Stomach wall, surface	30	1.037	1.036	185.286	165.012
7300	Stomach contents	33	1.040	1.040	250.000	230.000
7400	Small intestine wall, 130 µm	31	1.037	1.036	14.547	12.341
7401	Small intestine wall, 150 µm	31	1.037	1.036	2.264	1.922
7402	Small intestine wall, 200 µm	31	1.037	1.036	5.692	4.831
7403	Small intestine wall, surface	31	1.037	1.036	840.096	736.674
7500	Small intestine contents, -500 µm	33	1.040	1.040	53.337	45.227
7501	Small intestine contents, 0 µm	33	1.040	1.040	296.663	234.773
7600	Ascending colon wall, 280 µm	32	1.037	1.036	3.071	4.451
7601	Ascending colon wall, 300 µm	32	1.037	1.036	0.223	0.322
7602	Ascending colon wall, surface	32	1.037	1.036	116.634	107.784
7700	Ascending colon contents	33	1.040	1.040	55.000	100.007
7800	Transverse colon wall, right, 280 µm	32	1.037	1.036	3.993	3.680
7801	Transverse colon wall, right, 300 µm	32	1.037	1.036	0.289	0.266
7802	Transverse colon wall, right, surface	32	1.037	1.036	75.671	64.847
7900	Transverse colon contents, right	33	1.040	1.040	95.000	59.995
8000	Transverse colon wall, left, 280 µm	32	1.037	1.036	2.824	2.196
8001	Transverse colon wall, left, 300 µm	32	1.037	1.036	0.205	0.160
8002	Transverse colon wall, left, surface	32	1.037	1.036	76.924	66.428
8100	Transverse colon contents, left	33	1.040	1.040	40.000	30.005
8200	Descending colon wall, 280 µm	32	1.037	1.036	2.779	3.021
8201	Descending colon wall, 300 µm	32	1.037	1.036	0.203	0.220
8202	Descending colon wall, surface	32	1.037	1.036	116.946	109.320
8300	Descending colon contents	33	1.040	1.040	35.000	50.003
8400	Sigmoid colon wall, 280 µm	32	1.037	1.036	4.451	4.222
8401	Sigmoid colon wall, 300 µm	32	1.037	1.036	0.324	0.306
8402	Sigmoid colon wall, surface	32	1.037	1.036	48.527	51.761
8500	Sigmoid colon contents	33	1.040	1.040	75.000	79.993
8600	Rectum wall	32	1.037	1.036	39.976	31.268
8700	Heart wall	34	1.051	1.051	385.839	290.890
8800	Blood in heart chamber	4	1.060	1.060	510.000	370.000
8900	Kidney, left, cortex	35	1.053	1.052	162.338	149.091
9000	Kidney, left, medulla	35	1.053	1.052	38.359	37.441
9100	Kidney, left, pelvis	35	1.053	1.052	7.652	7.494
9200	Kidney, right, cortex	35	1.053	1.052	166.542	125.147
9300	Kidney, right, medulla	35	1.053	1.052	39.362	31.440
9400	Kidney, right, pelvis	35	1.053	1.052	7.892	6.292
9500	Liver	36	1.060	1.060	2360.000	1810.000
9700	Lung (AI), left	37	0.415	0.413	545.877	427.256
9900	Lung (AI), right	37	0.415	0.413	652.861	522.518
10000	Lymphatic nodes, ET	38	1.032	1.032	15.949	12.695
10001	Lymphatic nodes, cervical	38	1.032	1.032	5.510	4.386
10002	Lymphatic nodes, axillary	38	1.032	1.032	6.670	5.309
10003	Lymphatic nodes, breast	38	1.032	1.032	11.019	8.771
10004	Lymphatic nodes, thoracic	38	1.032	1.032	15.949	12.695
10005	Lymphatic nodes, cubital	38	1.032	1.032	11.019	8.771
10006	Lymphatic nodes, mesentery	38	1.032	1.032	101.495	80.789
10007	Lymphatic nodes, inguinal	38	1.032	1.032	11.019	8.771
10008	Lymphatic nodes, popliteal	38	1.032	1.032	11.019	8.771
10600	Muscle	39	1.050	1.050	29776.580	17926.439
11000	Oesophagus wall, 190 µm	40	1.037	1.036	1.919	1.871
11001	Oesophagus wall, 200 µm	40	1.037	1.036	0.103	0.101
11002	Oesophagus wall, surface	40	1.037	1.036	49.783	41.247

11003	Oesophagus contents	33	1.040	1.040	22.870	21.240
11100	Ovary, left	41		1.051		6.318
11200	Ovary, right	41		1.051		6.318
11300	Pancreas	42	1.044	1.043	173.631	144.552
11400	Pituitary gland	2	1.031	1.031	0.622	0.615
11500	Prostate	43	1.031		17.618	
11600	RST	44	0.939	0.946	18212.525	22325.388
12000	Salivary glands, left	2	1.031	1.031	44.045	35.880
12100	Salivary glands, right	2	1.031	1.031	44.045	35.880
12200	Skin, surface	45	1.089	1.088	103.981	89.399
12201	Skin, 50 µm	45	1.089	1.088	103.521	89.317
12202	Skin, 100 µm	45	1.089	1.088	3262.067	2243.313
12600	Spinal cord	2	1.031	1.031	37.952	19.098
12700	Spleen	46	1.060	1.060	228.400	187.400
12800	Teeth	47	2.688	2.690	50.727	40.562
12801	Teeth, retention region	33	1.040	1.040	0.043	0.036
12900	Testis, left	41	1.041		18.617	
13000	Testis, right	41	1.041		18.617	
13100	Thymus	2	1.031	1.031	25.909	20.503
13200	Thyroid	48	1.051	1.051	23.351	19.455
13300	Tongue, upper (food)	3	1.050	1.050	20.993	20.995
13301	Tongue, lower, surface	3	1.050	1.050	1.648	1.269
13302	Tongue, lower, -200 µm	3	1.050	1.050	52.904	39.146
13400	Tonsils	2	1.031	1.031	3.109	3.075
13500	Ureter, left	2	1.031	1.031	8.809	7.689
13600	Ureter, right	2	1.031	1.031	7.773	7.689
13700	Urinary bladder wall	49	1.040	1.040	47.719	37.209
13701	Urinary bladder wall, 75/69‡ µm	49	1.040	1.040	1.309	1.337
13702	Urinary bladder wall, 193/185‡ µm	49	1.040	1.040	2.071	2.259
13800	Urinary bladder contents	50	1.040	1.040	200.000	200.000
13900	Uterus	43		1.021		81.993
14000	ET$_1$ contents, 0 µm (air)	51	0.001	0.001	0.008	0.000198
14001	ET$_2$ contents, -15 µm (air)	51	0.001	0.001	0.029	0.014
14002	Trachea contents (air)	51	0.001	0.001	0.015	0.011
14003	BB$_1$ contents†, -11 µm (air)	51	0.001	0.001	0.016	0.004
14004	Air, remaining	51	0.001	0.001	0.072	0.007

† Only the main bronchi (BB$_1$) was defined in the PM-version phantoms. The other generations of the bronchi (BB) and all generations of the bronchioles (bb) were modelled in CSG format (see Chapter 5.3).

‡ Male/female.

ANNEX B. LIST OF MEDIA AND THEIR ELEMENTAL COMPOSITION

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

Medium no.		H	C	N	O	Na	Mg	P	S	Cl	K	Ca	Fe	I	Density (g/cm^3)
1	Adrenal	10.4	22.8	2.8	63.0	0.1		0.2	0.3	0.2	0.2				1.036
2	ET, Trachea, BB, bb, Gall bladder wall, Pituitary gland, Salivary glands, Spinal cord, Thymus, Tonsils, Ureter	10.5	25.1	2.7	60.7	0.1		0.2	0.3	0.2	0.2				1.031
3	Oral mucosa, Tongue	10.2	14.2	3.4	71.1	0.1		0.2	0.3	0.1	0.4				1.050
4	Blood	10.2	11.0	3.3	74.5	0.1		0.1	0.2	0.3	0.2		0.1		1.060
5	Cortical bone	3.6	15.9	4.2	44.8	0.3	0.2	9.4	0.3			21.3			1.904
6	Medullary cavity	11.5	63.6	0.7	23.9	0.1			0.1	0.1					0.981
7	Humeri, upper, spongiosa	8.1	35.4	2.8	41.0	0.2	0.1	3.7	0.2	0.1	0.1	8.3			1.233
8	Humeri, lower, Ulnae and radii, Wrists and hand bones, Femora, lower, Tibiae, Ankles and foot, spongiosa	9.6	50.4	1.7	30.8	0.1		2.2	0.2	0.1		4.9			1.109
9	Clavicles, spongiosa	8.9	40.9	2.5	38.5	0.1		2.7	0.2	0.1	0.1	6.0			1.157
10	Cranium, spongiosa	8.8	39.5	2.6	39.5	0.1	0.1	2.8	0.2	0.1	0.1	6.2			1.165
11	Femora, upper, spongiosa	9.3	44.1	2.3	36.5	0.1	0.1	2.2	0.2	0.1	0.1	5.0			1.125
12	Mandible, spongiosa	7.7	33.2	3.0	42.0	0.2	0.1	4.1	0.2	0.1	0.1	9.3			1.271
13	Pelvis, spongiosa	9.4	40.9	2.6	40.0	0.1	0.1	2.0	0.2	0.1	0.1	4.5			1.121
14	Ribs, spongiosa	8.8	34.6	3.1	44.4	0.1	0.1	2.6	0.2	0.1	0.1	5.8	0.1		1.170
15	Scapulae, spongiosa	8.4	37.3	2.7	40.4	0.1	0.1	3.3	0.2	0.1	0.1	7.3			1.201
16	Cervical spine, spongiosa	10.3	41.6	2.8	42.8	0.1		0.6	0.2	0.2	0.1	1.2	0.1		1.049
17	Thoracic spine, spongiosa	10.0	40.3	2.8	43.1	0.1		1.0	0.2	0.2	0.1	2.1	0.1		1.070
18	Lumbar spine, spongiosa	9.5	38.0	3.0	43.6	0.1		1.6	0.2	0.2	0.1	3.6	0.1		1.108
19	Sacrum, spongiosa	10.5	42.6	2.7	42.6	0.1		0.3	0.2	0.2	0.1	0.6	0.1		1.033
20	Sternum, spongiosa	10.4	42.1	2.8	42.7			0.5	0.2	0.2	0.1	0.9	0.1		1.041
21	Cartilage	9.6	9.9	2.2	74.4	0.5		2.2	0.9	0.3					1.099
22	Brain	10.7	14.3	2.3	71.3	0.2		0.4	0.2	0.3	0.3				1.041
23	Breast, adipose tissue	11.4	58.1	0.8	29.4	0.1			0.1	0.1					0.953
24	Breast, glandular tissue	10.6	32.4	3.0	53.5	0.1		0.1	0.2	0.1					1.021
25	Eye lens	9.6	19.5	5.7	64.6	0.1		0.1	0.3	0.1					1.060
26	Cornea	10.1	12.5	3.7	73.2	0.1		0.1	0.2	0.1					1.100
27	Aqueous	11.2	0.4	0.1	88.3										1.025
28	Vitreous	11.2	0.4	0.1	88.3										1.031
29	Gall bladder contents	10.5	25.6	2.7	60.2	0.1		0.2	0.3	0.2	0.2				1.030
30	Stomach wall	10.5	11.4	2.5	75.0	0.1		0.1	0.1	0.2	0.1				1.037
31	Small intestine wall	10.5	11.4	2.5	75.0	0.1		0.1	0.1	0.2	0.1				1.037
32	Colon wall	10.5	11.4	2.5	75.0	0.1		0.1	0.1	0.2	0.1				1.037
33	GI contents	10.0	22.2	2.2	64.4	0.1		0.2	0.3	0.1	0.4	0.1			1.040
34	Heart wall	10.4	13.5	2.9	72.2	0.1		0.2	0.2	0.2	0.3				1.051
35	Kidney	10.3	12.6	3.1	72.9	0.2		0.2	0.2	0.2	0.2	0.1			1.053
36	Liver	10.2	13.2	3.1	72.3	0.2		0.2	0.3	0.2	0.3				1.060
37	Lung	10.2	10.8	3.2	74.8	0.1		0.1	0.2	0.3	0.2		0.1		0.415
38	Lymphatic nodes	10.8	4.5	1.2	82.7	0.3			0.1	0.4					1.032
39	Muscle	10.2	14.2	3.4	71.1	0.1		0.2	0.3	0.1	0.4				1.050
40	Oesophagus	10.4	22.3	2.8	63.5	0.1		0.2	0.3	0.2	0.2				1.037

41	Gonads	10.6	9.9	2.1	76.5	0.2		0.1	0.2	0.2	0.2				1.041
42	Pancreas	10.5	15.8	2.4	70.4	0.2		0.2	0.1	0.2	0.2				1.044
43	Prostate	10.5	25.1	2.7	60.7	0.1		0.2	0.3	0.2	0.2				1.031
44	RST	11.2	51.7	1.1	35.5	0.1		0.1	0.2	0.1					0.939
45	Skin	10.0	19.9	4.2	65.0	0.2		0.1	0.2	0.3	0.1				1.089
46	Spleen	10.3	11.2	3.2	74.3	0.1		0.2	0.2	0.2	0.3				1.060
47	Teeth	2.3	9.5	2.9	42.6		0.7	13.5				28.5			2.688
48	Thyroid	10.4	11.8	2.5	74.5	0.2		0.1	0.1	0.2	0.1			0.1	1.051
49	Urinary bladder wall	10.5	9.6	2.6	76.1	0.2		0.2	0.2	0.3	0.3				1.040
50	Urine	10.7	0.3	1.0	87.3	0.4		0.1			0.2				1.040
51	Air inside body			80.0	20.0										0.001
52	Water	11.2			88.8										1.000

Table B.2. List of media, their elemental compositions (percentage by mass) and their densities for the adult female mesh-type reference phantom.

Medium no.		H	C	N	O	Na	Mg	P	S	Cl	K	Ca	Fe	I	Density (g/cm^3)
1	Adrenal	10.4	23.3	2.8	62.5	0.1		0.2	0.3	0.2	0.2				1.035
2	ET, Trachea, BB, bb, Gall bladder wall, Pituitary gland, Salivary glands, Spinal cord, Thymus, Tonsils, Ureter	10.5	25.2	2.7	60.6	0.1		0.2	0.3	0.2	0.2				1.031
3	Oral mucosa, Tongue	10.2	14.2	3.4	71.1	0.1		0.2	0.3	0.1	0.4				1.050
4	Blood	10.2	11.0	3.3	74.5	0.1		0.1	0.2	0.3	0.2		0.1		1.060
5	Cortical bone	3.6	15.9	4.2	44.8	0.3	0.2	9.4	0.3			21.3			1.904
6	Medullary cavity	11.5	63.7	0.7	23.8	0.1			0.1	0.1					0.981
7	Humeri, upper, spongiosa	8.6	39.2	2.6	39.0	0.1	0.1	3.1	0.2	0.1	0.1	6.9			1.185
8	Humeri, lower, Ulnae and radii, Wrists and hand bones, Femora, lower, Tibiae, Ankles and foot, spongiosa	9.5	49.8	1.7	31.1	0.1		2.3	0.2	0.1		5.2			1.117
9	Clavicles, spongiosa	8.5	38.8	2.6	39.2	0.1	0.1	3.2	0.2	0.1	0.1	7.1			1.192
10	Cranium, spongiosa	7.9	34.5	2.9	41.3	0.2	0.1	3.9	0.2	0.1	0.1	8.8			1.252
11	Femora, upper, spongiosa	10.4	50.1	1.9	34.2	0.1		0.9	0.2	0.1	0.1	2.0			1.046
12	Mandible, spongiosa	8.6	38.3	2.7	39.8	0.1	0.1	3.1	0.2	0.1	0.1	6.9			1.189
13	Pelvis, spongiosa	9.6	42.2	2.5	39.4	0.1		1.8	0.2	0.1	0.1	3.9	0.1		1.105
14	Ribs, spongiosa	9.8	39.4	2.9	43.1	0.1		1.3	0.2	0.2	0.1	2.8	0.1		1.087
15	Scapulae, spongiosa	9.3	42.6	2.4	38.2	0.1		2.2	0.2	0.1	0.1	4.8			1.125
16	Cervical spine, spongiosa	9.2	37.1	3.0	43.6	0.1		2.0	0.2	0.2	0.1	4.4	0.1		1.129
17	Thoracic spine, spongiosa	9.8	39.9	2.9	43.0	0.1		1.2	0.2	0.2	0.1	2.5	0.1		1.080
18	Lumbar spine, spongiosa	8.8	35.2	3.1	44.0	0.1	0.1	2.6	0.2	0.1	0.1	5.7			1.165
19	Sacrum, spongiosa	10.2	41.6	2.8	42.6	0.1		0.7	0.2	0.2	0.1	1.4	0.1		1.052
20	Sternum, spongiosa	10.0	40.3	2.8	42.9	0.1		1.1	0.2	0.2	0.1	2.2	0.1		1.073
21	Cartilage	9.6	9.9	2.2	74.4	0.5		2.2	0.9	0.3					1.099
22	Brain	10.7	14.4	2.2	71.3	0.2		0.4	0.2	0.3	0.3				1.041
23	Breast, adipose tissue	11.4	58.6	0.8	28.9	0.1			0.1	0.1					0.952
24	Breast, glandular tissue	10.6	32.7	3.0	53.2	0.1		0.1	0.2	0.1					1.021
25	Eye lens	9.6	19.5	5.7	64.6	0.1		0.1	0.3	0.1					1.060
26	Cornea	10.1	12.6	3.7	73.1	0.1		0.1	0.2	0.1					1.087
27	Aqueous	11.2	0.3	0.1	88.4										1.014
28	Vitreous	11.2	0.3	0.1	88.4										1.019
29	Gall bladder contents	10.5	25.6	2.7	60.2	0.1		0.2	0.3	0.2	0.2				1.030
30	Stomach wall	10.6	11.4	2.4	75.0	0.1		0.1	0.1	0.2	0.1				1.036
31	Small intestine wall	10.5	11.4	2.5	75.0	0.1		0.1	0.1	0.2	0.1				1.036
32	Colon wall	10.5	11.4	2.5	75.0	0.1		0.1	0.1	0.2	0.1				1.036
33	GI contents	10.0	22.2	2.2	64.4	0.1		0.2	0.3	0.1	0.4	0.1			1.040
34	Heart wall	10.4	13.5	2.9	72.2	0.1		0.2	0.2	0.2	0.3				1.051
35	Kidney	10.3	12.7	3.0	72.9	0.2		0.2	0.2	0.2	0.2	0.1			1.052
36	Liver	10.2	13.2	3.1	72.3	0.2		0.2	0.3	0.2	0.3				1.060
37	Lung	10.2	10.8	3.2	74.8	0.1		0.1	0.2	0.3	0.2		0.1		0.413
38	Lymphatic nodes	10.8	4.5	1.2	82.7	0.3			0.1	0.4					1.032
39	Muscle	10.2	14.2	3.4	71.1	0.1		0.2	0.3	0.1	0.4				1.050
40	Oesophagus	10.5	22.8	2.8	62.9	0.1		0.2	0.3	0.2	0.2				1.036
41	Gonads	10.5	9.5	2.5	76.5	0.2		0.2	0.2	0.2	0.2				1.051
42	Pancreas	10.5	15.9	2.4	70.3	0.2		0.2	0.1	0.2	0.2				1.043
43	Uterus	10.6	31.0	2.4	55.2	0.1		0.2	0.2	0.1	0.2				1.021
44	RST	11.2	54.5	1	32.9	0.1		0.1	0.1	0.1					0.946

45	Skin	10.0	19.9	4.2	65.0	0.2		0.1	0.2	0.3	0.1				1.088
46	Spleen	10.3	11.2	3.2	74.2	0.1		0.3	0.2	0.2	0.3				1.060
47	Teeth	2.3	9.5	2.9	42.6		0.7	13.5				28.5			2.690
48	Thyroid	10.4	11.8	2.5	74.5	0.2		0.1	0.1	0.2	0.1			0.1	1.051
49	Urinary bladder wall	10.5	9.6	2.6	76.1	0.2		0.2	0.2	0.3	0.3				1.040
50	Urine	10.7	0.3	1.0	87.3	0.4		0.1			0.2				1.040
51	Air inside body			80.0	20.0										0.001
52	Water	11.2			88.8										1.000

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

Table C.1. List of anatomical source regions, their acronyms and corresponding ID numbers in the phantoms.

Source region	Acronym	ID number(s)
Oral cavity	O-cavity	13300
Oral mucosa	O-mucosa	500, 501, 600
Teeth surface	Teeth-S	12801
Teeth volume	Teeth-V	12800
Tongue	Tongue	500, 13300, 13301
Tonsils	Tonsils	13400
Oesophagus fast	Oesophag-f	11003
Oesophagus slow	Oesophag-s	11003
Oesophagus	Oesophagus-w	11000, 11001, 11002
Stomach contents	St-cont	7300
Stomach wall	St-wall	7200, 7201, 7202, 7203
Stomach mucosa	St-mucosa	7200, 7201, 7202
Small intestine contents	SI-cont	7501
Small intestine villi	SI-villi	7500
Small intestine wall	SI-wall	7400, 7401, 7402, 7403
Small intestine mucosa	SI-mucosa	7400, 7401, 7402
Right colon contents	RC-cont	7700, 7900
Right colon wall	RC-wall	7600, 7601, 7602, 7800, 7801, 7802
Right colon mucosa	RC-mucosa	7600, 7601, 7800, 7801
Left colon contents	LC-cont	8100, 8300
Left colon wall	LC-wall	8000, 8001, 8002, 8200, 8201, 8202
Left colon mucosa	LC-mucosa	8000, 8001, 8200, 8201
Rectosigmoid colon contents	RS-cont	8500
Rectosigmoid colon wall	RS-wall	8400, 8401, 8402, 8600
Rectosigmoid colon mucosa	RS-mucosa	8400, 8401
ET1 surface	ET1-sur	300
ET2 surface	ET2-sur	400
ET1 wall	ET1-wall	300, 301, 302, 303
ET2 wall	ET2-wall	401, 402, 403, 404, 405
ET2 bound region	ET2-bnd	401, 402, 403
ET2 sequestered region	ET2-seq	404
Extrathoracic lymph nodes	LN-ET	10000
Bronchial – fast	Bronchi-f	800
Bronchial – slow	Bronchi-s	801
Bronchi bound region	Bronchi-b	802, 803, 804, 805, 806
Bronchi sequestered region	Bronchi-q	807
Bronchiolar – fast	Brchiole-f	810
Bronchiolar – slow	Brchiole-s	811
Bronchiolar bound region	Brchiole-b	812, 813, 814
Bronchiolar sequestered region	Brchiole-q	815
Alveolar-interstitium	AI	9700, 9900
Thoracic lymph nodes	LN-Th	10100
Right lung lobe	RLung	9900
Left lung lobe	LLung	9700
RLung + LLung	Lungs	9700, 9900
Right adrenal gland	RAdrenal	200
Left adrenal gland	LAdrenal	100
RAdrenal + LAdrenal	Adrenals	100, 200
Blood vessels of head	HBlood	900, 910

Blood vessels of trunk	TBlood	1000, 1010
Blood vessels of arms	ABlood	1100, 1110
Blood vessels of legs	LBlood	1200, 1210
Blood in heart	Ht-cont	8800
Total blood	Blood	†
Cortical bone surface	C-bone-S	‡
Cortical bone volume	C-bone-V	‡
Trabecular bone surface	T-bone-S	¶
Trabecular bone volume	T-bone-V	¶
Cortical bone marrow	C-marrow	§
Trabecular bone marrow	T-marrow	††
Brain	Brain	6100
Right breast adipose	RBreast-a	6400
Right breast glandular	RBreast-g	6500
Left breast adipose	LBreast-a	6200
Left breast glandular	LBreast-g	6300
RBreast-a + RBreast-g	RBreast	6400, 6500
LBreast-a + LBreast-g	LBreast	6200, 6300
RBreast-a + LBreast-a	Breast-a	6200, 6400
RBreast-g + LBreast-g	Breast-g	6300, 6500
Breast-a + Breast-g	Breast	6200, 6300, 6400, 6500
Lens of eye	Eye-lens	6600, 6601, 6800, 6801
Gall bladder	GB-wall	7000
Gall bladder contents	GB-cont	7100
Heart	Ht-wall	8700
Right kidney cortex	RKidney-C	9200
Right kidney medulla	RKidney-M	9300
Right kidney pelvis	RKidney-P	9400
Right kidney C+M+P	RKidney	9200, 9300, 9400
Left kidney cortex	LKidney-C	8900
Left kidney medulla	LKidney-M	9000
Left kidney pelvis	LKidney-P	9100
Left kidney C+M+P	LKidney	8900, 9000, 9100
RKidney + LKidney	Kidneys	8900, 9000, 9100, 9200, 9300, 9400
Liver	Liver	9500
Systemic lmyph nodes	LN-Sys	10200, 10300, 10400, 10500
Muscle	Muscle	10600, 10700, 10800, 10900
Right ovary	ROvary	11200
Left ovary	LOvary	11100
ROvary + LOvary	Ovaries	11100, 11200
Pancreas	Pancreas	11300
Pituitary gland	P-gland	11400
Prostate	Prostate	11500
Salivary glands	S-glands	12000, 12100
Skin	Skin	12200, 12201, 12300, 12301, 12400, 12401, 12500, 12501
Spinal cord	Sp-cord	12600
Spleen	Spleen	12700
Testes	Testes	12900, 13000
Thymus	Thymus	13100
Thyroid	Thyroid	13200
Ureters	Ureters	13500, 13600
Urinary bladder	UB-wall	13700, 13701
Urinary bladder content	UB-cont	13800
Uterus/cervix	Uterus	13900
Adipose/residual tissue	Adipose	11600, 11700, 11800, 11900
Total body tissues (total body minus contents of walled organs)	T-body	*

Soft tissue (T-body – mineral bone)	S-tissue	**

[†] Blood: 900, 910, 1000, 1010, 1100, 1110, 1200, 1210, 8800, plus blood included in the organs and tissues.

[‡] Cortical bone mineral: 1300, 1600, 1900, 2200, 2400, 2600, 2800, 3100, 3400, 3700, 3900, 4100, 4300, 4500, 4700, 4900, 5100, 5300, 5500.

[¶] Trabecular bone mineral: mineral bone fraction of 1400, 1700, 2000, 2300, 2500, 2700, 2900, 3200, 3500, 3800, 4000, 4200, 4400, 4600, 4800, 5000, 5200, 5400, 5600.

[§] Cortical bone marrow: 1500, 1800, 2100, 3000, 3300, 3600.

[††] Trabecular bone marrow: marrow fraction of 1400, 1700, 2000, 2300, 2500, 2700, 2900, 3200, 3500, 3800, 4000, 4200, 4400, 4600, 4800, 5000, 5200, 5400, 5600 (red and yellow marrow).

[*] Total body tissues: 100-7000, 7200-7203, 7400-7403, 7600-7602, 7800-7802, 8000-8002, 8200-8202, 8400-8402, 8600-11002, 11100-13701, 13900.

[**] Soft tissue: 100-1210, 1500, 1800, 2100, 3000, 3300, 3600, 5700-7000, 7200-7203, 7400-7403, 7600-7602, 7800-7802, 8000-8002, 8200-8202, 8400-8402, 8600-11002, 11100-12700, 12900-13701, 13900, plus soft tissue fraction of 1400, 1700, 2000, 2300, 2500, 2700, 2900, 3200, 3500, 3800, 4000, 4200, 4400, 4600, 4800, 5000, 5200, 5400, 5600.

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

Table D.1. List of target regions, their acronyms and corresponding ID numbers in the phantoms.

Target region	Acronym	ID number(s)
Red (active) marrow	R-marrow	†
Colon wall	Colon	7600, 7601, 7602, 7800, 7801, 7802, 8000, 8001, 8002, 8200, 8201, 8202, 8400, 8401, 8402, 8600
Stem cells of colon	Colon-stem	7601, 7801, 8001, 8201, 8401
RLung + LLung	Lungs	9700, 9900
Stomach wall	St-wall	7200, 7201, 7202, 7203
Stem cells of stomach	St-stem	7201
Breast-a + Breast-g	Breast	6200, 6300, 6400, 6500
ROvary + LOvary	Ovaries	11100, 11200
Testes	Testes	12900, 13000
Urinary bladder wall	UB-wall	13700, 13701
Urinary bladder basal cells	UB-basal	13701
Oesophagus wall	Oesophagus	11000, 11001, 11002
Oesophagus basal cells	Oesophagus-bas	11001
Liver	Liver	9500
Thyroid	Thyroid	13200
50-μm endosteal region	Endost-BS	‡
Brain	Brain	6100
Salivary glands	S-glands	12000, 12100
Skin	Skin	12200, 12201, 12300, 12301, 12400, 12401, 12500, 12501
Basal cells of skin	Skin-bas	12201, 12301, 12401, 12501
RAdrenal + LAdrenal	Adrenals	100, 200
ET region	ET	300, 301, 302, 303, 401, 402, 403, 404, 405
Gall bladder wall	GB-wall	7000
Heart wall	Ht-wall	8700
RKidney + LKidney	Kidneys	8900, 9000, 9100, 9200, 9300, 9400
Sysyemic lymph nodes	LN-Sys	10200, 10300, 10400, 10500
Muscle	Muscle	10600, 10700, 10800, 10900
Oral mucosa	O-mucosa	500, 501, 600
Pancreas	Pancreas	11300
Prostate	Prostate	11500
Small intestine wall	SI-wall	7400, 7401, 7402, 7403
Stem cells of small intestine	SI-stem	7401
Spleen	Spleen	12700
Thymus	Thymus	13100
Uterus/cervix	Uterus	13900
Tongue	Tongue	500, 13300, 13301
Tonsils	Tonsils	13400
Right colon wall (ascending + right transverse)	RC-wall	7600, 7601, 7602, 7800, 7801, 7802
Left colon wall (left transverse + descending)	LC-wall	8000, 8001, 8002, 8200, 8201, 8202
Rectosigmoid colon wall (sigmoid + rectum)	RS-wall	8400, 8401, 8402, 8600
Stem cells of right colon (ascending + right transverse)	RC-stem	7601, 7801
Stem cells of left colon (left transverse + descending)	LC-stem	8001, 8201
Stem cells of rectosigmoid colon (sigmoid + rectum)	RSig-stem	8401
Basal cells of anterior nasal passages	ET1-bas	302
Basal cells of posterior nasal passages + pharynx	ET2-bas	402
Extrathoracic lymph nodes	LN-ET	10000
Bronchi basal cells	Bronch-bas	804, 805
Bronchi secretory cells	Bronch-sec	803, 804

Bronchiolar secretory cells	Brchiol-sec	813
Alveolar-interstitial	AI	9700, 9900
Thoracic lymph nodes	LN-Th	10100
Right lung lobe	RLung	9900
Left lung lobe	LLung	9700
Right adrenal gland	RAdrenal	200
Left adrenal gland	LAdrenal	100
Right breast adipose	RBreast-a	6400
Right breast glandular	RBreast-g	6500
Left breast adipose	LBreast-a	6200
Left breast glandular	LBreast-g	6300
RBreast-a + RBreast-g	RBreast	6400, 6500
LBreast-a + LBresat-g	LBreast	6200, 6300
RBreast-a + LBreast-a	Breast-a	6200, 6400
RBreast-g + LBreast-g	Breast-g	6300, 6500
Entire lenses of eye	Lens-ent	6600, 6601, 6800, 6801
Sensitive lenses of eye	Lens-sen	6600, 6800
Right kidney cortex	RKidney-C	9200
Right kidney medulla	RKidney-M	9300
Right kidney pelvis	RKidney-P	9400
Right kidney C+M+P	RKidney	9200, 9300, 9400
Left kidney cortex	LKidney-C	8900
Left kidney medulla	LKidney-M	9000
Left kidney pelvis	LKidney-P	9100
Left kidney C+M+P	LKidney	8900, 9000, 9100
Right ovary	ROvary	11200
Left ovary	LOvary	11100
Pituitary gland	P-gland	11400
Spinal cord	Sp-cord	12600
Ureters	Ureters	13500, 13600
Adipose/residual tissue	Adipose	11600, 11700, 11800, 11900

† Red bone marrow fraction in organ IDs 1400, 2500, 2700, 2900, 4000, 4200, 4400, 4600, 4800, 5000, 5200, 5400, 5600.
‡ Endosteum fraction in organ IDs 1400, 1500, 1700, 1800, 2000, 2100, 2300, 2500, 2700, 2900, 3000, 3200, 3300, 3500, 3600, 3800, 4000, 4200, 4400, 4600, 4800, 5000, 5200, 5400, 5600.

ANNEX E. ORGAN DEPTH DISTRIBUTIONS OF SELECTED ORGANS/TISSUES

(E1) In Figs. E.1–E.13, organ depth distributions (ODDs) of the adult mesh-type reference computational phantoms and the *Publication 110* phantoms are shown for the selected organs and tissues (i.e. spongiosa, colon wall, lungs, stomach wall, breasts, gonads, urinary bladder wall, oesophagus, liver, thyroid, brain, salivary glands and skin). For the ODD calculation, ten million points were randomly sampled in the considered organ/tissue, and the distances from the sampled points to the outer surface (e.g. front, back, left, etc.) of the phantoms were calculated. The ODDs represent a depth of an organ/tissue below the outer surface of the phantoms, significantly influencing dose calculation for external exposure.

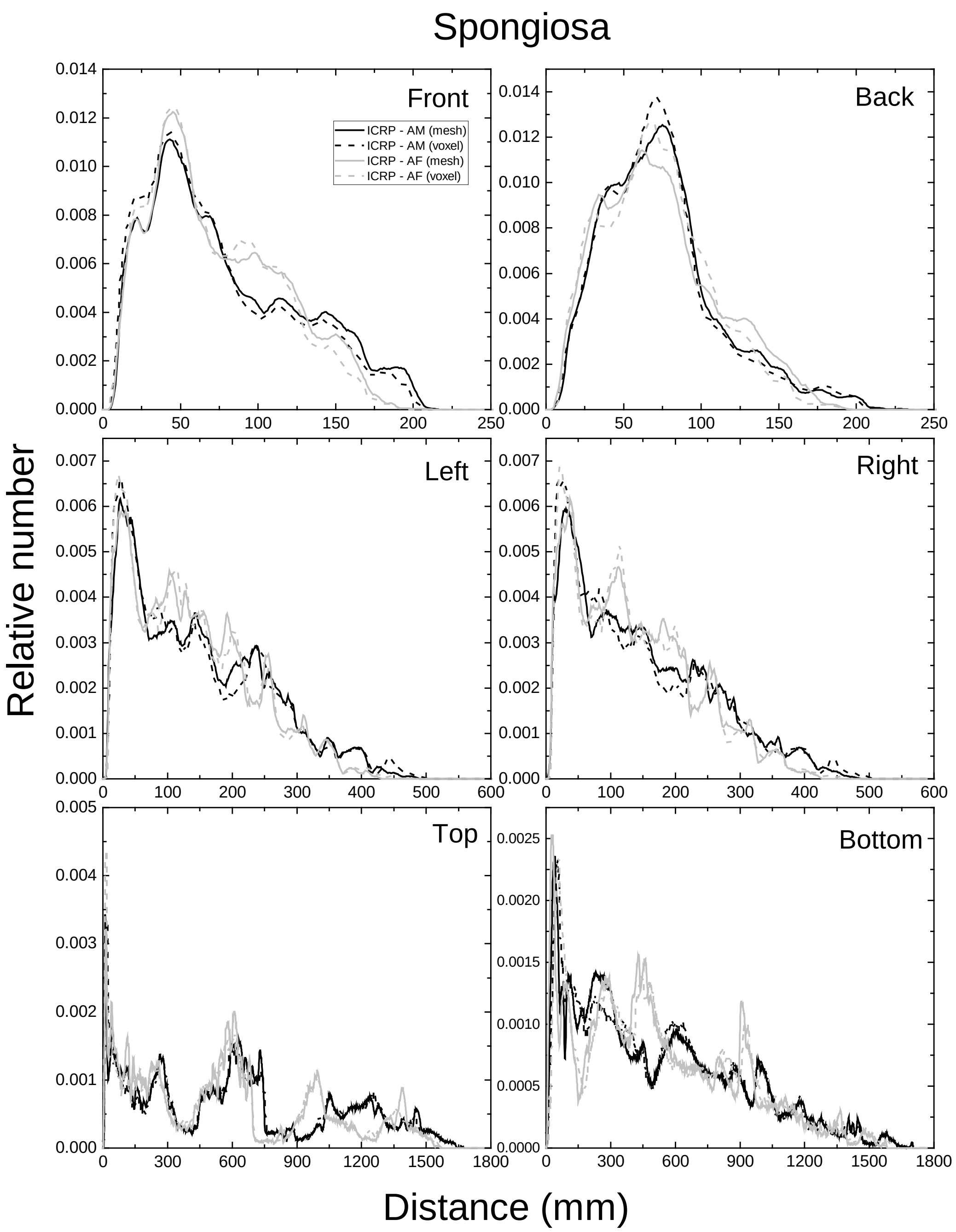


Fig. E.1. Distribution of depths of 10 million randomly sampled points in the spongiosa below the body surfaces at: front, back, left, right, top and bottom.

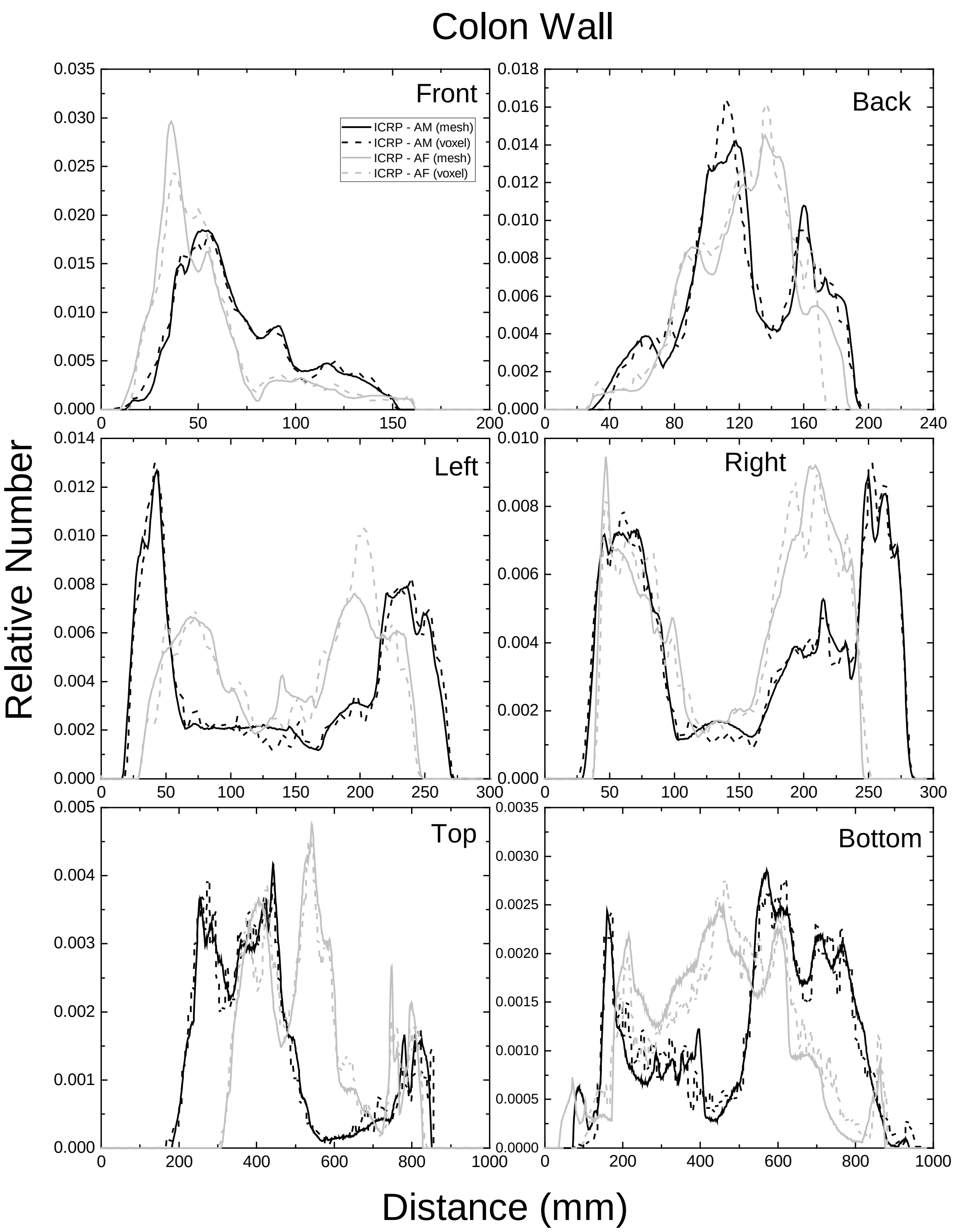


Fig. E.2. Distribution of depths of 10 million randomly sampled points in the colon wall below the body surfaces at: front, back, left, right, top and bottom.

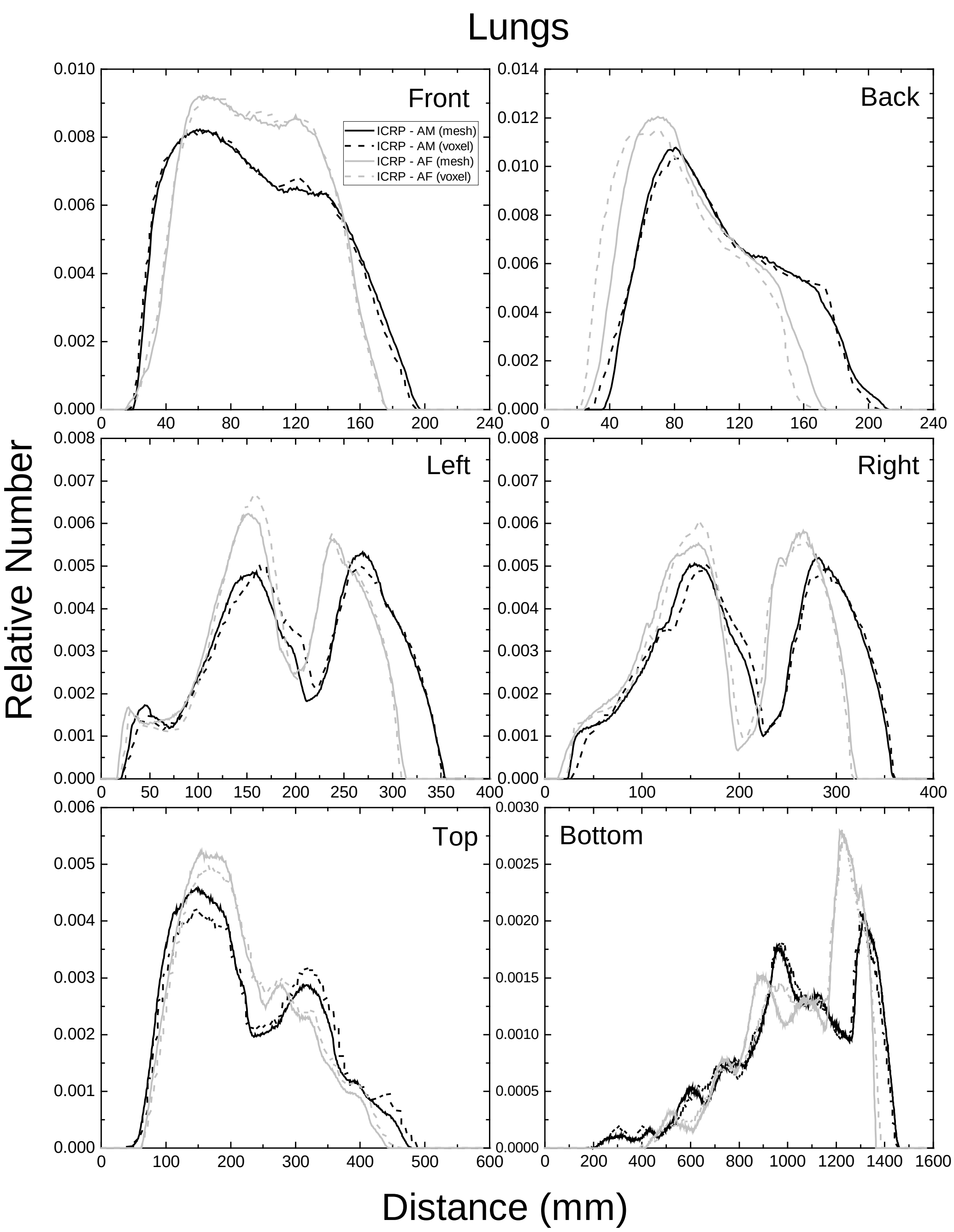
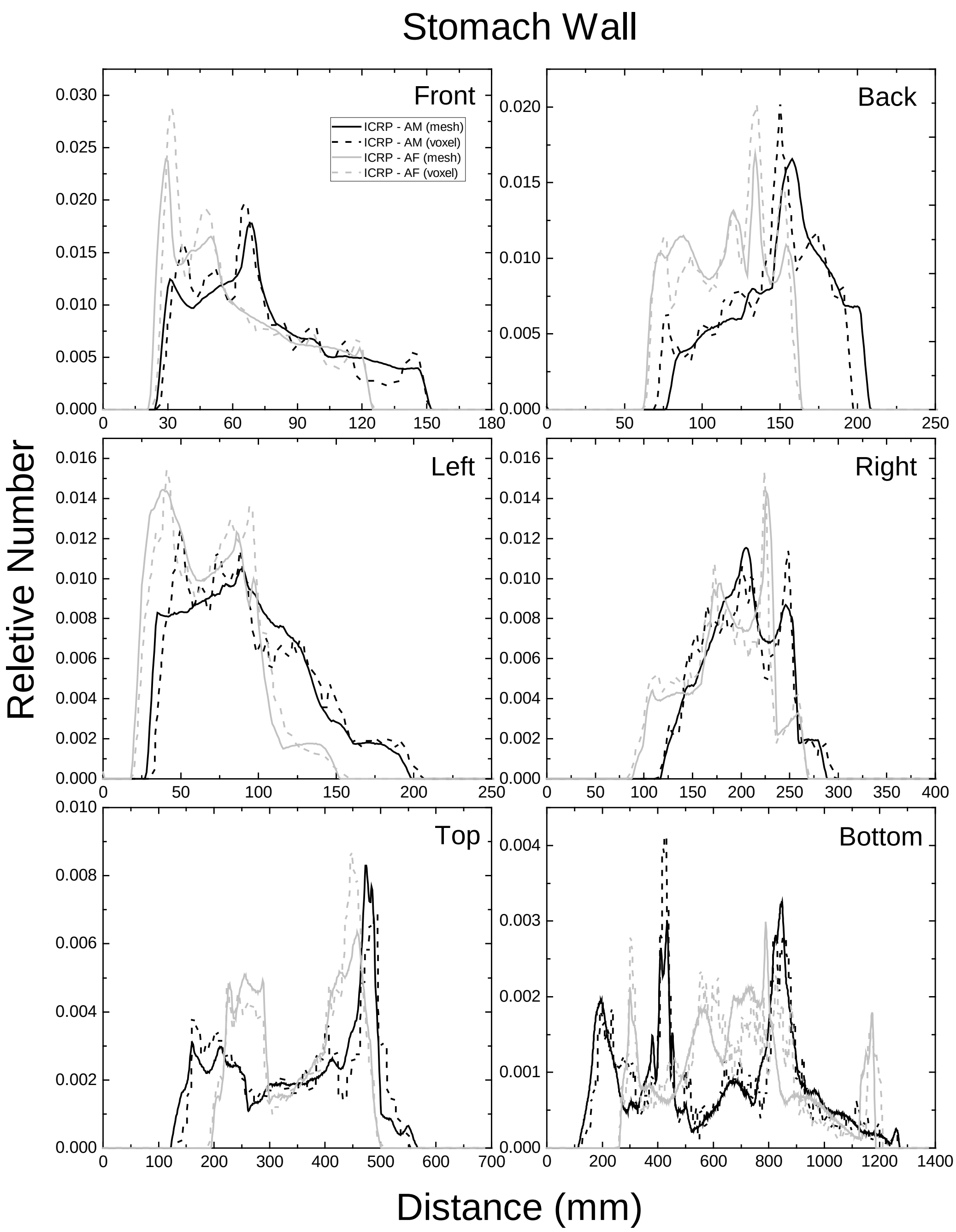
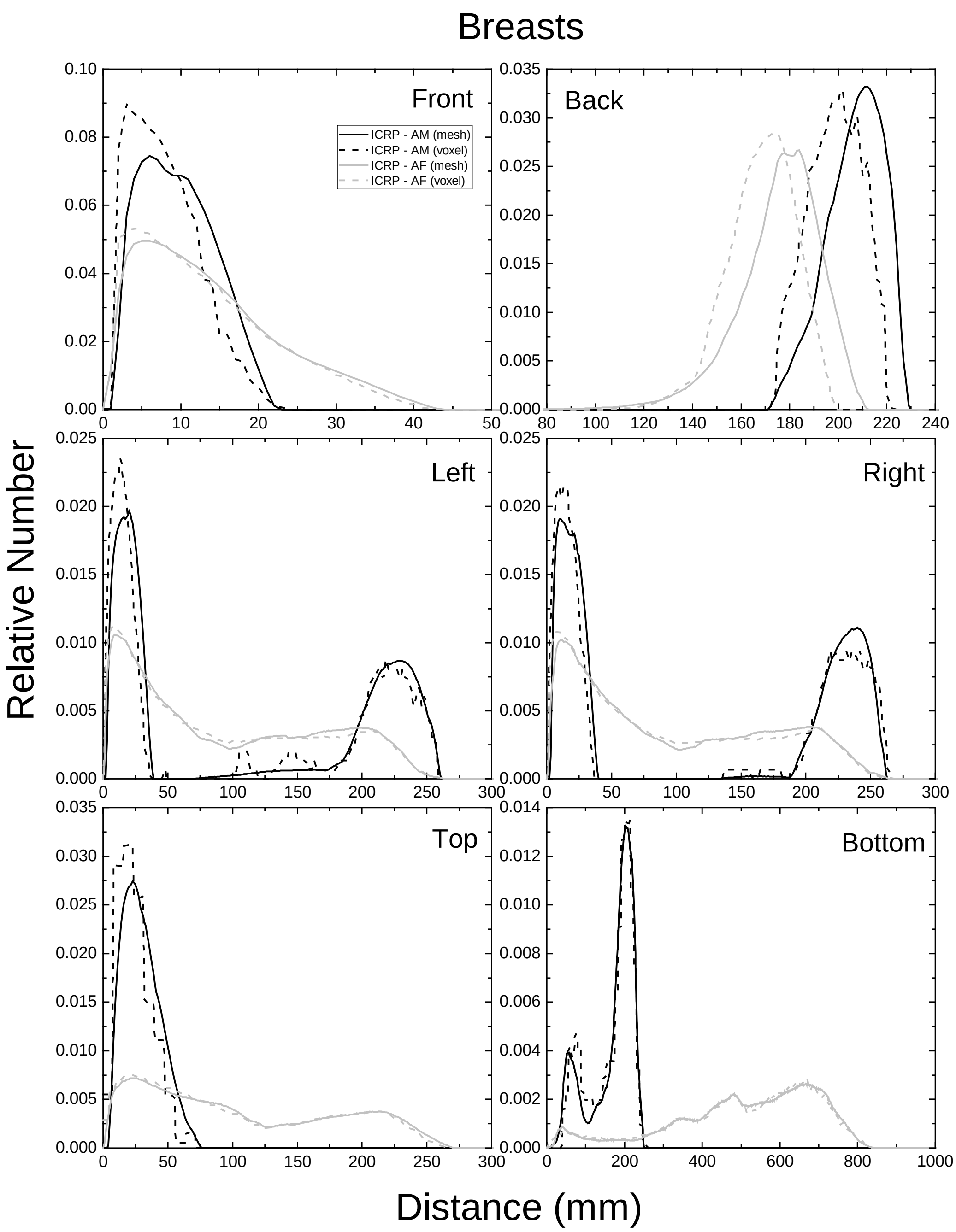


Fig. E.3. Distribution of depths of 10 million randomly sampled points in the lungs below the body surfaces at: front, back, left, right, top and bottom.



1728
1729 Fig. E.4. Distribution of depths of 10 million randomly sampled points in the stomach wall below the
1730 body surfaces at: front, back, left, right, top and bottom.
1731
1732



1734 Fig. E.5. Distribution of depths of 10 million randomly sampled points in the breasts below the body
1735 surfaces at: front, back, left, right, top and bottom.

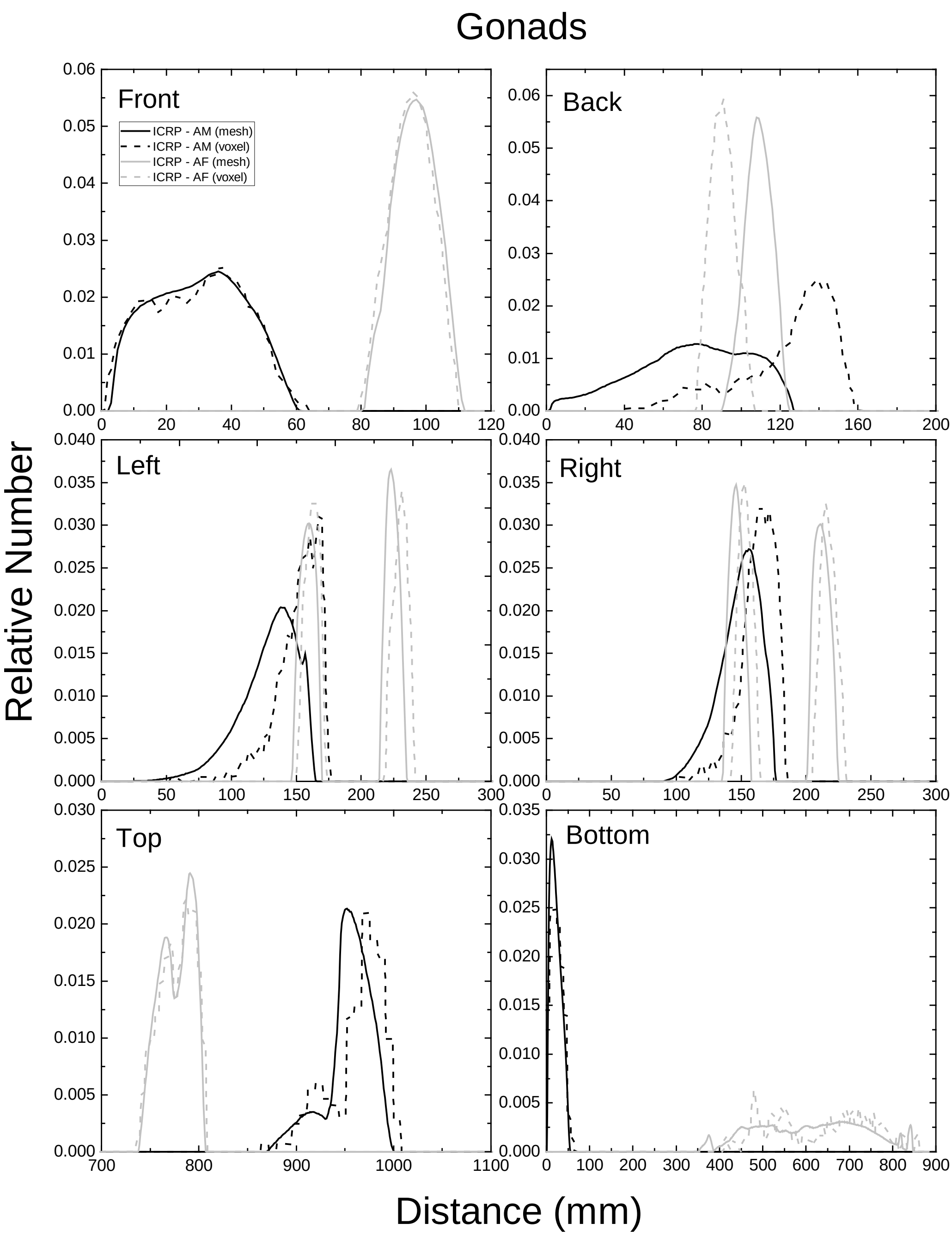


Fig. E.6. Distribution of depths of 10 million randomly sampled points in the gonads below the body surfaces at: front, back, left, right, top and bottom.

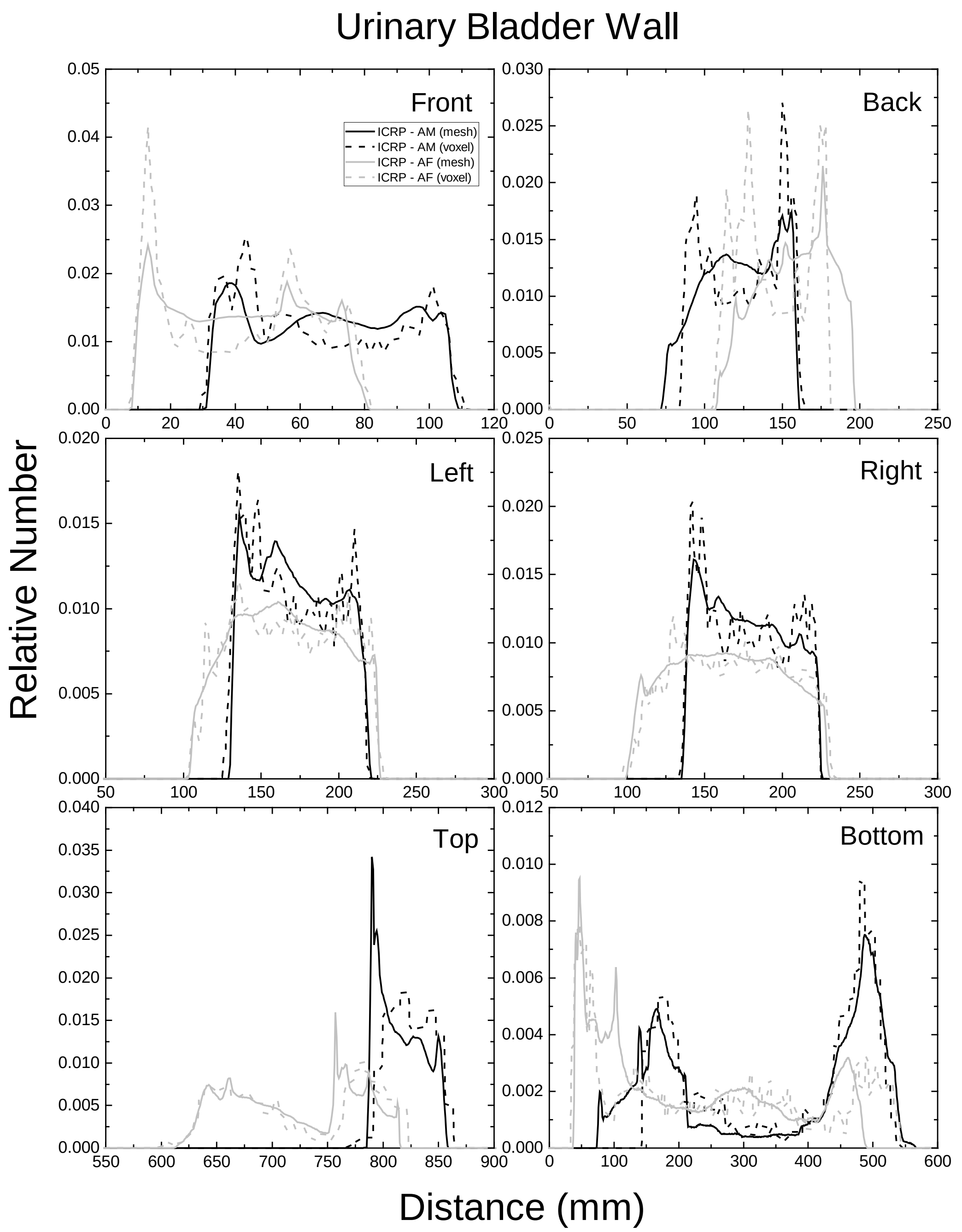


Fig. E.7. Distribution of depths of 10 million randomly sampled points in the urinary bladder wall below the body surfaces at: front, back, left, right, top and bottom.

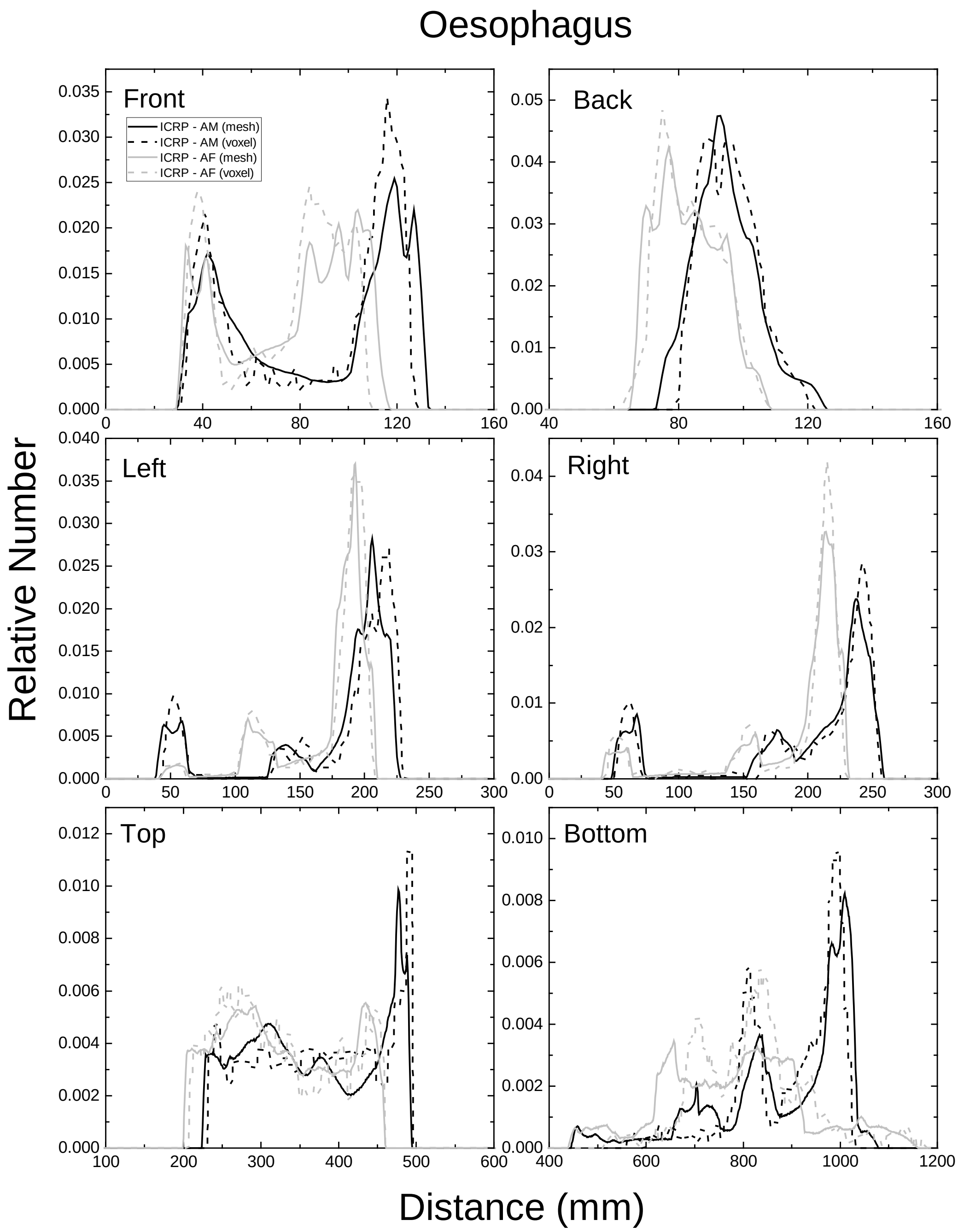


Fig. E.8. Distribution of depths of 10 million randomly sampled points in the oesophagus below the body surfaces at: front, back, left, right, top and bottom.

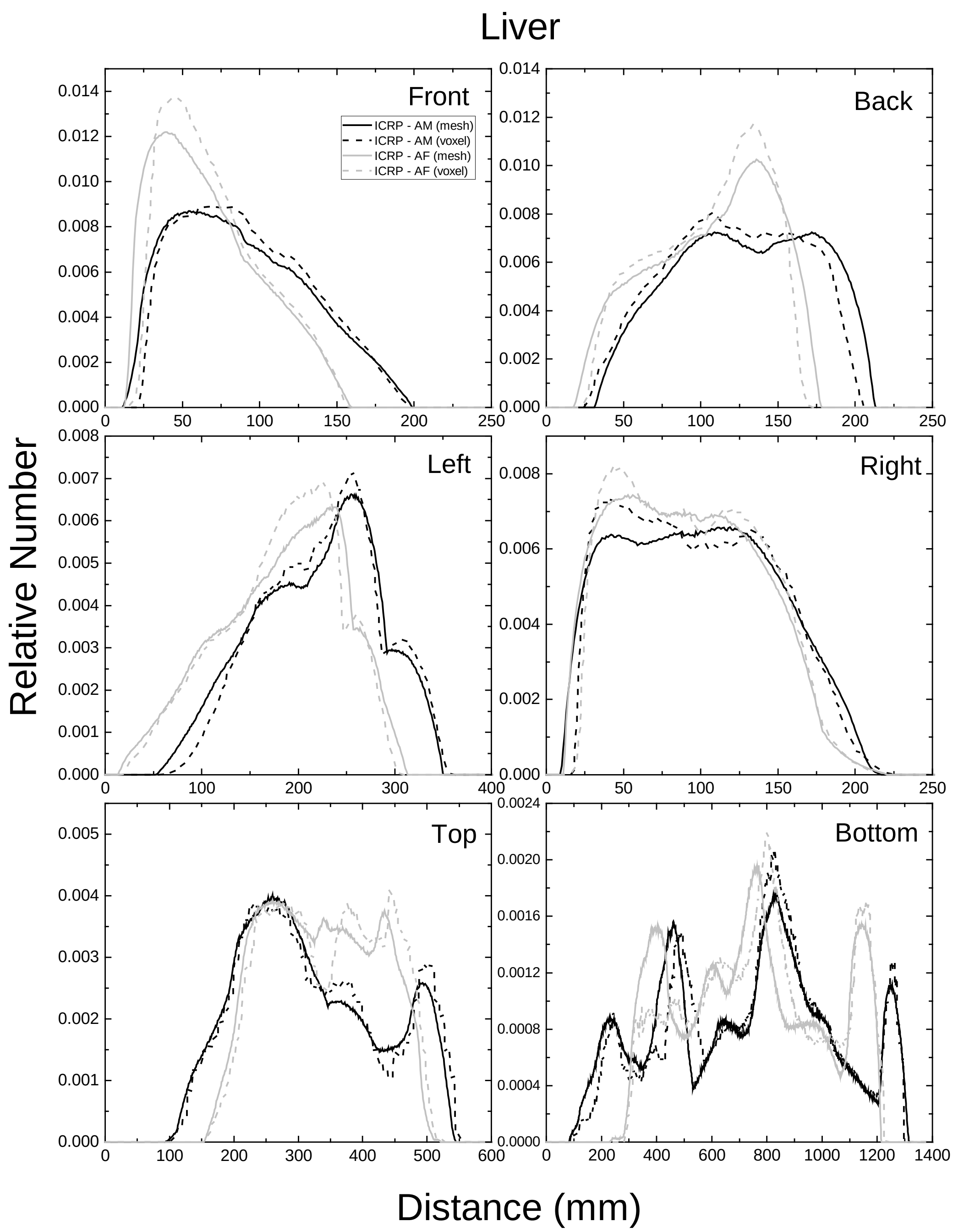
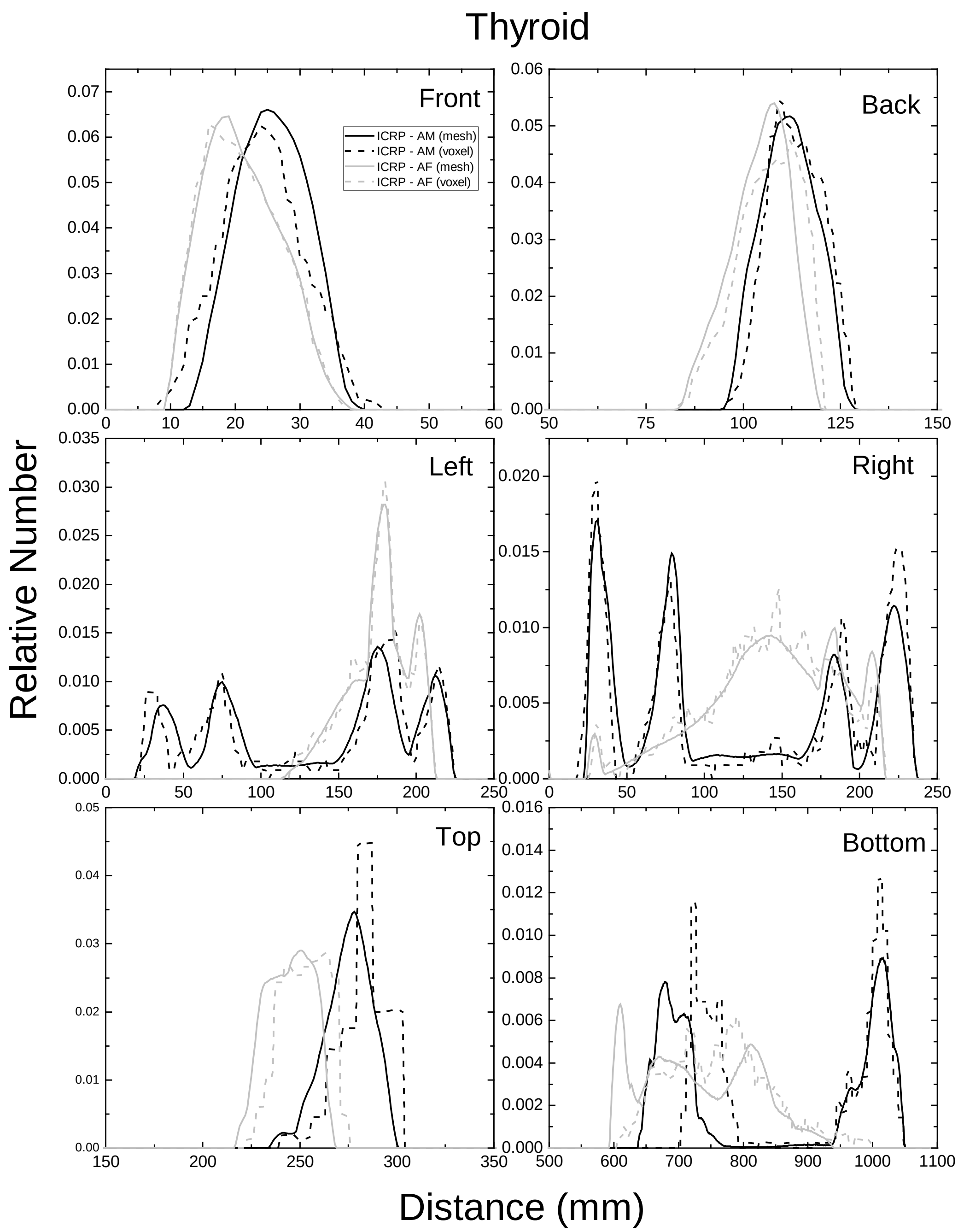


Fig. E.9. Distribution of depths of 10 million randomly sampled points in the liver below the body surfaces at: front, back, left, right, top and bottom.



1754
1755 Fig. E.10. Distribution of depths of 10 million randomly sampled points in the thyroid below the body
1756 surfaces at: front, back, left, right, top and bottom.
1757

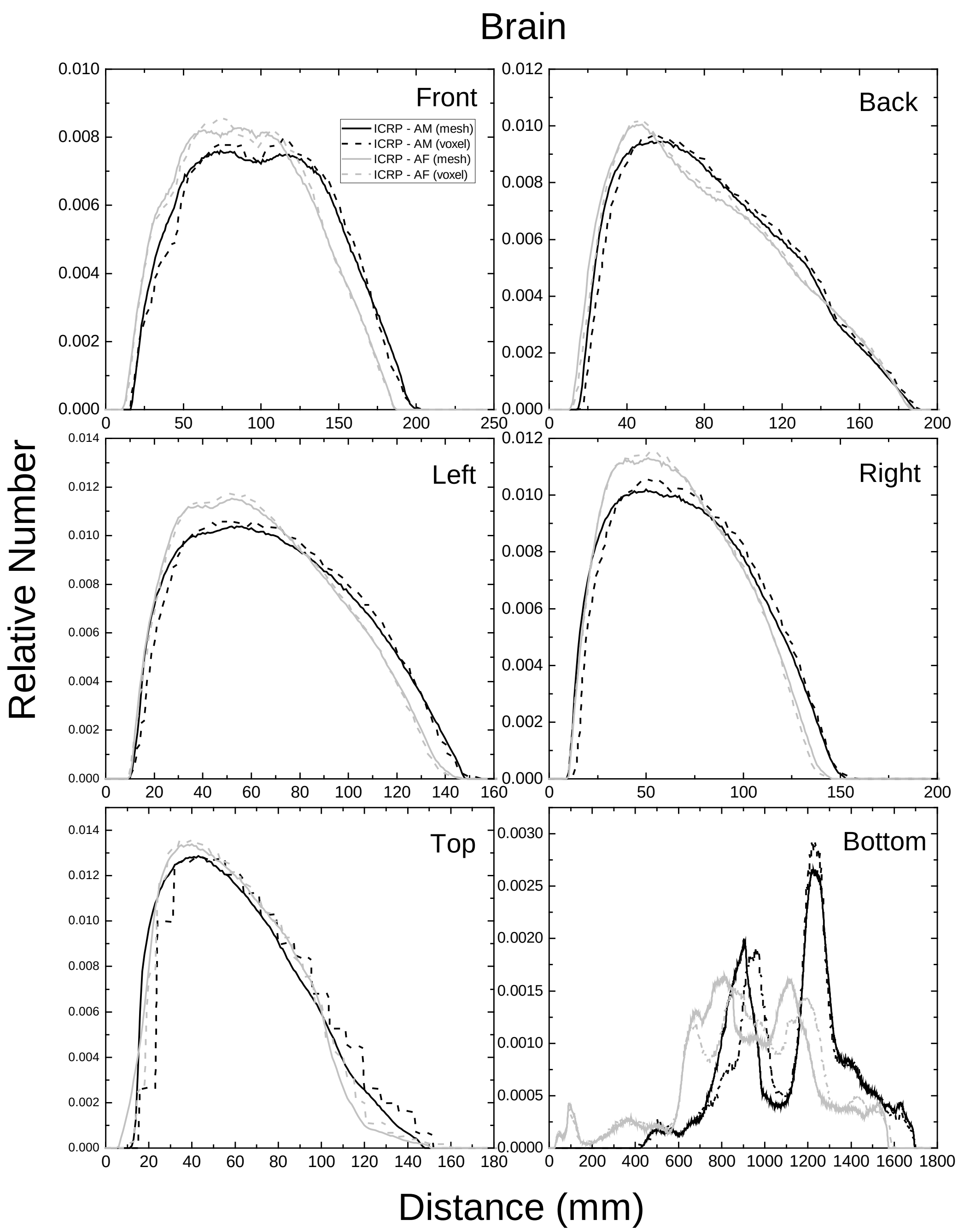
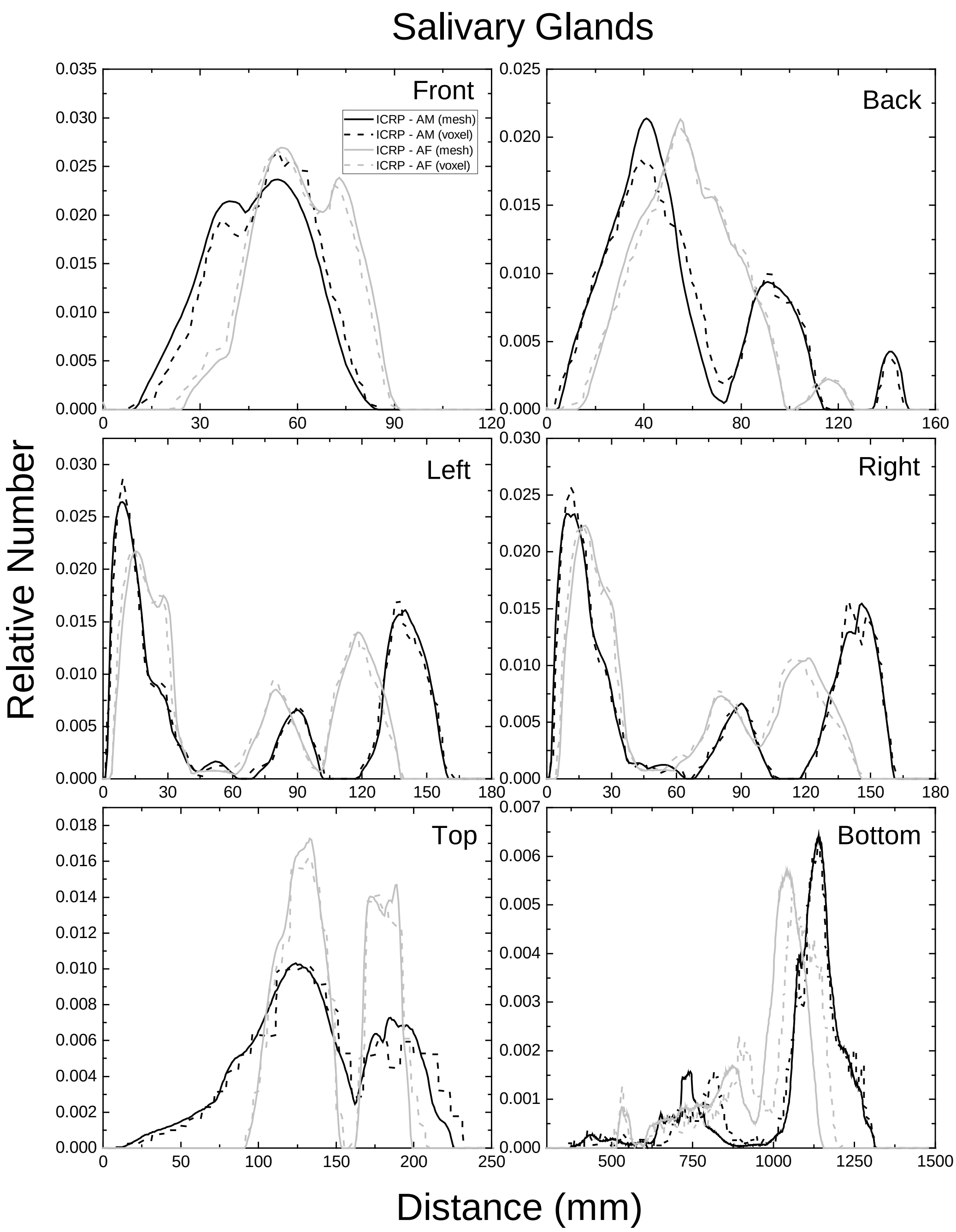


Fig. E.11. Distribution of depths of 10 million randomly sampled points in the brain below the body surfaces at: front, back, left, right, top and bottom.



1763
1764 Fig. E.12. Distribution of depths of 10 million randomly sampled points in the salivary glands below
1765 the body surfaces at: front, back, left, right, top and bottom.
1766
1767

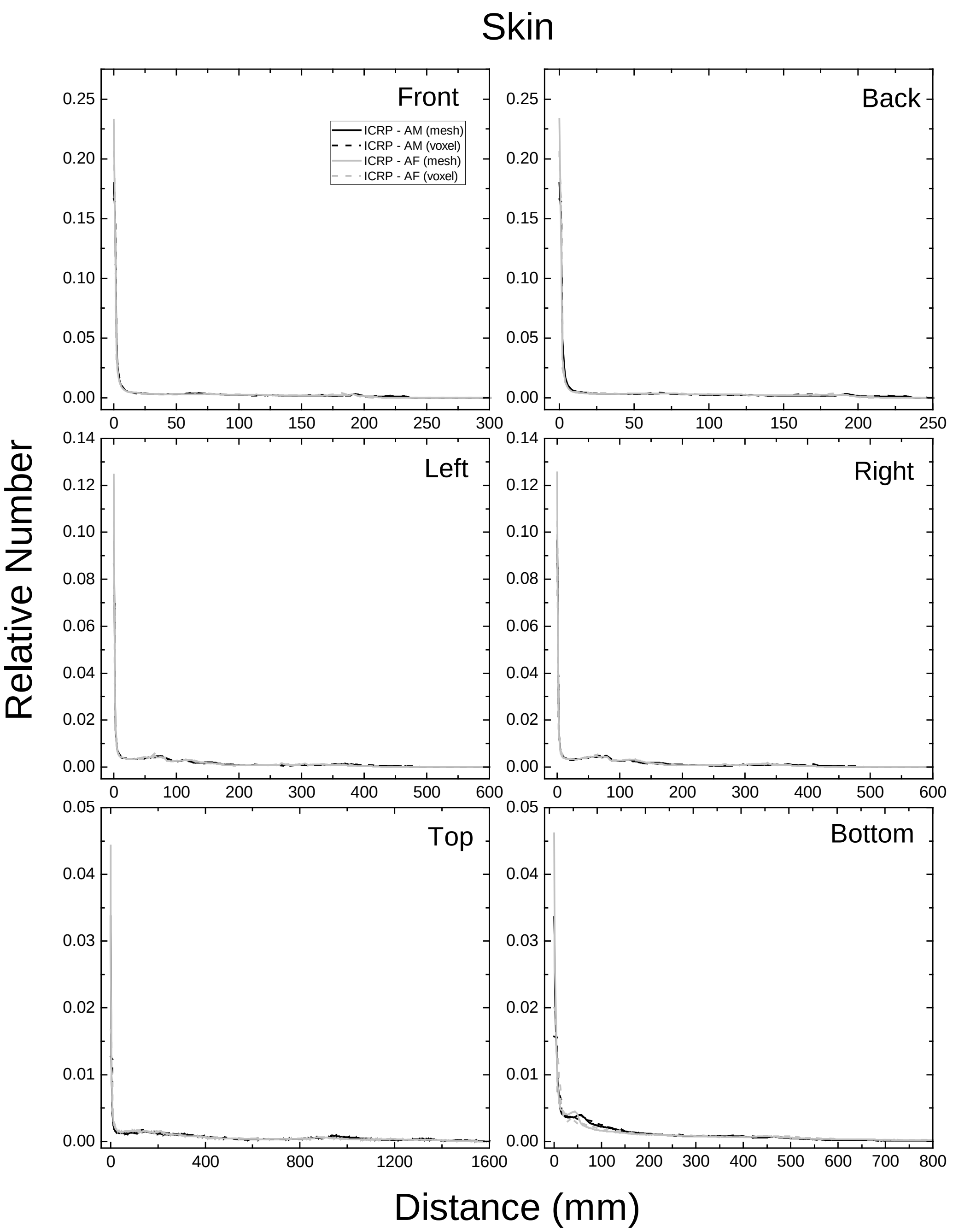


Fig. E.13. Distribution of depths of 10 million randomly sampled points in the skin below the body surfaces at: front, back, left, right, top and bottom.

ANNEX F. CHORD-LENGTH DISTRIBUTIONS BETWEEN SELECTED ORGAN PAIRS (SOURCE/TARGET TISSUES)

(F1) In Figs. F.1–F.5, chord-length distributions (CLDs) of the adult mesh-type reference computational phantoms and the *Publication 110* phantoms are shown for the selected organ/tissue pairs (i.e. source/target regions): source regions (cortical bone, liver, lungs, thyroid and urinary bladder contents); target regions (spongiosa, colon wall, lungs, stomach wall, breasts, gonads, urinary bladder wall, oesophagus, liver, thyroid, brain and salivary glands). For the CLD calculation, ten million point pairs were randomly sampled in the target and source regions considered, and distances of the points pairs were calculated. The CLDs represent a distance between the target and source regions, significantly influencing dose calculation for internal exposure.

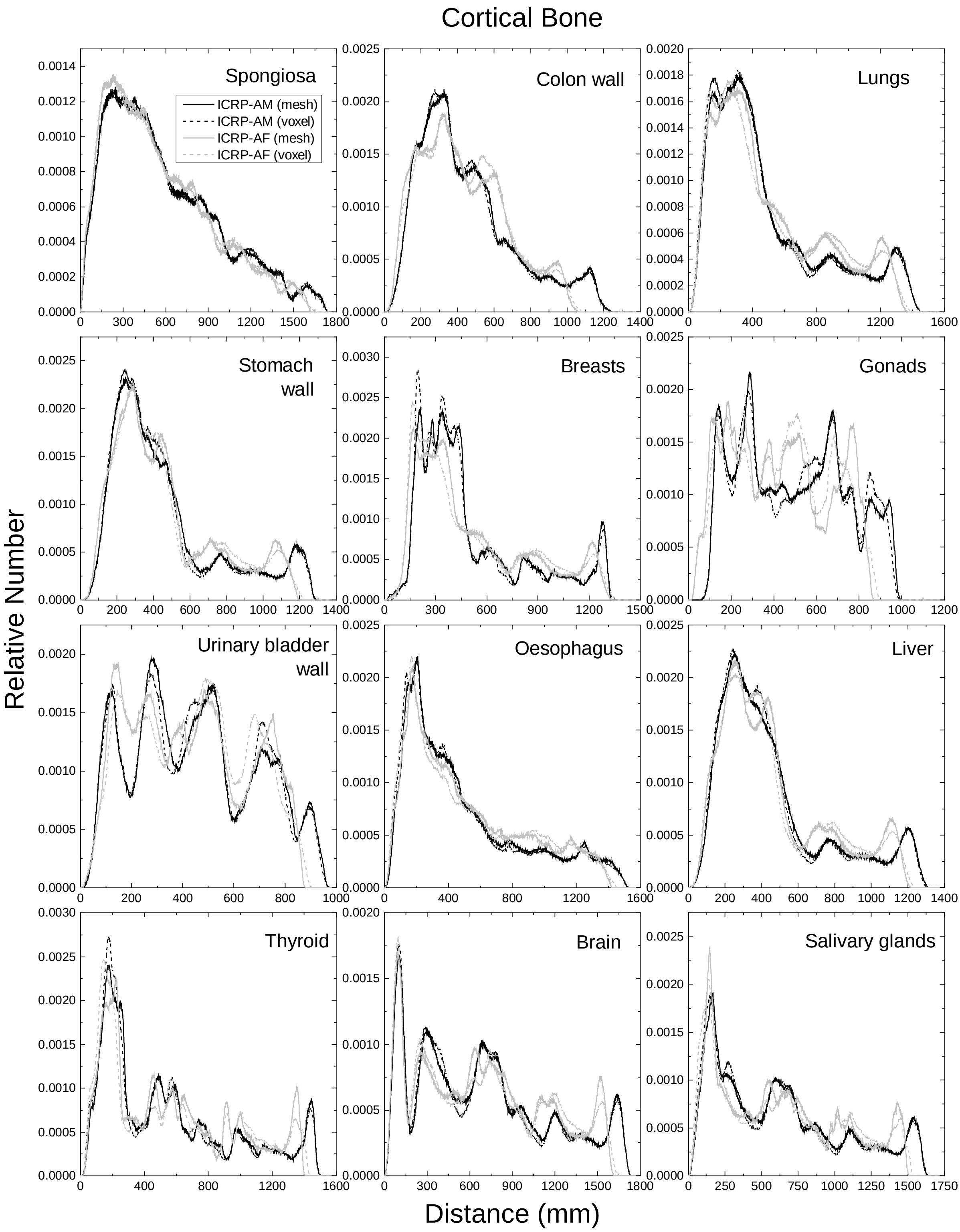


Fig. F.1. Distribution of distances between 10 million randomly sampled point pairs in the cortical bone (a source region and the spongiosa, colon wall, lungs, stomach wall, breasts, gonads, urinary bladder wall, oesophagus, liver, thyroid, brain and salivary glands (target regions).

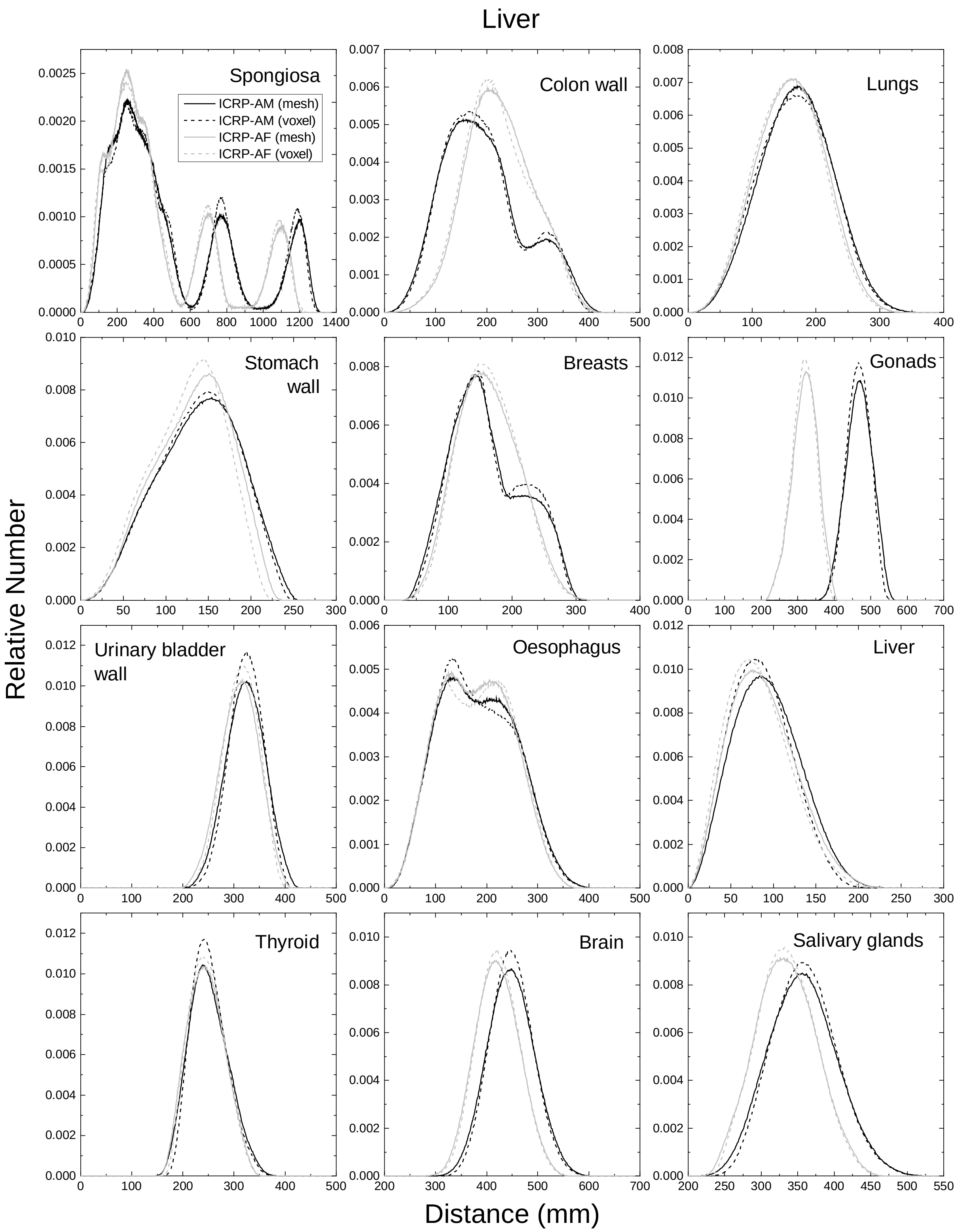


Fig. F.2. Distribution of distances between 10 million randomly sampled point pairs in the liver (a source region) and the spongiosa, colon wall, lungs, stomach wall, breasts, gonads, urinary bladder wall, oesophagus, liver, thyroid, brain and salivary glands (target regions).

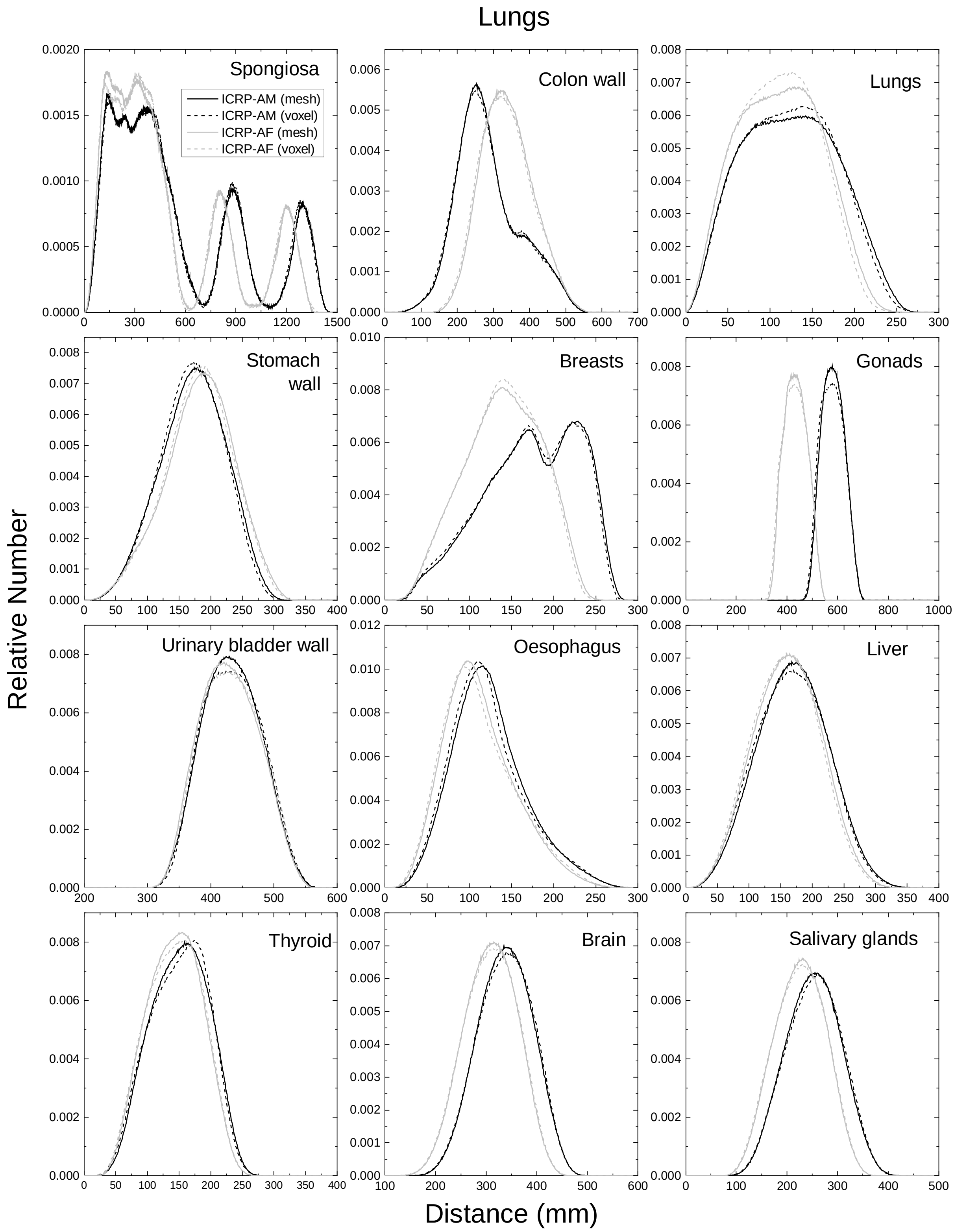


Fig. F.3. Distribution of distances between 10 million randomly sampled point pairs in the lungs (a source region) and the spongiosa, colon wall, lungs, stomach wall, breasts, gonads, urinary bladder wall, oesophagus, liver, thyroid, brain and salivary glands (target regions).

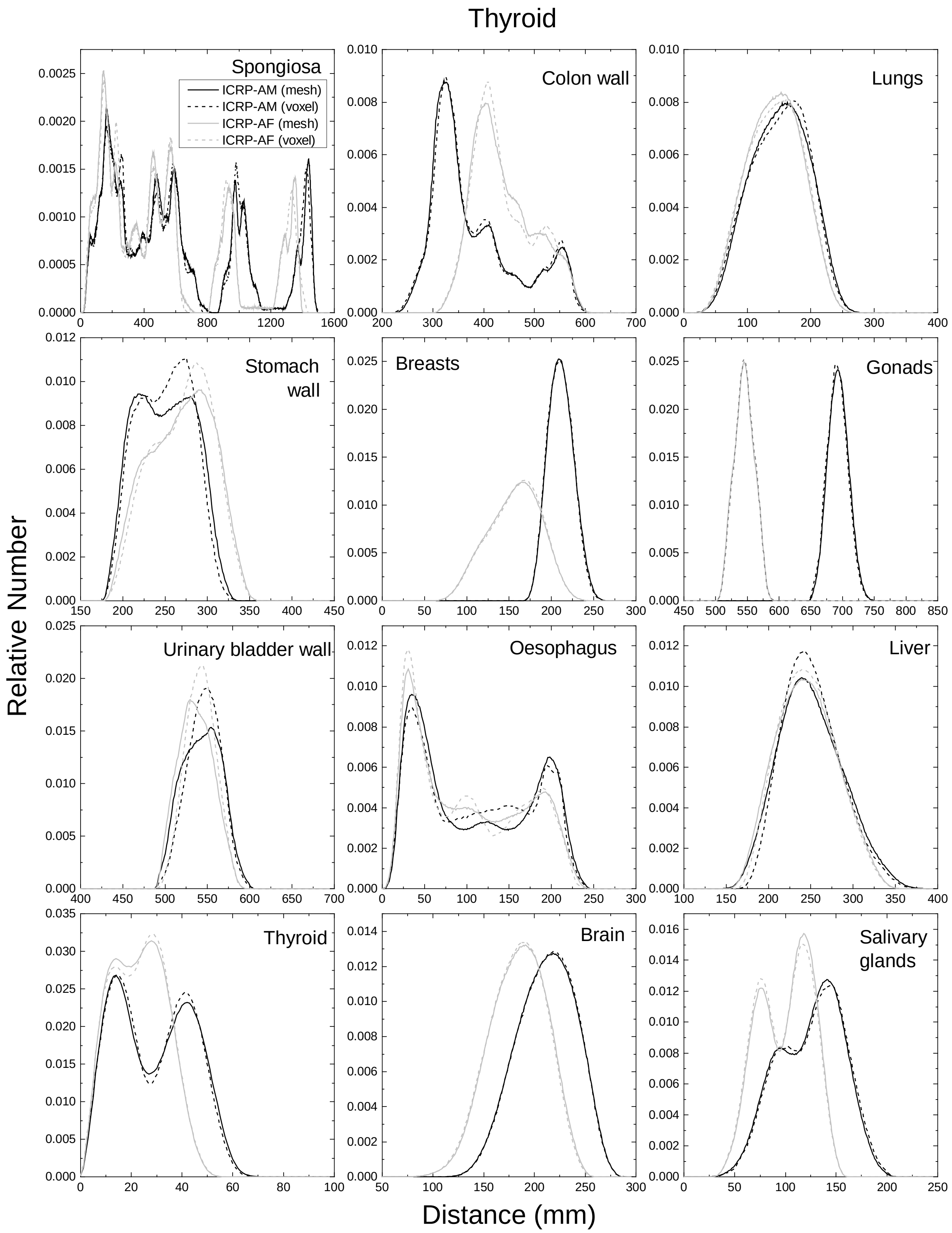


Fig. F.4. Distribution of distances between 10 million randomly sampled point pairs in the thyroid (a source region) and the spongiosa, colon wall, lungs, stomach wall, breasts, gonads, urinary bladder wall, oesophagus, liver, thyroid, brain and salivary glands (target regions).

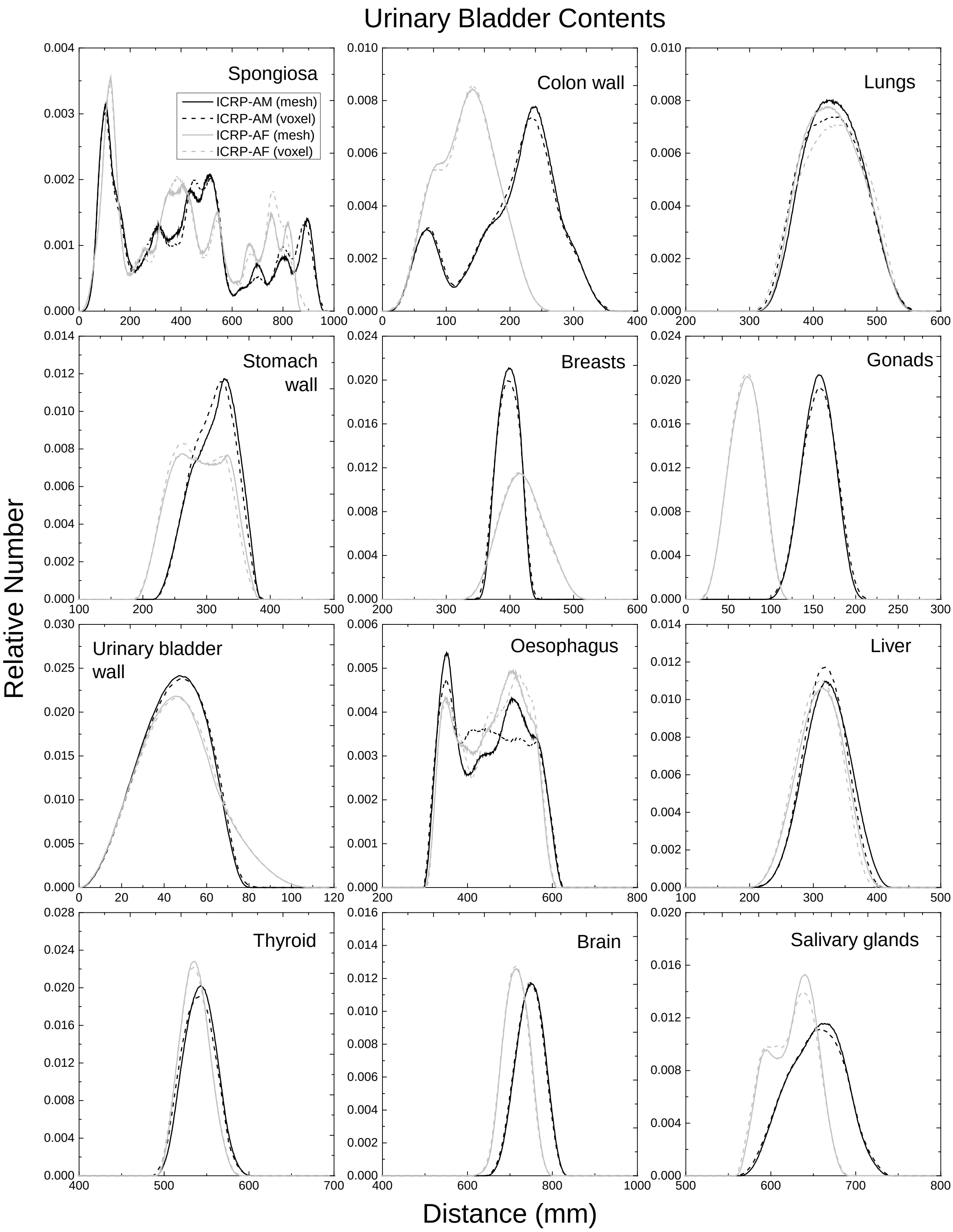
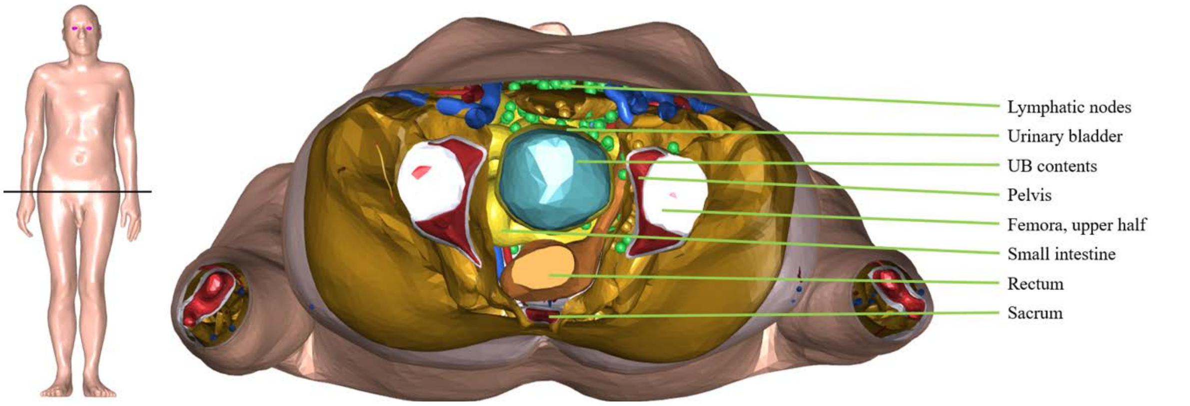


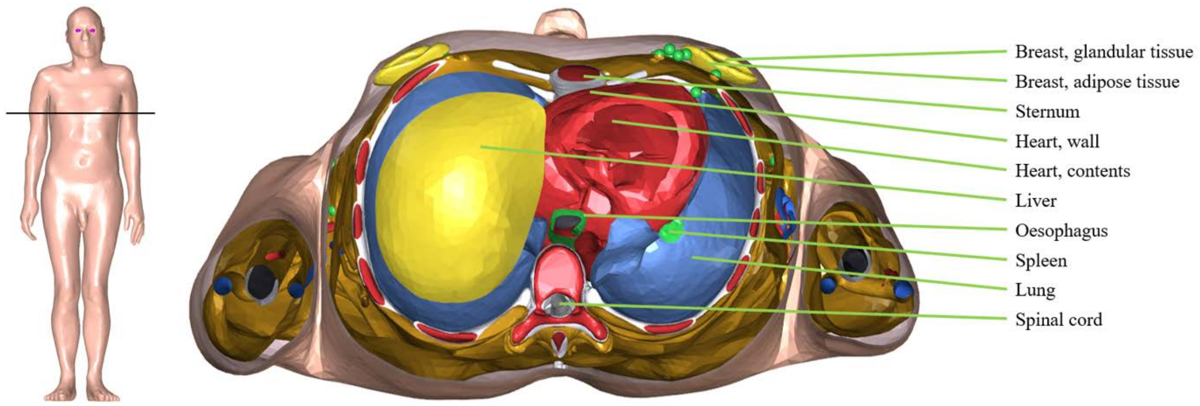
Fig. F.5. Distribution of distances between 10 million randomly sampled point pairs in the urinary bladder contents (a source region) and the spongiosa, colon wall, lungs, stomach wall, breasts, gonads, urinary bladder wall, oesophagus, liver, thyroid, brain and salivary glands (target regions)

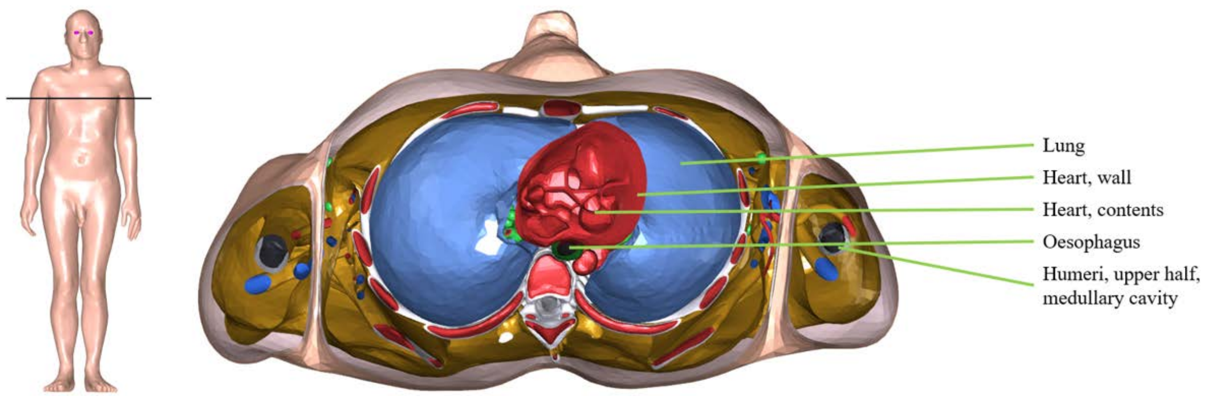
ANNEX G. CROSS-SECTIONAL IMAGES

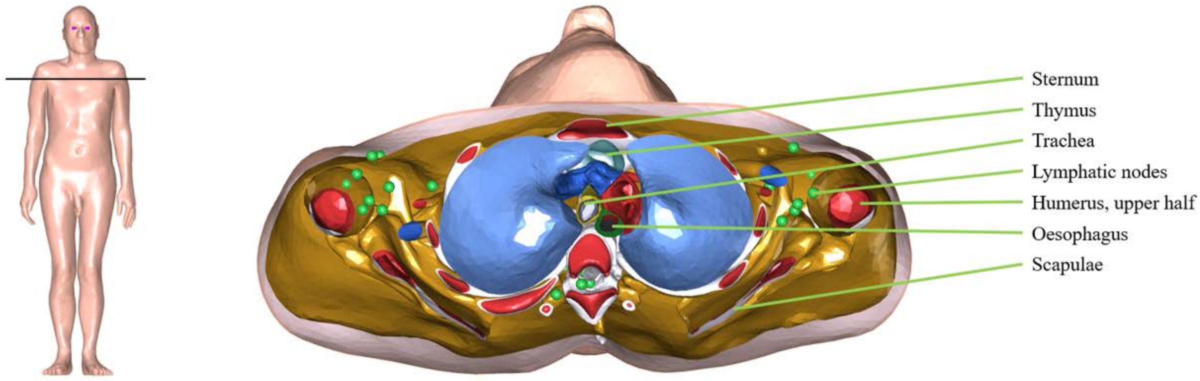
G.1. Images of the adult mesh-type reference computation phantom for male

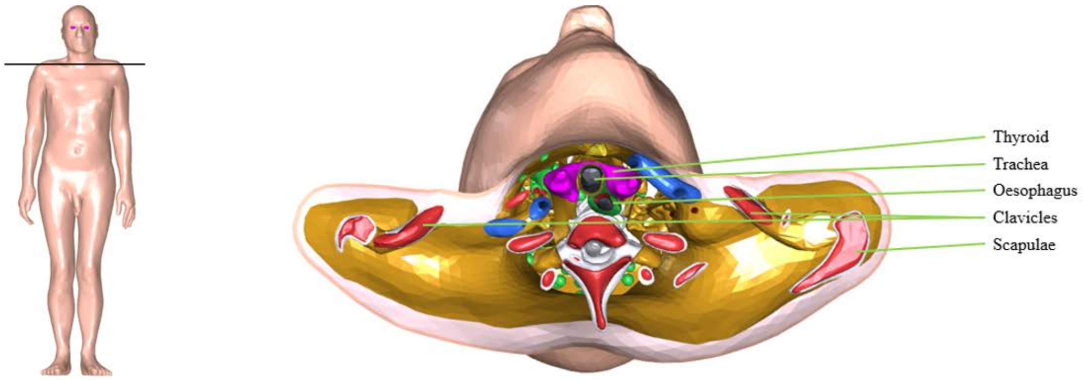
G.1.1. Transverse (axial) images

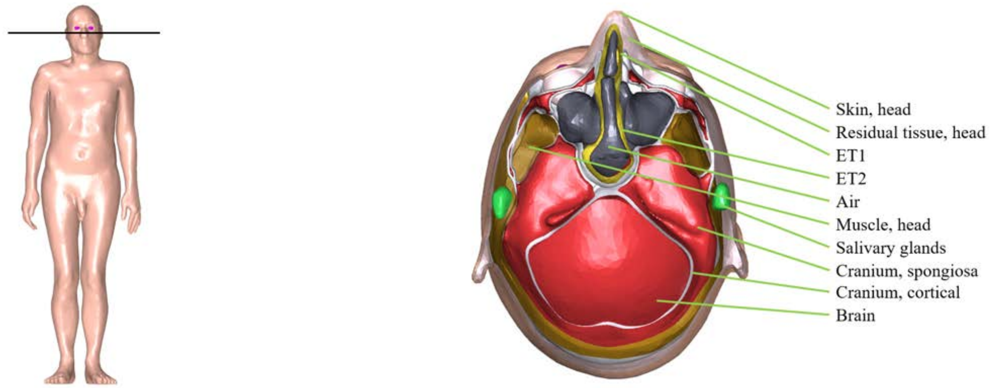




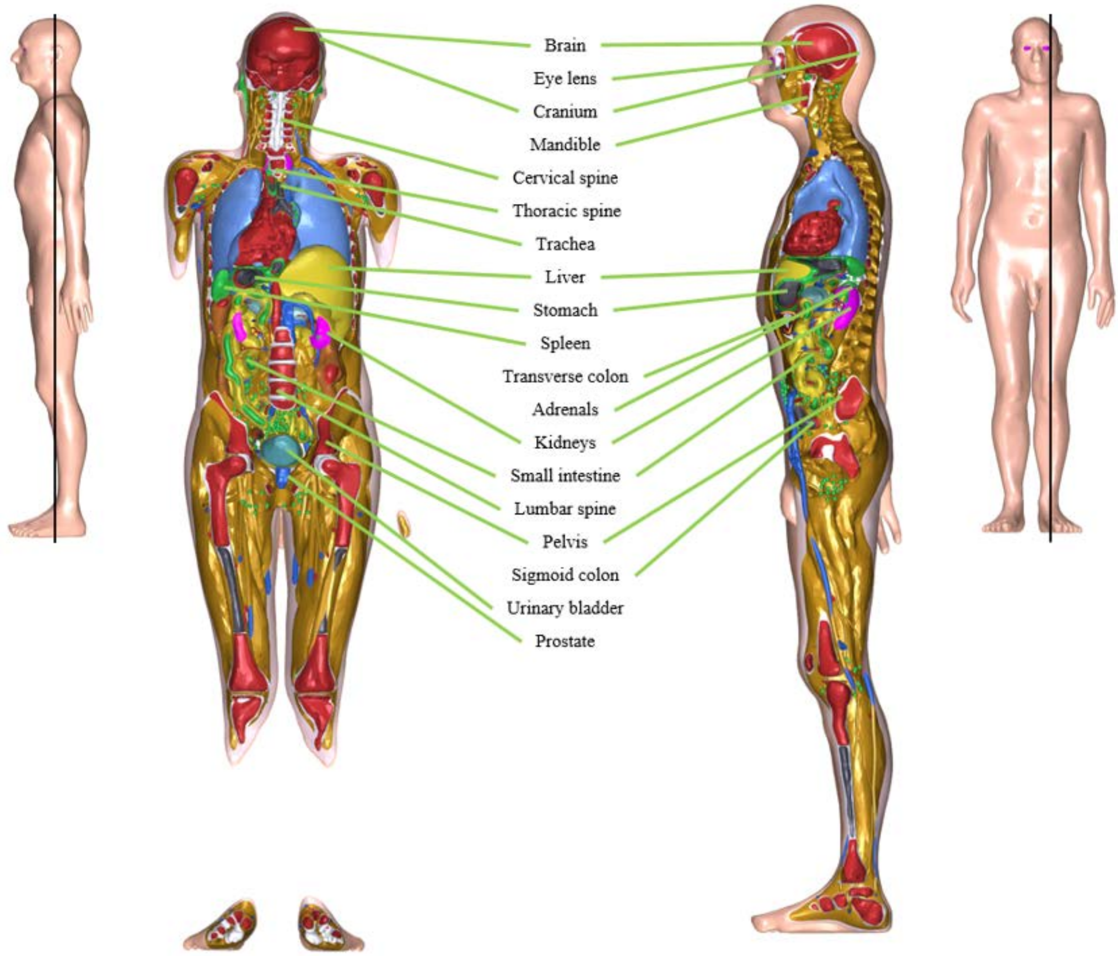



Sternum
Thymus
Trachea
Lymphatic nodes
Humerus, upper half
Oesophagus
Scapulae


Thyroid
Trachea
Oesophagus
Clavicles
Scapulae

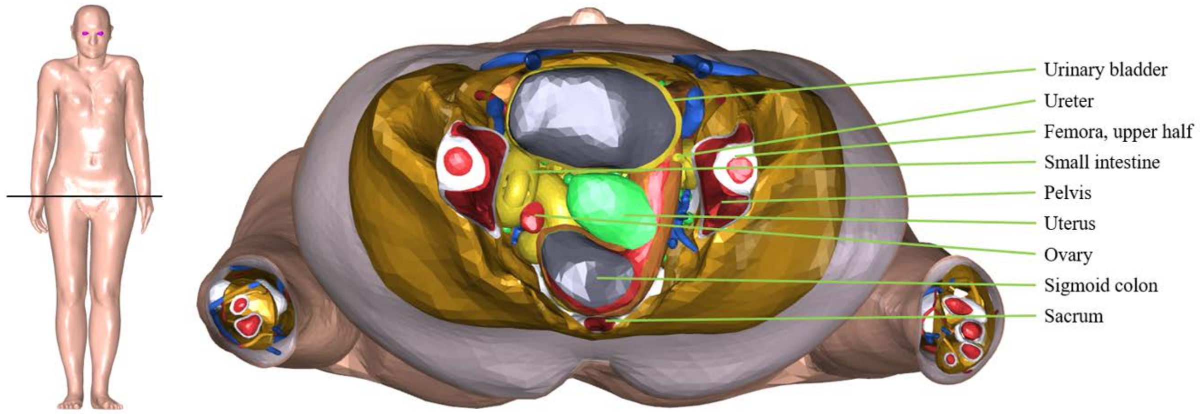

Skin, head
Residual tissue, head
ET1
ET2
Air
Muscle, head
Salivary glands
Cranium, spongiosa
Cranium, cortical
Brain

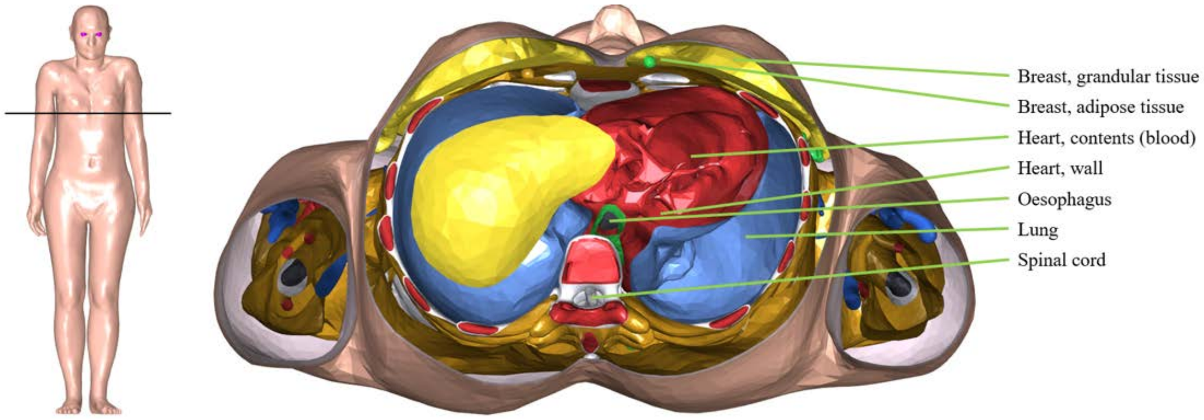
G.1.2. Coronal and sagittal images

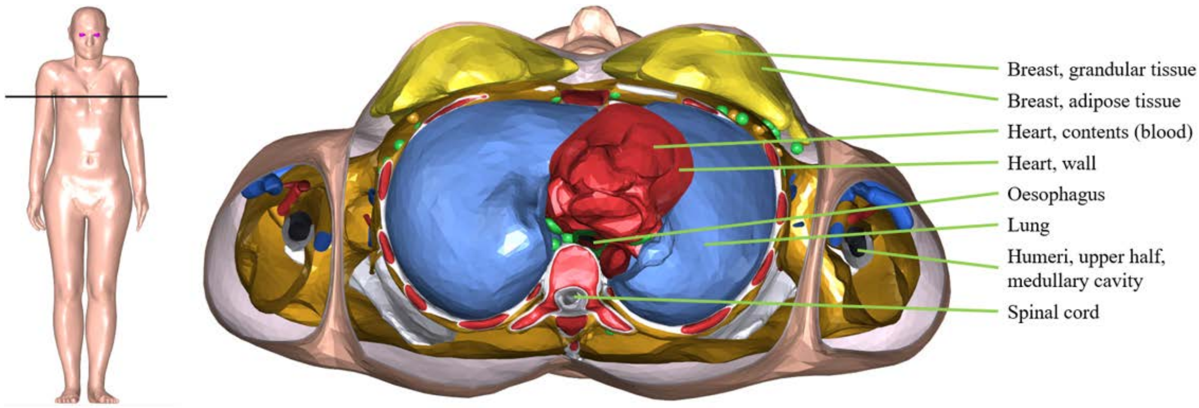


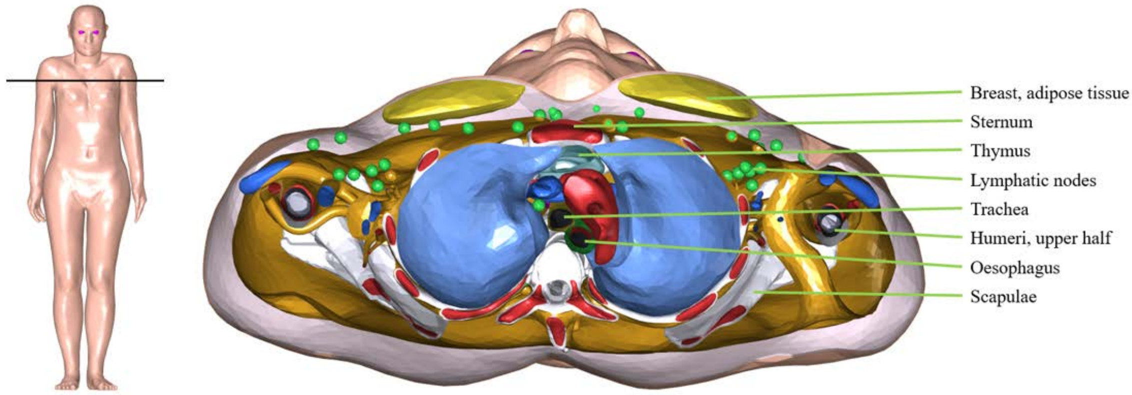
G.2. Images of the adult mesh-type reference computational phantom for female

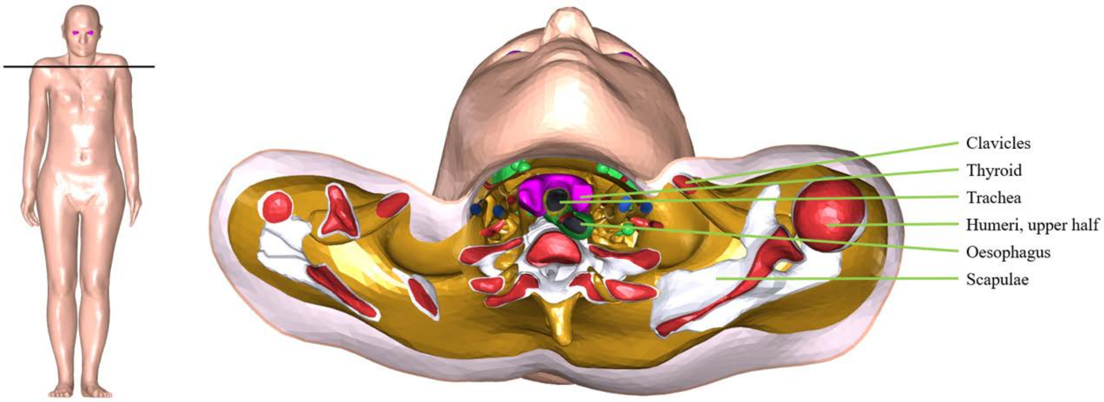
G.2.1. Transverse (axial) images

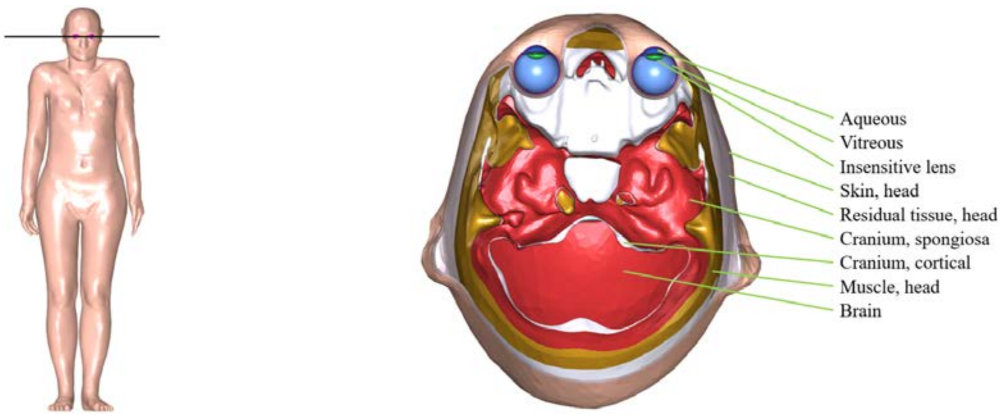




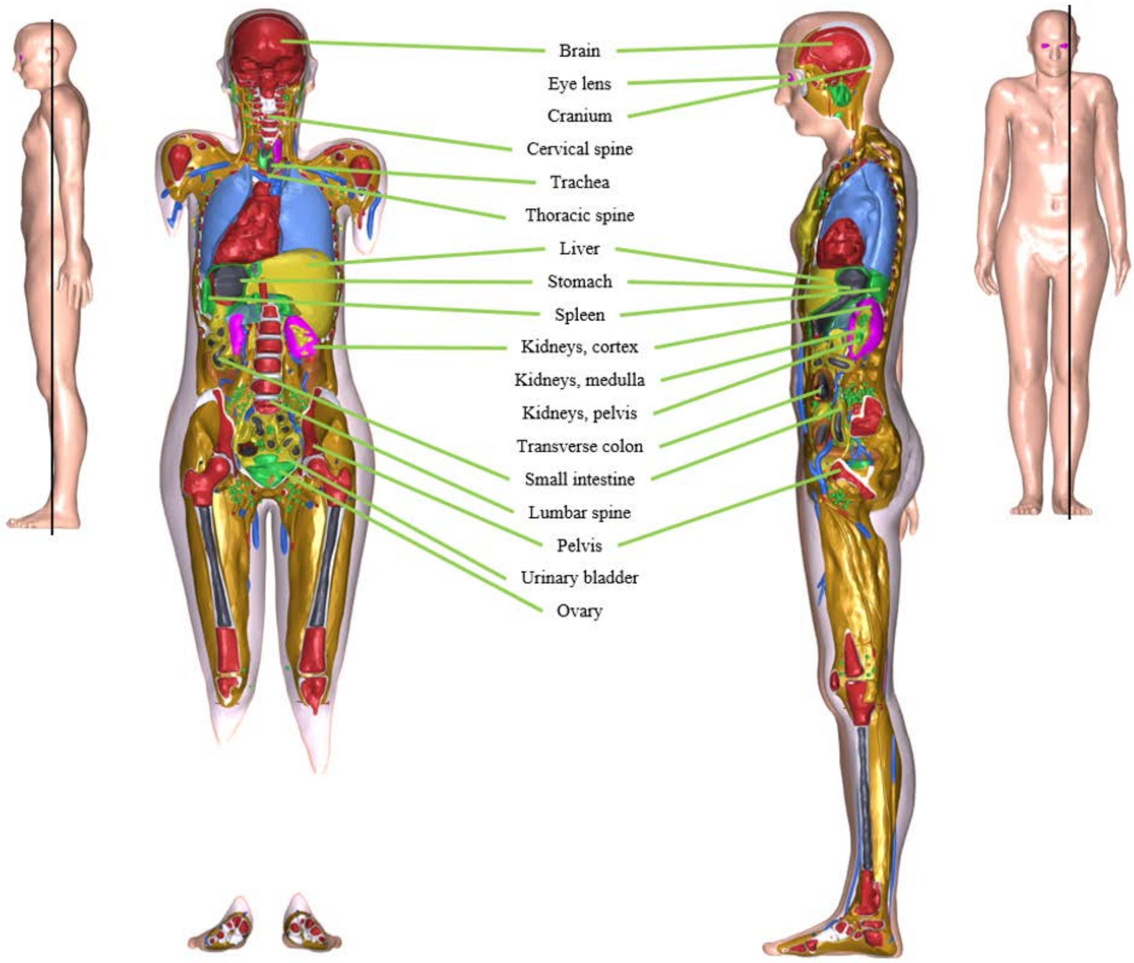



Breast, adipose tissue
Sternum
Thymus
Lymphatic nodes
Trachea
Humeri, upper half
Oesophagus
Scapulae


Clavicles
Thyroid
Trachea
Humeri, upper half
Oesophagus
Scapulae


Aqueous
Vitreous
Insensitive lens
Skin, head
Residual tissue, head
Cranium, spongiosa
Cranium, cortical
Muscle, head
Brain

1867 ### G.2.2. Coronal and sagittal images



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ANNEX H. COMPARISON OF DOSE COEFFICIENTS FOR EXTERNAL EXPOSURE

(H1) In order to investigate the impact of the improved morphology of the adult mesh-type reference computational phantoms (MRCPs) on the calculation of dose coefficients (DCs) for external exposures, the DCs for effective dose in terms of effective dose per fluence (pSv cm^2) were calculated using the MRCPs and subsequently compared with the reference values given in *Publication 116* that were produced with the *Publication 110* (ICRP, 2009) phantoms. For these calculations, a broad parallel beam of photons, neutrons, electrons and helium ions was assumed to be incident to the phantoms in the same irradiation geometries as considered in *Publication 116* (ICRP, 2010). Three Monte Carlo simulation codes, i.e. Geant4 (ver. 10.02), PHITS (ver. 2.92) and MCNP6 (ver. 2.0 prerelease), were used in the calculations. The Geant4 code was used for all of the energy points considered for the comparison, while the PHITS and MCNP6 codes were used only for some energy points for spot-check purposes. In order to facilitate the analysis, the effective dose DCs were also calculated using the *Publication 110* phantoms and the Geant4 code. For the Geant4 code, the physics libraries of *G4EmLivermorePhysics* and the *FTFP_BERT_HP* were used to transport all particles (Geant4 Physics Reference Manual). In addition, the thermal neutron scattering treatment S(α, β) for hydrogen (H) in light water at 300 K was applied for accurate transport of thermal neutrons. A range of 1 µm for the secondary production cut was applied to all of the particles. For both the PHITS and MCNP6 codes, the default physics models and cross-section data were used to transport all of the particles, and the thermal neutron scattering treatment was also applied. For the MCNP6 code, the default cut energies were used, which were also applied to set cut energies for the PHITS code. Note that absorbed doses to the skeletal target tissues (red bone marrow and endosteum) were taken as the mass-weighted average of the regional spongiosa and medullary cavity doses following the same approach used in *Publication 116* (ICRP, 2010).

H.1. Uncharged particles

(H2) Prior to the comparison of the effective dose DCs, the organ DCs in terms of organ-averaged absorbed dose per fluence (pGy cm^2) were compared with the *Publication 116* values for some selected organs (red bone marrow, colon, lungs, stomach, breasts and skin). The selected organs have the highest tissue-weighting factor (0.12) except for the skin which was selected in order to investigate the effect of the 50-µm-thick skin target layer of the MRCPs in skin dose calculation.

(H3) Figures H.1 and H.2 present the calculated organ DCs for uncharged particles (i.e. photons and neutrons, respectively) for the anterior-posterior (AP) irradiation geometry, along with the *Publication 116* values and DC values calculated with the *Publication 110* phantoms and the Geant4 code. For all of the calculated organ DCs shown in these figures, the statistical error is less than 5%.

(H4) For photons, it can be seen that with some exceptions at the lowest energy (0.01 MeV), the organ DCs of the MRCPs were very close to both the *Publication 116* values and the DC values calculated using the *Publication 110* phantoms and the Geant4 code. The differences were generally less than 2%. For the 0.01 MeV photons, larger differences were found and the results show that the differences are mainly due to the difference in the geometry or material composition of the phantoms. It can also be seen that the female values show relatively less difference than the male values, which seems due to the fact that the *Publication 110* female phantom has higher voxel resolution (1.775 × 1.775 × 4.8 mm^3) than the male phantom (2.137 × 2.137 × 8 mm^3).

(H5) Relatively large differences can be seen in the skin DCs over the entire energy range, which is due mainly to the consideration of the 50-µm-thick skin target layer in the MRCPs. Note that the 50-µm-thick skin target layer is explicitly modelled and used in the MRCPs, while the entire skin is used in the *Publication 110* phantoms. For the energies < 0.03 MeV, the skin DCs of the MRCPs are greater than the *Publication 110* values, e.g. by a factor of ~2 at 0.01 MeV. This difference is due to the fact that the low-energy photons establish the maximum dose very close to the 50-µm-thick skin target layer and that then, the dose rapidly decreases with depth within the skin by attenuation. On the other hand, for energies in the 0.2–10 MeV range, the skin DCs of the MRCPs are lower, e.g. by a factor of ~2 at 1 MeV. This reversal phenomenon is due to the fact that the high-energy photon beam establishes a dose build-up, resulting in the maximum dose at a depth much deeper than the depth of the 50-µm-thick skin target layer.

(H6) For neutrons, except for the skin DCs, the organ DCs of the MRCPs show relatively large differences from the *Publication 116* values, generally less than 20%, but are very close to the DC values calculated using the *Publication 110* phantoms and the Geant4 code, the differences being less than 5% for most cases. These results indicate that for neutrons, the differences from the *Publication 116* values are not mainly due to the difference in phantom geometry or material composition, but due to the difference in the Monte Carlo codes or cross section data / physics models used in the calculations. Note that the DCs of the MRCPs were calculated using the Geant4 code, but that the *Publication 116* values were calculated by using four different codes (MCNPX, PHITS, FLUKA and Geant4) for neutrons and then the calculated values were averaged and went through a smoothing process (ICRP, 2010). As expected, for the skin DCs, the DCs of the MRCPs tend to deviate from both the *Publication 116* values and the DCs calculated with the *Publication 110* phantoms and the Geant4 code, due mainly to the consideration of the 50-µm-thick skin target layer in the MRCPs.

(H7) Figures H.3 and H.4 present the effective dose DCs for the AP, PA, LL, RL, ROT and ISO irradiation geometries calculated with the MRCPs, along with the *Publication 116* values and DCs calculated with the *Publication 110* phantoms and Geant4 code. For all of the calculated effective dose DCs shown in these figures, the statistical error is less than 0.5%. It can be seen that for photons and neutrons, the effective dose DCs of the MRCPs are very close to both the *Publication 116* values and the DC values calculated with the *Publication 110* phantoms and the Geant4 code. For photons, with some exceptions at low energies (< 0.03 MeV), the differences are less than 2%. This result indicates that the relatively large differences of the skin DCs due to the consideration of the 50-µm-thick skin target layer in the MRCPs do not significantly affect the effective dose DCs for photons; this is because the doses of the other organs/tissues are more important than that of the skin, which has a small tissue-weighting factor (w_T = 0.01). For neutrons, the differences from the *Publication 116* values are less than 10% for most cases, but the differences from the values calculated with the *Publication 110* phantoms and the Geant4 code are much smaller (< 2% for most cases). These slightly larger differences from the *Publication 116* values are again due mainly to the different Monte Carlo codes or cross-section data / physics models used in the calculations, not to differences in phantom geometry or material composition.

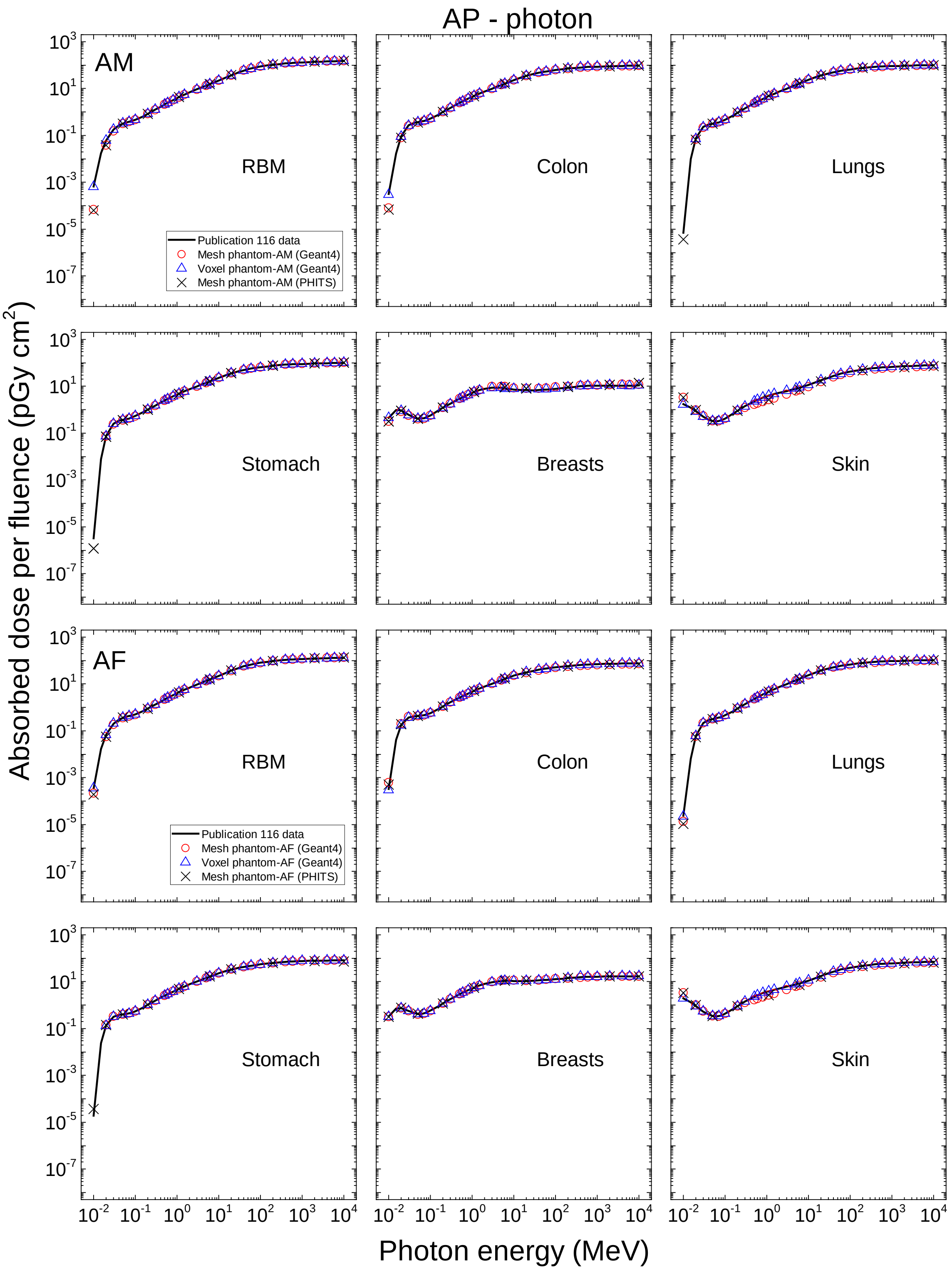


Fig. H.1. Absorbed dose per fluence (pGy cm^2) to the RBM, colon, lungs, stomach, breasts and skin in the anterior-posterior (AP) geometry for photon exposures calculated with the adult mesh-type reference phantoms (MRCPs), along with the *Publication 116* values (ICRP, 2010) and the values calculated with the *Publication 110* phantoms and the Geant4 code: adult male, AM (upper) and adult female, AF (lower).

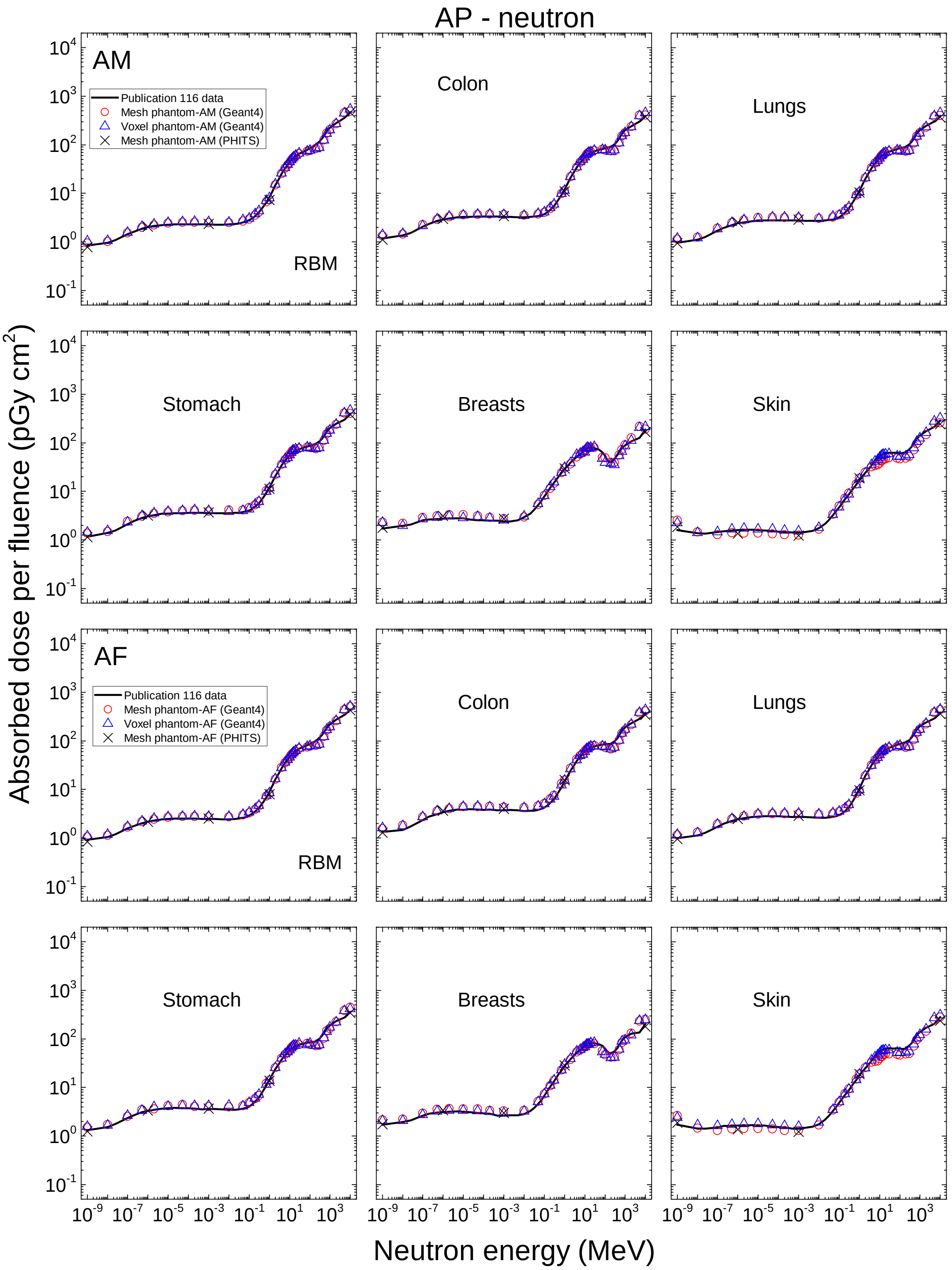


Fig. H.2. Absorbed dose per fluence (pGy cm^2) to the RBM, colon, lungs, stomach, breasts and skin in the AP geometry for neutron exposures calculated with the adult mesh-type reference phantoms (MRCPs), along with the *Publication 116* values (ICRP, 2010) and the values calculated with the *Publication 110* phantoms and the Geant4 code: adult male, AM (upper) and adult female, AF (lower).

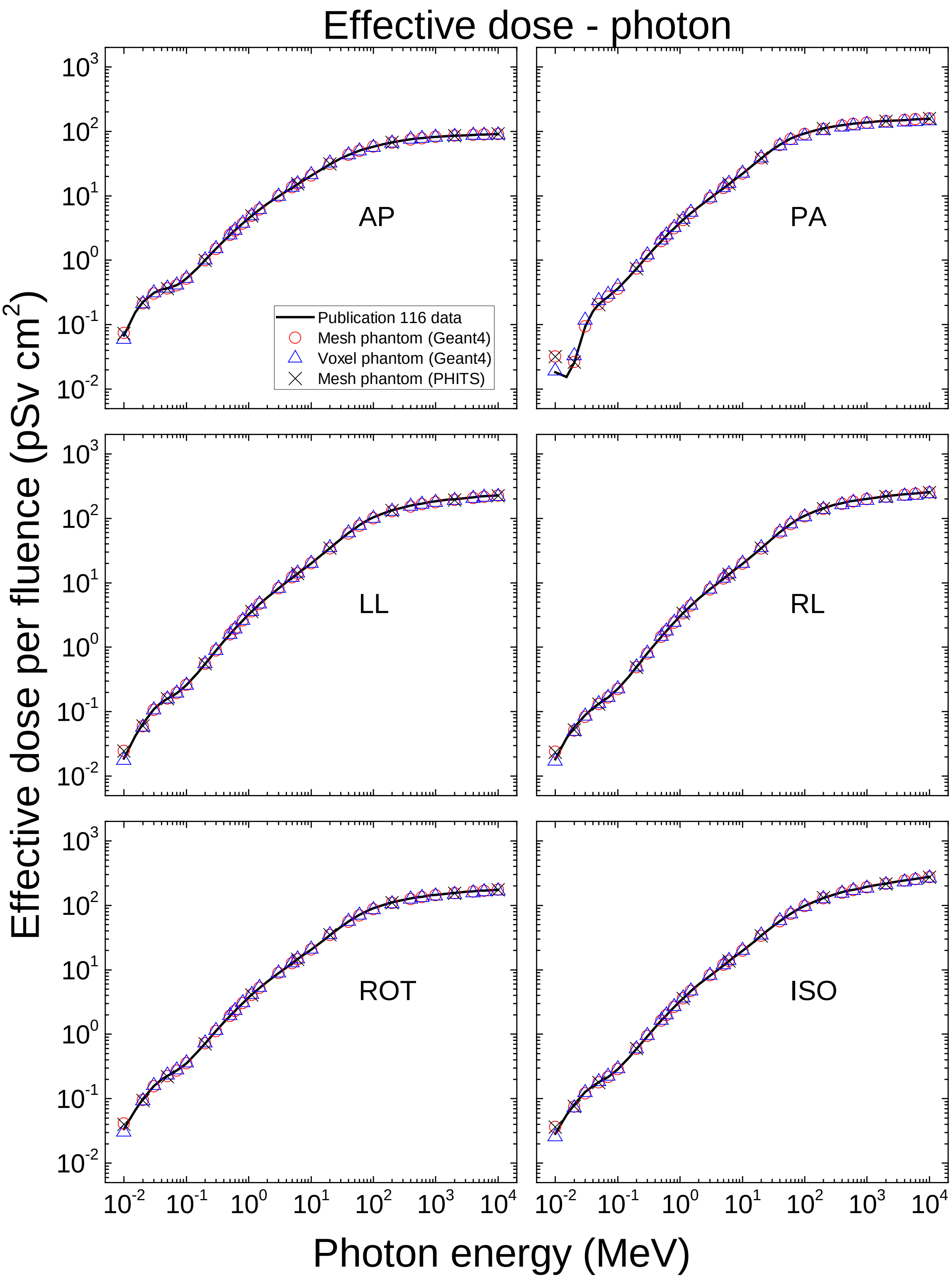


Fig. H.3. Effective dose per fluence (pSv cm^2) for photon exposures calculated with the adult mesh-type reference phantoms (MRCPs), along with the *Publication 116* values (ICRP, 2010) and the values calculated with the *Publication 110* phantoms and the Geant4 code.

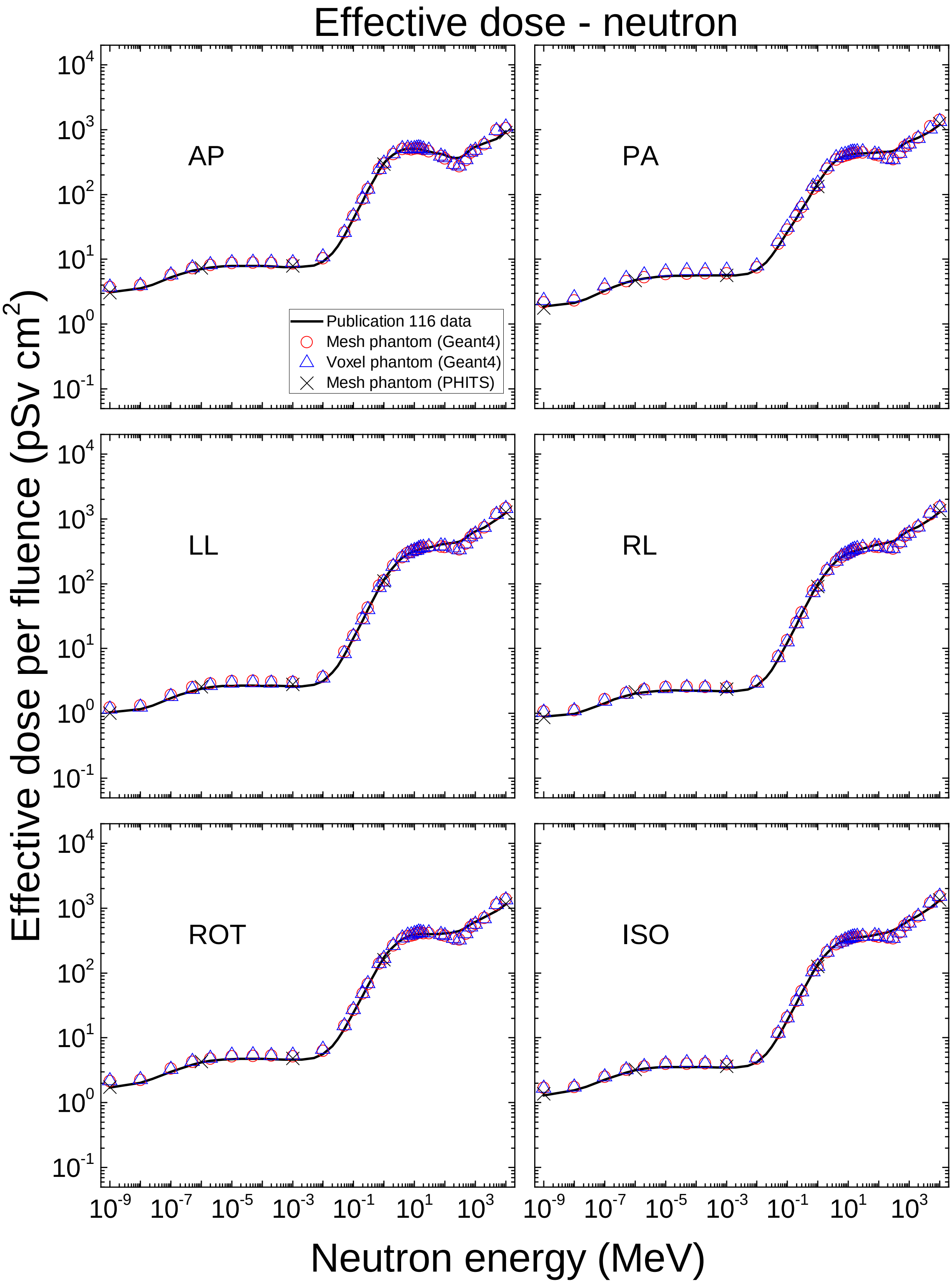


Fig. H.4. Effective dose per fluence (pSv cm^2) for neutron exposures calculated with the adult mesh-type reference phantoms (MRCPs), along with the *Publication 116* values (ICRP, 2010) and the values calculated with the *Publication 110* phantoms and the Geant4 code.

H.2. Charged particles

(H8) Figures H.5–H.6 present the calculated organ DCs for charged particles (i.e. electrons and helium ions) in terms of organ-averaged absorbed dose per fluence (pGy cm^2), along with the *Publication 116* values and DC values calculated with the *Publication 110* phantoms and Geant4 code for the selected organs (red bone marrow, colon, lungs, stomach, breasts and skin) in the ISO irradiation geometry. The statistical errors of the organ DCs presented in the figures are all less than 5%.

(H9) For electrons, it can be seen that the organ DCs of the MRCPs for the colon, lungs and stomach are not much different from the *Publication 116* values, whereas there are large differences in the DCs for the RBM, breasts and skin. The differences in the DCs for the RBM and breasts are due to the improvement in the MRCPs; that is, the skin and cortical bone of the MRCPs are continuous and fully cover the body and the spongiosa regions, respectively, whereas this is not the case in the *Publication 110* phantoms due to their finite voxel resolutions (see Figs. 6.4 and 6.5).

(H10) The skin DCs, when compared to the RBM and breast DCs, show larger differences, which is mainly due to the consideration of the 50-µm-thick skin target layer in the MRCPs. For electron energies < 0.08 MeV, the skin DCs of the MRCPs are much lower than the *Publication 116* values; this is due to the fact that for the MRCPs, the low-energy electrons cannot penetrate the dead layer of the skin and, therefore, only the bremsstrahlung photons contribute to the energy deposition in the thin target layer. For higher energies up to 1 MeV, on the other hand, the skin DCs of the MRCPs are greater, e.g. by a factor of ~13 at 0.1 MeV, which is due to the fact that the electrons penetrate the dead layer and establish the maximum dose within the thin target layer.

(H11) For helium ions, it can be seen that except for the skin, the organ DCs of the MRCPs are generally not much different from the *Publication 116* values. Relatively large differences are shown at very low energies, due mainly to the geometrical difference between the MRCPs and the *Publication 110* phantoms. The skin DCs for helium ions show larger differences, which is again due to the consideration of the 50-µm-thick skin target layer in the MRCPs. For the helium ions < 10 MeV/u, except for 1 MeV/u, the skin DCs of the MRCPs are significantly greater, e.g. by a factor of ~16 at 3 MeV/u, which is due to the establishment of the Bragg peak in the 50-µm-thick target layer. For 1 MeV/u (i.e. 4 MeV), the skin DCs of the MRCPs are essentially zero, whereas the *Publication 116* values show some significant values. Note that the 4-MeV helium ions do not penetrate the dead layer and deposit essentially their entire energy there, which fact is reflected in the results of the MRCPs.

(H12) Figures H.7 and H.8 present the effective dose DCs for the AP, PA and ISO irradiation geometries calculated with the MRCPs, along with the *Publication 116* values. For all of the calculated effective dose DCs shown in these figures, the statistical error is less than 0.5%. It can be seen that for high energy electrons and helium ions (i.e. > 1 MeV for electrons and > 10 MeV/u for helium ions), the effective dose DCs of the MRCPs are generally close to both the *Publication 116* values and the values calculated with the *Publication 110* phantoms and Geant4 code. For the lower energies, on the other hand, the effective dose DCs show large differences, due mainly to the differences in the skin DCs. For electrons, the effective dose DCs of the MRCPs for the energies (≤ 0.06 MeV) are smaller than the *Publication 116* values, but for the higher energies up to 1 MeV, greater by up to a factor of ~12 (at 0.1 MeV). For helium ions, for 1 MeV/u, the effective dose DCs of the MRCPs are essentially zero, which is due to the effect of the dead layer defined in the MRCPs, whereas the *Publication 116* values show some significant values. For the higher energies up to 10 MeV, the effective dose DCs of the MRCPs are greater than the *Publication 116* values by up to a factor of ~14 (at 3 MeV/u).

(H13) However, it is also true that the difference is overly exaggerated as we consider only monoenergetic electron beams; in real exposure situations, generally polyenergetic electrons (e.g. beta spectra) are encountered, where the differences in effective doses are much less significant. For example, the difference of effective dose between the MRCPs and the *Publication 110* phantoms resulting from the isotropic (ISO) irradiation of the beta radiation sources (^{14}C, ^{186}Re, ^{32}P, $^{90}Sr/^{90}Y$ and ^{106}Rh) is less than ~2 times, except for ^{14}C, for which the difference is ~4 times. Note that ^{14}C emits very low-energy electrons (maximum energy: 0.15 MeV) and thus is generally not of concern for external exposures. In real situations of helium ion exposures, alpha exposures are mostly encountered but practically considered not to be important for radiation protection purposes, considering that they can be easily shielded by a thin piece of paper or several centimetre-thick air.

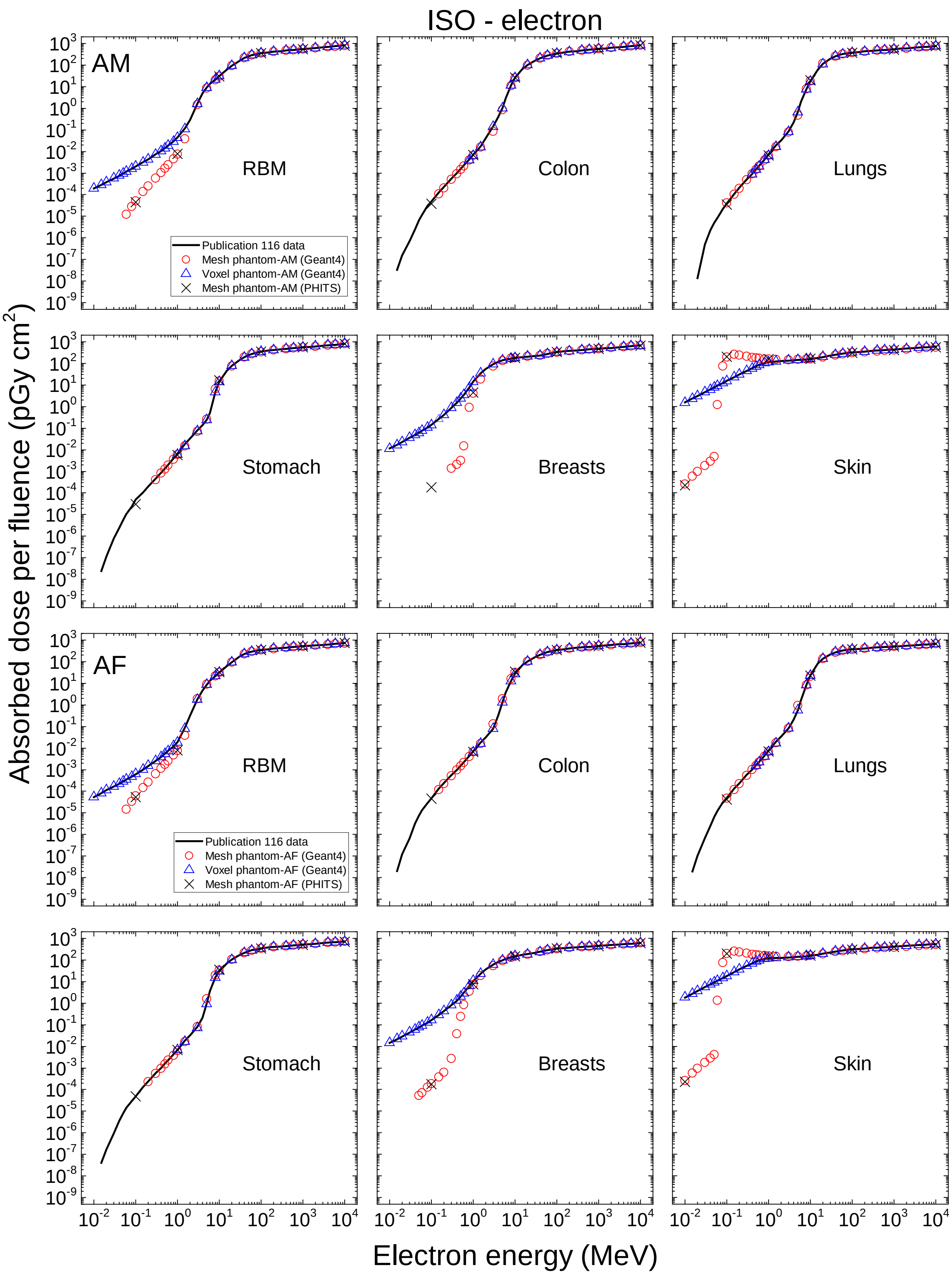


Fig. H.5. Absorbed dose per fluence (pGy cm^2) to the RBM, colon, lungs, stomach, breasts and skin in the ISO geometry for electron exposures calculated with the adult mesh-type reference phantoms (MRCPs), along with the *Publication 116* values (ICRP, 2010) and the values calculated with the *Publication 110* phantoms and the Geant4 code: adult male, AM (upper) and adult female, AF (lower).

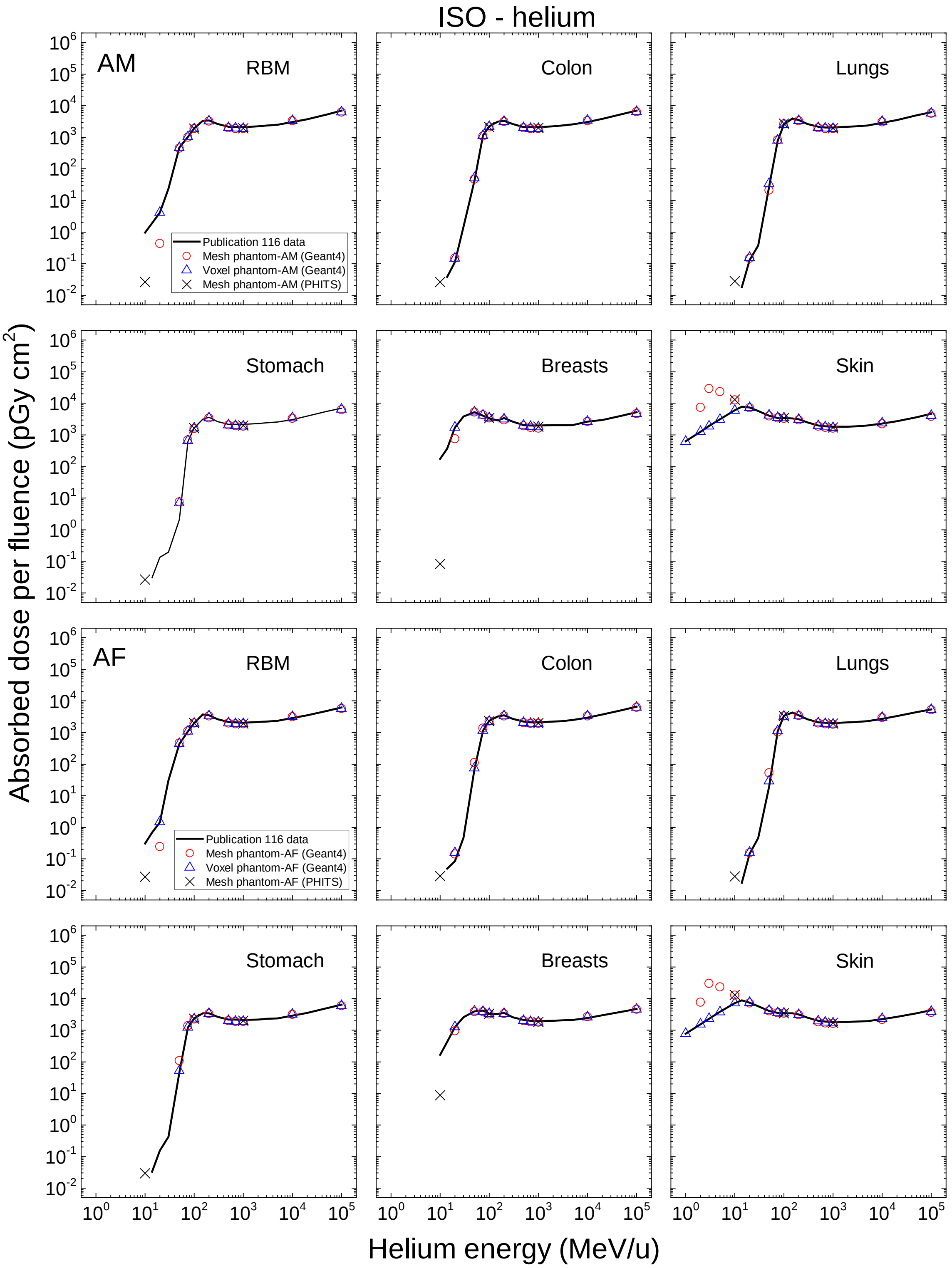


Fig. H.6. Absorbed dose per fluence (pGy cm^2) to the RBM, colon, lungs, stomach, breasts and skin in the ISO geometry for helium ion exposures calculated with the adult mesh-type reference phantoms (MRCPs), along with the *Publication 116* values (ICRP, 2010) and the values calculated with the *Publication 110* phantoms and the Geant4 code: adult male, AM (upper) and adult female, AF (lower).

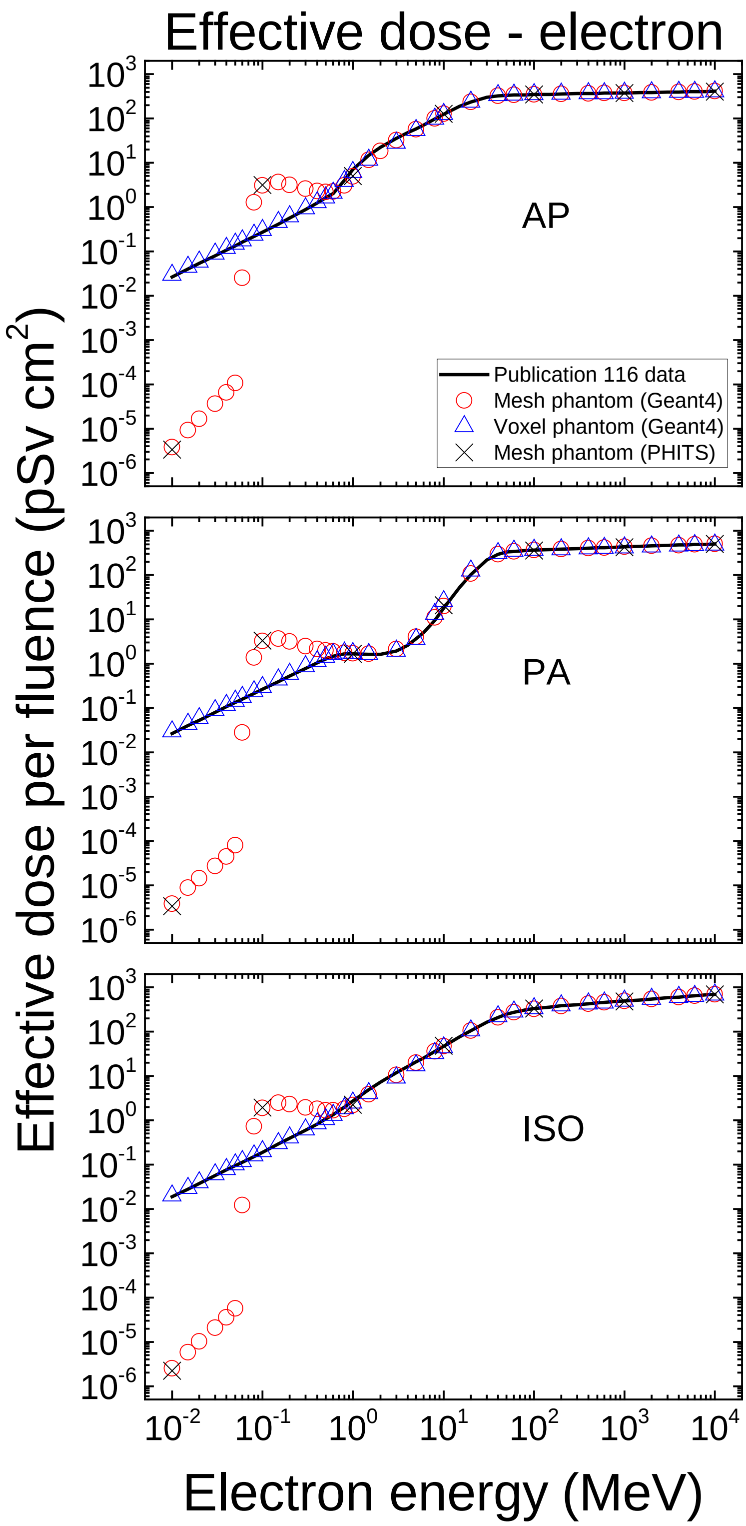


Fig. H.7. Effective dose per fluence (pSv cm^2) for electron exposures calculated with the adult mesh-type reference phantoms (MRCPs), along with the *Publication 116* values (ICRP, 2010) and the values calculated with the *Publication 110* phantoms and the Geant4 code.

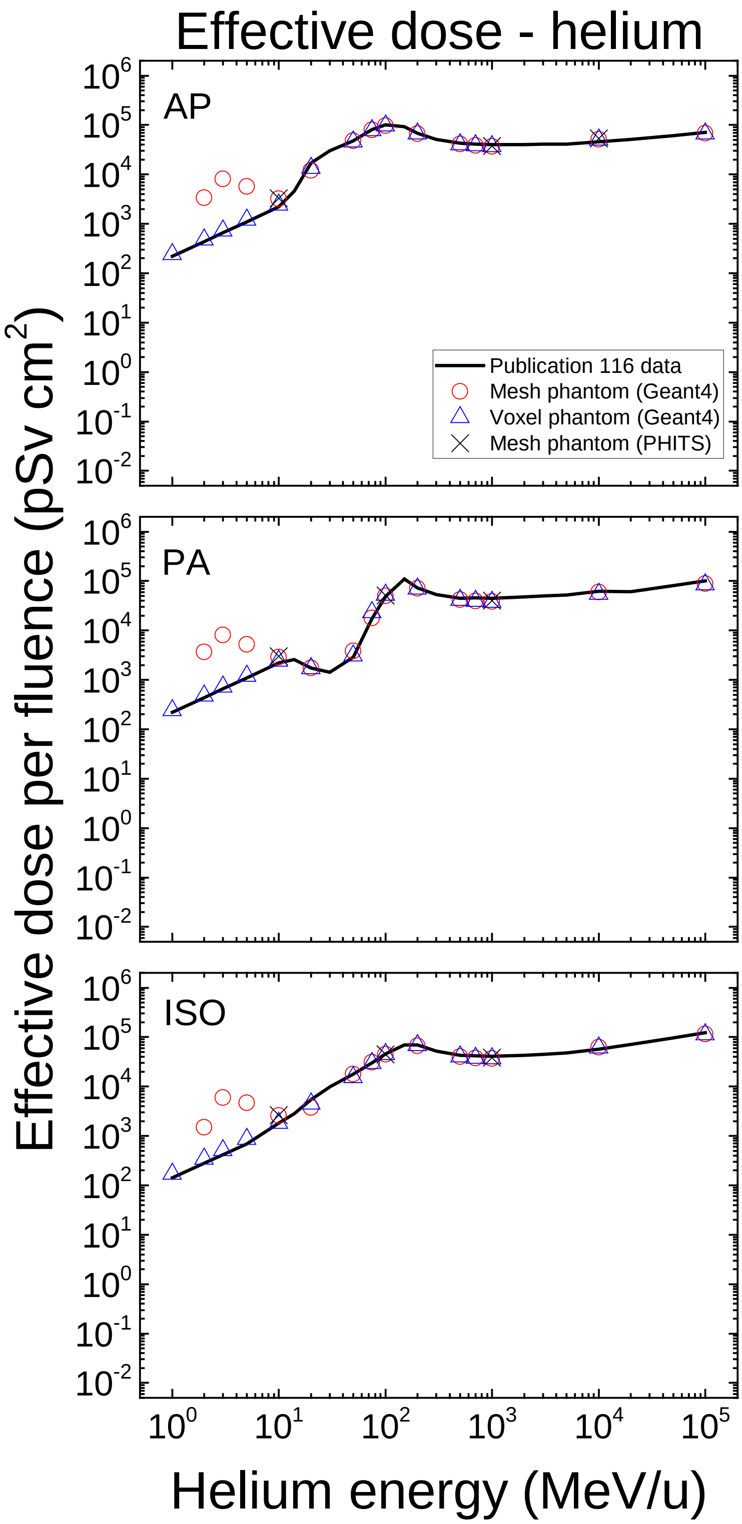


Fig. H.8. Effective dose per fluence (pSv cm^2) for helium ion exposures calculated with the adult mesh-type reference phantoms (MRCPs), along with the *Publication 116* values (ICRP, 2010) and the values calculated with the *Publication 110* phantoms and the Geant4 code.

ANNEX I. COMPARISON OF SPECIFIC ABSORBED FRACTIONS

(I1) In order to investigate the impact of the improved internal morphology of the adult mesh-type reference computational phantoms (MRCPs) on the calculation of dose coefficients (DCs) for internal exposures, the specific absorbed fractions (SAFs) for photons and electrons were calculated using the MRCPs for comparison with the values in *Publication 133* (ICRP, 2016a). For the calculations, the cortical bone, liver, lungs and thyroid were selected as source organs/tissues. The Geant4 code (ver. 10.02) was used for all the energy points considered for the comparison, while the PHITS (ver. 2.92) and MCNP6 (ver. 2.0 prerelease) codes were used only for some energies for spot-check purposes. The SAFs were also calculated using the *Publication 110* phantoms and the Geant4 code to facilitate the analysis. For the Geant4 code, the physics library of the G4EmLivermorePhysics to transport photons and electrons was used with a range of 1 μm for the secondary production cut (Geant4 Physics Reference Manual). For both the PHITS and MCNP6 codes, the default physics models and cross-section data were used to transport photons and electrons. For the MCNP6 code, the default cut energies were used, which were also applied to set cut energies for the PHITS code. Note that for photons, absorbed doses to the red bone marrow and endosteum were calculated based on the fluence-to-absorbed dose response functions (DRF) reported in Annex D of *Publication 116* (ICRP, 2010) as recommended in Section 4.4 of *Publication 133* (ICRP, 2016a).

(I2) The SAFs of the MRCPs were compared with the *Publication 133* values for six target organs/tissues which were selected considering the contribution to effective dose. Figures I.1–I.8 present the SAFs of the MRCPs for the selected source and target organs/tissues for photons and electrons, along with the *Publication 133* values. The statistical errors of the calculated values presented in the figures are less than 5%.

(I3) For photons, it can be seen that the SAFs of the MRCPs are generally not much different from the *Publication 133* values. Large differences, however, can be seen when the RBM is a target, where the SAFs of the MRCPs are much smaller than the *Publication 133* values at low energies. These differences are due mainly to the fact that in the MRCPs, the spongiosa is fully enclosed by cortical bone, whereas this is not the case in the voxel-type *Publication 110* reference phantoms (see Fig. 6.5). Even for the cortical bone as a source and the colon as a target, the SAFs show large differences, for which the values of the MRCPs are greater by a factor of ~5 at 0.01 MeV for the male phantom, which is again due to the difference in the distribution of the cortical bone; that is, in the *Publication 110* phantoms, the cortical bone dose not fully enclose the spongiosa and is not uniformly distributed, especially in the ribs where the cortical bone is rarely distributed in the regions that are very close to the colon.

(I4) For electrons, it can be seen that the SAFs of the MRCPs are close to the *Publication 133* values for self-irradiation cases (e.g. liver ← liver), whereas for cross-fire-irradiation cases (e.g. RBM ← liver), the SAFs show significant differences. For most of the cross-fire-irradiation cases, the SAFs of the MRCPs are generally smaller than the *Publication 133* values, which is mainly due to the fact that the contact area between the adjacent source and target organs/tissues of the MRCPs (smooth-surfaces) is smaller than that of the *Publication 110* phantoms (stair-stepped-surfaces, see Fig. 6.3). The differences were even larger when the thyroid is a source and the oesophagus and the thymus are a target, which is mainly due to the fact that the MRCPs overcome an anatomical limitation of the *Publication 110* phantoms wherein the thyroid slightly contacts the oesophagus for both the male and the female and the thymus only for the male (see Chapter 3.1). Larger differences can also be seen for the RBM as a target, which is due to the fact that in the MRCPs, the cortical bone fully encloses the spongiosa, whereas this is not the case in the *Publication 110* phantoms. Exceptionally, the SAFs of the MRCPs are generally greater than the *Publication 133* values only for the colon ← cortical bone case, which is again due to the fact that in the *Publication 110* phantoms, the cortical bone is not uniformly distributed, especially in the ribs where the cortical bone is rarely distributed in the regions that are very close to the colon.

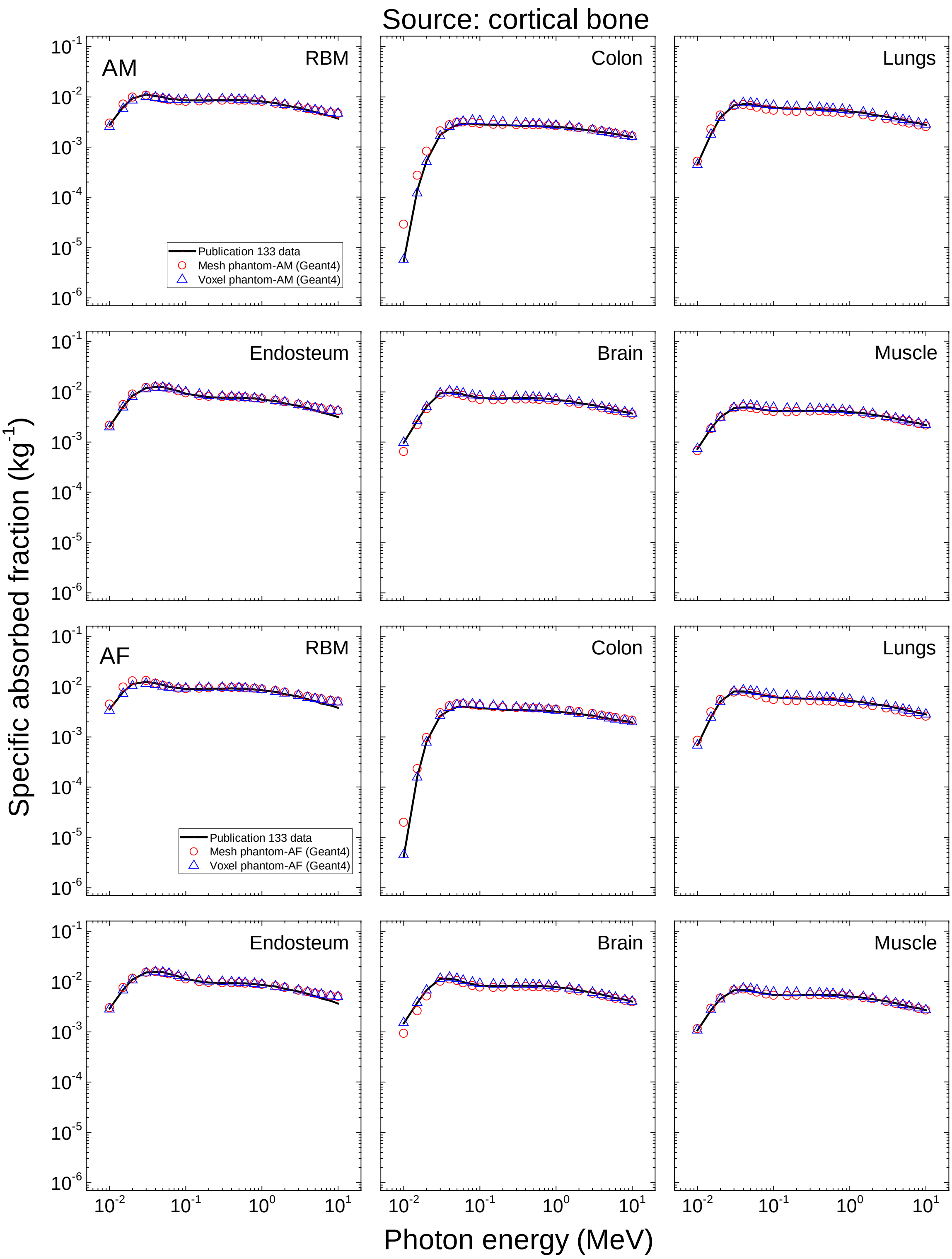
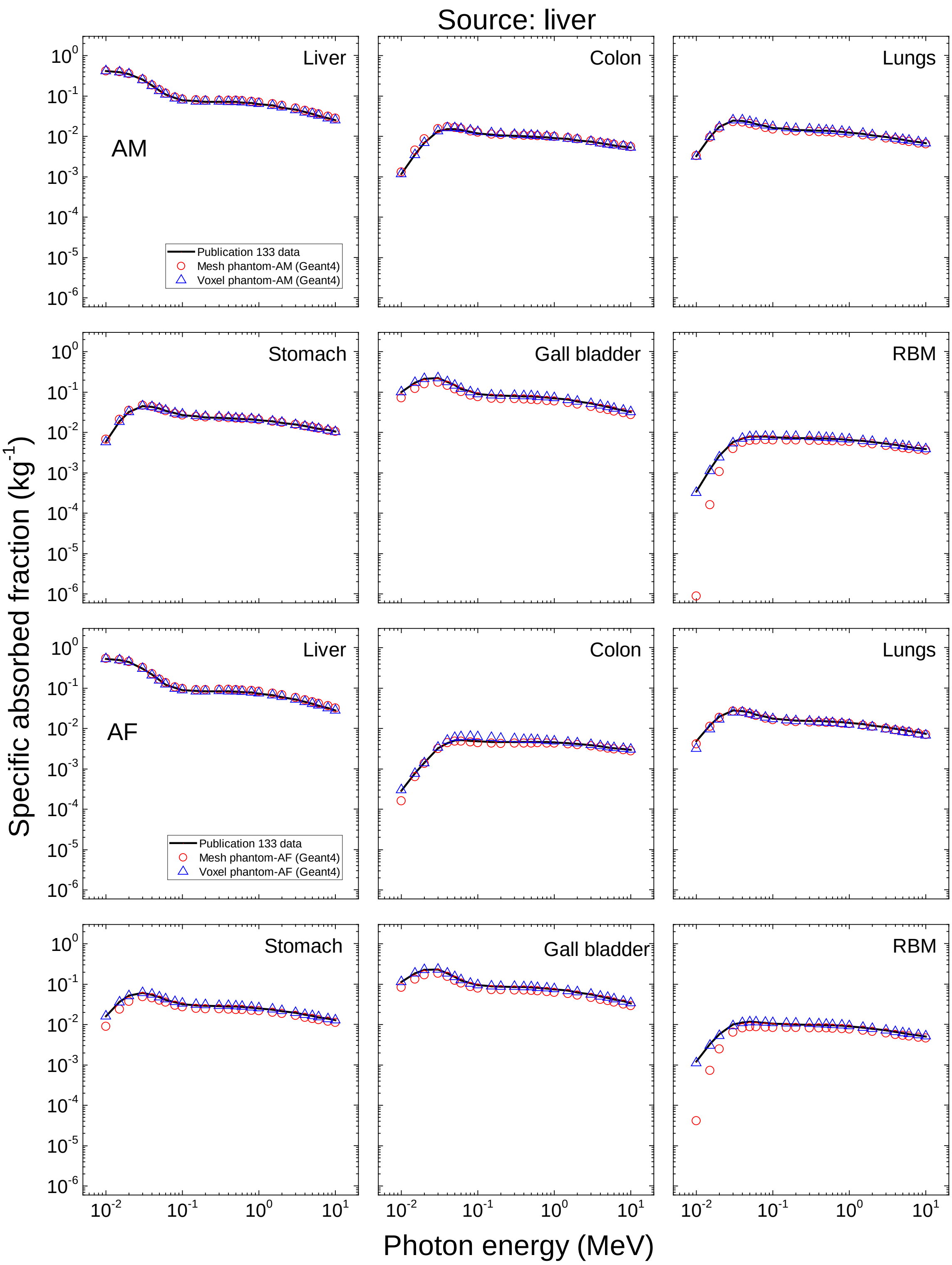


Fig. I.1. Specific absorbed fractions (SAFs) for cortical bone as a source and RBM, colon, lungs, endosteum, brain and muscle as a target for photon exposures calculated with the adult mesh-type reference phantoms (MRCPs), along with the *Publication 133* values (ICRP, 2016a) and the values calculated with the *Publication 110* phantoms and the Geant4 code: adult male, AM (upper) and adult female, AF (lower).



2119

2120 Fig. I.2. Specific absorbed fractions (SAFs) for liver as a source and liver, colon, lungs, stomach, gall
2121 bladder and RBM as a target for photon exposures calculated with the adult mesh-type reference
2122 phantoms (MRCPs), along with the *Publication 133* values (ICRP, 2016a) and the values calculated
2123 with the *Publication 110* phantoms and the Geant4 code: adult male, AM (upper) and adult female, AF
2124 (lower).

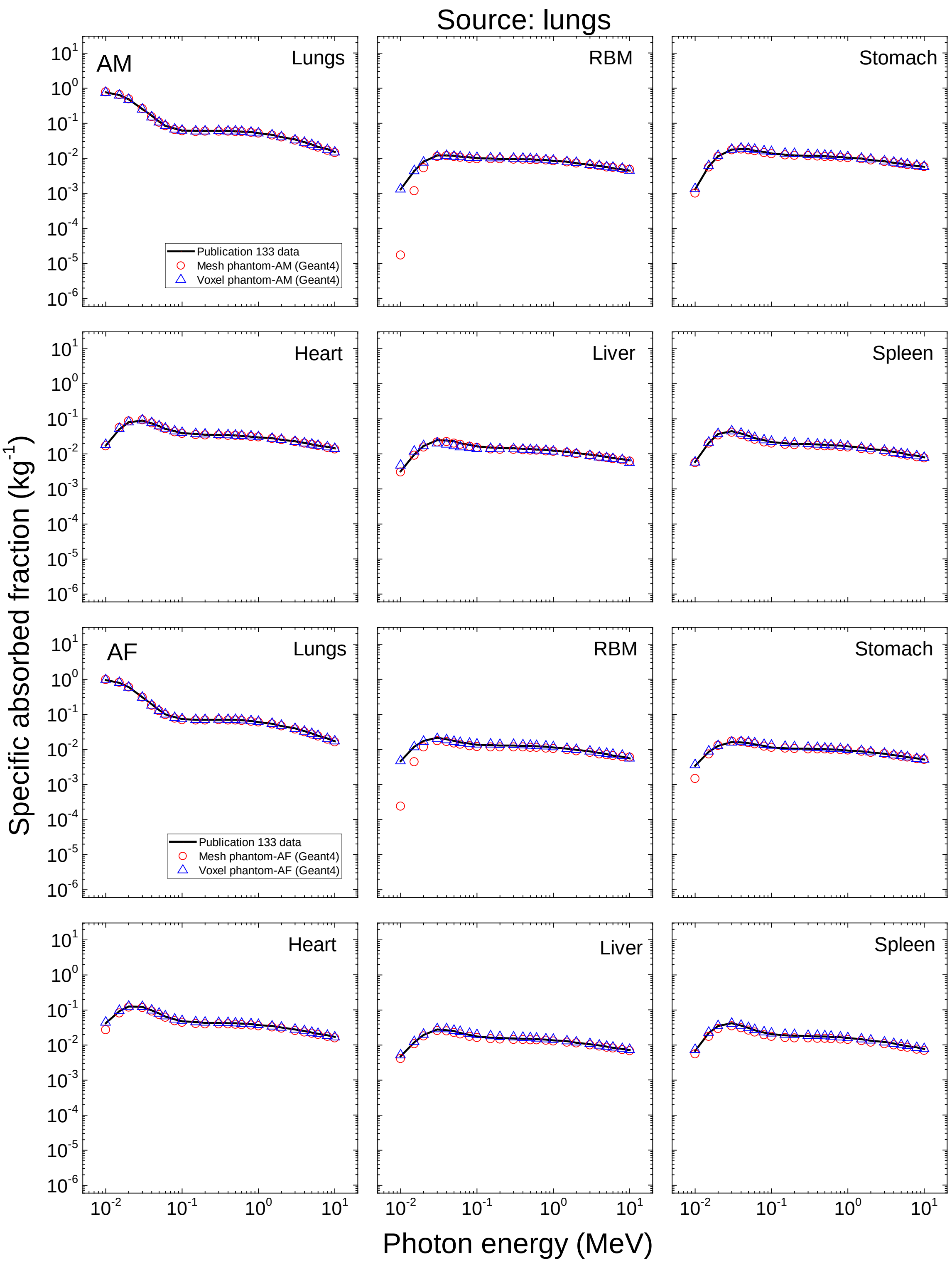


Fig. I.3. Specific absorbed fractions (SAFs) for lungs as a source and lungs, RBM, stomach, heart, liver and spleen as a target for photon exposures calculated with the adult mesh-type reference phantoms (MRCPs), along with the *Publication 133* values (ICRP, 2016a) and the values calculated with the *Publication 110* phantoms and the Geant4 code: adult male, AM (upper) and adult female, AF (lower).

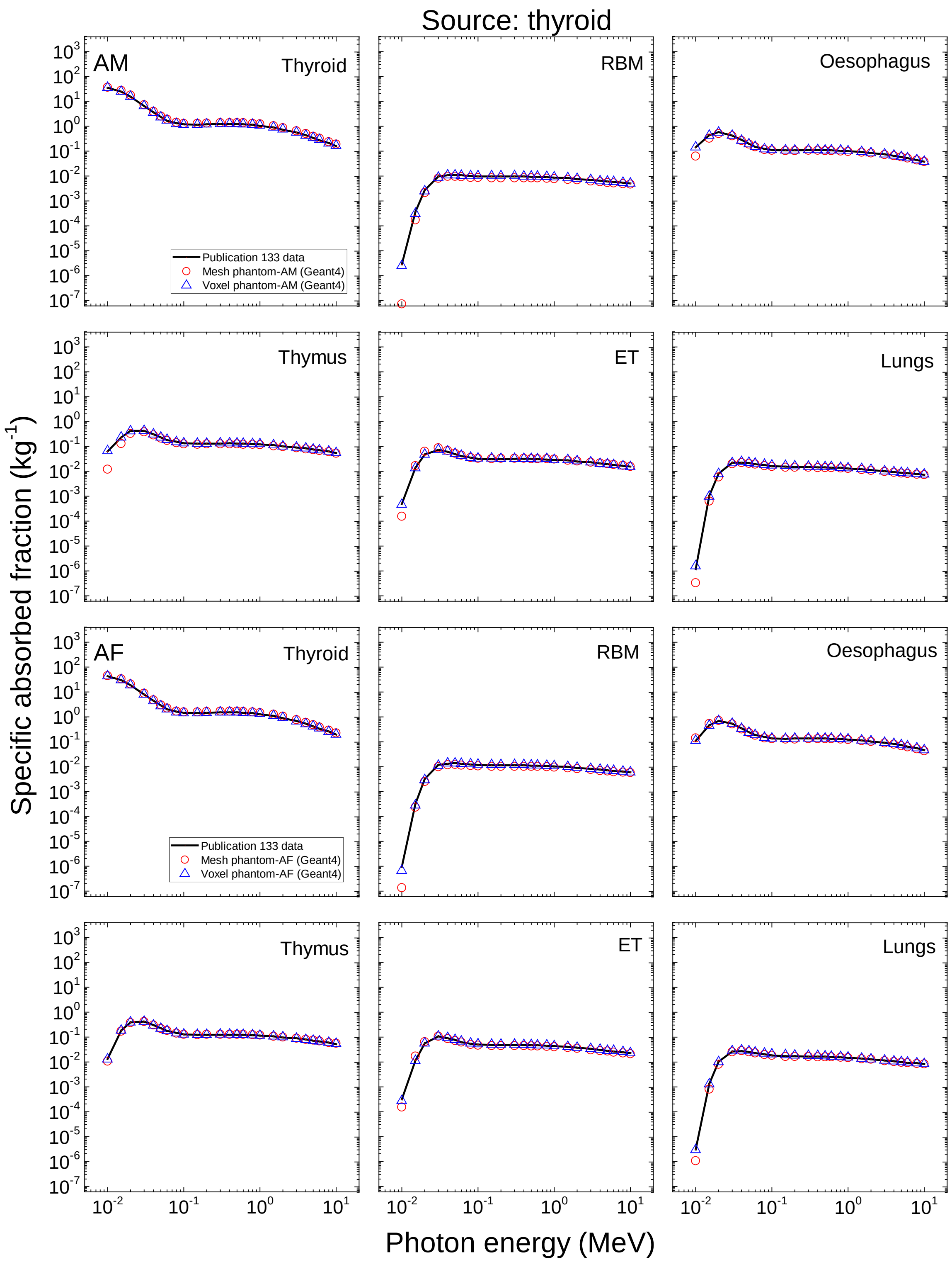


Fig. I.4. Specific absorbed fractions (SAFs) for thyroid as a source and thyroid, RBM, oesophagus, thymus, extrathoracic (ET) region and lungs as a target for photon exposures calculated with the adult mesh-type reference phantoms (MRCPs), along with the *Publication 133* values (ICRP, 2016a) and the values calculated with the *Publication 110* phantoms and the Geant4 code: adult male, AM (upper) and adult female, AF (lower).

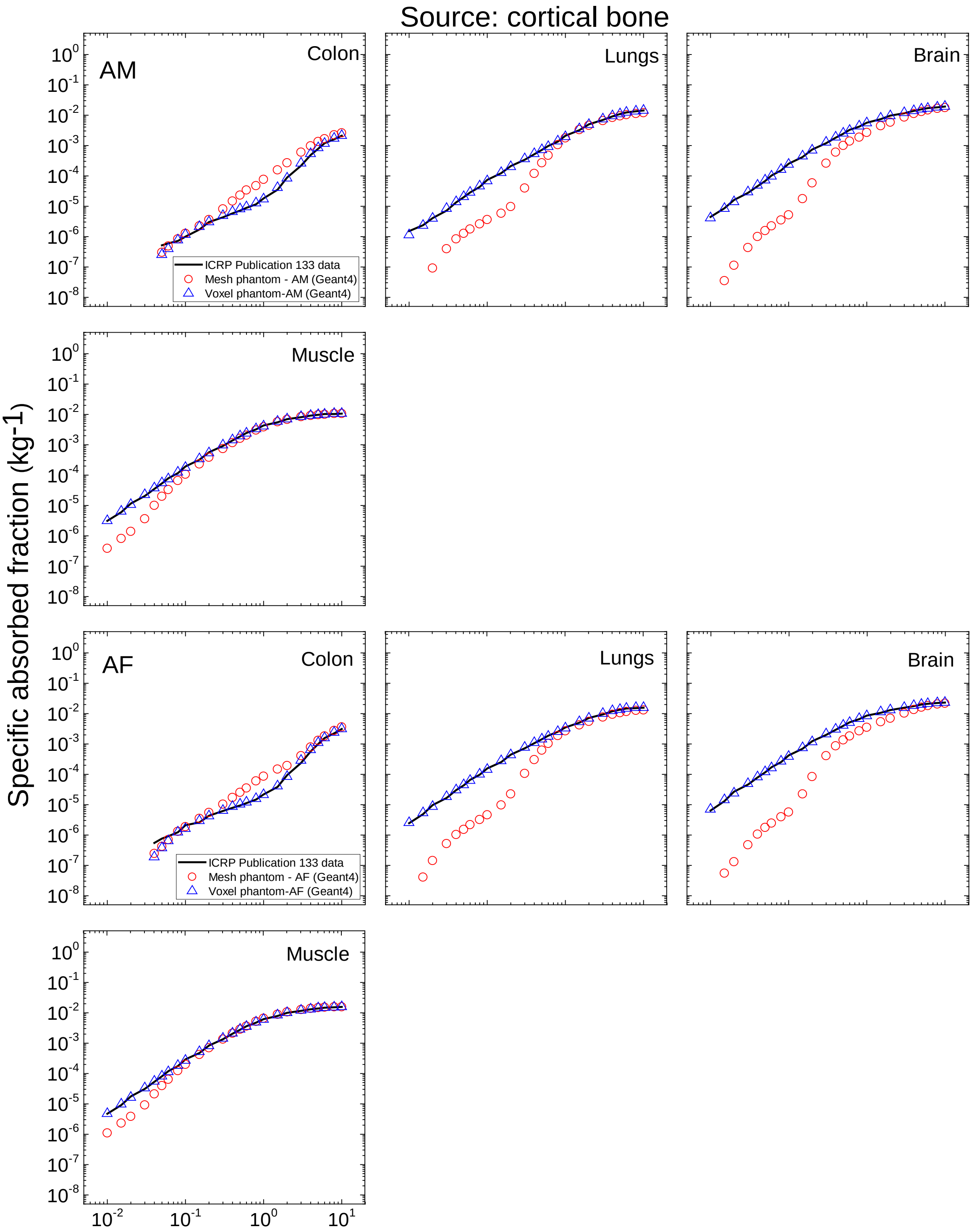


Fig. I.5. Specific absorbed fractions (SAFs) for cortical bone as a source and colon, lungs, brain and muscle as a target for electron exposures calculated with the adult mesh-type reference phantoms (MRCPs), along with the *Publication 133* values (ICRP, 2016a) and the values calculated with the *Publication 110* phantoms and the Geant4 code: adult male, AM (upper) and adult female, AF (lower). Note that SAFs for the RBM and endosteum as a target are not given here because these values of *Publication 133* were calculated not using the *Publication 110* phantoms but using the absorbed fractions (AFs) calculated by using the micro-CT imaging data for 38 cored samples of spongiosa provided by Hough et al. (2011).

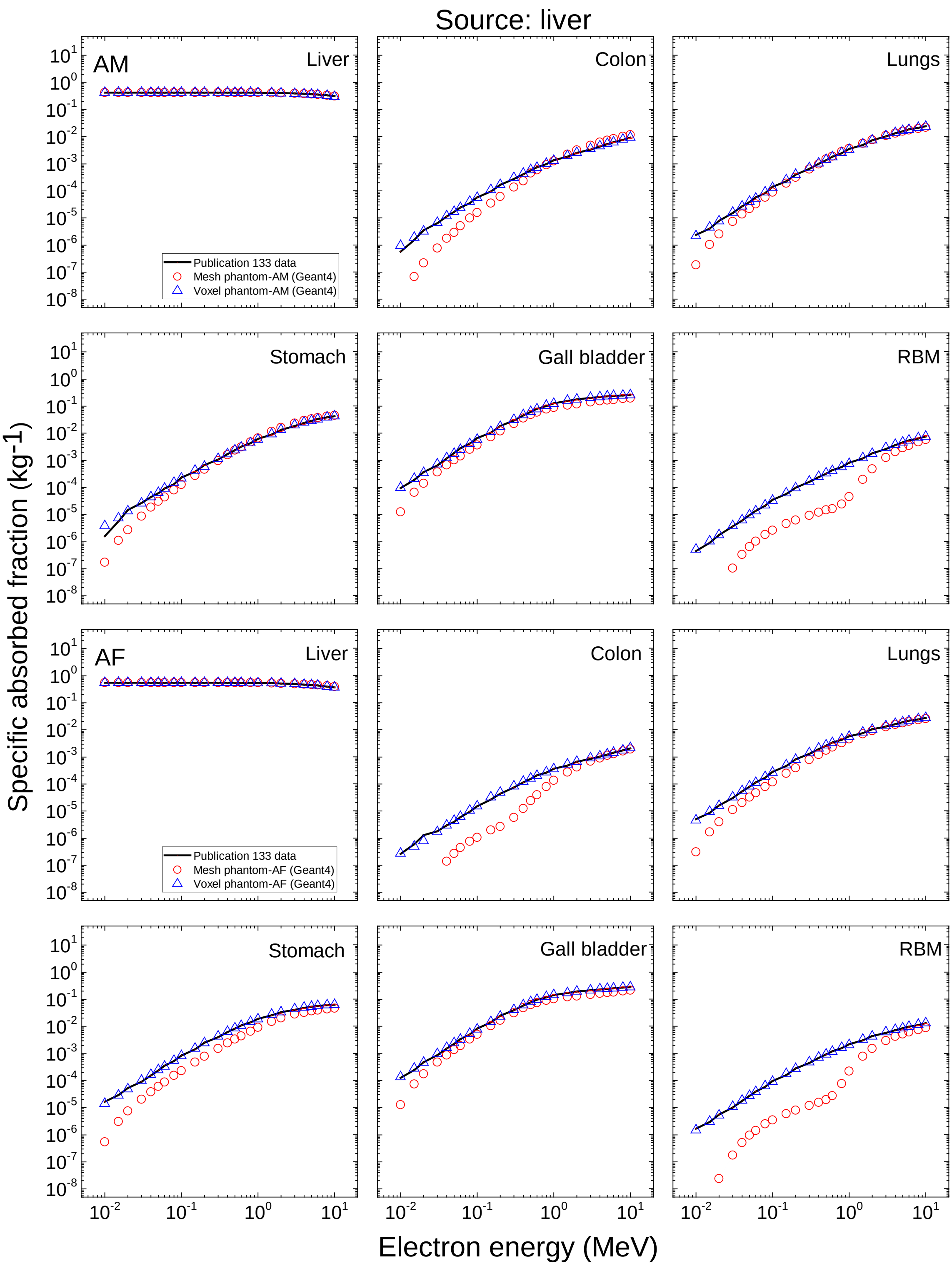


Fig. I.6. Specific absorbed fractions (SAFs) for liver as a source and liver, colon, lungs, stomach, gall bladder and RBM as a target for electron exposures calculated with the adult mesh-type reference phantoms (MRCPs), along with the *Publication 133* values (ICRP, 2016a) and the values calculated with the *Publication 110* phantoms and the Geant4 code: adult male, AM (upper) and adult female, AF (lower).

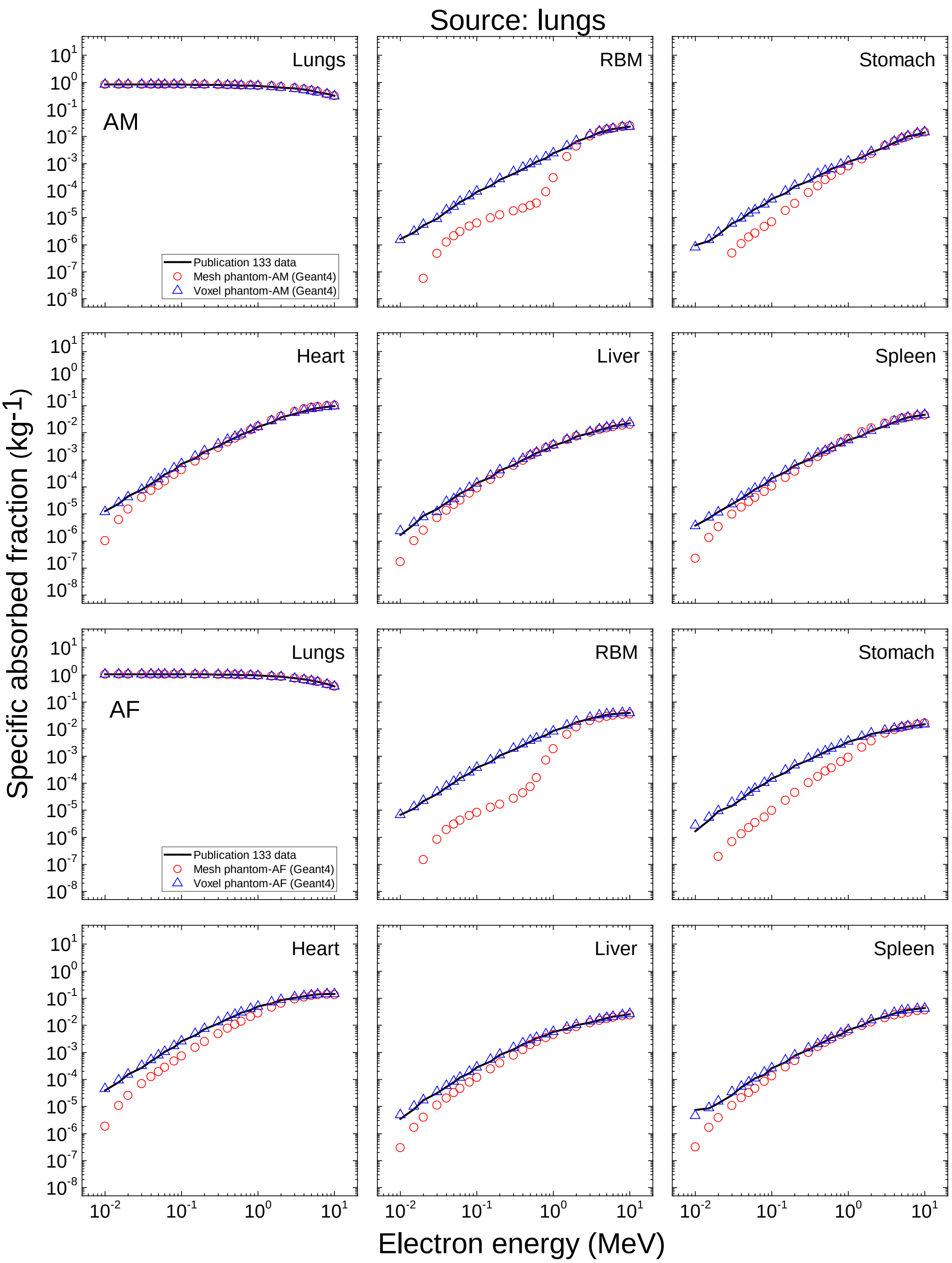


Fig. I.7. Specific absorbed fractions (SAFs) for lungs as a source and lungs, RBM, stomach, heart, liver and spleen as a target for electron exposures calculated with the adult mesh-type reference phantoms (MRCPs), along with the *Publication 133* values (ICRP, 2016a) and the values calculated with the *Publication 110* phantoms and the Geant4 code: adult male, AM (upper) and adult female, AF (lower).

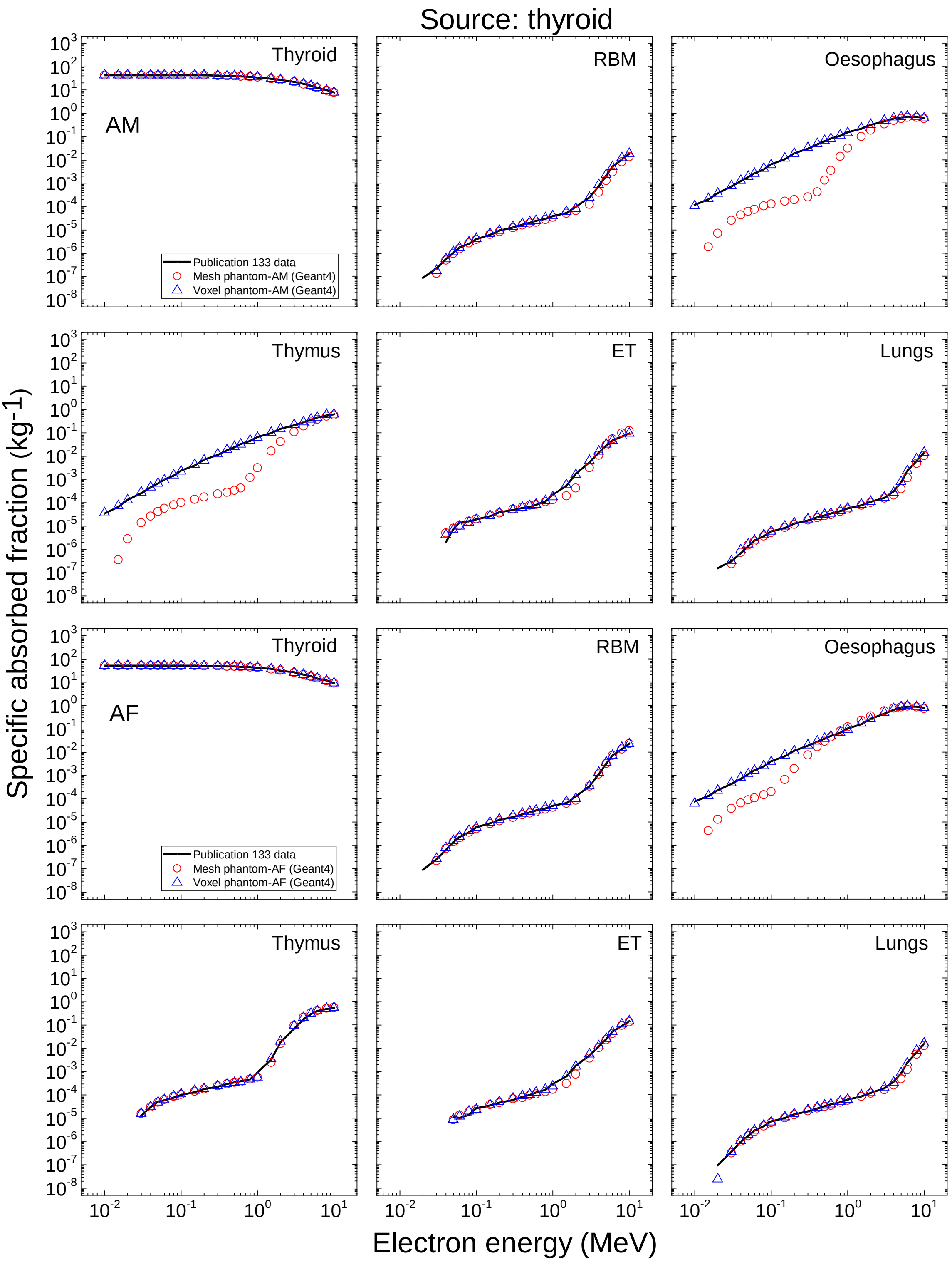


Fig. I.8. Specific absorbed fractions (SAFs) for thyroid as a source and thyroid, RBM, oesophagus, thymus, extrathoracic (ET) region and lungs as a target for electron exposures calculated with the adult mesh-type reference phantoms (MRCPs), along with the *Publication 133* values (ICRP, 2016a) and the values calculated with the *Publication 110* phantoms and the Geant4 code: adult male, AM (upper) and adult female, AF (lower).

ANNEX J. DOSE COEFFICIENTS FOR INDUSTRIAL RADIOGRAPHY SOURCES

(J1) Tables J.1–J.15 list the dose coefficients (DCs) (Gy s^{-1} Bq^{-1}) of red bone marrow, brain, lungs, small intestine and large intestine for the ^{192}Ir, ^{137}Cs/^{137m}Ba, and ^{60}Co point sources. Table J.16 lists the DCs of effective dose (Sv s^{-1} Bq^{-1}) for the same sources. The data are for point sources located at three source distances (0.005, 0.1 and 0.3 m) in four directions (anterior, right lateral, posterior and left lateral) at five levels (ground, middle thigh and lower, middle and upper torso) as described in Chapter 8 (see Fig. 8.2). In addition, three longer distances (1, 1.5 and 3 m) were calculated in the four directions at the lower-torso level. Table J.17 lists the source self-shielding factors for different thicknesses of radioactive material (1, 2, 3 and 4 mm) and capsule wall (1 and 2 mm) for the three isotopes.

Table J.1. ^{192}Ir: RBM absorbed dose per source disintegration Gy s^{-1} Bq^{-1}).

Level (see Fig. 8.2)	Distance (m)	Gender	Direction											
			Anterior			Right lateral			Posterior			Left lateral		
			10%ile	MRCP	90%ile	10%ile	MRCP	90%ile	10%ile	MRCP	90%ile	10%ile	MRCP	90%ile
Ground	0.005	Male	3.72E-18	2.96E-18	2.11E-18	1.22E-18	1.03E-18	7.70E-19	2.85E-18	2.30E-18	1.56E-18	1.29E-18	1.14E-18	8.06E-19
		Female	6.03E-18	4.25E-18	3.21E-18	2.48E-18	1.68E-18	1.38E-18	3.38E-18	1.91E-18	1.74E-18	2.57E-18	1.73E-18	1.39E-18
	0.1	Male	5.88E-18	4.46E-18	2.94E-18	1.94E-18	1.50E-18	1.00E-18	6.13E-18	4.66E-18	3.22E-18	2.20E-18	1.75E-18	1.13E-18
		Female	8.50E-18	6.08E-18	4.38E-18	2.49E-18	1.68E-18	1.36E-18	7.05E-18	4.55E-18	3.32E-18	2.91E-18	1.95E-18	1.54E-18
	0.3	Male	9.09E-18	6.87E-18	4.78E-18	4.13E-18	3.03E-18	1.88E-18	1.08E-17	8.17E-18	6.26E-18	4.09E-18	3.20E-18	2.00E-18
		Female	1.20E-17	9.04E-18	6.41E-18	5.22E-18	3.67E-18	2.32E-18	1.28E-17	9.38E-18	6.96E-18	5.57E-18	3.87E-18	2.67E-18
Middle thigh	0.005	Male	7.89E-17	6.59E-17	5.51E-17	3.89E-17	3.38E-17	2.50E-17	8.63E-17	6.90E-17	5.83E-17	3.88E-17	3.41E-17	2.58E-17
		Female	1.45E-16	1.18E-16	9.75E-17	6.66E-17	5.39E-17	4.18E-17	1.39E-16	1.13E-16	9.44E-17	6.97E-17	5.67E-17	4.61E-17
	0.1	Male	8.18E-17	6.62E-17	5.26E-17	4.78E-17	3.83E-17	2.78E-17	9.32E-17	7.52E-17	6.26E-17	4.69E-17	3.96E-17	2.79E-17
		Female	1.24E-16	1.03E-16	7.92E-17	6.82E-17	5.48E-17	4.04E-17	1.25E-16	1.04E-16	8.07E-17	6.88E-17	5.43E-17	4.28E-17
	0.3	Male	5.94E-17	5.13E-17	3.71E-17	3.15E-17	2.60E-17	1.99E-17	6.90E-17	5.95E-17	5.04E-17	3.14E-17	2.59E-17	1.95E-17
		Female	7.59E-17	6.60E-17	4.67E-17	4.17E-17	3.48E-17	2.62E-17	8.00E-17	6.92E-17	5.58E-17	4.11E-17	3.35E-17	2.59E-17
Lower torso	0.005	Male	5.36E-16	4.01E-16	1.91E-16	4.63E-16	3.56E-16	1.96E-16	1.33E-15	1.13E-15	9.46E-16	4.31E-16	3.59E-16	1.83E-16
		Female	6.36E-16	4.79E-16	2.94E-16	4.83E-16	4.32E-16	2.01E-16	1.38E-15	1.19E-15	9.15E-16	4.50E-16	4.05E-16	2.17E-16
	0.1	Male	2.65E-16	2.19E-16	1.18E-16	2.29E-16	1.88E-16	1.22E-16	5.08E-16	4.52E-16	3.98E-16	2.20E-16	1.88E-16	1.16E-16
		Female	3.18E-16	2.66E-16	1.63E-16	2.40E-16	2.16E-16	1.22E-16	5.28E-16	4.72E-16	3.90E-16	2.25E-16	2.03E-16	1.29E-16
	0.3	Male	1.12E-16	9.77E-17	6.13E-17	7.98E-17	6.78E-17	5.04E-17	1.62E-16	1.49E-16	1.36E-16	7.31E-17	6.25E-17	4.38E-17
		Female	1.23E-16	1.10E-16	7.37E-17	8.32E-17	7.52E-17	5.11E-17	1.65E-16	1.53E-16	1.34E-16	7.80E-17	6.93E-17	4.96E-17
	1	Male	2.01E-17	1.88E-17	1.42E-17	1.31E-17	1.18E-17	9.78E-18	2.50E-17	2.37E-17	2.26E-17	1.28E-17	1.16E-17	9.37E-18
		Female	2.15E-17	2.01E-17	1.55E-17	1.41E-17	1.27E-17	1.02E-17	2.52E-17	2.41E-17	2.24E-17	1.38E-17	1.25E-17	1.03E-17
	1.5	Male	9.92E-18	9.32E-18	7.32E-18	6.42E-18	5.77E-18	4.95E-18	1.19E-17	1.13E-17	1.09E-17	6.29E-18	5.69E-18	4.78E-18
		Female	1.05E-17	9.90E-18	7.90E-18	6.87E-18	6.27E-18	5.19E-18	1.21E-17	1.15E-17	1.09E-17	6.73E-18	6.18E-18	5.24E-18
	3	Male	2.67E-18	2.57E-18	2.11E-18	1.73E-18	1.58E-18	1.38E-18	3.12E-18	3.00E-18	2.93E-18	1.72E-18	1.56E-18	1.35E-18
		Female	2.83E-18	2.70E-18	2.21E-18	1.86E-18	1.71E-18	1.47E-18	3.17E-18	3.03E-18	2.89E-18	1.85E-18	1.68E-18	1.47E-18
Middle torso	0.005	Male	6.06E-16	4.33E-16	2.96E-16	7.37E-16	5.45E-16	4.17E-16	1.24E-15	1.06E-15	8.64E-16	6.17E-16	4.83E-16	3.62E-16
		Female	8.39E-16	7.28E-16	3.47E-16	1.00E-15	8.34E-16	5.52E-16	1.72E-15	1.43E-15	1.00E-15	9.02E-16	6.99E-16	5.16E-16
	0.1	Male	2.60E-16	2.11E-16	1.52E-16	2.29E-16	1.95E-16	1.53E-16	4.52E-16	4.02E-16	3.46E-16	2.03E-16	1.77E-16	1.38E-16
		Female	3.29E-16	2.90E-16	1.73E-16	2.67E-16	2.26E-16	1.71E-16	5.23E-16	4.65E-16	3.77E-16	2.66E-16	2.23E-16	1.77E-16
	0.3	Male	1.09E-16	9.52E-17	7.07E-17	7.92E-17	6.89E-17	5.52E-17	1.55E-16	1.42E-16	1.29E-16	7.08E-17	6.11E-17	4.68E-17
		Female	1.31E-16	1.20E-16	8.04E-17	9.03E-17	7.93E-17	6.15E-17	1.69E-16	1.56E-16	1.36E-16	8.69E-17	7.49E-17	5.86E-17
Upper torso	0.005	Male	7.72E-16	6.37E-16	5.36E-16	8.14E-16	6.28E-16	5.21E-16	8.69E-16	6.54E-16	5.34E-16	7.80E-16	6.30E-16	5.18E-16
		Female	9.99E-16	8.53E-16	7.02E-16	7.19E-16	4.80E-16	3.48E-16	1.06E-15	8.26E-16	6.63E-16	4.87E-16	3.57E-16	2.32E-16
	0.1	Male	3.32E-16	2.90E-16	2.52E-16	4.30E-16	3.61E-16	3.22E-16	3.62E-16	3.05E-16	2.59E-16	3.77E-16	3.22E-16	2.97E-16
		Female	3.94E-16	3.56E-16	2.95E-16	1.77E-16	1.40E-16	1.12E-16	4.00E-16	3.45E-16	2.93E-16	1.45E-16	1.18E-16	8.80E-17
	0.3	Male	1.12E-16	1.01E-16	8.58E-17	8.73E-17	7.60E-17	6.54E-17	1.38E-16	1.24E-16	1.10E-16	7.39E-17	6.43E-17	5.78E-17
		Female	1.29E-16	1.19E-16	9.45E-17	6.74E-17	5.68E-17	4.53E-17	1.44E-16	1.31E-16	1.16E-16	6.19E-17	5.27E-17	4.10E-17

Table J.2. ^{192}Ir: Brain absorbed dose per source disintegration (Gy s^{-1} Bq^{-1}).

Level	Distance (m)	Gender	Direction											
			Anterior			Right lateral			Posterior			Left lateral		
			10%ile	MRCP	90%ile	10%ile	MRCP	90%ile	10%ile	MRCP	90%ile	10%ile	MRCP	90%ile
Ground	0.005	Male	3.40E-19	1.80E-19	8.83E-20	9.88E-20	8.11E-20	6.28E-20	1.24E-19	1.02E-19	8.10E-20	1.09E-19	9.00E-20	6.61E-20
		Female	1.82E-18	1.01E-18	1.44E-19	1.12E-19	8.94E-20	7.05E-20	1.23E-19	9.17E-20	6.88E-20	1.21E-19	9.67E-20	7.24E-20
	0.1	Male	1.10E-18	5.43E-19	1.23E-19	1.49E-19	1.13E-19	8.32E-20	3.94E-19	1.96E-19	1.05E-19	1.63E-19	1.18E-19	8.51E-20
		Female	3.38E-18	2.32E-18	5.70E-19	2.09E-19	1.25E-19	8.23E-20	2.78E-19	1.49E-19	7.65E-20	2.83E-19	1.25E-19	9.49E-20
	0.3	Male	3.26E-18	2.25E-18	1.14E-18	8.43E-19	3.73E-19	1.13E-19	2.43E-18	1.39E-18	6.84E-19	7.21E-19	3.60E-19	1.22E-19
		Female	5.81E-18	4.58E-18	2.19E-18	2.26E-18	1.21E-18	1.52E-19	1.84E-18	9.05E-19	5.00E-19	2.22E-18	1.10E-18	2.09E-19
Middle thigh	0.005	Male	2.01E-19	1.72E-19	1.29E-19	1.79E-19	1.25E-19	1.05E-19	2.48E-19	1.81E-19	1.63E-19	1.77E-19	1.17E-19	9.59E-20
		Female	4.82E-19	3.68E-19	2.16E-19	2.67E-19	2.23E-19	1.44E-19	3.53E-19	3.07E-19	2.02E-19	2.27E-19	2.03E-19	1.36E-19
	0.1	Male	2.69E-18	1.19E-18	2.60E-19	9.53E-19	5.27E-19	3.21E-19	2.59E-18	1.14E-18	7.61E-19	1.33E-18	6.52E-19	3.35E-19
		Female	1.05E-17	8.34E-18	1.84E-18	4.16E-18	2.73E-18	6.57E-19	2.76E-18	1.92E-18	1.11E-18	3.70E-18	2.12E-18	6.63E-19
	0.3	Male	1.16E-17	9.23E-18	6.17E-18	4.47E-18	3.01E-18	1.69E-18	1.24E-17	8.50E-18	5.92E-18	3.27E-18	2.10E-18	1.31E-18
		Female	1.90E-17	1.77E-17	1.03E-17	9.20E-18	7.05E-18	3.09E-18	1.16E-17	8.39E-18	5.39E-18	9.47E-18	7.16E-18	3.12E-18
Lower torso	0.005	Male	3.08E-18	2.49E-18	1.99E-18	4.34E-18	4.20E-18	2.75E-18	2.42E-18	2.13E-18	1.46E-18	3.84E-18	3.05E-18	2.40E-18
		Female	1.49E-17	1.22E-17	3.22E-18	7.29E-18	6.20E-18	3.54E-18	4.15E-18	3.75E-18	2.58E-18	7.15E-18	5.03E-18	3.47E-18
	0.1	Male	2.97E-17	2.52E-17	2.00E-17	1.26E-17	9.87E-18	7.50E-18	2.16E-17	1.43E-17	7.85E-18	9.28E-18	7.29E-18	5.93E-18
		Female	4.65E-17	4.28E-17	2.43E-17	2.18E-17	1.76E-17	9.02E-18	1.52E-17	1.08E-17	6.41E-18	2.19E-17	1.75E-17	9.16E-18
	0.3	Male	3.16E-17	2.84E-17	2.32E-17	2.54E-17	1.85E-17	1.29E-17	3.95E-17	3.64E-17	2.94E-17	2.04E-17	1.38E-17	1.04E-17
		Female	4.35E-17	3.98E-17	3.31E-17	2.94E-17	2.24E-17	1.55E-17	3.95E-17	3.46E-17	2.60E-17	2.99E-17	2.33E-17	1.60E-17
	1	Male	1.32E-17	1.25E-17	1.07E-17	1.57E-17	1.50E-17	1.35E-17	1.53E-17	1.49E-17	1.39E-17	1.51E-17	1.44E-17	1.28E-17
		Female	1.53E-17	1.45E-17	1.32E-17	1.62E-17	1.58E-17	1.41E-17	1.57E-17	1.53E-17	1.44E-17	1.59E-17	1.56E-17	1.39E-17
	1.5	Male	7.28E-18	7.02E-18	6.28E-18	8.63E-18	8.31E-18	7.79E-18	8.31E-18	8.02E-18	7.68E-18	8.50E-18	8.14E-18	7.51E-18
		Female	8.14E-18	7.85E-18	7.32E-18	8.78E-18	8.69E-18	7.94E-18	8.52E-18	8.21E-18	7.87E-18	8.80E-18	8.63E-18	8.03E-18
	3	Male	2.19E-18	2.13E-18	1.97E-18	2.54E-18	2.51E-18	2.43E-18	2.39E-18	2.40E-18	2.29E-18	2.56E-18	2.49E-18	2.36E-18
		Female	2.30E-18	2.25E-18	2.15E-18	2.63E-18	2.60E-18	2.49E-18	2.45E-18	2.42E-18	2.36E-18	2.62E-18	2.58E-18	2.46E-18
Middle torso	0.005	Male	7.54E-17	6.78E-17	4.16E-17	3.05E-17	2.77E-17	2.16E-17	2.18E-17	1.91E-17	1.40E-17	2.80E-17	2.38E-17	1.84E-17
		Female	7.91E-17	7.98E-17	3.70E-17	4.51E-17	3.92E-17	2.90E-17	2.56E-17	2.43E-17	1.94E-17	4.02E-17	3.54E-17	2.89E-17
	0.1	Male	7.94E-17	7.14E-17	6.11E-17	3.32E-17	2.76E-17	1.96E-17	1.01E-16	8.81E-17	7.13E-17	2.99E-17	2.27E-17	1.62E-17
		Female	1.16E-16	1.06E-16	8.98E-17	4.10E-17	2.93E-17	2.19E-17	9.33E-17	7.68E-17	5.89E-17	4.60E-17	3.28E-17	2.70E-17
	0.3	Male	5.90E-17	5.23E-17	4.44E-17	7.32E-17	6.65E-17	5.56E-17	7.37E-17	6.90E-17	6.14E-17	6.70E-17	5.93E-17	4.78E-17
		Female	8.28E-17	7.75E-17	6.42E-17	7.85E-17	6.79E-17	5.44E-17	7.92E-17	7.46E-17	6.64E-17	7.66E-17	6.50E-17	5.06E-17
Upper torso	0.005	Male	4.50E-16	4.25E-16	3.89E-16	5.17E-16	5.27E-16	4.82E-16	5.20E-16	4.98E-16	4.52E-16	4.65E-16	4.61E-16	4.13E-16
		Female	6.99E-16	6.82E-16	6.54E-16	5.45E-16	4.62E-16	3.97E-16	6.44E-16	5.92E-16	5.34E-16	4.84E-16	4.00E-16	3.33E-16
	0.1	Male	2.99E-16	2.71E-16	2.38E-16	4.49E-16	4.02E-16	3.71E-16	4.04E-16	3.65E-16	3.31E-16	3.80E-16	3.45E-16	3.13E-16
		Female	5.11E-16	4.65E-16	4.24E-16	3.12E-16	2.65E-16	2.33E-16	4.07E-16	3.65E-16	3.33E-16	2.85E-16	2.45E-16	2.08E-16
	0.3	Male	1.42E-16	1.32E-16	1.24E-16	1.73E-16	1.57E-16	1.48E-16	1.47E-16	1.36E-16	1.27E-16	1.49E-16	1.37E-16	1.28E-16
		Female	1.89E-16	1.80E-16	1.71E-16	1.23E-16	1.10E-16	1.01E-16	1.41E-16	1.29E-16	1.23E-16	1.14E-16	1.04E-16	9.28E-17

Table J.3. ^{192}Ir: Lung absorbed dose per source disintegration (Gy s^{-1} Bq^{-1}).

Level	Distance (m)	Gender	Direction											
			Anterior			Right lateral			Posterior			Left lateral		
			10%ile	MRCP	90%ile	10%ile	MRCP	90%ile	10%ile	MRCP	90%ile	10%ile	MRCP	90%ile
Ground	0.005	Male	1.00E-18	8.21E-19	3.65E-19	2.88E-19	2.24E-19	1.56E-19	6.10E-19	4.39E-19	2.82E-19	3.86E-19	3.04E-19	1.76E-19
		Female	8.91E-19	6.05E-19	4.43E-19	2.92E-19	2.17E-19	1.63E-19	6.00E-19	3.51E-19	2.62E-19	3.10E-19	2.36E-19	1.75E-19
	0.1	Male	1.87E-18	1.47E-18	6.01E-19	6.44E-19	3.94E-19	2.39E-19	2.19E-18	1.35E-18	9.06E-19	1.02E-18	6.49E-19	3.05E-19
		Female	2.00E-18	1.38E-18	7.54E-19	5.20E-19	3.34E-19	2.42E-19	2.61E-18	1.41E-18	7.34E-19	5.74E-19	3.77E-19	2.71E-19
	0.3	Male	4.06E-18	3.08E-18	1.39E-18	2.46E-18	1.56E-18	6.85E-19	6.29E-18	4.45E-18	3.21E-18	3.52E-18	2.31E-18	9.99E-19
		Female	5.69E-18	4.09E-18	1.90E-18	3.62E-18	2.29E-18	8.01E-19	9.53E-18	6.70E-18	4.37E-18	3.86E-18	2.32E-18	9.30E-19
Middle thigh	0.005	Male	2.36E-18	2.09E-18	1.83E-18	1.27E-18	8.30E-19	6.42E-19	3.37E-18	2.31E-18	2.09E-18	1.45E-18	8.51E-19	6.20E-19
		Female	4.00E-18	3.75E-18	3.03E-18	2.25E-18	1.93E-18	1.33E-18	5.25E-18	4.74E-18	3.49E-18	2.12E-18	1.85E-18	1.31E-18
	0.1	Male	9.35E-18	7.61E-18	3.39E-18	6.38E-18	4.04E-18	2.56E-18	1.90E-17	1.27E-17	1.02E-17	1.27E-17	7.11E-18	3.77E-18
		Female	1.38E-17	1.10E-17	5.14E-18	1.77E-17	1.34E-17	5.25E-18	3.49E-17	2.72E-17	1.82E-17	1.68E-17	1.15E-17	5.07E-18
	0.3	Male	2.08E-17	1.64E-17	1.02E-17	1.79E-17	1.43E-17	9.66E-18	3.33E-17	2.68E-17	2.13E-17	1.92E-17	1.53E-17	1.08E-17
		Female	3.40E-17	2.88E-17	1.64E-17	2.72E-17	2.31E-17	1.42E-17	4.93E-17	4.22E-17	3.23E-17	2.53E-17	2.15E-17	1.43E-17
Lower torso	0.005	Male	9.82E-17	8.60E-17	5.54E-17	8.70E-17	8.52E-17	5.30E-17	1.05E-16	9.91E-17	7.46E-17	1.03E-16	8.70E-17	6.13E-17
		Female	9.83E-17	9.17E-17	6.90E-17	1.15E-16	1.03E-16	5.94E-17	1.51E-16	1.43E-16	1.09E-16	1.14E-16	9.39E-17	6.29E-17
	0.1	Male	1.23E-16	1.02E-16	7.87E-17	1.30E-16	1.12E-16	8.34E-17	1.83E-16	1.59E-16	1.26E-16	1.46E-16	1.27E-16	9.53E-17
		Female	1.60E-16	1.36E-16	8.85E-17	1.57E-16	1.45E-16	9.56E-17	2.25E-16	2.02E-16	1.55E-16	1.55E-16	1.39E-16	9.92E-17
	0.3	Male	1.04E-16	8.96E-17	6.19E-17	6.80E-17	5.93E-17	4.65E-17	1.22E-16	1.09E-16	9.53E-17	6.62E-17	5.99E-17	4.52E-17
		Female	1.08E-16	9.78E-17	6.59E-17	8.00E-17	7.14E-17	5.13E-17	1.41E-16	1.30E-16	1.10E-16	7.26E-17	6.60E-17	4.84E-17
	1	Male	2.33E-17	2.16E-17	1.69E-17	1.26E-17	1.16E-17	9.70E-18	2.38E-17	2.20E-17	2.11E-17	1.26E-17	1.20E-17	9.56E-18
		Female	2.23E-17	2.11E-17	1.51E-17	1.45E-17	1.33E-17	1.05E-17	2.63E-17	2.48E-17	2.37E-17	1.39E-17	1.29E-17	1.06E-17
	1.5	Male	1.15E-17	1.08E-17	8.69E-18	6.11E-18	5.69E-18	4.76E-18	1.14E-17	1.08E-17	1.04E-17	6.08E-18	5.76E-18	4.83E-18
		Female	1.09E-17	1.07E-17	7.76E-18	7.07E-18	6.39E-18	5.32E-18	1.26E-17	1.21E-17	1.14E-17	6.82E-18	6.30E-18	5.30E-18
	3	Male	3.12E-18	3.05E-18	2.58E-18	1.65E-18	1.53E-18	1.29E-18	3.06E-18	2.87E-18	2.79E-18	1.67E-18	1.59E-18	1.30E-18
		Female	3.01E-18	2.94E-18	2.22E-18	1.88E-18	1.74E-18	1.49E-18	3.32E-18	3.20E-18	3.06E-18	1.86E-18	1.69E-18	1.49E-18
Middle torso	0.005	Male	1.29E-15	9.76E-16	7.14E-16	1.58E-15	1.23E-15	9.48E-16	1.53E-15	1.31E-15	1.05E-15	1.86E-15	1.46E-15	1.10E-15
		Female	1.66E-15	1.41E-15	8.11E-16	2.29E-15	1.93E-15	1.40E-15	2.19E-15	1.83E-15	1.40E-15	2.40E-15	1.87E-15	1.38E-15
	0.1	Male	5.83E-16	4.76E-16	3.36E-16	4.42E-16	3.80E-16	3.20E-16	6.54E-16	5.62E-16	4.88E-16	4.41E-16	3.91E-16	3.24E-16
		Female	6.38E-16	5.59E-16	3.33E-16	5.43E-16	4.45E-16	3.68E-16	8.21E-16	7.16E-16	5.94E-16	5.41E-16	4.46E-16	3.80E-16
	0.3	Male	1.76E-16	1.56E-16	1.21E-16	1.04E-16	9.31E-17	7.86E-17	1.85E-16	1.65E-16	1.53E-16	9.72E-17	8.99E-17	7.20E-17
		Female	1.79E-16	1.67E-16	1.07E-16	1.23E-16	1.09E-16	9.25E-17	2.17E-16	1.98E-16	1.78E-16	1.18E-16	1.03E-16	8.44E-17
Upper torso	0.005	Male	1.16E-15	9.80E-16	8.16E-16	1.36E-15	1.11E-15	9.27E-16	1.05E-15	8.53E-16	6.95E-16	1.19E-15	9.80E-16	8.15E-16
		Female	1.40E-15	1.21E-15	9.38E-16	5.32E-16	4.03E-16	3.05E-16	1.24E-15	1.06E-15	8.48E-16	4.02E-16	3.23E-16	2.28E-16
	0.1	Male	7.14E-16	6.27E-16	5.32E-16	4.64E-16	3.86E-16	3.47E-16	6.05E-16	5.09E-16	4.29E-16	3.65E-16	3.06E-16	2.74E-16
		Female	7.24E-16	6.54E-16	5.17E-16	2.27E-16	1.77E-16	1.41E-16	6.66E-16	5.76E-16	4.98E-16	1.89E-16	1.49E-16	1.10E-16
	0.3	Male	2.24E-16	2.05E-16	1.81E-16	1.17E-16	9.76E-17	8.40E-17	1.97E-16	1.72E-16	1.56E-16	1.02E-16	8.62E-17	7.67E-17
		Female	2.10E-16	1.99E-16	1.60E-16	8.72E-17	7.08E-17	5.86E-17	2.08E-16	1.89E-16	1.74E-16	7.94E-17	6.56E-17	5.30E-17

Table J.4. ^{192}Ir: Small intestine absorbed dose per source disintegration (Gy s^{-1} Bq^{-1}).

Level	Distance (m)	Gender	Direction											
			Anterior			Right lateral			Posterior			Left lateral		
			10%ile	MRCP	90%ile	10%ile	MRCP	90%ile	10%ile	MRCP	90%ile	10%ile	MRCP	90%ile
Ground	0.005	Male	8.61E-18	6.63E-18	5.23E-18	1.21E-18	1.07E-18	1.17E-18	1.83E-18	1.55E-18	1.01E-18	1.40E-18	1.29E-18	1.20E-18
		Female	1.35E-17	9.70E-18	7.86E-18	4.47E-18	3.31E-18	2.57E-18	6.60E-18	3.22E-18	2.99E-18	3.62E-18	2.57E-18	2.15E-18
	0.1	Male	1.28E-17	1.00E-17	7.34E-18	1.46E-18	1.16E-18	1.20E-18	3.71E-18	2.92E-18	1.98E-18	1.95E-18	1.63E-18	1.35E-18
		Female	1.71E-17	1.27E-17	9.99E-18	2.70E-18	1.92E-18	1.89E-18	1.01E-17	6.72E-18	5.20E-18	3.22E-18	2.24E-18	2.09E-18
	0.3	Male	1.75E-17	1.50E-17	9.77E-18	3.31E-18	2.24E-18	1.91E-18	7.04E-18	5.02E-18	3.96E-18	4.61E-18	3.26E-18	2.36E-18
		Female	2.17E-17	1.72E-17	1.23E-17	4.14E-18	2.98E-18	2.63E-18	1.35E-17	1.02E-17	8.22E-18	6.01E-18	3.96E-18	3.40E-18
Middle thigh	0.005	Male	6.50E-17	5.45E-17	5.62E-17	1.82E-17	1.55E-17	1.19E-17	5.80E-17	4.46E-17	3.96E-17	1.78E-17	1.52E-17	1.19E-17
		Female	2.08E-16	1.79E-16	1.55E-16	6.36E-17	5.23E-17	3.98E-17	1.93E-16	1.63E-16	1.37E-16	6.54E-17	5.43E-17	4.34E-17
	0.1	Male	1.21E-16	1.04E-16	7.69E-17	3.10E-17	2.27E-17	1.94E-17	6.34E-17	5.19E-17	4.36E-17	3.50E-17	2.48E-17	2.06E-17
		Female	2.14E-16	1.86E-16	1.35E-16	6.64E-17	5.15E-17	4.09E-17	1.51E-16	1.29E-16	1.05E-16	7.28E-17	5.50E-17	4.63E-17
	0.3	Male	1.08E-16	1.00E-16	6.31E-17	3.28E-17	2.55E-17	2.11E-17	5.27E-17	4.34E-17	3.67E-17	4.38E-17	3.58E-17	2.55E-17
		Female	1.38E-16	1.24E-16	8.49E-17	4.40E-17	3.51E-17	2.84E-17	8.94E-17	7.48E-17	6.14E-17	5.75E-17	4.68E-17	3.60E-17
Lower torso	0.005	Male	4.00E-15	2.91E-15	1.15E-15	9.33E-16	6.70E-16	4.00E-16	1.21E-15	9.89E-16	8.16E-16	1.45E-15	1.18E-15	5.90E-16
		Female	3.04E-15	2.36E-15	1.35E-15	7.27E-16	6.27E-16	2.95E-16	1.69E-15	1.42E-15	1.11E-15	1.12E-15	1.03E-15	5.47E-16
	0.1	Male	1.04E-15	8.71E-16	4.54E-16	3.41E-16	2.73E-16	1.74E-16	4.96E-16	4.26E-16	3.70E-16	4.89E-16	4.26E-16	2.51E-16
		Female	9.26E-16	7.82E-16	5.11E-16	2.94E-16	2.59E-16	1.40E-16	6.63E-16	5.72E-16	4.76E-16	4.41E-16	4.05E-16	2.47E-16
	0.3	Male	2.41E-16	2.20E-16	1.42E-16	9.96E-17	8.52E-17	6.07E-17	1.46E-16	1.33E-16	1.20E-16	1.31E-16	1.18E-16	7.94E-17
		Female	2.28E-16	2.05E-16	1.50E-16	9.21E-17	8.13E-17	5.20E-17	1.75E-16	1.57E-16	1.41E-16	1.22E-16	1.13E-16	7.91E-17
	1	Male	2.89E-17	2.78E-17	2.12E-17	1.45E-17	1.31E-17	9.92E-18	2.05E-17	1.88E-17	1.77E-17	1.83E-17	1.70E-17	1.31E-17
		Female	2.86E-17	2.68E-17	2.15E-17	1.34E-17	1.23E-17	8.87E-18	2.28E-17	2.13E-17	1.96E-17	1.75E-17	1.64E-17	1.29E-17
	1.5	Male	1.33E-17	1.27E-17	1.01E-17	6.93E-18	6.29E-18	4.90E-18	9.56E-18	8.90E-18	8.56E-18	8.67E-18	8.10E-18	6.41E-18
		Female	1.32E-17	1.27E-17	1.03E-17	6.58E-18	5.97E-18	4.44E-18	1.06E-17	9.88E-18	9.36E-18	8.36E-18	7.79E-18	6.38E-18
	3	Male	3.41E-18	3.34E-18	2.74E-18	1.82E-18	1.67E-18	1.34E-18	2.54E-18	2.33E-18	2.23E-18	2.25E-18	2.09E-18	1.74E-18
		Female	3.45E-18	3.31E-18	2.71E-18	1.75E-18	1.61E-18	1.28E-18	2.75E-18	2.59E-18	2.40E-18	2.22E-18	2.02E-18	1.76E-18
Middle torso	0.005	Male	4.36E-16	3.62E-16	2.86E-16	2.09E-16	1.72E-16	1.41E-16	3.01E-16	2.57E-16	2.06E-16	4.16E-16	3.44E-16	2.80E-16
		Female	3.78E-16	3.48E-16	2.50E-16	1.75E-16	1.51E-16	1.22E-16	2.63E-16	2.28E-16	1.74E-16	3.79E-16	3.47E-16	2.78E-16
	0.1	Male	3.65E-16	2.94E-16	2.25E-16	1.70E-16	1.46E-16	1.13E-16	2.30E-16	1.92E-16	1.57E-16	2.77E-16	2.33E-16	1.91E-16
		Female	3.74E-16	3.27E-16	2.14E-16	1.55E-16	1.30E-16	9.31E-17	2.51E-16	2.18E-16	1.66E-16	2.94E-16	2.55E-16	2.02E-16
	0.3	Male	1.68E-16	1.44E-16	1.11E-16	8.00E-17	6.88E-17	5.29E-17	1.07E-16	9.35E-17	8.17E-17	1.05E-16	9.14E-17	7.36E-17
		Female	1.70E-16	1.55E-16	1.12E-16	7.42E-17	6.76E-17	4.59E-17	1.24E-16	1.10E-16	9.27E-17	1.11E-16	9.84E-17	7.75E-17
Upper torso	0.005	Male	4.49E-17	4.21E-17	3.45E-17	4.14E-17	3.65E-17	2.92E-17	3.02E-17	2.76E-17	2.13E-17	4.47E-17	4.08E-17	3.25E-17
		Female	3.30E-17	3.35E-17	2.30E-17	1.59E-17	1.39E-17	1.01E-17	2.23E-17	2.22E-17	1.73E-17	1.74E-17	1.65E-17	1.20E-17
	0.1	Male	6.90E-17	5.86E-17	4.22E-17	2.12E-17	1.89E-17	1.54E-17	4.51E-17	3.77E-17	2.89E-17	2.26E-17	2.02E-17	1.73E-17
		Female	6.39E-17	5.70E-17	2.73E-17	2.17E-17	1.76E-17	1.06E-17	5.03E-17	4.42E-17	3.20E-17	5.02E-17	4.22E-17	2.40E-17
	0.3	Male	8.60E-17	7.07E-17	5.36E-17	3.88E-17	3.14E-17	2.03E-17	5.50E-17	4.53E-17	3.70E-17	5.13E-17	4.25E-17	2.88E-17
		Female	8.76E-17	7.84E-17	5.18E-17	3.47E-17	2.99E-17	1.90E-17	6.25E-17	5.56E-17	4.33E-17	5.25E-17	4.51E-17	3.24E-17

Table J.5. ^{192}Ir: Large intestine absorbed dose per source disintegration (Gy s^{-1} Bq^{-1}).

Level	Distance (m)	Gender	Direction											
			Anterior			Right lateral			Posterior			Left lateral		
			10%ile	MRCP	90%ile	10%ile	MRCP	90%ile	10%ile	MRCP	90%ile	10%ile	MRCP	90%ile
Ground	0.005	Male	7.38E-18	6.19E-18	3.58E-18	1.31E-18	1.18E-18	1.00E-18	3.93E-18	3.04E-18	2.32E-18	1.25E-18	1.25E-18	9.12E-19
		Female	1.62E-17	1.13E-17	9.16E-18	6.01E-18	4.17E-18	3.47E-18	7.20E-18	3.62E-18	3.60E-18	5.05E-18	3.70E-18	3.09E-18
	0.1	Male	1.17E-17	9.27E-18	5.41E-18	1.50E-18	1.19E-18	1.01E-18	5.69E-18	4.51E-18	3.51E-18	2.45E-18	2.05E-18	1.20E-18
		Female	2.17E-17	1.56E-17	1.21E-17	3.65E-18	2.59E-18	2.47E-18	1.01E-17	6.97E-18	5.76E-18	4.37E-18	3.11E-18	2.69E-18
	0.3	Male	1.65E-17	1.38E-17	7.62E-18	3.69E-18	2.69E-18	1.88E-18	8.16E-18	6.19E-18	5.20E-18	6.93E-18	5.35E-18	2.58E-18
		Female	2.71E-17	2.14E-17	1.50E-17	5.40E-18	3.77E-18	3.43E-18	1.35E-17	1.00E-17	8.33E-18	7.01E-18	4.54E-18	4.07E-18
Middle thigh	0.005	Male	6.37E-17	5.42E-17	4.96E-17	1.92E-17	1.63E-17	1.21E-17	7.97E-17	6.45E-17	5.79E-17	1.98E-17	1.70E-17	1.27E-17
		Female	2.66E-16	2.21E-16	1.93E-16	7.37E-17	5.98E-17	4.60E-17	2.43E-16	2.00E-16	1.71E-16	8.17E-17	6.71E-17	5.44E-17
	0.1	Male	9.58E-17	8.24E-17	5.40E-17	3.02E-17	2.25E-17	1.86E-17	7.76E-17	6.66E-17	5.68E-17	4.32E-17	3.03E-17	2.13E-17
		Female	2.74E-16	2.38E-16	1.64E-16	7.54E-17	5.84E-17	4.85E-17	1.69E-16	1.44E-16	1.20E-16	8.67E-17	6.52E-17	5.60E-17
	0.3	Male	9.36E-17	8.34E-17	5.13E-17	3.85E-17	3.05E-17	2.20E-17	5.87E-17	4.86E-17	4.21E-17	4.80E-17	4.13E-17	2.64E-17
		Female	1.62E-16	1.50E-16	1.03E-16	5.56E-17	4.43E-17	3.60E-17	8.24E-17	6.98E-17	5.96E-17	6.17E-17	4.83E-17	4.06E-17
Lower torso	0.005	Male	1.57E-15	1.28E-15	7.02E-16	1.57E-15	1.12E-15	5.81E-16	8.38E-16	6.98E-16	5.75E-16	1.40E-15	1.18E-15	5.93E-16
		Female	4.40E-15	3.14E-15	1.72E-15	1.34E-15	1.21E-15	5.09E-16	1.25E-15	1.01E-15	7.95E-16	1.48E-15	1.38E-15	6.73E-16
	0.1	Male	8.19E-16	6.89E-16	3.86E-16	4.48E-16	3.73E-16	2.28E-16	4.42E-16	3.78E-16	3.29E-16	5.16E-16	4.63E-16	2.81E-16
		Female	1.11E-15	9.38E-16	6.12E-16	4.13E-16	3.83E-16	2.02E-16	5.27E-16	4.45E-16	3.69E-16	4.36E-16	4.12E-16	2.50E-16
	0.3	Male	2.21E-16	2.00E-16	1.37E-16	1.20E-16	1.05E-16	7.52E-17	1.43E-16	1.25E-16	1.14E-16	1.40E-16	1.27E-16	9.20E-17
		Female	2.55E-16	2.34E-16	1.76E-16	1.14E-16	1.05E-16	6.63E-17	1.52E-16	1.34E-16	1.19E-16	1.16E-16	1.07E-16	7.53E-17
	1	Male	2.84E-17	2.65E-17	2.16E-17	1.63E-17	1.47E-17	1.18E-17	2.07E-17	1.90E-17	1.79E-17	1.89E-17	1.79E-17	1.44E-17
		Female	3.04E-17	2.96E-17	2.45E-17	1.58E-17	1.48E-17	1.07E-17	2.04E-17	1.89E-17	1.80E-17	1.62E-17	1.52E-17	1.21E-17
	1.5	Male	1.33E-17	1.26E-17	1.04E-17	7.58E-18	7.04E-18	5.69E-18	9.78E-18	8.77E-18	8.71E-18	8.75E-18	8.31E-18	6.97E-18
		Female	1.41E-17	1.41E-17	1.14E-17	7.50E-18	7.07E-18	5.39E-18	9.65E-18	9.08E-18	8.35E-18	7.71E-18	7.30E-18	5.85E-18
	3	Male	3.31E-18	3.29E-18	2.86E-18	2.03E-18	1.87E-18	1.56E-18	2.54E-18	2.34E-18	2.32E-18	2.29E-18	2.15E-18	1.88E-18
		Female	3.67E-18	3.57E-18	3.06E-18	1.99E-18	1.89E-18	1.43E-18	2.49E-18	2.29E-18	2.22E-18	2.03E-18	1.94E-18	1.62E-18
Middle torso	0.005	Male	6.25E-16	5.24E-16	4.22E-16	3.37E-16	2.72E-16	2.34E-16	2.98E-16	2.50E-16	1.98E-16	7.78E-16	6.33E-16	5.32E-16
		Female	2.26E-16	2.12E-16	1.67E-16	1.61E-16	1.52E-16	1.32E-16	1.59E-16	1.39E-16	1.07E-16	1.55E-16	1.45E-16	1.17E-16
	0.1	Male	4.54E-16	3.80E-16	3.03E-16	2.66E-16	2.23E-16	1.83E-16	2.28E-16	1.89E-16	1.55E-16	4.08E-16	3.49E-16	2.94E-16
		Female	3.49E-16	2.99E-16	1.92E-16	1.91E-16	1.72E-16	1.18E-16	1.81E-16	1.52E-16	1.20E-16	1.90E-16	1.62E-16	1.24E-16
	0.3	Male	1.72E-16	1.51E-16	1.26E-16	1.02E-16	8.87E-17	7.33E-17	1.04E-16	9.03E-17	8.05E-17	1.23E-16	1.10E-16	9.37E-17
		Female	1.81E-16	1.72E-16	1.19E-16	9.07E-17	8.49E-17	5.82E-17	1.01E-16	8.90E-17	7.37E-17	9.27E-17	8.29E-17	6.18E-17
Upper torso	0.005	Male	6.23E-17	5.69E-17	4.83E-17	5.13E-17	4.47E-17	3.65E-17	3.96E-17	3.50E-17	2.73E-17	5.81E-17	5.24E-17	4.31E-17
		Female	2.21E-17	2.26E-17	1.55E-17	1.16E-17	1.05E-17	7.70E-18	1.39E-17	1.37E-17	1.05E-17	1.06E-17	1.00E-17	7.20E-18
	0.1	Male	9.74E-17	8.23E-17	5.74E-17	2.58E-17	2.24E-17	1.84E-17	5.46E-17	4.54E-17	3.52E-17	2.74E-17	2.43E-17	2.00E-17
		Female	5.57E-17	4.62E-17	1.96E-17	3.24E-17	2.82E-17	1.28E-17	3.50E-17	2.92E-17	2.21E-17	4.14E-17	3.52E-17	2.13E-17
	0.3	Male	9.66E-17	8.37E-17	6.62E-17	5.46E-17	4.69E-17	3.03E-17	5.64E-17	4.70E-17	3.84E-17	7.18E-17	6.09E-17	4.39E-17
		Female	9.21E-17	8.46E-17	5.30E-17	4.39E-17	3.93E-17	2.48E-17	5.02E-17	4.34E-17	3.38E-17	4.33E-17	3.76E-17	2.64E-17

Table J.6. ^{137}Cs: RBM absorbed dose per source disintegration (Gy s^{-1} Bq^{-1}).

Level	Distance (m)	Gender	Direction											
			Anterior			Right lateral			Posterior			Left lateral		
			10%ile	MRCP	90%ile	10%ile	MRCP	90%ile	10%ile	MRCP	90%ile	10%ile	MRCP	90%ile
Ground	0.005	Male	3.19E-18	2.57E-18	1.82E-18	1.12E-18	9.19E-19	6.81E-19	2.42E-18	1.96E-18	1.32E-18	1.22E-18	1.03E-18	7.24E-19
		Female	5.08E-18	3.66E-18	2.80E-18	2.18E-18	1.46E-18	1.21E-18	2.85E-18	1.64E-18	1.47E-18	2.27E-18	1.53E-18	1.23E-18
	0.1	Male	4.91E-18	3.76E-18	2.52E-18	1.74E-18	1.34E-18	8.89E-19	5.09E-18	3.90E-18	2.74E-18	1.95E-18	1.54E-18	1.01E-18
		Female	6.93E-18	5.02E-18	3.70E-18	2.24E-18	1.51E-18	1.20E-18	5.89E-18	3.88E-18	2.86E-18	2.57E-18	1.73E-18	1.35E-18
	0.3	Male	7.04E-18	5.46E-18	3.87E-18	3.43E-18	2.60E-18	1.64E-18	8.31E-18	6.43E-18	5.00E-18	3.48E-18	2.73E-18	1.74E-18
		Female	9.23E-18	7.02E-18	5.10E-18	4.51E-18	3.13E-18	2.03E-18	9.83E-18	7.34E-18	5.59E-18	4.72E-18	3.28E-18	2.30E-18
Middle thigh	0.005	Male	6.03E-17	5.06E-17	4.20E-17	3.25E-17	2.81E-17	2.08E-17	6.54E-17	5.29E-17	4.46E-17	3.23E-17	2.83E-17	2.15E-17
		Female	1.06E-16	8.65E-17	7.11E-17	5.38E-17	4.36E-17	3.39E-17	1.02E-16	8.35E-17	6.89E-17	5.61E-17	4.58E-17	3.69E-17
	0.1	Male	6.00E-17	4.92E-17	3.91E-17	3.73E-17	3.03E-17	2.21E-17	6.82E-17	5.58E-17	4.63E-17	3.68E-17	3.12E-17	2.22E-17
		Female	8.91E-17	7.44E-17	5.73E-17	5.26E-17	4.26E-17	3.15E-17	9.03E-17	7.55E-17	5.92E-17	5.30E-17	4.23E-17	3.31E-17
	0.3	Male	4.22E-17	3.67E-17	2.71E-17	2.45E-17	2.04E-17	1.57E-17	4.83E-17	4.20E-17	3.58E-17	2.43E-17	2.04E-17	1.55E-17
		Female	5.37E-17	4.71E-17	3.39E-17	3.15E-17	2.67E-17	2.03E-17	5.57E-17	4.89E-17	3.98E-17	3.14E-17	2.60E-17	2.03E-17
Lower torso	0.005	Male	3.77E-16	2.85E-16	1.41E-16	3.34E-16	2.58E-16	1.45E-16	9.16E-16	7.77E-16	6.50E-16	3.12E-16	2.59E-16	1.36E-16
		Female	4.51E-16	3.42E-16	2.11E-16	3.48E-16	3.10E-16	1.48E-16	9.50E-16	8.16E-16	6.24E-16	3.25E-16	2.92E-16	1.59E-16
	0.1	Male	1.88E-16	1.57E-16	8.83E-17	1.65E-16	1.36E-16	8.96E-17	3.44E-16	3.08E-16	2.71E-16	1.59E-16	1.36E-16	8.59E-17
		Female	2.24E-16	1.88E-16	1.19E-16	1.72E-16	1.55E-16	9.04E-17	3.57E-16	3.20E-16	2.66E-16	1.63E-16	1.47E-16	9.49E-17
	0.3	Male	7.83E-17	6.87E-17	4.48E-17	5.83E-17	5.00E-17	3.80E-17	1.09E-16	1.00E-16	9.21E-17	5.40E-17	4.68E-17	3.33E-17
		Female	8.55E-17	7.65E-17	5.32E-17	6.08E-17	5.52E-17	3.84E-17	1.11E-16	1.04E-16	9.09E-17	5.73E-17	5.14E-17	3.76E-17
	1	Male	1.40E-17	1.30E-17	1.01E-17	9.71E-18	8.74E-18	7.35E-18	1.68E-17	1.59E-17	1.53E-17	9.54E-18	8.65E-18	7.11E-18
		Female	1.48E-17	1.38E-17	1.10E-17	1.03E-17	9.45E-18	7.65E-18	1.70E-17	1.62E-17	1.52E-17	1.02E-17	9.33E-18	7.71E-18
	1.5	Male	6.85E-18	6.48E-18	5.23E-18	4.74E-18	4.29E-18	3.72E-18	8.02E-18	7.67E-18	7.43E-18	4.67E-18	4.26E-18	3.65E-18
		Female	7.16E-18	6.78E-18	5.57E-18	5.05E-18	4.64E-18	3.88E-18	8.10E-18	7.75E-18	7.34E-18	4.98E-18	4.56E-18	3.92E-18
	3	Male	1.86E-18	1.77E-18	1.49E-18	1.29E-18	1.18E-18	1.05E-18	2.10E-18	2.05E-18	1.98E-18	1.27E-18	1.17E-18	1.02E-18
		Female	1.92E-18	1.84E-18	1.57E-18	1.37E-18	1.27E-18	1.11E-18	2.13E-18	2.04E-18	1.96E-18	1.35E-18	1.26E-18	1.11E-18
Middle torso	0.005	Male	4.31E-16	3.10E-16	2.12E-16	5.16E-16	3.82E-16	2.91E-16	8.66E-16	7.41E-16	5.99E-16	4.33E-16	3.39E-16	2.53E-16
		Female	5.89E-16	5.13E-16	2.45E-16	6.99E-16	5.79E-16	3.79E-16	1.19E-15	9.88E-16	6.92E-16	6.29E-16	4.88E-16	3.58E-16
	0.1	Male	1.85E-16	1.51E-16	1.10E-16	1.67E-16	1.42E-16	1.12E-16	3.09E-16	2.76E-16	2.37E-16	1.50E-16	1.30E-16	1.02E-16
		Female	2.33E-16	2.05E-16	1.26E-16	1.95E-16	1.66E-16	1.26E-16	3.57E-16	3.18E-16	2.58E-16	1.94E-16	1.63E-16	1.29E-16
	0.3	Male	7.63E-17	6.68E-17	5.11E-17	5.84E-17	5.12E-17	4.15E-17	1.05E-16	9.65E-17	8.78E-17	5.31E-17	4.59E-17	3.57E-17
		Female	9.10E-17	8.35E-17	5.77E-17	6.66E-17	5.89E-17	4.65E-17	1.14E-16	1.05E-16	9.23E-17	6.43E-17	5.60E-17	4.43E-17
Upper torso	0.005	Male	5.35E-16	4.42E-16	3.70E-16	5.67E-16	4.38E-16	3.64E-16	6.09E-16	4.60E-16	3.75E-16	5.46E-16	4.41E-16	3.63E-16
		Female	6.86E-16	5.87E-16	4.81E-16	5.10E-16	3.42E-16	2.48E-16	7.45E-16	5.79E-16	4.63E-16	3.52E-16	2.60E-16	1.70E-16
	0.1	Male	2.31E-16	2.02E-16	1.75E-16	3.09E-16	2.59E-16	2.30E-16	2.51E-16	2.13E-16	1.82E-16	2.72E-16	2.32E-16	2.13E-16
		Female	2.74E-16	2.48E-16	2.06E-16	1.31E-16	1.04E-16	8.29E-17	2.77E-16	2.40E-16	2.03E-16	1.08E-16	8.85E-17	6.62E-17
	0.3	Male	7.83E-17	7.05E-17	6.07E-17	6.49E-17	5.66E-17	4.85E-17	9.50E-17	8.51E-17	7.61E-17	5.50E-17	4.83E-17	4.32E-17
		Female	8.95E-17	8.34E-17	6.71E-17	4.99E-17	4.22E-17	3.37E-17	9.82E-17	8.96E-17	7.97E-17	4.58E-17	3.94E-17	3.08E-17

Table J.7. $^{137}Cs/^{137m}Ba$: Brain absorbed dose per source disintegration (unit: Gy s^{-1} Bq^{-1}).

Level	Distance (m)	Gender	Anterior			Right lateral			Posterior			Left lateral		
			10%ile	MRCP	90%ile	10%ile	MRCP	90%ile	10%ile	MRCP	90%ile	10%ile	MRCP	90%ile
Ground	0.005	Male	2.96E-19	1.57E-19	6.01E-20	5.21E-20	4.35E-20	3.11E-20	8.87E-20	6.46E-20	4.30E-20	6.04E-20	4.84E-20	3.49E-20
		Female	1.40E-18	7.77E-19	1.06E-19	6.67E-20	4.95E-20	3.47E-20	9.02E-20	5.83E-20	4.08E-20	6.67E-20	5.11E-20	3.40E-20
	0.1	Male	9.55E-19	4.85E-19	1.18E-19	1.03E-19	7.30E-20	4.94E-20	3.80E-19	2.05E-19	1.05E-19	1.17E-19	8.28E-20	4.88E-20
		Female	2.74E-18	1.88E-18	5.05E-19	1.48E-19	8.12E-20	4.75E-20	3.17E-19	1.61E-19	7.95E-20	2.00E-19	8.69E-20	5.88E-20
	0.3	Male	2.72E-18	1.84E-18	1.01E-18	8.40E-19	3.98E-19	1.18E-19	1.96E-18	1.18E-18	6.51E-19	7.71E-19	4.16E-19	1.45E-19
		Female	4.79E-18	3.86E-18	1.87E-18	2.02E-18	1.04E-18	1.61E-19	1.67E-18	9.42E-19	5.54E-19	2.04E-18	9.88E-19	2.21E-19
Middle thigh	0.005	Male	1.84E-19	1.64E-19	1.30E-19	1.42E-19	9.49E-20	7.35E-20	2.65E-19	1.81E-19	1.52E-19	1.29E-19	8.40E-20	6.43E-20
		Female	5.37E-19	4.19E-19	2.40E-19	2.73E-19	2.18E-19	1.37E-19	3.94E-19	3.51E-19	2.32E-19	2.32E-19	1.99E-19	1.20E-19
	0.1	Male	2.46E-18	1.21E-18	3.06E-19	1.10E-18	5.90E-19	3.32E-19	2.35E-18	1.23E-18	8.37E-19	1.53E-18	7.19E-19	3.67E-19
		Female	8.49E-18	6.67E-18	1.79E-18	4.16E-18	2.90E-18	7.28E-19	2.89E-18	2.11E-18	1.34E-18	3.64E-18	2.20E-18	6.77E-19
	0.3	Male	9.41E-18	7.74E-18	5.23E-18	4.01E-18	2.88E-18	1.80E-18	9.32E-18	6.63E-18	4.70E-18	3.11E-18	2.16E-18	1.46E-18
		Female	1.48E-17	1.36E-17	8.70E-18	7.70E-18	6.06E-18	3.07E-18	9.47E-18	6.67E-18	4.57E-18	7.84E-18	6.30E-18	3.13E-18
Lower torso	0.005	Male	3.44E-18	2.97E-18	2.30E-18	4.85E-18	4.95E-18	3.03E-18	2.74E-18	2.44E-18	1.71E-18	4.56E-18	3.47E-18	2.71E-18
		Female	1.32E-17	1.11E-17	3.73E-18	7.78E-18	6.79E-18	3.88E-18	4.64E-18	4.27E-18	3.00E-18	7.71E-18	5.31E-18	3.75E-18
	0.1	Male	2.44E-17	2.11E-17	1.73E-17	1.18E-17	9.56E-18	7.78E-18	1.70E-17	1.23E-17	7.25E-18	9.25E-18	7.74E-18	6.25E-18
		Female	3.57E-17	3.29E-17	1.98E-17	1.90E-17	1.61E-17	9.15E-18	1.37E-17	1.03E-17	6.63E-18	1.89E-17	1.59E-17	9.44E-18
	0.3	Male	2.44E-17	2.25E-17	1.81E-17	1.97E-17	1.49E-17	1.07E-17	2.99E-17	2.73E-17	2.28E-17	1.66E-17	1.17E-17	8.98E-18
		Female	3.24E-17	2.94E-17	2.51E-17	2.23E-17	1.78E-17	1.31E-17	2.96E-17	2.64E-17	2.02E-17	2.29E-17	1.88E-17	1.34E-17
	1	Male	9.82E-18	9.33E-18	7.96E-18	1.11E-17	1.06E-17	9.53E-18	1.11E-17	1.07E-17	9.98E-18	1.08E-17	1.03E-17	9.26E-18
		Female	1.13E-17	1.08E-17	9.61E-18	1.14E-17	1.12E-17	9.90E-18	1.13E-17	1.09E-17	1.03E-17	1.15E-17	1.11E-17	9.96E-18
	1.5	Male	5.40E-18	5.18E-18	4.80E-18	6.07E-18	5.82E-18	5.48E-18	5.86E-18	5.65E-18	5.63E-18	6.04E-18	5.81E-18	5.30E-18
		Female	5.92E-18	5.61E-18	5.27E-18	6.20E-18	6.19E-18	5.60E-18	5.96E-18	5.76E-18	5.62E-18	6.21E-18	6.08E-18	5.76E-18
	3	Male	1.54E-18	1.53E-18	1.47E-18	1.78E-18	1.74E-18	1.71E-18	1.70E-18	1.72E-18	1.67E-18	1.82E-18	1.76E-18	1.67E-18
		Female	1.67E-18	1.64E-18	1.56E-18	1.83E-18	1.80E-18	1.75E-18	1.73E-18	1.70E-18	1.71E-18	1.83E-18	1.81E-18	1.74E-18
Middle torso	0.005	Male	6.12E-17	5.77E-17	3.63E-17	2.86E-17	2.44E-17	1.99E-17	2.05E-17	1.79E-17	1.36E-17	2.61E-17	2.27E-17	1.75E-17
		Female	6.31E-17	6.55E-17	3.31E-17	3.84E-17	3.54E-17	2.59E-17	2.51E-17	2.28E-17	1.81E-17	3.71E-17	3.31E-17	2.50E-17
	0.1	Male	6.29E-17	5.71E-17	4.86E-17	3.13E-17	2.49E-17	1.92E-17	7.57E-17	6.73E-17	5.45E-17	2.59E-17	2.08E-17	1.56E-17
		Female	8.67E-17	8.11E-17	6.89E-17	3.57E-17	2.79E-17	2.08E-17	6.99E-17	6.06E-17	4.73E-17	4.03E-17	3.04E-17	2.48E-17
	0.3	Male	4.42E-17	3.97E-17	3.41E-17	5.20E-17	4.74E-17	4.08E-17	5.31E-17	5.04E-17	4.50E-17	4.81E-17	4.37E-17	3.58E-17
		Female	6.09E-17	5.66E-17	4.78E-17	5.71E-17	4.97E-17	4.05E-17	5.70E-17	5.46E-17	4.89E-17	5.53E-17	4.79E-17	3.77E-17
Upper torso	0.005	Male	3.42E-16	3.23E-16	2.98E-16	3.81E-16	3.80E-16	3.45E-16	3.85E-16	3.68E-16	3.34E-16	3.43E-16	3.32E-16	3.01E-16
		Female	5.20E-16	5.05E-16	4.78E-16	3.80E-16	3.20E-16	2.76E-16	4.64E-16	4.26E-16	3.84E-16	3.42E-16	2.84E-16	2.36E-16
	0.1	Male	2.30E-16	2.09E-16	1.86E-16	3.15E-16	2.82E-16	2.59E-16	2.89E-16	2.60E-16	2.36E-16	2.69E-16	2.42E-16	2.20E-16
		Female	3.79E-16	3.45E-16	3.17E-16	2.18E-16	1.87E-16	1.63E-16	2.91E-16	2.60E-16	2.37E-16	1.99E-16	1.73E-16	1.46E-16
	0.3	Male	1.04E-16	9.66E-17	9.05E-17	1.19E-16	1.09E-16	1.03E-16	1.04E-16	9.62E-17	9.14E-17	1.04E-16	9.69E-17	9.13E-17
		Female	1.36E-16	1.30E-16	1.24E-16	8.58E-17	7.62E-17	7.02E-17	9.89E-17	9.21E-17	8.64E-17	7.96E-17	7.25E-17	6.50E-17

Table J.8. ^{137}Cs/^{137m}Ba: Lung absorbed dose per source disintegration (unit: Gy s^{-1} Bq^{-1}).

Level	Distance (m)	Gender	Direction											
			Anterior			Right lateral			Posterior			Left lateral		
			10%ile	MRCP	90%ile	10%ile	MRCP	90%ile	10%ile	MRCP	90%ile	10%ile	MRCP	90%ile
Ground	0.005	Male	9.67E-19	7.98E-19	4.08E-19	2.13E-19	1.67E-19	1.20E-19	5.18E-19	3.90E-19	2.35E-19	2.75E-19	2.27E-19	1.36E-19
		Female	8.72E-19	6.66E-19	4.44E-19	2.51E-19	1.90E-19	1.38E-19	5.94E-19	3.30E-19	2.52E-19	2.61E-19	1.96E-19	1.47E-19
	0.1	Male	1.83E-18	1.42E-18	6.49E-19	4.51E-19	2.95E-19	1.81E-19	1.81E-18	1.12E-18	7.49E-19	7.91E-19	5.08E-19	2.36E-19
		Female	1.87E-18	1.31E-18	7.49E-19	4.17E-19	2.88E-19	2.04E-19	2.20E-18	1.25E-18	7.06E-19	4.92E-19	3.26E-19	2.30E-19
	0.3	Male	3.61E-18	2.67E-18	1.31E-18	2.08E-18	1.29E-18	5.93E-19	4.94E-18	3.57E-18	2.59E-18	2.88E-18	1.94E-18	8.58E-19
		Female	4.65E-18	3.46E-18	1.67E-18	3.06E-18	1.78E-18	6.93E-19	7.49E-18	5.31E-18	3.50E-18	3.20E-18	1.81E-18	7.92E-19
Middle thigh	0.005	Male	2.78E-18	2.44E-18	2.17E-18	1.30E-18	9.79E-19	7.31E-19	3.62E-18	2.71E-18	2.35E-18	1.45E-18	9.86E-19	7.39E-19
		Female	4.64E-18	4.41E-18	3.50E-18	2.53E-18	2.20E-18	1.57E-18	5.62E-18	5.15E-18	3.86E-18	2.46E-18	2.17E-18	1.58E-18
	0.1	Male	9.08E-18	7.48E-18	3.73E-18	5.81E-18	3.85E-18	2.40E-18	1.57E-17	1.07E-17	8.60E-18	1.07E-17	6.22E-18	3.37E-18
		Female	1.31E-17	1.07E-17	5.10E-18	1.47E-17	1.12E-17	4.94E-18	2.77E-17	2.17E-17	1.49E-17	1.43E-17	9.98E-18	4.69E-18
	0.3	Male	1.70E-17	1.35E-17	8.71E-18	1.43E-17	1.17E-17	8.26E-18	2.48E-17	2.06E-17	1.63E-17	1.50E-17	1.24E-17	8.87E-18
		Female	2.66E-17	2.23E-17	1.34E-17	2.11E-17	1.77E-17	1.16E-17	3.48E-17	3.07E-17	2.37E-17	1.97E-17	1.68E-17	1.15E-17
Lower torso	0.005	Male	8.16E-17	7.11E-17	4.70E-17	7.10E-17	6.79E-17	4.22E-17	8.59E-17	8.03E-17	6.17E-17	8.25E-17	7.03E-17	4.88E-17
		Female	8.28E-17	7.71E-17	5.75E-17	9.09E-17	8.14E-17	4.72E-17	1.21E-16	1.13E-16	8.62E-17	9.17E-17	7.50E-17	4.97E-17
	0.1	Male	9.50E-17	7.97E-17	6.11E-17	9.80E-17	8.42E-17	6.30E-17	1.35E-16	1.17E-16	9.32E-17	1.08E-16	9.34E-17	7.04E-17
		Female	1.19E-16	1.03E-16	6.80E-17	1.14E-16	1.06E-16	7.15E-17	1.61E-16	1.44E-16	1.13E-16	1.14E-16	1.02E-16	7.35E-17
	0.3	Male	7.38E-17	6.37E-17	4.54E-17	5.10E-17	4.43E-17	3.49E-17	8.40E-17	7.51E-17	6.66E-17	4.97E-17	4.45E-17	3.43E-17
		Female	7.52E-17	6.83E-17	4.84E-17	5.77E-17	5.28E-17	3.77E-17	9.69E-17	8.93E-17	7.55E-17	5.36E-17	4.82E-17	3.65E-17
	1	Male	1.58E-17	1.49E-17	1.17E-17	9.46E-18	8.68E-18	7.31E-18	1.63E-17	1.51E-17	1.42E-17	9.70E-18	9.04E-18	7.45E-18
		Female	1.52E-17	1.43E-17	1.08E-17	1.08E-17	9.80E-18	7.90E-18	1.76E-17	1.69E-17	1.61E-17	1.04E-17	9.68E-18	7.90E-18
	1.5	Male	7.74E-18	7.40E-18	6.13E-18	4.62E-18	4.29E-18	3.63E-18	7.74E-18	7.29E-18	7.16E-18	4.69E-18	4.41E-18	3.74E-18
		Female	7.53E-18	7.09E-18	5.56E-18	5.16E-18	4.75E-18	4.02E-18	8.52E-18	8.07E-18	7.82E-18	5.07E-18	4.77E-18	3.94E-18
	3	Male	2.09E-18	2.02E-18	1.80E-18	1.25E-18	1.19E-18	1.01E-18	2.12E-18	1.95E-18	1.92E-18	1.26E-18	1.18E-18	1.02E-18
		Female	2.06E-18	2.00E-18	1.58E-18	1.40E-18	1.29E-18	1.13E-18	2.25E-18	2.17E-18	2.12E-18	1.37E-18	1.28E-18	1.10E-18
Middle torso	0.005	Male	9.04E-16	6.79E-16	4.93E-16	1.09E-15	8.32E-16	6.41E-16	1.06E-15	8.99E-16	7.23E-16	1.27E-15	9.92E-16	7.41E-16
		Female	1.14E-15	9.71E-16	5.51E-16	1.56E-15	1.30E-15	9.32E-16	1.51E-15	1.26E-15	9.55E-16	1.65E-15	1.27E-15	9.29E-16
	0.1	Male	3.99E-16	3.25E-16	2.35E-16	3.17E-16	2.67E-16	2.24E-16	4.43E-16	3.87E-16	3.32E-16	3.11E-16	2.77E-16	2.29E-16
		Female	4.41E-16	3.88E-16	2.35E-16	3.85E-16	3.18E-16	2.57E-16	5.60E-16	4.86E-16	4.01E-16	3.78E-16	3.17E-16	2.62E-16
	0.3	Male	1.19E-16	1.07E-16	8.34E-17	7.59E-17	6.85E-17	5.81E-17	1.25E-16	1.14E-16	1.04E-16	7.33E-17	6.64E-17	5.42E-17
		Female	1.22E-16	1.14E-16	7.61E-17	9.09E-17	8.03E-17	6.72E-17	1.47E-16	1.35E-16	1.21E-16	8.69E-17	7.57E-17	6.26E-17
Upper torso	0.005	Male	8.00E-16	6.68E-16	5.56E-16	9.41E-16	7.65E-16	6.40E-16	7.38E-16	6.03E-16	4.90E-16	8.25E-16	6.82E-16	5.66E-16
		Female	9.52E-16	8.21E-16	6.35E-16	3.99E-16	3.05E-16	2.30E-16	8.76E-16	7.42E-16	5.94E-16	3.10E-16	2.49E-16	1.76E-16
	0.1	Male	4.84E-16	4.21E-16	3.61E-16	3.50E-16	2.92E-16	2.59E-16	4.24E-16	3.49E-16	2.98E-16	2.81E-16	2.36E-16	2.07E-16
		Female	4.94E-16	4.43E-16	3.51E-16	1.77E-16	1.38E-16	1.11E-16	4.62E-16	4.00E-16	3.41E-16	1.49E-16	1.18E-16	8.76E-17
	0.3	Male	1.50E-16	1.38E-16	1.23E-16	9.02E-17	7.55E-17	6.48E-17	1.33E-16	1.18E-16	1.08E-16	7.82E-17	6.66E-17	6.00E-17
		Female	1.43E-16	1.34E-16	1.11E-16	6.58E-17	5.34E-17	4.47E-17	1.42E-16	1.28E-16	1.18E-16	5.94E-17	4.99E-17	4.03E-17

Table J.9. $^{137}Cs/^{137m}Ba$: Small intestine absorbed dose per source disintegration (unit: Gy s^{-1} Bq^{-1}).

Level	Distance (m)	Gender	Direction											
			Anterior			Right lateral			Posterior			Left lateral		
			10%ile	MRCP	90%ile	10%ile	MRCP	90%ile	10%ile	MRCP	90%ile	10%ile	MRCP	90%ile
Ground	0.005	Male	7.11E-18	5.63E-18	4.38E-18	1.16E-18	1.02E-18	9.44E-19	1.54E-18	1.36E-18	8.59E-19	1.30E-18	1.13E-18	9.42E-19
		Female	1.10E-17	8.26E-18	6.65E-18	4.05E-18	2.95E-18	2.19E-18	5.45E-18	2.69E-18	2.47E-18	3.18E-18	2.20E-18	1.78E-18
	0.1	Male	1.02E-17	8.10E-18	6.02E-18	1.42E-18	1.12E-18	9.80E-19	3.30E-18	2.61E-18	1.78E-18	1.81E-18	1.43E-18	1.15E-18
		Female	1.37E-17	1.03E-17	8.18E-18	2.52E-18	1.75E-18	1.58E-18	8.34E-18	5.70E-18	4.40E-18	3.03E-18	2.13E-18	1.82E-18
	0.3	Male	1.29E-17	1.11E-17	7.54E-18	2.95E-18	2.11E-18	1.61E-18	5.86E-18	4.38E-18	3.44E-18	3.94E-18	2.84E-18	2.06E-18
		Female	1.59E-17	1.31E-17	9.44E-18	3.91E-18	2.95E-18	2.33E-18	1.07E-17	8.20E-18	6.78E-18	5.33E-18	3.64E-18	3.02E-18
Middle thigh	0.005	Male	5.33E-17	4.52E-17	4.42E-17	1.79E-17	1.53E-17	1.18E-17	4.81E-17	3.75E-17	3.30E-17	1.75E-17	1.50E-17	1.19E-17
		Female	1.54E-16	1.33E-16	1.14E-16	5.52E-17	4.54E-17	3.44E-17	1.43E-16	1.21E-16	1.01E-16	5.69E-17	4.73E-17	3.75E-17
	0.1	Male	8.87E-17	7.72E-17	5.74E-17	2.75E-17	2.08E-17	1.71E-17	5.01E-17	4.15E-17	3.47E-17	3.04E-17	2.26E-17	1.82E-17
		Female	1.52E-16	1.32E-16	9.72E-17	5.46E-17	4.39E-17	3.37E-17	1.10E-16	9.44E-17	7.72E-17	5.96E-17	4.63E-17	3.83E-17
	0.3	Male	7.34E-17	6.85E-17	4.46E-17	2.62E-17	2.10E-17	1.72E-17	3.87E-17	3.24E-17	2.73E-17	3.36E-17	2.79E-17	2.07E-17
		Female	9.39E-17	8.39E-17	5.99E-17	3.48E-17	2.76E-17	2.29E-17	6.28E-17	5.40E-17	4.44E-17	4.40E-17	3.60E-17	2.83E-17
Lower torso	0.005	Male	2.72E-15	1.98E-15	7.82E-16	6.58E-16	4.77E-16	2.85E-16	8.36E-16	6.83E-16	5.60E-16	1.01E-15	8.23E-16	4.13E-16
		Female	2.09E-15	1.62E-15	9.17E-16	5.25E-16	4.49E-16	2.14E-16	1.16E-15	9.72E-16	7.55E-16	7.97E-16	7.26E-16	3.87E-16
	0.1	Male	7.00E-16	5.88E-16	3.13E-16	2.44E-16	1.96E-16	1.26E-16	3.43E-16	2.91E-16	2.55E-16	3.40E-16	2.96E-16	1.77E-16
		Female	6.26E-16	5.29E-16	3.48E-16	2.14E-16	1.87E-16	1.04E-16	4.51E-16	3.91E-16	3.25E-16	3.11E-16	2.85E-16	1.76E-16
	0.3	Male	1.60E-16	1.45E-16	9.62E-17	7.31E-17	6.25E-17	4.47E-17	1.01E-16	8.99E-17	8.23E-17	9.24E-17	8.30E-17	5.78E-17
		Female	1.50E-16	1.38E-16	1.01E-16	6.76E-17	6.04E-17	3.98E-17	1.21E-16	1.08E-16	9.48E-17	8.86E-17	8.10E-17	5.73E-17
	1	Male	1.95E-17	1.86E-17	1.44E-17	1.08E-17	9.57E-18	7.60E-18	1.41E-17	1.29E-17	1.25E-17	1.29E-17	1.21E-17	9.61E-18
		Female	1.92E-17	1.79E-17	1.49E-17	1.03E-17	9.41E-18	7.03E-18	1.57E-17	1.46E-17	1.36E-17	1.26E-17	1.18E-17	9.69E-18
	1.5	Male	8.88E-18	8.56E-18	7.02E-18	5.13E-18	4.70E-18	3.75E-18	6.79E-18	6.18E-18	6.08E-18	6.14E-18	5.80E-18	4.69E-18
		Female	8.71E-18	8.34E-18	6.90E-18	4.99E-18	4.54E-18	3.44E-18	7.32E-18	6.76E-18	6.35E-18	6.05E-18	5.66E-18	4.64E-18
	3	Male	2.30E-18	2.19E-18	1.82E-18	1.39E-18	1.29E-18	1.04E-18	1.76E-18	1.67E-18	1.64E-18	1.60E-18	1.53E-18	1.29E-18
		Female	2.31E-18	2.19E-18	1.86E-18	1.33E-18	1.23E-18	9.63E-19	1.88E-18	1.81E-18	1.69E-18	1.60E-18	1.44E-18	1.28E-18
Middle torso	0.005	Male	3.19E-16	2.61E-16	2.09E-16	1.62E-16	1.31E-16	1.06E-16	2.22E-16	1.88E-16	1.52E-16	2.97E-16	2.48E-16	1.98E-16
		Female	2.78E-16	2.59E-16	1.83E-16	1.38E-16	1.18E-16	9.15E-17	2.00E-16	1.71E-16	1.29E-16	2.78E-16	2.50E-16	1.97E-16
	0.1	Male	2.56E-16	2.08E-16	1.59E-16	1.30E-16	1.08E-16	8.55E-17	1.63E-16	1.40E-16	1.14E-16	1.94E-16	1.64E-16	1.35E-16
		Female	2.61E-16	2.31E-16	1.52E-16	1.18E-16	1.00E-16	7.16E-17	1.80E-16	1.54E-16	1.19E-16	2.09E-16	1.84E-16	1.43E-16
	0.3	Male	1.12E-16	9.88E-17	7.79E-17	5.92E-17	5.14E-17	4.02E-17	7.43E-17	6.64E-17	5.83E-17	7.53E-17	6.63E-17	5.29E-17
		Female	1.14E-16	1.05E-16	7.70E-17	5.60E-17	5.00E-17	3.62E-17	8.55E-17	7.63E-17	6.44E-17	7.93E-17	7.10E-17	5.61E-17
Upper torso	0.005	Male	3.84E-17	3.53E-17	2.91E-17	3.49E-17	3.17E-17	2.53E-17	2.75E-17	2.43E-17	1.90E-17	3.80E-17	3.45E-17	2.86E-17
		Female	2.86E-17	2.99E-17	2.06E-17	1.62E-17	1.41E-17	1.03E-17	2.09E-17	2.03E-17	1.54E-17	1.74E-17	1.59E-17	1.19E-17
	0.1	Male	5.66E-17	4.84E-17	3.36E-17	2.03E-17	1.78E-17	1.49E-17	3.65E-17	3.11E-17	2.37E-17	2.16E-17	1.92E-17	1.61E-17
		Female	5.13E-17	4.63E-17	2.39E-17	1.98E-17	1.60E-17	1.01E-17	3.95E-17	3.47E-17	2.51E-17	4.06E-17	3.46E-17	1.98E-17
	0.3	Male	6.11E-17	5.19E-17	3.99E-17	3.16E-17	2.65E-17	1.75E-17	4.05E-17	3.43E-17	2.77E-17	3.96E-17	3.41E-17	2.36E-17
		Female	6.19E-17	5.51E-17	3.83E-17	2.79E-17	2.38E-17	1.55E-17	4.66E-17	4.02E-17	3.17E-17	3.81E-17	3.40E-17	2.47E-17

Table J.10. $^{137}Cs/^{137m}Ba$: Large intestine absorbed dose per source disintegration (unit: Gy s^{-1} Bq^{-1}).

Level	Distance (m)	Gender	Direction											
			Anterior			Right lateral			Posterior			Left lateral		
			10%ile	MRCP	90%ile	10%ile	MRCP	90%ile	10%ile	MRCP	90%ile	10%ile	MRCP	90%ile
Ground	0.005	Male	6.34E-18	5.22E-18	3.21E-18	1.20E-18	1.07E-18	8.35E-19	3.05E-18	2.41E-18	1.81E-18	1.17E-18	1.04E-18	7.55E-19
		Female	1.31E-17	9.34E-18	7.52E-18	5.36E-18	3.76E-18	2.99E-18	5.53E-18	2.91E-18	2.80E-18	4.72E-18	3.35E-18	2.68E-18
	0.1	Male	9.28E-18	7.59E-18	4.70E-18	1.44E-18	1.09E-18	8.92E-19	4.52E-18	3.57E-18	2.79E-18	2.20E-18	1.74E-18	1.07E-18
		Female	1.68E-17	1.23E-17	9.68E-18	3.46E-18	2.46E-18	2.10E-18	8.00E-18	5.51E-18	4.57E-18	4.08E-18	2.93E-18	2.31E-18
	0.3	Male	1.21E-17	1.03E-17	6.21E-18	3.52E-18	2.37E-18	1.69E-18	6.30E-18	4.87E-18	4.06E-18	5.61E-18	4.38E-18	2.29E-18
		Female	1.95E-17	1.59E-17	1.12E-17	5.15E-18	3.58E-18	2.94E-18	1.05E-17	7.79E-18	6.62E-18	6.42E-18	4.31E-18	3.57E-18
Middle thigh	0.005	Male	5.19E-17	4.39E-17	3.97E-17	1.79E-17	1.53E-17	1.14E-17	6.01E-17	4.91E-17	4.36E-17	1.86E-17	1.60E-17	1.22E-17
		Female	1.94E-16	1.62E-16	1.39E-16	6.30E-17	5.14E-17	3.93E-17	1.74E-16	1.44E-16	1.22E-16	6.98E-17	5.72E-17	4.57E-17
	0.1	Male	7.14E-17	6.29E-17	4.20E-17	2.65E-17	2.03E-17	1.66E-17	5.74E-17	4.91E-17	4.13E-17	3.56E-17	2.60E-17	1.87E-17
		Female	1.92E-16	1.67E-16	1.17E-16	6.31E-17	4.93E-17	3.95E-17	1.22E-16	1.03E-16	8.58E-17	6.97E-17	5.45E-17	4.53E-17
	0.3	Male	6.40E-17	5.79E-17	3.75E-17	2.94E-17	2.44E-17	1.77E-17	4.28E-17	3.49E-17	3.02E-17	3.56E-17	3.09E-17	2.07E-17
		Female	1.10E-16	1.03E-16	7.17E-17	4.24E-17	3.45E-17	2.83E-17	5.85E-17	5.15E-17	4.23E-17	4.69E-17	3.80E-17	3.13E-17
Lower torso	0.005	Male	1.09E-15	8.88E-16	4.90E-16	1.10E-15	7.80E-16	4.06E-16	5.91E-16	4.91E-16	4.01E-16	9.87E-16	8.22E-16	4.17E-16
		Female	3.03E-15	2.17E-15	1.16E-15	9.52E-16	8.54E-16	3.58E-16	8.70E-16	7.01E-16	5.45E-16	1.04E-15	9.65E-16	4.70E-16
	0.1	Male	5.65E-16	4.71E-16	2.65E-16	3.10E-16	2.57E-16	1.59E-16	3.10E-16	2.65E-16	2.27E-16	3.58E-16	3.16E-16	1.94E-16
		Female	7.45E-16	6.34E-16	4.14E-16	2.92E-16	2.69E-16	1.45E-16	3.62E-16	3.11E-16	2.57E-16	3.09E-16	2.89E-16	1.79E-16
	0.3	Male	1.49E-16	1.35E-16	9.27E-17	8.46E-17	7.42E-17	5.32E-17	1.00E-16	8.98E-17	7.96E-17	9.80E-17	8.89E-17	6.47E-17
		Female	1.70E-16	1.55E-16	1.17E-16	8.02E-17	7.70E-17	4.89E-17	1.05E-16	9.34E-17	8.35E-17	8.22E-17	7.71E-17	5.54E-17
	1	Male	1.90E-17	1.79E-17	1.42E-17	1.17E-17	1.05E-17	8.52E-18	1.43E-17	1.33E-17	1.24E-17	1.32E-17	1.24E-17	1.02E-17
		Female	2.05E-17	1.96E-17	1.61E-17	1.15E-17	1.07E-17	7.95E-18	1.41E-17	1.35E-17	1.23E-17	1.19E-17	1.09E-17	8.87E-18
	1.5	Male	8.70E-18	8.35E-18	7.08E-18	5.61E-18	5.18E-18	4.23E-18	6.78E-18	6.25E-18	6.04E-18	6.30E-18	5.82E-18	4.96E-18
		Female	9.30E-18	9.22E-18	7.62E-18	5.51E-18	5.32E-18	4.00E-18	6.76E-18	6.50E-18	5.87E-18	5.49E-18	5.29E-18	4.36E-18
	3	Male	2.34E-18	2.15E-18	1.87E-18	1.44E-18	1.41E-18	1.14E-18	1.85E-18	1.66E-18	1.63E-18	1.65E-18	1.51E-18	1.36E-18
		Female	2.32E-18	2.34E-18	2.02E-18	1.46E-18	1.39E-18	1.10E-18	1.78E-18	1.68E-18	1.55E-18	1.45E-18	1.44E-18	1.19E-18
Middle torso	0.005	Male	4.51E-16	3.77E-16	3.02E-16	2.51E-16	2.02E-16	1.68E-16	2.23E-16	1.87E-16	1.47E-16	5.45E-16	4.49E-16	3.70E-16
		Female	1.72E-16	1.62E-16	1.25E-16	1.30E-16	1.22E-16	9.82E-17	1.24E-16	1.11E-16	8.28E-17	1.27E-16	1.12E-16	9.28E-17
	0.1	Male	3.20E-16	2.70E-16	2.13E-16	1.90E-16	1.58E-16	1.29E-16	1.64E-16	1.37E-16	1.12E-16	2.79E-16	2.42E-16	2.03E-16
		Female	2.46E-16	2.11E-16	1.37E-16	1.41E-16	1.29E-16	8.93E-17	1.33E-16	1.13E-16	8.77E-17	1.40E-16	1.22E-16	9.29E-17
	0.3	Male	1.17E-16	1.03E-16	8.76E-17	7.24E-17	6.42E-17	5.29E-17	7.48E-17	6.39E-17	5.63E-17	8.62E-17	7.72E-17	6.52E-17
		Female	1.22E-16	1.16E-16	8.10E-17	6.56E-17	6.09E-17	4.29E-17	7.14E-17	6.31E-17	5.27E-17	6.78E-17	6.08E-17	4.59E-17
Upper torso	0.005	Male	5.23E-17	4.71E-17	3.84E-17	4.32E-17	3.84E-17	3.03E-17	3.57E-17	3.11E-17	2.41E-17	4.82E-17	4.44E-17	3.59E-17
		Female	2.04E-17	2.15E-17	1.45E-17	1.19E-17	1.10E-17	7.83E-18	1.38E-17	1.32E-17	1.00E-17	1.11E-17	1.03E-17	7.77E-18
	0.1	Male	7.25E-17	6.43E-17	4.67E-17	2.40E-17	2.14E-17	1.76E-17	4.44E-17	3.70E-17	2.91E-17	2.54E-17	2.29E-17	2.02E-17
		Female	4.51E-17	3.83E-17	1.79E-17	2.75E-17	2.42E-17	1.15E-17	2.88E-17	2.58E-17	1.81E-17	3.39E-17	2.85E-17	1.81E-17
	0.3	Male	6.87E-17	6.10E-17	4.80E-17	4.33E-17	3.52E-17	2.42E-17	4.28E-17	3.52E-17	2.91E-17	5.21E-17	4.55E-17	3.31E-17
		Female	6.58E-17	5.91E-17	3.86E-17	3.28E-17	2.96E-17	1.96E-17	3.71E-17	3.17E-17	2.50E-17	3.22E-17	2.86E-17	2.03E-17

Table J.11. ^{60}Co: RBM absorbed dose per source disintegration (unit: Gy s^{-1} Bq^{-1}).

Level	Distance (m)	Gender	Direction: Anterior			Right lateral			Posterior			Left lateral		
			10%ile	MRCP	90%ile	10%ile	MRCP	90%ile	10%ile	MRCP	90%ile	10%ile	MRCP	90%ile
Ground	0.005	Male	1.85E-17	1.49E-17	1.09E-17	7.53E-18	6.08E-18	4.54E-18	1.40E-17	1.14E-17	7.92E-18	8.09E-18	6.60E-18	4.82E-18
		Female	2.77E-17	2.06E-17	1.61E-17	1.30E-17	9.01E-18	7.59E-18	1.64E-17	9.88E-18	8.74E-18	1.36E-17	9.49E-18	7.73E-18
	0.1	Male	2.58E-17	2.04E-17	1.43E-17	1.08E-17	8.36E-18	5.78E-18	2.72E-17	2.11E-17	1.54E-17	1.20E-17	9.39E-18	6.46E-18
		Female	3.52E-17	2.66E-17	2.01E-17	1.38E-17	9.54E-18	7.59E-18	3.15E-17	2.15E-17	1.64E-17	1.54E-17	1.08E-17	8.44E-18
	0.3	Male	3.37E-17	2.69E-17	1.97E-17	1.88E-17	1.46E-17	9.67E-18	3.90E-17	3.10E-17	2.48E-17	1.89E-17	1.50E-17	1.02E-17
		Female	4.30E-17	3.38E-17	2.53E-17	2.39E-17	1.74E-17	1.19E-17	4.60E-17	3.57E-17	2.80E-17	2.48E-17	1.82E-17	1.31E-17
Middle thigh	0.005	Male	2.67E-16	2.39E-16	1.97E-16	1.71E-16	1.48E-16	1.11E-16	2.78E-16	2.50E-16	2.10E-16	1.70E-16	1.49E-16	1.13E-16
		Female	4.71E-16	3.90E-16	3.20E-16	2.70E-16	2.21E-16	1.72E-16	4.54E-16	3.77E-16	3.11E-16	2.81E-16	2.30E-16	1.85E-16
	0.1	Male	2.70E-16	2.24E-16	1.79E-16	1.81E-16	1.49E-16	1.11E-16	3.00E-16	2.51E-16	2.09E-16	1.78E-16	1.53E-16	1.12E-16
		Female	3.90E-16	3.28E-16	2.55E-16	2.49E-16	2.05E-16	1.54E-16	3.94E-16	3.32E-16	2.65E-16	2.50E-16	2.04E-16	1.60E-16
	0.3	Male	1.83E-16	1.61E-16	1.22E-16	1.16E-16	9.87E-17	7.75E-17	2.02E-16	1.81E-16	1.54E-16	1.16E-16	9.92E-17	7.70E-17
		Female	2.26E-16	2.00E-16	1.50E-16	1.47E-16	1.26E-16	9.75E-17	2.34E-16	2.08E-16	1.72E-16	1.46E-16	1.24E-16	9.83E-17
Lower torso	0.005	Male	1.63E-15	1.25E-15	6.44E-16	1.46E-15	1.14E-15	6.61E-16	3.82E-15	3.24E-15	2.71E-15	1.37E-15	1.15E-15	6.23E-16
		Female	1.94E-15	1.50E-15	9.35E-16	1.53E-15	1.36E-15	6.73E-16	3.94E-15	3.39E-15	2.59E-15	1.43E-15	1.28E-15	7.19E-16
	0.1	Male	8.15E-16	6.81E-16	4.02E-16	7.17E-16	5.97E-16	4.03E-16	1.41E-15	1.26E-15	1.11E-15	6.92E-16	5.99E-16	3.89E-16
		Female	9.44E-16	7.98E-16	5.25E-16	7.50E-16	6.76E-16	4.10E-16	1.46E-15	1.32E-15	1.09E-15	7.11E-16	6.42E-16	4.26E-16
	0.3	Male	3.28E-16	2.91E-16	1.98E-16	2.57E-16	2.23E-16	1.73E-16	4.42E-16	4.10E-16	3.76E-16	2.42E-16	2.12E-16	1.55E-16
		Female	3.54E-16	3.18E-16	2.31E-16	2.67E-16	2.45E-16	1.74E-16	4.51E-16	4.21E-16	3.72E-16	2.54E-16	2.31E-16	1.73E-16
	1	Male	5.78E-17	5.45E-17	4.38E-17	4.34E-17	3.94E-17	3.38E-17	6.72E-17	6.46E-17	6.18E-17	4.28E-17	3.94E-17	3.29E-17
		Female	6.06E-17	5.70E-17	4.71E-17	4.56E-17	4.23E-17	3.50E-17	6.84E-17	6.56E-17	6.16E-17	4.51E-17	4.18E-17	3.54E-17
	1.5	Male	2.82E-17	2.69E-17	2.24E-17	2.12E-17	1.96E-17	1.71E-17	3.21E-17	3.10E-17	2.99E-17	2.10E-17	1.95E-17	1.67E-17
		Female	2.94E-17	2.81E-17	2.37E-17	2.24E-17	2.07E-17	1.78E-17	3.25E-17	3.13E-17	2.99E-17	2.21E-17	2.06E-17	1.80E-17
	3	Male	7.69E-18	7.37E-18	6.40E-18	5.79E-18	5.36E-18	4.82E-18	8.52E-18	8.21E-18	8.05E-18	5.76E-18	5.35E-18	4.76E-18
		Female	7.93E-18	7.67E-18	6.72E-18	6.12E-18	5.72E-18	5.04E-18	8.61E-18	8.29E-18	7.99E-18	6.06E-18	5.70E-18	5.09E-18
Middle torso	0.005	Male	1.84E-15	1.35E-15	9.32E-16	2.17E-15	1.62E-15	1.24E-15	3.64E-15	3.10E-15	2.52E-15	1.83E-15	1.45E-15	1.09E-15
		Female	2.50E-15	2.17E-15	1.07E-15	2.90E-15	2.41E-15	1.59E-15	4.92E-15	4.10E-15	2.88E-15	2.63E-15	2.05E-15	1.50E-15
	0.1	Male	7.94E-16	6.53E-16	4.90E-16	7.34E-16	6.30E-16	5.05E-16	1.27E-15	1.14E-15	9.89E-16	6.70E-16	5.83E-16	4.64E-16
		Female	9.87E-16	8.77E-16	5.58E-16	8.61E-16	7.38E-16	5.68E-16	1.45E-15	1.30E-15	1.06E-15	8.44E-16	7.20E-16	5.72E-16
	0.3	Male	3.20E-16	2.83E-16	2.23E-16	2.61E-16	2.30E-16	1.91E-16	4.24E-16	3.93E-16	3.59E-16	2.40E-16	2.10E-16	1.68E-16
		Female	3.77E-16	3.48E-16	2.51E-16	2.94E-16	2.64E-16	2.13E-16	4.58E-16	4.26E-16	3.75E-16	2.87E-16	2.53E-16	2.05E-16
Upper torso	0.005	Male	2.23E-15	1.85E-15	1.55E-15	2.38E-15	1.85E-15	1.54E-15	2.57E-15	1.96E-15	1.60E-15	2.30E-15	1.87E-15	1.54E-15
		Female	2.83E-15	2.43E-15	2.00E-15	2.16E-15	1.47E-15	1.07E-15	3.13E-15	2.45E-15	1.97E-15	1.53E-15	1.14E-15	7.56E-16
	0.1	Male	9.68E-16	8.50E-16	7.38E-16	1.33E-15	1.11E-15	9.89E-16	1.05E-15	8.98E-16	7.71E-16	1.18E-15	1.01E-15	9.25E-16
		Female	1.14E-15	1.04E-15	8.72E-16	5.84E-16	4.70E-16	3.76E-16	1.15E-15	1.00E-15	8.51E-16	4.88E-16	4.03E-16	3.06E-16
	0.3	Male	3.30E-16	2.99E-16	2.61E-16	2.90E-16	2.54E-16	2.22E-16	3.90E-16	3.52E-16	3.17E-16	2.50E-16	2.20E-16	1.99E-16
		Female	3.75E-16	3.49E-16	2.91E-16	2.23E-16	1.91E-16	1.55E-16	3.99E-16	3.68E-16	3.27E-16	2.05E-16	1.79E-16	1.42E-16

Table J.12. ^{60}Co: Brain absorbed dose per source disintegration (unit: Gy s^{-1} Bq^{-1}).

Level	Distance (m)	Gender	Direction											
			Anterior			Right lateral			Posterior			Left lateral		
			10%ile	MRCP	90%ile	10%ile	MRCP	90%ile	10%ile	MRCP	90%ile	10%ile	MRCP	90%ile
Ground	0.005	Male	2.11E-18	1.28E-18	5.71E-19	2.91E-19	2.17E-19	1.50E-19	7.77E-19	5.50E-19	3.34E-19	3.38E-19	2.68E-19	1.57E-19
		Female	7.25E-18	4.29E-18	9.30E-19	4.26E-19	2.94E-19	2.02E-19	8.57E-19	5.05E-19	3.59E-19	4.46E-19	3.28E-19	2.11E-19
	0.1	Male	5.59E-18	3.30E-18	9.99E-19	6.50E-19	4.57E-19	2.72E-19	2.82E-18	1.61E-18	9.65E-19	8.39E-19	5.54E-19	3.08E-19
		Female	1.40E-17	1.01E-17	3.14E-18	9.49E-19	5.59E-19	3.24E-19	2.68E-18	1.48E-18	8.57E-19	1.19E-18	6.06E-19	3.82E-19
	0.3	Male	1.42E-17	9.77E-18	5.64E-18	5.89E-18	2.98E-18	1.01E-18	1.04E-17	6.87E-18	4.16E-18	5.43E-18	3.37E-18	1.36E-18
		Female	2.30E-17	1.81E-17	1.03E-17	1.14E-17	6.40E-18	1.46E-18	9.87E-18	6.21E-18	4.17E-18	1.10E-17	6.19E-18	1.98E-18
Middle thigh	0.005	Male	1.80E-18	1.86E-18	1.52E-18	1.48E-18	1.07E-18	8.09E-19	2.11E-18	2.14E-18	1.67E-18	1.39E-18	9.09E-19	6.74E-19
		Female	5.25E-18	4.66E-18	2.86E-18	2.87E-18	2.50E-18	1.67E-18	4.33E-18	3.76E-18	2.64E-18	2.56E-18	2.21E-18	1.56E-18
	0.1	Male	1.53E-17	8.86E-18	3.14E-18	9.21E-18	5.20E-18	2.98E-18	1.60E-17	9.63E-18	6.95E-18	1.25E-17	6.13E-18	3.43E-18
		Female	4.46E-17	3.63E-17	1.15E-17	2.66E-17	2.05E-17	6.21E-18	1.98E-17	1.59E-17	1.06E-17	2.37E-17	1.57E-17	6.02E-18
	0.3	Male	4.63E-17	3.93E-17	2.79E-17	2.28E-17	1.83E-17	1.23E-17	4.47E-17	3.34E-17	2.48E-17	1.89E-17	1.52E-17	1.09E-17
		Female	6.82E-17	6.35E-17	4.47E-17	3.97E-17	3.36E-17	1.98E-17	4.57E-17	3.59E-17	2.58E-17	4.00E-17	3.38E-17	2.02E-17
Lower torso	0.005	Male	2.85E-17	2.47E-17	1.96E-17	3.62E-17	3.63E-17	2.31E-17	2.22E-17	2.10E-17	1.47E-17	3.50E-17	2.67E-17	2.16E-17
		Female	7.42E-17	6.35E-17	2.86E-17	5.41E-17	4.98E-17	2.94E-17	3.58E-17	3.22E-17	2.38E-17	5.19E-17	4.08E-17	2.85E-17
	0.1	Male	1.22E-16	1.05E-16	8.85E-17	7.24E-17	5.80E-17	4.86E-17	8.93E-17	6.71E-17	4.33E-17	6.10E-17	5.15E-17	4.25E-17
		Female	1.68E-16	1.57E-16	1.03E-16	1.00E-16	8.79E-17	5.60E-17	7.81E-17	6.24E-17	4.45E-17	9.91E-17	8.92E-17	5.84E-17
	0.3	Male	1.14E-16	1.08E-16	8.70E-17	9.23E-17	7.29E-17	5.62E-17	1.34E-16	1.24E-16	1.03E-16	8.04E-17	6.21E-17	4.89E-17
		Female	1.42E-16	1.34E-16	1.14E-16	1.06E-16	8.79E-17	6.59E-17	1.31E-16	1.18E-16	9.37E-17	1.07E-16	8.96E-17	6.75E-17
	1	Male	4.26E-17	4.14E-17	3.60E-17	4.63E-17	4.43E-17	4.03E-17	4.71E-17	4.58E-17	4.28E-17	4.58E-17	4.40E-17	3.93E-17
		Female	4.82E-17	4.62E-17	4.23E-17	4.79E-17	4.69E-17	4.20E-17	4.87E-17	4.76E-17	4.44E-17	4.79E-17	4.71E-17	4.21E-17
	1.5	Male	2.37E-17	2.30E-17	2.05E-17	2.54E-17	2.45E-17	2.28E-17	2.51E-17	2.48E-17	2.37E-17	2.50E-17	2.43E-17	2.27E-17
		Female	2.55E-17	2.50E-17	2.32E-17	2.61E-17	2.54E-17	2.36E-17	2.55E-17	2.53E-17	2.40E-17	2.57E-17	2.56E-17	2.37E-17
	3	Male	6.92E-18	6.75E-18	6.45E-18	7.55E-18	7.42E-18	7.10E-18	7.35E-18	7.27E-18	7.08E-18	7.46E-18	7.41E-18	7.15E-18
		Female	7.20E-18	7.11E-18	6.85E-18	7.59E-18	7.60E-18	7.26E-18	7.33E-18	7.28E-18	7.13E-18	7.62E-18	7.53E-18	7.31E-18
Middle torso	0.005	Male	3.00E-16	2.72E-16	1.85E-16	1.64E-16	1.41E-16	1.16E-16	1.25E-16	1.08E-16	8.56E-17	1.53E-16	1.33E-16	1.03E-16
		Female	3.25E-16	3.28E-16	1.84E-16	2.18E-16	1.95E-16	1.50E-16	1.50E-16	1.37E-16	1.13E-16	2.07E-16	1.84E-16	1.47E-16
	0.1	Male	2.95E-16	2.68E-16	2.31E-16	1.70E-16	1.36E-16	1.12E-16	3.40E-16	3.03E-16	2.51E-16	1.48E-16	1.26E-16	9.56E-17
		Female	3.96E-16	3.68E-16	3.19E-16	1.94E-16	1.55E-16	1.22E-16	3.25E-16	2.84E-16	2.29E-16	2.10E-16	1.68E-16	1.43E-16
	0.3	Male	1.99E-16	1.83E-16	1.56E-16	2.20E-16	2.03E-16	1.76E-16	2.28E-16	2.15E-16	1.93E-16	2.10E-16	1.90E-16	1.59E-16
		Female	2.67E-16	2.49E-16	2.11E-16	2.42E-16	2.19E-16	1.81E-16	2.45E-16	2.34E-16	2.10E-16	2.38E-16	2.11E-16	1.72E-16
Upper torso	0.005	Male	1.59E-15	1.49E-15	1.37E-15	1.70E-15	1.66E-15	1.53E-15	1.72E-15	1.62E-15	1.48E-15	1.55E-15	1.48E-15	1.33E-15
		Female	2.34E-15	2.26E-15	2.14E-15	1.58E-15	1.33E-15	1.14E-15	2.02E-15	1.84E-15	1.66E-15	1.43E-15	1.20E-15	9.91E-16
	0.1	Male	1.07E-15	9.83E-16	8.87E-16	1.33E-15	1.18E-15	1.09E-15	1.24E-15	1.12E-15	1.02E-15	1.15E-15	1.03E-15	9.36E-16
		Female	1.69E-15	1.55E-15	1.44E-15	9.05E-16	7.71E-16	6.79E-16	1.23E-15	1.10E-15	9.98E-16	8.30E-16	7.24E-16	6.15E-16
	0.3	Male	4.55E-16	4.28E-16	4.03E-16	4.98E-16	4.53E-16	4.31E-16	4.47E-16	4.15E-16	3.90E-16	4.40E-16	4.06E-16	3.81E-16
		Female	5.84E-16	5.60E-16	5.38E-16	3.59E-16	3.20E-16	2.89E-16	4.19E-16	3.91E-16	3.67E-16	3.33E-16	3.03E-16	2.70E-16

Table J.13. ^{60}Co: Lung absorbed dose per source disintegration (unit: Gy s^{-1} Bq^{-1}).

Level	Distance (m)	Gender	Direction											
			Anterior			Right lateral			Posterior			Left lateral		
			10%ile	MRCP	90%ile	10%ile	MRCP	90%ile	10%ile	MRCP	90%ile	10%ile	MRCP	90%ile
Ground	0.005	Male	6.89E-18	5.57E-18	3.48E-18	1.47E-18	1.22E-18	8.66E-19	3.67E-18	2.88E-18	1.74E-18	1.77E-18	1.54E-18	9.86E-19
		Female	6.86E-18	5.25E-18	3.88E-18	2.04E-18	1.56E-18	1.16E-18	4.79E-18	2.78E-18	2.18E-18	2.12E-18	1.57E-18	1.25E-18
	0.1	Male	1.16E-17	9.14E-18	5.18E-18	2.85E-18	2.03E-18	1.31E-18	1.03E-17	6.69E-18	4.60E-18	4.44E-18	3.07E-18	1.66E-18
		Female	1.20E-17	9.22E-18	5.77E-18	3.13E-18	2.17E-18	1.58E-18	1.30E-17	8.10E-18	5.25E-18	3.65E-18	2.60E-18	1.88E-18
	0.3	Male	1.90E-17	1.50E-17	8.14E-18	1.15E-17	7.28E-18	3.82E-18	2.42E-17	1.81E-17	1.37E-17	1.52E-17	1.06E-17	5.35E-18
		Female	2.47E-17	1.86E-17	1.02E-17	1.65E-17	1.03E-17	4.87E-18	3.48E-17	2.58E-17	1.82E-17	1.66E-17	1.04E-17	5.45E-18
Middle thigh	0.005	Male	2.03E-17	2.00E-17	1.77E-17	1.12E-17	9.28E-18	6.96E-18	2.35E-17	2.21E-17	1.87E-17	1.20E-17	9.44E-18	7.23E-18
		Female	3.69E-17	3.46E-17	2.75E-17	2.07E-17	1.83E-17	1.39E-17	4.08E-17	3.70E-17	2.88E-17	2.10E-17	1.88E-17	1.42E-17
	0.1	Male	5.47E-17	4.72E-17	2.66E-17	3.73E-17	2.53E-17	1.71E-17	8.20E-17	5.80E-17	4.72E-17	5.64E-17	3.60E-17	2.23E-17
		Female	7.31E-17	6.42E-17	3.44E-17	8.07E-17	6.18E-17	3.22E-17	1.34E-16	1.10E-16	7.79E-17	7.59E-17	5.59E-17	3.02E-17
	0.3	Male	8.34E-17	6.97E-17	4.76E-17	7.08E-17	5.98E-17	4.33E-17	1.09E-16	9.32E-17	7.66E-17	7.42E-17	6.21E-17	4.55E-17
		Female	1.22E-16	1.04E-16	6.86E-17	9.71E-17	8.71E-17	5.84E-17	1.49E-16	1.34E-16	1.06E-16	9.40E-17	8.15E-17	5.88E-17
Lower torso	0.005	Male	4.17E-16	3.68E-16	2.51E-16	3.59E-16	3.40E-16	2.19E-16	4.37E-16	4.10E-16	3.21E-16	4.14E-16	3.54E-16	2.49E-16
		Female	4.37E-16	3.99E-16	3.00E-16	4.43E-16	4.00E-16	2.43E-16	5.84E-16	5.46E-16	4.23E-16	4.43E-16	3.80E-16	2.53E-16
	0.1	Male	4.56E-16	3.77E-16	2.93E-16	4.38E-16	3.82E-16	2.89E-16	5.89E-16	5.19E-16	4.21E-16	4.77E-16	4.21E-16	3.15E-16
		Female	5.28E-16	4.61E-16	3.18E-16	5.05E-16	4.64E-16	3.23E-16	6.90E-16	6.23E-16	4.92E-16	4.97E-16	4.54E-16	3.28E-16
	0.3	Male	3.10E-16	2.75E-16	1.99E-16	2.27E-16	2.03E-16	1.61E-16	3.49E-16	3.11E-16	2.81E-16	2.26E-16	2.05E-16	1.57E-16
		Female	3.14E-16	2.88E-16	2.13E-16	2.54E-16	2.34E-16	1.72E-16	3.92E-16	3.67E-16	3.13E-16	2.40E-16	2.18E-16	1.66E-16
	1	Male	6.39E-17	5.99E-17	4.92E-17	4.28E-17	3.96E-17	3.40E-17	6.51E-17	6.19E-17	5.96E-17	4.33E-17	4.15E-17	3.43E-17
		Female	6.25E-17	5.95E-17	4.65E-17	4.68E-17	4.40E-17	3.65E-17	7.12E-17	6.78E-17	6.47E-17	4.63E-17	4.32E-17	3.65E-17
	1.5	Male	3.15E-17	3.00E-17	2.57E-17	2.11E-17	1.94E-17	1.70E-17	3.15E-17	3.04E-17	2.92E-17	2.13E-17	2.03E-17	1.72E-17
		Female	3.06E-17	2.92E-17	2.34E-17	2.31E-17	2.13E-17	1.83E-17	3.41E-17	3.32E-17	3.14E-17	2.28E-17	2.14E-17	1.86E-17
	3	Male	8.57E-18	8.34E-18	7.40E-18	5.77E-18	5.48E-18	4.75E-18	8.44E-18	8.08E-18	7.91E-18	5.85E-18	5.50E-18	4.80E-18
		Female	8.40E-18	8.26E-18	6.69E-18	6.21E-18	5.86E-18	5.22E-18	8.99E-18	8.81E-18	8.47E-18	6.17E-18	5.79E-18	5.24E-18
Middle torso	0.005	Male	3.75E-15	2.88E-15	2.08E-15	4.43E-15	3.43E-15	2.63E-15	4.42E-15	3.74E-15	3.02E-15	5.17E-15	4.04E-15	3.03E-15
		Female	4.75E-15	4.00E-15	2.29E-15	6.34E-15	5.24E-15	3.76E-15	6.22E-15	5.16E-15	3.95E-15	6.67E-15	5.15E-15	3.76E-15
	0.1	Male	1.63E-15	1.34E-15	9.92E-16	1.33E-15	1.14E-15	9.61E-16	1.81E-15	1.58E-15	1.37E-15	1.34E-15	1.17E-15	9.70E-16
		Female	1.82E-15	1.60E-15	1.01E-15	1.61E-15	1.36E-15	1.11E-15	2.27E-15	1.98E-15	1.64E-15	1.60E-15	1.35E-15	1.12E-15
	0.3	Male	4.81E-16	4.29E-16	3.51E-16	3.38E-16	3.05E-16	2.64E-16	5.08E-16	4.63E-16	4.27E-16	3.26E-16	2.99E-16	2.48E-16
		Female	5.01E-16	4.65E-16	3.23E-16	3.91E-16	3.48E-16	3.01E-16	5.84E-16	5.41E-16	4.84E-16	3.81E-16	3.36E-16	2.85E-16
Upper torso	0.005	Male	3.32E-15	2.80E-15	2.32E-15	3.89E-15	3.20E-15	2.65E-15	3.13E-15	2.57E-15	2.10E-15	3.45E-15	2.87E-15	2.36E-15
		Female	3.89E-15	3.36E-15	2.62E-15	1.81E-15	1.39E-15	1.06E-15	3.70E-15	3.13E-15	2.53E-15	1.43E-15	1.16E-15	8.30E-16
	0.1	Male	1.93E-15	1.69E-15	1.44E-15	1.61E-15	1.33E-15	1.17E-15	1.75E-15	1.47E-15	1.26E-15	1.30E-15	1.10E-15	9.62E-16
		Female	1.98E-15	1.79E-15	1.45E-15	8.27E-16	6.56E-16	5.32E-16	1.90E-15	1.64E-15	1.42E-15	6.97E-16	5.67E-16	4.28E-16
	0.3	Male	5.90E-16	5.43E-16	4.92E-16	4.10E-16	3.52E-16	3.10E-16	5.50E-16	4.88E-16	4.45E-16	3.69E-16	3.18E-16	2.84E-16
		Female	5.74E-16	5.44E-16	4.57E-16	2.96E-16	2.48E-16	2.08E-16	5.72E-16	5.24E-16	4.82E-16	2.70E-16	2.32E-16	1.88E-16

Table J.14. ^{60}Co: Small intestine absorbed dose per source disintegration (unit: Gy s^{-1} Bq^{-1}).

Level	Distance (m)	Gender	Anterior 10%ile	Anterior MRCP	Anterior 90%ile	Right lateral 10%ile	Right lateral MRCP	Right lateral 90%ile	Posterior 10%ile	Posterior MRCP	Posterior 90%ile	Left lateral 10%ile	Left lateral MRCP	Left lateral 90%ile
Ground	0.005	Male	3.81E-17	3.00E-17	2.39E-17	8.35E-18	7.19E-18	5.90E-18	9.53E-18	8.26E-18	5.37E-18	9.34E-18	7.73E-18	6.09E-18
		Female	5.56E-17	4.29E-17	3.54E-17	2.39E-17	1.79E-17	1.31E-17	2.93E-17	1.56E-17	1.38E-17	1.93E-17	1.38E-17	1.08E-17
	0.1	Male	4.89E-17	3.99E-17	3.10E-17	1.03E-17	7.94E-18	6.41E-18	1.99E-17	1.62E-17	1.12E-17	1.24E-17	9.86E-18	7.50E-18
		Female	6.54E-17	5.05E-17	4.14E-17	1.62E-17	1.18E-17	1.01E-17	4.38E-17	3.07E-17	2.46E-17	2.02E-17	1.41E-17	1.16E-17
	0.3	Male	5.60E-17	4.90E-17	3.58E-17	1.77E-17	1.31E-17	9.90E-18	3.05E-17	2.38E-17	1.91E-17	2.26E-17	1.67E-17	1.21E-17
		Female	6.94E-17	5.78E-17	4.38E-17	2.41E-17	1.78E-17	1.41E-17	5.25E-17	4.16E-17	3.47E-17	3.08E-17	2.21E-17	1.76E-17
Middle thigh	0.005	Male	2.46E-16	2.33E-16	2.16E-16	1.15E-16	9.83E-17	7.57E-17	2.18E-16	1.98E-16	1.72E-16	1.13E-16	9.77E-17	7.73E-17
		Female	6.93E-16	6.02E-16	5.09E-16	3.00E-16	2.47E-16	1.88E-16	6.43E-16	5.45E-16	4.55E-16	3.10E-16	2.59E-16	2.05E-16
	0.1	Male	3.88E-16	3.42E-16	2.61E-16	1.52E-16	1.19E-16	9.62E-17	2.38E-16	2.04E-16	1.71E-16	1.66E-16	1.29E-16	1.03E-16
		Female	6.57E-16	5.66E-16	4.28E-16	2.79E-16	2.27E-16	1.75E-16	4.91E-16	4.26E-16	3.46E-16	3.04E-16	2.43E-16	1.98E-16
	0.3	Male	3.04E-16	2.78E-16	1.95E-16	1.29E-16	1.06E-16	8.75E-17	1.76E-16	1.51E-16	1.28E-16	1.58E-16	1.35E-16	1.03E-16
		Female	3.80E-16	3.49E-16	2.59E-16	1.68E-16	1.39E-16	1.14E-16	2.71E-16	2.37E-16	1.96E-16	2.07E-16	1.73E-16	1.39E-16
Lower torso	0.005	Male	1.10E-14	8.08E-15	3.25E-15	2.84E-15	2.08E-15	1.25E-15	3.54E-15	2.90E-15	2.38E-15	4.24E-15	3.48E-15	1.78E-15
		Female	8.56E-15	6.68E-15	3.80E-15	2.28E-15	1.97E-15	9.71E-16	4.87E-15	4.07E-15	3.15E-15	3.42E-15	3.10E-15	1.69E-15
	0.1	Male	2.80E-15	2.36E-15	1.29E-15	1.04E-15	8.45E-16	5.66E-16	1.44E-15	1.24E-15	1.08E-15	1.42E-15	1.24E-15	7.65E-16
		Female	2.51E-15	2.14E-15	1.43E-15	9.43E-16	8.29E-16	4.81E-16	1.86E-15	1.62E-15	1.34E-15	1.31E-15	1.20E-15	7.59E-16
	0.3	Male	6.36E-16	5.85E-16	3.96E-16	3.17E-16	2.74E-16	2.03E-16	4.21E-16	3.86E-16	3.48E-16	3.91E-16	3.55E-16	2.52E-16
		Female	6.01E-16	5.49E-16	4.18E-16	3.02E-16	2.74E-16	1.85E-16	4.93E-16	4.52E-16	3.98E-16	3.75E-16	3.48E-16	2.55E-16
	1	Male	7.57E-17	7.31E-17	5.90E-17	4.73E-17	4.38E-17	3.53E-17	5.86E-17	5.55E-17	5.22E-17	5.53E-17	5.23E-17	4.23E-17
		Female	7.33E-17	7.08E-17	5.96E-17	4.63E-17	4.28E-17	3.28E-17	6.41E-17	6.09E-17	5.63E-17	5.43E-17	5.10E-17	4.22E-17
	1.5	Male	3.53E-17	3.39E-17	2.84E-17	2.30E-17	2.11E-17	1.75E-17	2.80E-17	2.65E-17	2.52E-17	2.65E-17	2.49E-17	2.08E-17
		Female	3.43E-17	3.37E-17	2.86E-17	2.24E-17	2.08E-17	1.62E-17	3.02E-17	2.85E-17	2.70E-17	2.57E-17	2.43E-17	2.09E-17
	3	Male	9.03E-18	8.78E-18	7.61E-18	6.16E-18	5.82E-18	4.87E-18	7.61E-18	7.13E-18	6.73E-18	6.99E-18	6.69E-18	5.78E-18
		Female	9.04E-18	8.79E-18	7.67E-18	6.05E-18	5.70E-18	4.67E-18	7.93E-18	7.58E-18	7.19E-18	6.88E-18	6.59E-18	5.77E-18
Middle torso	0.005	Male	1.42E-15	1.19E-15	9.34E-16	7.61E-16	6.24E-16	4.97E-16	1.02E-15	8.66E-16	7.00E-16	1.33E-15	1.10E-15	8.82E-16
		Female	1.27E-15	1.18E-15	8.32E-16	6.70E-16	5.82E-16	4.48E-16	9.31E-16	8.07E-16	6.02E-16	1.27E-15	1.13E-15	8.85E-16
	0.1	Male	1.08E-15	8.97E-16	6.94E-16	5.81E-16	4.84E-16	3.91E-16	7.19E-16	6.11E-16	5.11E-16	8.40E-16	7.20E-16	5.87E-16
		Female	1.09E-15	9.76E-16	6.58E-16	5.43E-16	4.69E-16	3.42E-16	7.74E-16	6.75E-16	5.28E-16	8.83E-16	7.85E-16	6.15E-16
	0.3	Male	4.53E-16	4.03E-16	3.23E-16	2.59E-16	2.29E-16	1.86E-16	3.15E-16	2.82E-16	2.47E-16	3.20E-16	2.84E-16	2.37E-16
		Female	4.64E-16	4.28E-16	3.22E-16	2.55E-16	2.28E-16	1.71E-16	3.54E-16	3.20E-16	2.72E-16	3.38E-16	3.07E-16	2.48E-16
Upper torso	0.005	Male	2.08E-16	1.92E-16	1.52E-16	1.89E-16	1.68E-16	1.37E-16	1.56E-16	1.39E-16	1.08E-16	1.99E-16	1.86E-16	1.50E-16
		Female	1.66E-16	1.63E-16	1.13E-16	1.04E-16	8.96E-17	6.73E-17	1.24E-16	1.21E-16	9.31E-17	1.08E-16	1.02E-16	7.56E-17
	0.1	Male	2.73E-16	2.36E-16	1.73E-16	1.25E-16	1.09E-16	9.03E-17	1.88E-16	1.63E-16	1.29E-16	1.28E-16	1.16E-16	9.65E-17
		Female	2.55E-16	2.34E-16	1.34E-16	1.10E-16	9.49E-17	6.15E-17	2.01E-16	1.78E-16	1.31E-16	2.05E-16	1.76E-16	1.06E-16
	0.3	Male	2.65E-16	2.27E-16	1.81E-16	1.56E-16	1.30E-16	9.06E-17	1.84E-16	1.58E-16	1.32E-16	1.89E-16	1.62E-16	1.19E-16
		Female	2.62E-16	2.43E-16	1.75E-16	1.32E-16	1.15E-16	8.10E-17	2.01E-16	1.79E-16	1.42E-16	1.73E-16	1.53E-16	1.15E-16

Table J.15. ^{60}Co: Large intestine absorbed dose per source disintegration (unit: Gy s^{-1} Bq^{-1}).

Level	Distance (m)	Gender	Direction											
			Anterior			Right lateral			Posterior			Left lateral		
			10%ile	MRCP	90%ile	10%ile	MRCP	90%ile	10%ile	MRCP	90%ile	10%ile	MRCP	90%ile
Ground	0.005	Male	3.37E-17	2.78E-17	1.85E-17	8.70E-18	7.56E-18	5.60E-18	1.48E-17	1.22E-17	9.12E-18	8.36E-18	7.16E-18	5.18E-18
		Female	6.38E-17	4.79E-17	3.92E-17	3.14E-17	2.26E-17	1.81E-17	2.71E-17	1.54E-17	1.44E-17	2.82E-17	2.08E-17	1.62E-17
	0.1	Male	4.64E-17	3.85E-17	2.54E-17	1.01E-17	8.02E-18	6.05E-18	2.30E-17	1.87E-17	1.45E-17	1.43E-17	1.08E-17	7.11E-18
		Female	7.73E-17	5.95E-17	4.71E-17	2.20E-17	1.64E-17	1.31E-17	4.02E-17	2.83E-17	2.36E-17	2.61E-17	1.89E-17	1.45E-17
	0.3	Male	5.47E-17	4.56E-17	3.01E-17	2.01E-17	1.49E-17	1.05E-17	3.11E-17	2.45E-17	2.05E-17	2.86E-17	2.31E-17	1.35E-17
		Female	8.22E-17	6.92E-17	5.20E-17	2.95E-17	2.17E-17	1.80E-17	5.08E-17	3.84E-17	3.29E-17	3.44E-17	2.52E-17	2.01E-17
Middle thigh	0.005	Male	2.37E-16	2.20E-16	1.98E-16	1.11E-16	9.46E-17	7.16E-17	2.55E-16	2.31E-16	2.01E-16	1.14E-16	9.83E-17	7.62E-17
		Female	8.50E-16	7.18E-16	6.13E-16	3.39E-16	2.77E-16	2.13E-16	7.59E-16	6.33E-16	5.31E-16	3.70E-16	3.06E-16	2.45E-16
	0.1	Male	3.25E-16	2.85E-16	2.01E-16	1.47E-16	1.15E-16	9.33E-17	2.54E-16	2.23E-16	1.87E-16	1.82E-16	1.39E-16	1.03E-16
		Female	7.98E-16	7.02E-16	5.10E-16	3.13E-16	2.56E-16	2.02E-16	5.33E-16	4.55E-16	3.78E-16	3.53E-16	2.81E-16	2.30E-16
	0.3	Male	2.70E-16	2.42E-16	1.66E-16	1.38E-16	1.17E-16	8.68E-17	1.83E-16	1.58E-16	1.34E-16	1.59E-16	1.42E-16	1.01E-16
		Female	4.38E-16	4.06E-16	3.04E-16	1.99E-16	1.66E-16	1.35E-16	2.57E-16	2.25E-16	1.89E-16	2.16E-16	1.81E-16	1.51E-16
Lower torso	0.005	Male	4.58E-15	3.75E-15	2.10E-15	4.59E-15	3.28E-15	1.74E-15	2.57E-15	2.13E-15	1.74E-15	4.17E-15	3.47E-15	1.80E-15
		Female	1.24E-14	8.96E-15	4.77E-15	4.01E-15	3.62E-15	1.56E-15	3.68E-15	2.97E-15	2.29E-15	4.38E-15	4.05E-15	2.01E-15
	0.1	Male	2.27E-15	1.91E-15	1.12E-15	1.30E-15	1.07E-15	6.98E-16	1.31E-15	1.12E-15	9.64E-16	1.46E-15	1.30E-15	8.31E-16
		Female	2.98E-15	2.54E-15	1.68E-15	1.25E-15	1.15E-15	6.42E-16	1.52E-15	1.31E-15	1.08E-15	1.32E-15	1.22E-15	7.74E-16
	0.3	Male	6.02E-16	5.34E-16	3.80E-16	3.58E-16	3.07E-16	2.35E-16	4.15E-16	3.64E-16	3.39E-16	4.02E-16	3.70E-16	2.76E-16
		Female	6.64E-16	6.10E-16	4.74E-16	3.49E-16	3.30E-16	2.21E-16	4.42E-16	3.98E-16	3.54E-16	3.57E-16	3.38E-16	2.43E-16
	1	Male	7.54E-17	7.10E-17	5.91E-17	5.01E-17	4.61E-17	3.85E-17	5.97E-17	5.56E-17	5.24E-17	5.53E-17	5.28E-17	4.41E-17
		Female	7.90E-17	7.67E-17	6.45E-17	5.03E-17	4.75E-17	3.64E-17	6.05E-17	5.61E-17	5.22E-17	5.09E-17	4.82E-17	3.98E-17
	1.5	Male	3.55E-17	3.34E-17	2.84E-17	2.38E-17	2.27E-17	1.87E-17	2.88E-17	2.72E-17	2.56E-17	2.61E-17	2.50E-17	2.15E-17
		Female	3.64E-17	3.52E-17	3.07E-17	2.37E-17	2.27E-17	1.81E-17	2.87E-17	2.72E-17	2.50E-17	2.42E-17	2.34E-17	1.94E-17
	3	Male	8.92E-18	8.68E-18	7.74E-18	6.37E-18	5.94E-18	5.20E-18	7.47E-18	7.09E-18	6.84E-18	7.01E-18	6.70E-18	5.98E-18
		Female	9.26E-18	9.26E-18	8.13E-18	6.43E-18	6.20E-18	4.97E-18	7.61E-18	7.21E-18	6.66E-18	6.56E-18	6.27E-18	5.36E-18
Middle torso	0.005	Male	2.01E-15	1.69E-15	1.32E-15	1.12E-15	9.34E-16	7.68E-16	1.03E-15	8.50E-16	6.87E-16	2.34E-15	1.92E-15	1.59E-15
		Female	8.48E-16	7.98E-16	6.09E-16	6.33E-16	5.85E-16	4.67E-16	6.10E-16	5.42E-16	4.13E-16	6.23E-16	5.58E-16	4.46E-16
	0.1	Male	1.34E-15	1.13E-15	9.03E-16	8.00E-16	6.87E-16	5.59E-16	7.16E-16	6.12E-16	5.03E-16	1.16E-15	9.87E-16	8.42E-16
		Female	1.02E-15	9.01E-16	6.01E-16	6.24E-16	5.63E-16	4.12E-16	5.83E-16	5.08E-16	3.98E-16	6.08E-16	5.47E-16	4.08E-16
	0.3	Male	4.78E-16	4.24E-16	3.57E-16	3.09E-16	2.75E-16	2.30E-16	3.16E-16	2.81E-16	2.46E-16	3.58E-16	3.24E-16	2.80E-16
		Female	4.82E-16	4.60E-16	3.38E-16	2.86E-16	2.68E-16	1.98E-16	3.02E-16	2.71E-16	2.28E-16	2.91E-16	2.62E-16	2.05E-16
Upper torso	0.005	Male	2.72E-16	2.48E-16	2.03E-16	2.32E-16	2.04E-16	1.61E-16	1.95E-16	1.72E-16	1.34E-16	2.56E-16	2.32E-16	1.85E-16
		Female	1.29E-16	1.25E-16	8.74E-17	8.33E-17	7.40E-17	5.43E-17	9.10E-17	8.71E-17	6.74E-17	7.73E-17	7.04E-17	5.24E-17
	0.1	Male	3.48E-16	3.02E-16	2.23E-16	1.50E-16	1.30E-16	1.06E-16	2.25E-16	1.95E-16	1.51E-16	1.54E-16	1.34E-16	1.13E-16
		Female	2.26E-16	2.03E-16	1.01E-16	1.47E-16	1.25E-16	6.85E-17	1.50E-16	1.34E-16	9.97E-17	1.71E-16	1.46E-16	9.66E-17
	0.3	Male	2.92E-16	2.62E-16	2.12E-16	2.01E-16	1.71E-16	1.21E-16	1.96E-16	1.65E-16	1.36E-16	2.32E-16	2.01E-16	1.57E-16
		Female	2.71E-16	2.52E-16	1.75E-16	1.49E-16	1.36E-16	9.49E-17	1.67E-16	1.48E-16	1.17E-16	1.47E-16	1.33E-16	9.76E-17

Table J.16. Effective dose per source disintegration (Sv s^{-1} Bq^{-1}) of ^{192}Ir, $^{137}Cs/^{137m}Ba$ and ^{60}Co.

Level	Distance (m)	Direction											
		Anterior			Right lateral			Posterior			Left lateral		
		^{192}Ir	$^{137}Cs/^{137m}Ba$	^{60}Co	^{192}Ir	$^{137}Cs/^{137m}Ba$	^{60}Co	^{192}Ir	$^{137}Cs/^{137m}Ba$	^{60}Co	^{192}Ir	$^{137}Cs/^{137m}Ba$	^{60}Co
Ground	0.005	1.08E-17	7.95E-18	3.64E-17	8.32E-18	5.88E-18	2.64E-17	8.04E-18	5.65E-18	2.49E-17	7.81E-18	5.49E-18	2.45E-17
	0.1	1.12E-17	8.33E-18	3.89E-17	3.99E-18	3.03E-18	1.53E-17	6.90E-18	5.16E-18	2.48E-17	4.26E-18	3.31E-18	1.66E-17
	0.3	1.33E-17	9.64E-18	4.32E-17	4.24E-18	3.40E-18	1.80E-17	8.46E-18	6.44E-18	3.02E-17	4.66E-18	3.77E-18	1.99E-17
Middle thigh	0.005	1.89E-16	1.30E-16	5.39E-16	4.85E-17	3.77E-17	1.87E-16	1.31E-16	9.14E-17	3.88E-16	5.21E-17	4.05E-17	2.00E-16
	0.1	1.37E-16	9.52E-17	4.00E-16	3.85E-17	3.06E-17	1.52E-16	8.89E-17	6.30E-17	2.71E-16	4.23E-17	3.34E-17	1.65E-16
	0.3	7.86E-17	5.45E-17	2.24E-16	2.96E-17	2.29E-17	1.09E-16	5.27E-17	3.77E-17	1.62E-16	3.38E-17	2.61E-17	1.24E-16
Lower torso	0.005	6.04E-16	4.27E-16	1.84E-15	3.28E-16	2.38E-16	1.06E-15	4.67E-16	3.30E-16	1.43E-15	3.70E-16	2.68E-16	1.19E-15
	0.1	3.63E-16	2.52E-16	1.04E-15	1.82E-16	1.31E-16	5.73E-16	2.68E-16	1.88E-16	8.04E-16	2.20E-16	1.58E-16	6.77E-16
	0.3	1.49E-16	1.01E-16	4.13E-16	7.15E-17	5.28E-17	2.33E-16	1.09E-16	7.62E-17	3.22E-16	8.31E-17	5.99E-17	2.62E-16
	1	2.50E-17	1.72E-17	6.74E-17	1.26E-17	9.49E-18	4.21E-17	1.93E-17	1.34E-17	5.64E-17	1.46E-17	1.06E-17	4.66E-17
	1.5	1.22E-17	8.13E-18	3.26E-17	6.28E-18	4.67E-18	2.09E-17	9.41E-18	6.54E-18	2.77E-17	7.15E-18	5.22E-18	2.27E-17
	3	3.29E-18	2.16E-18	8.72E-18	1.72E-18	1.29E-18	5.74E-18	2.51E-18	1.77E-18	7.43E-18	1.94E-18	1.40E-18	6.23E-18
Middle torso	0.005	1.12E-15	7.79E-16	3.28E-15	6.59E-16	4.60E-16	1.95E-15	7.33E-16	5.12E-16	2.17E-15	9.21E-16	6.37E-16	2.67E-15
	0.1	5.47E-16	3.77E-16	1.52E-15	2.53E-16	1.82E-16	7.85E-16	3.19E-16	2.24E-16	9.46E-16	3.31E-16	2.33E-16	9.86E-16
	0.3	1.71E-16	1.16E-16	4.64E-16	8.10E-17	5.97E-17	2.62E-16	1.14E-16	7.94E-17	3.34E-16	9.45E-17	6.84E-17	2.96E-16
Upper torso	0.005	1.46E-15	1.00E-15	4.09E-15	3.96E-16	2.82E-16	1.21E-15	4.70E-16	3.35E-16	1.45E-15	3.62E-16	2.59E-16	1.13E-15
	0.1	4.78E-16	3.26E-16	1.32E-15	1.58E-16	1.18E-16	5.41E-16	2.35E-16	1.67E-16	7.25E-16	1.49E-16	1.13E-16	5.22E-16
	0.3	1.64E-16	1.12E-16	4.50E-16	6.68E-17	4.98E-17	2.24E-16	9.63E-17	6.85E-17	2.92E-16	7.01E-17	5.22E-17	2.32E-16

Table J.17. Source self-shielding factors

Radioactive material thickness (diameter/height)	Capsule-wall thickness					
	1 mm			2 mm		
	^{192}Ir	^{137}Cs/^{137m}Ba	^{60}Co	^{192}Ir	^{137}Cs/^{137m}Ba	^{60}Co
1 mm	0.840	0.963	0.972	0.803	0.941	0.953
2 mm	0.717	0.961	0.965	0.694	0.935	0.947
3 mm	0.627	0.957	0.958	0.606	0.931	0.938
4 mm	0.556	0.952	0.949	0.536	0.927	0.929

ANNEX K. DESCRIPTION OF ELECTRONIC FILES

(K1) The compressed package of electronic files containing the detailed data on the adult mesh-type reference computational phantoms (MRCPs) can be found in the supplementary CD that accompanies the printed publication. The package is organised in 7 folders: (1) *PM-version Adult MRCP*, (2) *TM-version Adult MRCP*, (3) *Material Information*, (4) *Spongiosa Information*, (5) *Blood Information*, (6) *MC Input Examples* and (7) *Phantom Visualisation.* This annex briefly explains the files in these folders and their features.

K.1. Data files in *PM-version Adult MRCP*

(K2) This folder contains the following two data files:

MRCP_AM.obj
MRCP_AF.obj

The data files in the OBJ format contain the polygon mesh (PM) version of the adult mesh-type reference computational phantoms. These OBJ files can be imported in various 3D commercial programs such as *3ds Max*^{TM} (Autodesk, USA), *MAYA*^{TM} (Autodesk, USA), *Rapidform*^{TM} (INUS Technology Inc., Korea) and Rhinoceros (Robert McNeel, USA).

K.2. Data files in TM-version Adult MRCP

(K3) This folder contains the following four data files:

MRCP_AM.node
MRCP_AF.node
MRCP_AM.ele
MRCP_AF.ele

The data files in the NODE and ELE formats contain the tetrahedral mesh (TM) version of the adult mesh-type reference computational phantoms. The NODE-format files contain a list of node coordinates composing the TM-version phantoms. The ELE-format files contain a list of tetrahedrons composing the TM-version phantoms and each tetrahedron is represented as four node IDs listed in the corresponding NODE-format files and an organ ID number with respect to the tetrahedron.

K.3. Data files in Material Information

(K4) This folder contains the following two data files:

MRCP_AM_media.dat
MRCP_AF_media.dat

The data files contain lists of the media, elemental compositions and densities (Annex B).

K.4. Data files in Spongiosa Information

(K5) This folder contains the following two data files:

MRCP_AM_spongiosa.dat
MRCP_AF_spongiosa.dat

The data files contain the mass fractions of bone components (i.e. mineral bone, active marrow, inactive marrow, blood and skeletal miscellaneous) in the spongiosa region.

K.5. Data files in *Blood Information*

(K6) This folder contains the following two data files:

MRCP_AM_blood.dat
MRCP_AF_blood.dat

The data files contain the mass fractions of blood in the organs and tissues of the phantoms.

K.6. Data files in *MC Input Examples*

(K7) This folder contains the following three compressed files:

MRCP_GEANT4.tar.gz
MRCP_MCNP6.tar.gz
MRCP_PHITS.tar.gz

The data files contain input examples for implementation of the TM-version phantoms in the three Monte Carlo codes, i.e. Geant4 (Agostinelli et al., 2003), MCNP6 (Goorley et al., 2013) and PHITS (Sato et al., 2013). In these examples, a point source emitting 662-keV photons is located at 1 m in front of the phantom. Detailed information on the implementation is described in the 'readme' text file included in each compressed file.

K.7. Data files in Phantom Visualisation

(K8) This folder contains the following three PDF files:

MRCP_AM.pdf
MRCP_AF.pdf
How_to_use_3DPDF.pdf

The two PDF files (i.e. ‘MRCP_AM.pdf’ and ‘MRCP_AF.pdf’) visualise the mesh-type adult reference computational phantoms in a 3D view, as shown in Fig. M.1. The PDF files are read in the Acrobat program (Adobe Systems, San Jose, CA, USA) where one can navigate the phantoms in detail, e.g. by rotating or enlarging each of the organ/tissue models. Detailed instruction on these PDF files can be found in ‘How_to_use_3DPDF.pdf’.

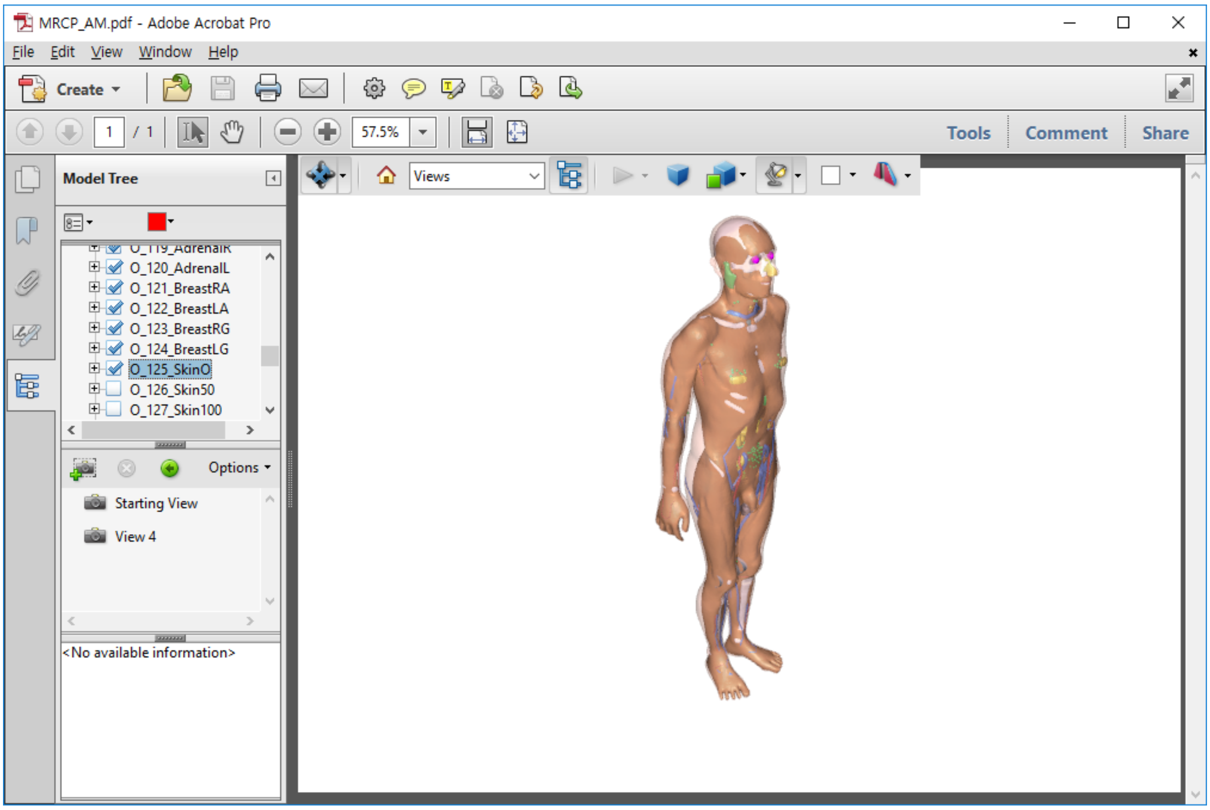


Fig. K.1. 3D view of the adult mesh-type reference phantom for the male visualised in the Adobe Acrobat program importing the MRCP_AM.pdf file.