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Specific Absorbed Fractions for Reference Paediatric Individuals

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67   **Abstract**–The calculation of doses to organs and tissues of interest due to internally emitting
68   radionuclides requires knowledge of the time-dependent distribution of the radionuclide, its
69   physical decay properties, and the fraction of emitted energy absorbed per mass of the target.
70   The latter property is quantified as the specific absorbed fraction (SAF). This document
71   provides photon, electron, alpha-particle, and neutron (for nuclides undergoing spontaneous
72   fission) SAF values for the suite of reference individuals.
73
74   The reference individuals are defined largely by information provided in *Publication 89*. Some
75   improvements and additional data are provided in this publication which define the reference
76   individual's source and target region masses used in the Occupational Intake of Radionuclides
77   (OIR) and Dose Coefficients for Intakes of Radionuclides by Members of the Public (EIR)
78   series of publications. The set of reference individuals includes males and females at ages of
79   0y (newborn), 1y, 5y, 10y, 15y, and 20y (adult). The reference adult masses and SAFs provided
80   in this publication are identical to those in *Publication 133* and those used in the OIR series of
81   publications.
82
83   Computation of SAF values involves simulating radiation transport in computational models
84   which represent the geometry of the reference individuals. The reference voxel phantoms of
85   *Publication 143* are used for photon and neutron transport and most of the electron transport.
86   Alpha particle transport is not necessary for large tissue regions as the short range allows for
87   an assumption of full energy absorption (absorbed fraction of unity) for self-irradiation
88   geometries. Additional computational models are needed for charged particles in small,
89   overlapping or interlaced geometries. Stylised models are described and used for electrons and
90   alpha particles in the alimentary and respiratory tract regions. For charged particles within the
91   skeleton image-based models are used to compute SAFs.
92
93   This publication is accompanied by an electronic supplement which includes files containing
94   SAFs for each radiation type in each reference individual. The supplement also includes source
95   and target region masses for each reference individual, as well as skeletal dose response
96   functions for photons incident upon the skeleton.
97
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99
100   *Keywords:* Specific absorbed fraction; absorbed fraction; internal dosimetry; reference
101   individuals; computational phantoms
102

MAIN POINTS

103

104 - **Specific absorbed fraction (SAF) values are provided for ICRP male and female**
105   **reference individuals at 6 ages (0y, 1y, 5y, 10y, 15y, and 20y) for internally emitted**
106   **photons, electrons, alpha particles, and fission-spectrum neutrons associated with**
107   **radionuclides which decay by spontaneous fission.**

108 - **Source and target region masses for the reference individuals consistent with these**
109   **SAF values are tabulated and their origins defined.**

110 - **SAF values and source and target region masses for the adults are the same as those**
111   **in *Publication 133* and utilised in the Occupational Intake of Radionuclides (OIR)**
112   **series of publications.**

113 - **Computational models used to obtain energy absorption data include the reference**
114   **voxel phantoms of *Publication 143*, stylised models for charged particles in intra-**
115   **respiratory and intra-alimentary tract geometries, and image-based models for**
116   **charged particles emitted within the skeleton.**

117 - **The reference SAFs presented in this publication will be coupled to the nuclear**
118   **decay data of *Publication 107* and the biokinetic models describing temporal**
119   **distribution of radionuclide activity to calculate reference dose coefficients to**
120   **members of the public in a forthcoming series of publications and dose to patients**
121   **from radiopharmaceuticals.**

122 - **In addition to photons, energy-dependent SAFs for electrons and alpha particles**
123   **are provided representing a significant improvement to radiation protection**
124   **dosimetry compared to the non-energy dependent SAFs in *Publication 30*.**

1. INTRODUCTION

(1) *Publication 103* (ICRP 2007) describes the latest revisions to the radiation protection quantities, equivalent and effective dose. Since issued, Committee 2 of the ICRP has been involved in an effort to publish dose coefficients for external (ICRP 2010, 2013, 2020c) and internal exposures. Specific absorbed fractions are required in the ICRP methodology for computing internal dose coefficients. *Publication 133* (ICRP 2016a) contains the SAFs for the reference adults utilised in computing the dose coefficients of the Occupational Intake of Radionuclides (OIR) series (ICRP 2015, 2016b, 2017, 2019, 2022). This publication provides specific absorbed fractions (SAFs) for members of the public including children. These SAFs will be used in the computation of internal dose coefficients in the forthcoming Dose Coefficients for Intakes of Radionuclides by Members of the Public (EIR) series.

(2) The computation of internal dose coefficients first requires definition of the individuals for whom the dose coefficients are being computed. A group of 12 reference individuals are defined – a male and female of the newborn, 1-year old, 5-years old, 10-years old, 15-years old, and adult. The definition of the tissue masses comes largely from *Publication 89* (ICRP 2002). In this publication these masses are restated and expanded upon or replaced when appropriate.

(3) The SAF is defined as the fraction of energy emitted within a source region which is absorbed in a target region per mass of the target region. Target regions may be whole organs or tissue layers. Source regions may be whole organs, tissue regions, surfaces, contents of hollow organs, or distributed around the body in the case of a blood source. To compute the fractional energy absorption, a series of reference computational phantoms and models provide a representative geometry for radiation transport calculations. Reference voxel phantoms (ICRP 2009, 2020b) are used for many of the source-target geometries. Additional computational models provide the intricate geometry needed for charged particle transport in smaller, overlapping or interlaced source and target regions within the alimentary tract, respiratory tract, and skeleton. While the phantoms and models were designed with *Publication 89* (ICRP 2002) in mind, they are constructs of theoretical anatomical geometries. For a variety of reasons, the masses of regions in the phantoms or models may not exactly match the reference individual definitions. In such cases adjustments are made to phantom/model SAFs to derive appropriate reference SAFs.

(4) The masses provided in Table 2.8 of *Publication 89* provide reference values for the masses for each age and sex. Importantly, the mass of the organs and tissues in this table, unless specifically noted, do not include the contribution from blood perfusing organs and tissues. Rather, Table 2.8 generally provides the masses of the organ and tissue parenchyma. To arrive at an organ or tissue mass inclusive of the perfused blood, a blood distribution model must be coupled to the masses in Table 2.8. Section 3.2 of this publication describes in detail how such masses are computed.

(5) The reference voxel phantoms in *Publications 110* and *143* were designed based on the parenchyma masses in Table 2.8 of *Publication 89*. As a result, organs and tissues in the reference voxel phantoms are generally smaller than desired due to the missing contribution from perfused blood. Section 5.1 of this publication describes how and which SAFs were adjusted from values computed in reference voxel phantoms to be consistent with target masses inclusive of blood (provided in Section 3.3.) Note that the reference adult mesh-type phantoms in *Publication 145* (ICRP 2020a) did properly account for perfused blood. Forthcoming mesh-type phantoms for reference paediatric individuals will also include the contribution of perfused blood in tissue. However, the mesh-phantoms were not available at the time Monte Carlo transport simulations supporting this publication were performed and therefore reference voxel phantoms were used as described in Section 4.1.

174   (6) The SAFs for the reference adults were provided in *Publication 133*. Since they are also
175   used in the EIR series and radiopharmaceutical dosimetry, adult SAFs have been included in
176   this publication for ease of access. The adult SAFs do not differ from those used in the OIR
177   series.

178

2. ICRP SCHEMA FOR INTERNAL DOSE ASSESSMENT

179

180   (7) Doses to members of the public may result from environmental exposure to
181   radionuclides. If such a radionuclide is inhaled or ingested, the potential exists for it to be
182   transferred to the blood and incorporated into tissue thereby creating a source of radiation
183   emissions internal to the body. The resulting dose from an intake of radioactive material takes
184   place over an extended period of time, with that extent depending on the physical properties of
185   the nucleus and physiological properties of the chemical form of the material.
186   (8) The methods described in this section will be used to compute internal dose coefficients
187   for members of the public. Internal dose coefficients provide the dose per unit intake activity.
188   Depending on the interest, the coefficient could provide equivalent dose to a specific target
189   tissue or effective dose.
190   (9) The methodology is similar to that presented in the OIR series of publications (ICRP
191   2015, 2016a, 2016b, 2017, 2019) with an important difference in the handling of age. In the
192   OIR series, dose calculations were performed only for the reference adults. Since parameters
193   associated with the reference adults are constant with age, determining the dose delivered over
194   time involved a simple integration of the activity term. The energy absorption term (*S*-
195   coefficient) for the reference adults is time invariant.
196   (10) The EIR series, however, includes dose coefficients for intakes occurring as children.
197   Unless the radionuclide's physical or biological removal from the body is very fast, growth of
198   the child should be considered. For these individuals, both the activity term and the energy
199   absorption term are varying with time. The section below describes these terms and how their
200   time-variant nature need to be handled in computing internal dose coefficients.
201   (11) The methodology presented here can also be applied to patients in diagnostic nuclear
202   medicine. For such patients, organ absorbed dose coefficients would be the desired quantity
203   rather than equivalent dose coefficients. Finally, the caveat described in section 2.2.1 applies
204   to patient dosimetry.

2.1. Methodology for dose calculations

205

206   (12) The ICRP dosimetry system is presented below as applied to assessment of organ
207   equivalent dose and effective dose following intakes of radionuclides. The system involves
208   numerical solution of reference biokinetic models, yielding the time-dependent activity in
209   various source tissues. These solutions are then coupled with reference data on nuclear decay
210   information and specific absorbed fractions.

2.1.1. Computational solutions to the ICRP reference biokinetic models

211

212   (13) The Human Respiratory Tract Model (HRTM), the Human Alimentary Tract Model
213   (HATM), and the systemic biokinetic models describe the dynamic behaviour of radionuclide
214   movement within the body. Given the route(s) of intake, these models predict the subsequent
215   uptake to the systemic circulation, the distribution among tissues of the body, and the routes of
216   elimination from the body. The physical decay of the radionuclide and its radioactive progeny
217   are also modelled. The result is a coupled system of first-order differential equations. The
218   solution to the set of equations is the time-dependent distribution of the radionuclide and its
219   radioactive progeny in mathematical compartments associated with anatomical regions in the
220   body.

221   (14) Let $N_{i,j}(t)$ represents the number of nuclides of radionuclide i in compartment j at time
222   t. The rate of change of the number of nuclides i of the decay chain, $i = 1, 2, …, n$ with $i = 1$
223   being the parent nuclide taken into the body, is given in Eq. (2.1). Note that in addition to the
224   number of nuclei terms, the biokinetic transfer rates may also vary with age and are therefore
225   functions of time. The function of time notation, (t), has been omitted from these quantities
226   on the right-hand side of Eq. 2.1 to improve readability.

$$\frac{dN_{i,j}(t)}{dt} = \sum_{\substack{k=1 \\ k\neq j}}^{M} N_{i,k}\lambda_{i,k,j} - N_{i,j}\left[\sum_{\substack{k=1 \\ k\neq j}}^{M} \lambda_{i,j,k} + \lambda_i^P\right] + \sum_{h=1}^{i-1} N_{h,j}\lambda_h^P\beta_{h,i} \tag{2.1}$$

227   where:
228   M is the number of compartments describing the kinetics;
229   $N_{i,k}$ is the number of nuclei of chain member i in donor compartment k and varies with
230   time;
231   $\lambda_{i,j,k}$ is the fractional transfer rate of chain member i from compartment j (donor
232   compartment) to compartment k (receiving compartment) in the biokinetic model and may
233   vary with time (age);
234   λ_i^p is the physical decay constant of chain member i;
235   $N_{h,j}$ is the number of nuclei of precursor nuclide h in compartment j and varies with time;
236   λ_h^P is the physical decay constant of precursor chain member h; and
237   $\beta_{h,i}$ is the fraction of the decays of chain member h forming member i.
238   (15) Given the initial conditions specified for the compartments, $N_{i,j}(0)$, Eq. (2.1) defines
239   the dynamic behaviour of the radionuclide and its progeny within the human body. The first
240   term on the right-hand side of Eq. (2.1) represents the rate of flow of chain member i into
241   compartment j from all donor compartments. The second term represents the rate of removal
242   of member i from compartment j both by transfer to receiving compartments and by physical
243   decay. The third term addresses the ingrowth of member i within compartment j due to the
244   presence of its precursors h in the compartment. The number of nuclei of the precursor
245   multiplied by its physical decay is the activity of the precursor, $A_{h,j}$. Note that the members of
246   the decay chain are assumed to be of order such that the precursors of member i have indexes
247   less than i. An ordered listing of the chain members can be obtained using the DECDATA
248   software distributed with *Publication 107* (ICRP, 2008).
249   (16) If all terms in Eq. (2.1) are multiplied by the physical decay constant of the chain
250   member being considered, λ_i^P, the rate of change of the activity of chain member i in
251   compartment j is obtained as shown in Eq. (2.2).
252

$$\frac{dA_{i,j}(t)}{dt} = \sum_{\substack{k=1 \\ k\neq j}}^{M} A_{i,k}\lambda_{i,k,j} - A_{i,j}\left[\sum_{\substack{k=1 \\ k\neq j}}^{M} \lambda_{i,j,k} + \lambda_i^P\right] + \sum_{h=1}^{i-1} A_{h,j}\beta_{h,i}\lambda_i^P \tag{2.2}$$

253   (17) The system of $n \times M$ ordinary first-order differential equations is solved using suitable
254   numerical methods, under the assumption that $A_{i,j}(0) = 0$ for all compartments with the
255   exception of compartments of intake, where nonzero initial conditions are only applied to the
256   parent nuclide; i.e. $i = 1$. Information on the physical decay constants and branching fraction,
257   $\beta_{k,i}$, are available from *Publication 107* (ICRP 2008a).
258   (18) To calculate the numerical values of the dose coefficients, it is necessary to associate
259   the biokinetic compartments of Eq. (2.2) with anatomical source regions indexed by r_s. A

260 source region may or may not be a living tissue (for example, the stomach contents may be a
261 source region but is not a living tissue) and may consist of more than one biokinetic
262 compartment. The time-dependent activity in source region r_s is the sum of the time-dependent
263 activity in each biokinetic compartment j comprising the source region:

$$A_i\left(r_S,t\right) = \sum_{j}^{Q} A_{i,j}\left(t\right) \qquad (2.3)$$

264 where Q represents the total number of compartments comprising the source region being
265 considered.
266   (19) For intakes in reference adults, dosimetric quantities are invariant with time and it is
267 convenient to integrate the activity in Eq. (2.3) over the 50-year commitment period to obtain
268 the total number of nuclear transformations as in the OIR series (ICRP 2015). For intakes in
269 reference children the dosimetric quantities vary as the reference individual ages. The
270 integration must then wait until after the time-varying activity is multiplied by a time-varying
271 dose per nuclear transformation (S-coefficient.)
272   (20) Dividing the activity in Eq. (2.3) by the total intake activity gives the rate of nuclear
273 transformations per activity intake, $a_i(r_S, t)$:

$$a_i\left(r_S,t\right) = \frac{A_i\left(r_S,t\right)}{A_{\text{exhaled},0} + \sum_{j} A_{1,j}\left(0\right)} \qquad (2.4)$$

274
275 where the denominator includes the prompt exhaled activity $A_{\text{exhaled},0}$, (pertinent for
276 inhalations, as only a fraction of the intake activity is deposited in the compartments of the
277 HRTM) and the summation of parent activity ($i=1$) in all compartments at t = 0. Note that in
278 *Publication 130*, the denominator was erroneously described as excluding this exhaled activity.
279 This error was corrected in *Publication 133*. The denominator in Eq. (2.4) has been updated in
280 this publication to be consistent with the description in *Publication 133*.

2.1.2. Computation of the ICRP reference dose coefficients for organ equivalent dose

282   (21) The equivalent dose rate coefficient in target region r_T of the Reference Adult Male,
283 $\dot{h}^M(r_T, t)$ and the Reference Adult Female, $\dot{h}^F(r_T, t)$, are given by:
284

$$\dot{h}^M(r_T, t) = \sum_{i=1}^{n} \sum_{r_S}^{m} a_i(r_S, t)\, S_w^M(r_T \leftarrow r_S, t)_i \qquad (2.5)$$

$$\dot{h}^F(r_T, t) = \sum_{i=1}^{n} \sum_{r_S}^{m} a_i(r_S, t)\, S_w^F(r_T \leftarrow r_S, t)_i \qquad (2.6)$$

285 The S-coefficients, $S_w^M(r_T \leftarrow r_S, t)_i$ and $S_w^F(r_T \leftarrow r_S, t)_i$ give the radiation-weighted equivalent
286 dose in target region r_T per nuclear transformation (Sv Bq^{-1} s^{-1}) of chain member i (of n
287 members in the chain) in a source regions r_S (of m source regions) for the male and female
288 reference individuals, respectively.
289   (22) The committed equivalent dose coefficients in each target region are given by
290 integrating the time-dependent equivalent dose rate coefficients over the commitment period
291 as shown in Eqs. (2.5) and (2.6) where t_o is the age at intake and τ is the commitment period.
292

$$h_{\mathrm{T}}^{\mathrm{M}}(\tau) = \int_{t_o}^{t_o+\tau} \dot{h}^{\mathrm{M}}(r_{\mathrm{T}}, t)\, dt \tag{2.7}$$

$$h_{\mathrm{T}}^{\mathrm{F}}(\tau) = \int_{t_o}^{t_o+\tau} \dot{h}^{\mathrm{F}}(r_{\mathrm{T}}, t)\, dt \tag{2.8}$$

293
294 (23) Dose coefficients resulting from occupational intakes of radionuclides were published
295 in the OIR series and based on a commitment period of 50 years in the reference adults. In the
296 EIR series, committed dose coefficients are computed for reference individuals based on
297 intakes at ages 3-month, 1-year, 5-year, 10-year, 15-year, and adult. For these individuals, the
298 commitment period is 50 years for intakes as an adult and through age 70 years for intakes at
299 all other ages. The age at intake for the adult may be 20y or 25y depending on the biokinetics
300 of the considered radionuclide (for skeletal seeking radionuclides adult maturity is defined at
301 age 25y.) Regardless of the age at intake for the adult, the commitment period for the adult is
302 50y. In the OIR series of publications, all quantities contributing to the *S*-coefficient calculation
303 are invariant with respect to time since the reference workers are adults from the time of intake
304 throughout the entire commitment period. As a result, only the activity content in source
305 regions required integration over time and yielded the total number of nuclear transformations
306 taking place during the commitment period. In the EIR series, this remains true for intakes by
307 the reference adult. For children, however, the SAF varies with respect to time as the child
308 grows and the shape, volume, mass, and distance between tissues changes.
309 (24) A number of target tissues are represented by a single target region r_{T}. In cases where
310 more than one tissue region defines the target tissue, fractional weighting of the equivalent
311 dose must be made. The committed equivalent dose coefficients for tissue T in the reference
312 adult male, $h_{\mathrm{T}}^{\mathrm{M}}(\tau)$, and adult female, $h_{\mathrm{T}}^{\mathrm{F}}(\tau)$, are thus given in Eqs. (2.9) and (2.10) as

$$h_{\mathrm{T}}^{\mathrm{M}}(\tau) = \sum_{r_{\mathrm{T}}} f(r_{\mathrm{T}}, T)\, h^{\mathrm{M}}(r_{\mathrm{T}}, \tau) \tag{2.9}$$

$$h_{\mathrm{T}}^{\mathrm{F}}(\tau) = \sum_{r_{\mathrm{T}}} f(r_{\mathrm{T}}, T)\, h^{\mathrm{F}}(r_{\mathrm{T}}, \tau) \tag{2.10}$$

313 where the target region fractional weights $f(r_{\mathrm{T}}, T)$, are the proportions of the equivalent dose
314 in tissue T associated with target region r_{T}. With the exception of the target tissues addressed
315 in Table 2.1, the target tissues of Table 2.2 are represented by a single target region and thus
316 for these tissues $f(r_{\mathrm{T}}, T) = 1$. In Table 2.1, values of $f(r_{\mathrm{T}}, T)$ for the extrathoracic (ET) and
317 thoracic (TH or Lung) regions are taken to be equivalent to their risk apportionment factors as
318 assigned in the revised HRTM. These are assumed to be the same for children, in the absence
319 of information (ICRP, 1995b). For the colon, values of $f(r_{\mathrm{T}}, T)$ are taken to be the fractional
320 masses of the stem cell layers within the alimentary tract walls (see Table 7.8 of *Publication
321 100* (ICRP, 2006)). Sugiyama et al. (2020) found excess relative risks among a cohort of atomic
322 bomb survivors were not significantly different for proximal and distal colon cancer. The same
323 study found no variation in risk by age at exposure. For the lymphatic nodes, values of $f(r_{\mathrm{T}}, T)$
324 are taken to be the fractional masses of lymphatic nodes (not lymphatic tissues) within the ET,
325 TH, and non-respiratory regions consistent with data given previously in *Publication 66* (ICRP,
326 1994b). These values are independent of age of the reference individual.
327
328
329

330 Table 2.1. Target region fractional weights, $f(r_T,T)$

Tissue, T	r_T	$f(r_T,T)$
ET	ET_1	0.001
	ET_2	0.999
TH	BB*	1/3
	bb	1/3
	AI	1/3
Colon	Right colon	0.4
	Left colon	0.4
	Rectosigmoid	0.2
Lymphatic nodes	LN_{ET}	0.08
	LN_{TH}	0.08
	Lymph (systemic)	0.84

331 ET, extrathoracic; TH, thoracic; ET_1, anterior nasal passage; ET_2, posterior nasal passage, pharynx, and
332 larynx; BB, bronchial; bb, bronchiolar; AI, alveolar–interstitial; LN_{ET}, ET lymph nodes; LN_{TH}, TH
333 lymph nodes.
334 *The basal and secretory cells are two target regions weighted equally.
335

336 **2.1.3. Computation of the ICRP reference dose coefficients for effective dose**

337 As defined in *Publication 103* (ICRP, 2007), the committed effective dose coefficient, $e(\tau)$, is
338 then:
339

$$e(\tau) = \sum_T w_T \left[\frac{h_T^M(\tau) + h_T^F(\tau)}{2} \right] \qquad (2.11)$$

340 where w_T is the tissue weighting factor for tissue T of Table 2.2 and $h_T^M(\tau)$, and $h_T^F(\tau)$, are the
341 corresponding committed equivalent dose coefficients for these same tissues in the Reference
342 Male and Reference Female, respectively. The tissue weighting factor for the remainder tissues
343 is applied to the arithmetic mean of the equivalent doses to the thirteen tissues for each sex.
344
345 Table 2.2. *Publication 103* (ICRP, 2007) tissue weighting factors

Tissue	w_T	$\sum w_T$
Bone-marrow, breast, colon, lung, stomach, remainder tissues (13 for each sex*)	0.12	0.72
Gonads	0.08	0.08
Urinary bladder, oesophagus, liver, thyroid	0.04	0.16
Bone surface, brain, salivary glands, skin	0.01	0.04

346 *Remainder tissues: adrenals, ET regions of the respiratory tract, gall bladder, heart, kidneys, lymphatic
347 nodes, muscle, oral mucosa, pancreas, prostate (male), small intestine, spleen, thymus, uterus/cervix
348 (female).

349 **2.2. *S*-coefficients and the Specific Absorbed Fraction**

350 (25) The radiation-weighted *S*-coefficient is the equivalent dose to a target tissue per nuclear
351 transformation taking place in a source region. The *S*-coefficient is computed as shown in Eq.
352 (2.12) and incorporates nuclear decay data, the radiation weighting factor, and the specific
353 absorbed fraction, $\Phi(r_T \leftarrow r_S, E_{R,i}, t)$.

354

$$S_w(r_T \leftarrow r_S, t) = \sum_R w_R \sum_i E_{R,i} \, Y_{R,i} \, \Phi(r_T \leftarrow r_S, E_{R,i}, t) \qquad (2.12)$$

355

356 The energy and yield of the *i*th emission of radiation type R are denoted by $E_{R,i}$ and $Y_{R,i}$ and
357 are tabulated in *Publication 107*. For the continuous energy spectrum associated with beta
358 emissions, an integral is required rather than a summation, as shown in Eq. (2.13).

359

$$S_{w\text{-beta}}(r_T \leftarrow r_S, t) = \int_{i=0}^{i_{max}} w_R \, E_{R,i} \, Y_{R,i}(E_{R,i}) \, \Phi(r_T \leftarrow r_S, E_{R,i}, t) \, dE_R \qquad (2.13)$$

360

361 (26) In practice it is necessary to separately compute the beta contribution given by Eq.
362 (2.13) to the S-coefficient from the contribution due to other radiation types. The two
363 contributions are simply summed to give the total S-coefficient for all emissions from a
364 particular radionuclide.
365 (27) The radiation weighting factors, w_R, were provided in *Publication 103* (ICRP 2007),
366 and are found in Table 2.3.

367

368 Table 2.3. *Publication 103* (ICRP, 2007) radiation weighting factors

Tissue	w_R
Photons	1
Electrons and muons	1
Protons and charged pions	2
Alpha particles, fission fragments, heavy ions	20
Neutrons	$\begin{cases} 2.5 + 18.2 \, e^{-[\ln(E_n)]^2/6}, & E_n < 1 \text{ MeV} \\ 5.0 + 17.0 \, e^{-[\ln(2E_n)]^2/6}, & 1 \text{ MeV} \leq E_n \leq 50 \text{ MeV} \\ 2.5 + 3.2 \, e^{-[\ln(0.04E_n)]^2/6}, & E_n > 50 \text{ MeV} \end{cases}$

369

370 (28) The SAF, Φ, is defined in Eq. (2.14) as the fraction of energy, E_R, emitted from a source
371 region, r_S, which is absorbed in a target region, r_T, per mass of the target region, m_T. The
372 absorbed fraction term, ϕ, is a function of the source-target geometry and the energy of
373 radiation type R.

374

$$\Phi(r_T \leftarrow r_S, E_R) = \frac{\phi(r_T \leftarrow r_S, E_R)}{m_T} \qquad (2.14)$$

375 (29) The absorbed fraction is calculated by radiation transport simulation in voxel phantoms
376 or other geometrical models as described in Section 4. To calculate a SAF corresponding to the
377 phantom or model, the absorbed fraction is divided by the target mass in that phantom or model.
378 If the target mass represented within the phantom or model is not equal to that of the reference
379 individual, then it may be necessary to scale the computed SAF. Section 5.1 describes the
380 scaling process and when it is desirable. Other portions of Section 5 describe additional quality
381 checks performed on the phantom and model SAFs.
382 (30) As described in *Publication 133* (ICRP 2016a), the internal dose calculation includes
383 contributions from activity in the systemic region denoted as Other which consists of systemic
384 tissue not explicitly invoked in a particular systemic biokinetic model. Users of SAFs will find

385   it desirable to compute a custom SAF for the Other systemic tissue based on its composition
386   for a particular case. This SAF is computed using a source-tissue-mass-weighted average of
387   the constituents as shown in Eq. (2.15), where m_{r_S} is the mass of a constituent source region
388   and m_{Other} is the total mass of all the systemic tissues not explicitly invoked in the systemic
389   biokinetic model. Later in this publication, Table 3.16 provides a list of systemic tissues eligible
390   for inclusion in the Other source region.
391

$$\Phi(r_T \leftarrow \text{Other}, E_{R,i}) = \frac{1}{m_{\text{Other}}} \sum_{r_S} m_{r_S} \Phi(r_T \leftarrow r_S) \qquad (2.15)$$

392
393   (31) The specific absorbed fractions provided in this publication for electrons, photons, and
394   alpha particles are tabulated at discrete energies. It is necessary to interpolate between these
395   energies when seeking the specific absorbed fractions at a specific energy associated with a
396   particular radionuclide emission. More than 20 energies are tabulated to minimise the impact
397   of different interpolation techniques. In the OIR and EIR series, a monotone interpolation using
398   piecewise cubic Hermite spline (PCHIP) is used (Fritsch and Carlson 1980). This interpolation
399   algorithm uses all known data points to inform the desired interpolated value(s).
400   (32) For intakes in children, the *S*-coefficient varies with respect to time. Interpolation is
401   also performed to obtain *S*-coefficients at non-reference ages. At ages between 1 and 20 years
402   old, the same PCHIP interpolation technique described above is applied using *S*-coefficients at
403   each of the reference ages as input into the interpolation algorithm.
404   (33) *Publication 89* describes the complexities associated with growth rates in different
405   tissues in the first year of life. Accordingly, during the first year of life a weighted linear
406   interpolation is used as given in Eq. (2.16) and (2.17) to find the *S*-coefficient at the desired
407   time, $S_w(t)$, where x is a fractional factor determined using Eq. (2.17).
408

$$S_w(t) = x[S_w(1y) - S_w(0y)] + S_w(0y) \qquad (2.16)$$

$$x = \begin{cases} t^{[0.3+0.7(1-t)^{10}]}, & 0 \le t < \dfrac{100\,d}{365\,d} \\[2ex] t^{[0.16+0.84(1-t)^5]}, & \dfrac{100\,d}{365\,d} \le t < 1y \end{cases} \qquad (2.17)$$

409
410   In Eq. (2.17), t is given as the fraction of 1 year (365 days).
411   (34) Figure 2.1 provides justification for the interpolation described in Eqs. (2.16) and
412   (2.17). Table 4.3 in *Publication 89* provides the total body mass of European infants (Eveleth
413   and Tanner 1990; ICRP 2002). The interpolated function is designed to provide a better fit for
414   the variable growth patterns taking place within the first year of life.
415
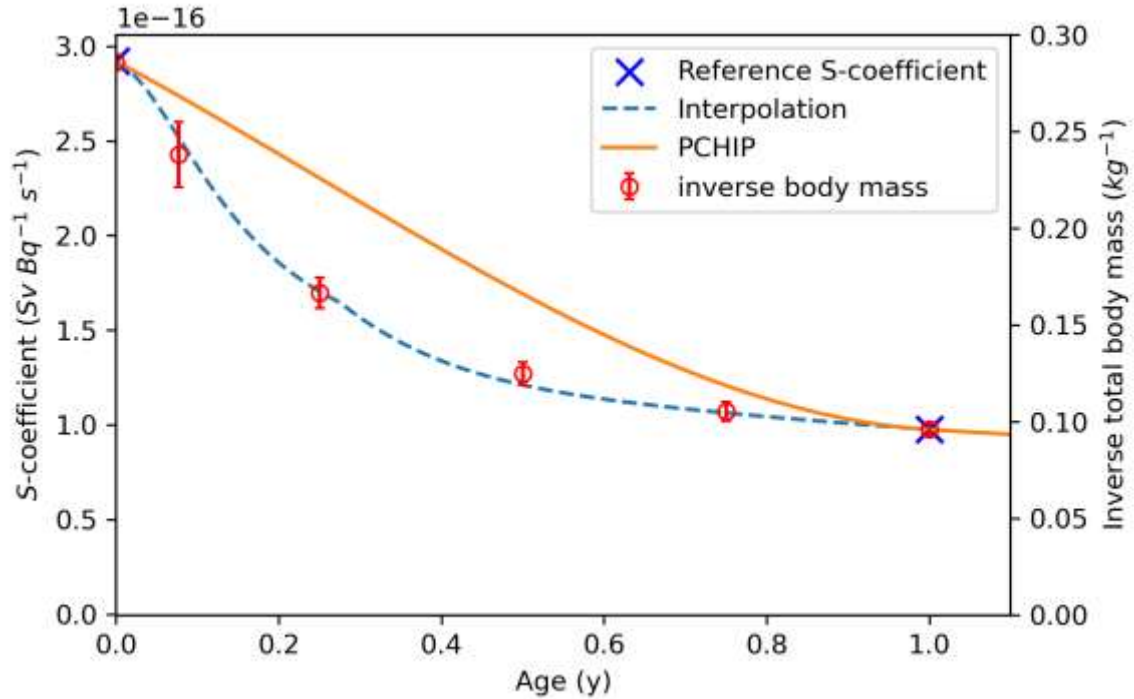
Fig. 2.1. S-coefficient interpolation within the first year. The X's represent S-coefficients at ages 0 and 1-year for the emissions from tritiated water from Other systemic tissue irradiating the Muscle. The dashed line is the interpolated function provided in Eq. (2.16). The circles are plotted against the right-hand y-axis and are the inverse of the total body mass provided in Eq. (4.3) of *Publication 89*. The PCHIP curve is the result if a piecewise cubic Hermite spline interpolation was applied between birth and age 1y.

2.2.1. Other uses of reference SAFs

(35) The SAFs in this publication have been computed for the primary purpose of computing organ equivalent dose and effective dose coefficients for use in radiation protection. However, these SAFs are likely to be useful for a variety of additional internal dosimetry applications including nuclear medicine (studied by ICRP Task Group 36) and internal dose reconstruction. Users of these SAFs are advised to keep in mind that they are consistent with the reference individuals as defined in Section 3. Care should therefore be taken when applying them to non-reference individuals. Use of these SAFs should be made with an understanding that one is treating at least one component of the internal dosimetry calculation (fraction of emitted energy absorbed per unit mass) as equivalent to that in ICRP reference individuals.

433   **3. ICRP REFERENCE INDIVIDUALS**

434

435   (36) The reference individuals are idealised persons used for the calculation of effective
436 dose (ICRP 2007). The parameters defining the reference individuals include anatomical and
437 physiological parameters. The physiological parameters inform the biokinetic modelling of
438 activity while the anatomical parameters form the basis for of computational phantoms and
439 models used to compute SAFs. While the calculation can be thought of in terms of the product
440 of a source (or biokinetic) term and an energy absorption term, the two terms should be
441 computed in a manner consistent with one another. The characterization and definition of the
442 reference individuals serves as a guiding mechanism for ensuring the two terms involved in the
443 calculation of internal doses maintain consistency with one another. The reference SAFs
444 provided in this document are therefore reference values and consistent with the reference
445 individual definition.

446 **3.1. Sources of reference mass data**

447 **3.1.1. Publication 89**

448   (37) *Publication 89* (ICRP 2002) provides most of the reference masses of the reference
449 individuals for males and females of six ages (newborn, 1 year, 5 years, 10 years, 15 years, and
450 adult.) In addition to publishing reference masses based on research in the literature,
451 *Publication 89* included reference values previously published in *Publication 66* (ICRP 1994)
452 on the respiratory tract, *Publication 70* (ICRP 1995b) on the skeleton, *Publication 88* (ICRP
453 2001) on the embryo/foetus and *Publication 23* (ICRP 1975) on the definition of Reference
454 Man.
455   (38) Table 2.8 in *Publication 89* provides a summary table of reference masses of organs
456 and tissues by sex and age. For almost all organs and tissues listed in Table 2.8 the listed mass
457 values do not include the blood perfusing that organ or tissue (i.e., organ parenchyma mass
458 only). When performing the internal dose calculation, it is necessary to describe source masses,
459 generally, as without blood since activity presumably is taken up in tissue in proportion to the
460 parenchyma tissue mass. But since the energy absorption takes place in the entire mass of an
461 organ or tissue which contains blood, the target mass needs to include the mass of blood
462 perfusing the tissue.
463   (39) Table 2.14 in *Publication 89* provides a reference blood distribution for the adult male
464 and female but does not contain similar information for the younger reference ages. Table 2.14
465 gives the percentage of the total body blood volume which is found in each of the organs or
466 tissues listed.

467 **3.1.2. Publication 66**

468   (40) *Publication 66* (ICRP 1994) provides detailed information on the human respiratory
469 tract model. Table 5 in *Publication 66* was reprinted as Table 5.3 in *Publication 89* and provides
470 reference masses of epithelial target tissues in the respiratory tract, as well as masses for the
471 extrathoracic and thoracic lymph nodes.
472   (41) Table 5 of *Publication 66* did not provide masses for the newborn but newborn masses
473 were provided in Table 5.3 of *Publication 89*. During the preparation of the EIR series of
474 publications, it became clear that the reference newborn masses for the bronchi and bronchiole
475 source and target regions were not computed in *Publications 71* (ICRP 1995a) and *89* in a

476 manner consistent with the methods of *Publication 66*. In this work, new reference masses are
477 provided for the newborn bronchi and bronchiole regions. Note that considerable uncertainty
478 exists in the applicability of *Publication 66* methodology for the newborn. Nevertheless, it is
479 desirable to proceed with a method consistent with that used at other reference ages.
480   (42) The newborn masses are computed here in a method consistent with the method
481 described in *Publication 66*. Figure 2 in *Publication 66* depicts the stylised cylindrical
482 dosimetry model for the airway regions. The mass of a tissue layer beginning at some depth d_1
483 through a depth d_2 could be computed as given in Eq. (3.1) where D is the diameter and L is
484 the length of the cylindrical airway and ρ is the mass density of the tissue (taken as 1.00 g cm^{-3}
485 ^{3} in *Publication 66*).
486

$$m_r = \rho L \pi \left[\left(\frac{D}{2} + d_2 \right)^2 - \left(\frac{D}{2} + d_1 \right)^2 \right] \tag{3.1}$$

487 Since the depths and thicknesses of the tissue layers are small compared to the airway diameter,
488 the mass can be more simply approximated as the product of mass density, the surface area of
489 the airway, S, and the thickness of the layer of interest, d.
490

$$m_r \cong \rho S d = \rho S(d_2 - d_1) \tag{3.2}$$

491
492   (43) The airway surface area is computed using the dimensional model of the
493 tracheobronchial tree provided in *Publication 66* and repeated here in Table 3.1. The surface
494 area of the bronchial region is given by summing the relative contributions of each branch (1
495 through 8) in the bronchial tree as shown in Eq. (3.3) where z is the generation of the branch
496 and D_z and L_z are the diameter and length of the branch.
497

$$S = \sum_{z=1}^{8} 2^z \pi D_z L_z \tag{3.3}$$

498
499 Table 3.1. Dimensions of the adult tracheobronchial tree of *Publication 66*.

Region	Generation (z)	Diameter (m)	Length (m)
Bronchial	0 Trachea	1.65×10^{-2}	9.1×10^{-2}
	1 Main bronchi	1.20×10^{-2}	3.8×10^{-2}
	2	0.85×10^{-2}	1.5×10^{-2}
	3	0.61×10^{-2}	0.83×10^{-2}
	4	0.44×10^{-2}	0.90×10^{-2}
	5	0.36×10^{-2}	0.81×10^{-2}
	6	0.29×10^{-2}	0.66×10^{-2}
	7	0.24×10^{-2}	0.60×10^{-2}
	8	0.20×10^{-2}	0.53×10^{-2}
Bronchiolar	9	0.1651×10^{-2}	0.4367×10^{-2}
	10	0.1348×10^{-2}	0.3620×10^{-2}
	11	0.1092×10^{-2}	0.3009×10^{-2}
	12	0.0882×10^{-2}	0.2500×10^{-2}
	13	0.0720×10^{-2}	0.2069×10^{-2}
	14	0.0603×10^{-2}	0.1700×10^{-2}
	15 Terminal bronchioles	0.0533×10^{-2}	0.1380×10^{-2}

500

501   (44) *Publication 66* provides information on scaling the airway dimensions to account for
502 differences in age and sex. For the bronchi region, Table 4 of *Publication 66* provides
503 instructions on scaling each generation 1-8 based on a study by Phalen et al. (1985). The
504 footnote of that table provides an equation for a scaling factor, SF, dependent on body height,
505 H, and a constant, a. The scaling factors are reproduced here in Table 3.2 based on a reference
506 height for the newborn of 0.51 m.

$$SF = a(H - 1.76) + 1 \qquad (3.4)$$

507
508 Table 3.2. Parameters for scaling bronchi dimensions for the reference newborn.

Region	Generation (z)	Constant (a)		Scaling Factors (SF)		Newborn	
		Diameter	Length	Diameter	Length	Diameter (mm)	Length (mm)
Bronchial	0	0.540	0.559	0.325	0.301	5.36	27.4
	1	0.530	0.468	0.338	0.415	4.05	15.8
	2	0.507	0.474	0.366	0.408	3.11	6.11
	3	0.489	0.502	0.389	0.373	2.37	3.09
	4	0.429	0.431	0.464	0.461	2.04	4.15
	5	0.441	0.476	0.449	0.405	1.62	3.28
	6	0.452	0.441	0.435	0.449	1.26	2.96
	7	0.405	0.359	0.494	0.551	1.19	3.31
	8	0.333	0.273	0.584	0.659	1.17	3.49

509
510   (45) Applying Eq. (3.4) with the newborn airway dimensions yields a surface area for the
511 newborn bronchial region of 7.39×10^{-3} m^2. Table 3.3 summarises the computation of the
512 newborn bronchi source and target regions.
513
514 Table 3.3. Revised masses for newborn bronchi regions.

Region	Inner depth, d_1 (μm)	Outer depth, d_2 (μm)	Thickness, d (μm)	Mass (g)
Bronch-bas	35	50	15	0.111
Bronch-sec	10	40	30	0.222
Bronchi-b	0	60	60	0.443
Bronchi-q	60	70	10	0.0740

515
516   (46) A similar calculation is performed to determine the masses of the bronchiolar regions
517 in the newborn. Equation (3.3) can be applied to scaled dimensions for generations 9 through
518 15. *Publication 66* provides the following description for scaling the bronchiole diameter and
519 length:
520
521   "The diameter of the bronchioles (generations 9 to 15) is obtained by interpolating
522   between the reference diameter of the last generation of bronchi (generation 8) and the
523   first generation of respiratory bronchioles (generation 16). The unique parabola, which
524   has its minimum at the diameter of the 16th airway generation, provides a good fit to
525   the bronchiolar airway diameters measured by Phalen et al. (1985) for adult subjects.
526   This parabolic interpolation is assumed to apply to younger subjects also. In a similar
527   manner, the lengths of the bronchioles (generations 9 to 15) are obtained by hyperbolic
528   interpolation between the reference lengths of airways in the 8th and 16th generations."
529

530　(47) The parabolic interpolation for the diameters is applied as given in Eq. 3.5 while the
531　hyperbolic interpolation for the lengths in each generation is given in Eq. 3.6.
532

$$D_z = D_{16} + (D_8 - D_{16})\frac{(z-16)^2}{(8-16)^2} \tag{3.5}$$

533

$$L_z = L_{16} + (L_8 - L_{16})\left(\frac{16}{z} - 1\right) \tag{3.6}$$

534
535　In order to apply the above equations, the newborn diameters and lengths for generations 8 and
536　16 must be determined. The values for generation 8 were previously determined (see Table
537　3.2.) For generation 16, *Publication 66* describes scaling by the one-third power of the
538　functional residual capacity (FRC). However, *Publication 66* only provides FRC values down
539　to an age of 3-months old. Gaultier et al. (1979) provides an equation (Eq. 3.7) for FRC for
540　children from birth to age 3-years.
541

$$\begin{aligned} FRC_{\text{male}}\ (mL) &= -269 + 6.9H(cm) \\ FRC_{\text{female}}\ (mL) &= -204 + 5.92H(cm) \end{aligned} \tag{3.7}$$

542
543　Using the newborn reference height of 0.51 m gives a sex averaged FRC of 90 mL. Equation
544　(3.8) applies the cube root scaling to determine the diameter and length (designated as
545　$X_{16,\text{newborn}}$) for generation 16.
546

$$\begin{aligned} X_{16,\text{newborn}} &= X_{16,\text{adult}}\left(\frac{FRC_{\text{newborn}}}{FRC_{\text{adult}}}\right)^{1/3} \\ D_{16,\text{newborn}} &= 1.535 \times 10^{-4} m \\ L_{16,\text{newborn}} &= 3.311 \times 10^{-4} m \end{aligned} \tag{3.8}$$

547　(48) Equations (3.5) and (3.6) can now be applied to determine the newborn airway
548　dimensions for generations 9 through 15 given in

549   (49) Table 3.4. Equation (3.3) is then adapted to the bronchiolar generations to give a
550 newborn bronchiole surface area of 4.91×10^{-2} m^2. The masses of the newborn bronchiole
551 source and target regions are computed via Eq. (3.2) and provided in Table 3.5.
552
553

554   Table 3.4. Bronchiolar airway dimensions for the reference newborn.

Region	Generation (z)	Diameter (mm)	Length (mm)
Bronchiolar	9	0.9298	2.789
	10	0.7239	2.227
	11	0.5496	1.768
	12	0.4070	1.385
	13	0.2961	1.060
	14	0.2169	0.7826
	15	0.1693	0.5418

555

556   Table 3.5. Revised masses for newborn bronchiolar regions with a surface area of 4.91×10^{-2}
557   m^2.

Region	Inner depth, d_1 (μm)	Outer depth, d_2 (μm)	Thickness, d (μm)	Mass (g)
Bchiol-sec	4	12	8	0.393
Brchiole-b	0	20	20	0.982
Brchiole-q	20	25	5	0.246

558
559

560   **3.1.3. Publication 100**

561   (50) *Publication 100* (ICRP 2006) provides detailed information on the human alimentary
562   tract model. While *Publication 100* does not tabulate masses for the alimentary tract target
563   tissues, Section 7 of that publication provides reference geometrical information about the size
564   of the different alimentary tract regions. This information is used to compute reference masses
565   for the alimentary tract target tissues.

566   (51) For example, Table 7.4 of *Publication 100* provides reference lengths and Table 7.5 of
567   *Publication 100* provides internal diameters for the small intestine. From the accompanying
568   text, the target is assumed to be a continuous layer at 130 to 150 µm from the inner surface and
569   is independent of age and sex. Modelling the small intestine as a cylinder means the mass of
570   the target layer can be computed as:

$$m_{SI-stem} = \rho_{tissue} \left[\pi \left(\frac{d}{2} + depth_{outer} \right)^2 - \pi \left(\frac{d}{2} + depth_{inner} \right)^2 \right] l_{cylinder} \qquad (3.9)$$

571   where ρ_{tissue} is the mass density of tissue, d is the internal diameter, $l_{cylinder}$ is the length of the
572   small intestine, and $depth_{outer}$ and $depth_{inner}$ are the outer and inner boundaries of the target
573   layer. For the reference 10-year-old, the mass is computed as:

$$m_{SI-stem} = 1.04 \frac{g}{cm^3} \left[\pi \left(\frac{1.6 \, cm}{2} + 0.0150 \, cm \right)^2 - \pi \left(\frac{1.6 \, cm}{2} + 0.0130 \, cm \right)^2 \right] 220 \, cm \qquad (3.10)$$

$$m_{SI-stem} = 2.34 \, g \qquad (3.11)$$

574   (52) Table 3.6 summarises the reference information provided in *Publication 100* and the
575   resulting masses for the target tissues modelled as cylinders (oesophagus, small intestine, and
576   colon). Table 3.7 contains the information for the stomach which is modelled as a sphere.

577 Table 3.6. Reference values used to compute target tissue masses in the cylindrical geometries of the alimentary tract.

Target region	Abbreviation	Age and sex	Length (cm)	Internal diameter (cm)	Inner depth (µm)	Outer depth (µm)	Mass (g)
Oesophagus stem cells	Oesophagus	Newborn f&m[†]	10	0.5	190	200	0.018
		1-year f&m	13	0.6	190	200	0.027
		5-year f&m	18	0.7	190	200	0.043
		10-year f&m	23	0.8	190	200	0.063
		15-year f&m	26.5[*]	1	190	200	0.090
		Adult female	26	1	190	200	0.088
		Adult male	28	1	190	200	0.095
Small intestine stem cells	SI-stem	Newborn f&m	80	1	130	150	0.537
		1-year f&m	120	1.2	130	150	0.963
		5-year f&m	170	1.4	130	150	1.586
		10-year f&m	220	1.6	130	150	2.340
		15-year f&m	265[*]	2	130	150	3.512
		Adult female	260	2	130	150	3.446
		Adult male	280	2	130	150	3.711
Right colon stem cells	RC-stem	Newborn f&m	14	3	280	300	0.280
		1-year f&m	18	4	280	300	0.477
		5-year f&m	23	4.5	280	300	0.685
		10-year f&m	28	5	280	300	0.925
		15-year f&m	30	6	280	300	1.188
		Adult female	30	6	280	300	1.188
		Adult male	34	6	280	300	1.346
Left colon stem cells	LC-stem	Newborn f&m	16	2.5	280	300	0.267
		1-year f&m	21	3	280	300	0.420
		5-year f&m	26	3.5	280	300	0.604
		10-year f&m	31	4	280	300	0.822
		15-year f&m	35	5	280	300	1.157

Target region	Abbreviation	Age and sex	Length (cm)	Internal diameter (cm)	Inner depth (µm)	Outer depth (µm)	Mass (g)
		Adult female	35	5	280	300	1.157
		Adult male	38	5	280	300	1.256
Rectosigmoid stem cells	RS-stem	Newborn f&m	15	1.5	280	300	0.153
		1-year f&m	21	2	280	300	0.282
		5-year f&m	26	2.3	280	300	0.401
		10-year f&m	31	2.5	280	300	0.518
		15-year f&m	35	3	280	300	0.699
		Adult female	35	3	280	300	0.699
		Adult male	38	3	280	300	0.759

578 *The sex-specific lengths in Pub. 100 for the 15-year-old oesophagus and small intestine are close to one another and were averaged which results
579 in sex-independency in the 15-year-old.
580 †f&m is female and male.

22

581   Table 3.7. Reference values used to compute target tissue masses in the spherical geometry of the stomach.

Target region	Abbreviation	Age and sex	Volume (cm^3)	Internal diameter (cm)	Inner depth (µm)	Outer depth (µm)	Mass (g)
Stomach stem cells	St-stem	Newborn f&m	30	1.9025	60	100	0.191
		1-year f&m	40	2.094	60	100	0.231
		5-year f&m	60	2.397	60	100	0.302
		10-year f&m	80	2.6383	60	100	0.366
		15-year f&m	120	3.0201	60	100	0.479
		Adult f&m	175	3.4248	60	100	0.616

582

3.2. Inclusion of blood and blood distribution model

(53) The mass for most target regions requires the addition of blood to the masses listed in Table 2.8 of *Publication 89*. While Table 2.14 of *Publication 89* provides the blood distribution for the reference adults, the publication does not report explicitly a blood distribution model for younger ages. Wayson et al. (2018) provides such blood distributions.

(54) The values in Table 6 of Wayson et al. are rounded for publication purposes. Since they represent an intermediate step in the target mass calculation, unrounded values are used to compute the blood contribution to target masses (using a density of blood of 1.06 g cm^{-3}.) Table 3.8 provides the unrounded blood distribution values used in this publication to compute reference target masses inclusive of blood.

Table 3.8. Reference values for regional blood distribution (% total blood volume).

Organ or Tissue	Newborn F & M	1-Year F & M	5-Year F & M	10-Year F & M	15-Year Female	15-Year Male
Fat	2.212	4.958	4.061	4.159	6.608	3.602
Brain	5.413	5.276	4.310	2.670	1.370	1.568
Stomach & oesophagus wall	0.767	0.745	0.935	0.987	0.866	0.932
Small intestine wall	2.837	2.809	3.805	3.933	3.327	3.590
Colon wall	1.596	1.641	2.062	2.217	1.852	2.107
Right heart contents	4.50	4.50	4.50	4.50	4.50	4.50
Left heart contents	4.50	4.50	4.50	4.50	4.50	4.50
Coronary tissues	1.088	0.951	0.846	0.857	0.897	0.831
Kidneys	0.704	1.759	2.159	2.171	1.763	1.905
Liver	12.92	11.36	10.27	9.19	9.38	8.53
Lungs						
Pulmonary gas exchange blood	10.5	10.5	10.5	10.5	10.5	10.5
Pulmonary nutrient blood	2.0	2.0	2.0	2.0	2.0	2.0
Skeletal muscle	6.667	5.536	8.538	10.306	10.303	13.684
Pancreas	0.431	0.502	0.459	0.484	0.505	0.557
Skeletal tissues						
Active marrow	5.190	4.969	4.918	4.916	4.983	4.841
Trabecular bone	3.639	4.388	4.376	4.397	4.352	4.051
Cortical bone	1.294	1.584	1.607	1.612	1.490	1.387
Other skeletal tissues	0.659	0.660	0.672	0.797	0.858	0.856
Skin	3.067	2.066	1.761	1.557	2.240	2.147
Spleen	1.505	1.576	1.422	1.398	1.414	1.433
Thyroid	0.066	0.032	0.031	0.045	0.043	0.043
Lymphatic nodes	0.163	0.165	0.164	0.168	0.177	0.181
Ovaries or testes	0.0123	0.0087	0.0077	0.0071	0.0110	0.0216
Adrenal glands	0.415	0.097	0.063	0.054	0.042	0.051
Urinary bladder wall	0.028	0.022	0.020	0.019	0.018	0.019

Organ or Tissue	Newborn F & M	1-Year F & M	5-Year F & M	10-Year F & M	15-Year Female	15-Year Male
All other tissues	3.826	3.397	2.013	2.558	2.002	2.162
Aorta and large arteries	6.0	6.0	6.0	6.0	6.0	6.0
Large veins	18.0	18.0	18.0	18.0	18.0	18.0

595

596   (55) For many target regions, the mass calculation is described in Eq. (3.12) where f_{blood} is the
597   fraction by volume of blood in the target region, m_{wb} is the mass of blood in the body, and
598    $m_{\text{Tparenchyma}}$ is the mass of the target region without blood.

599

$$m_{\text{T}} = f_{\text{blood}} m_{\text{wb}} + m_{\text{Tparenchyma}} \tag{3.12}$$

600

601   (56) As an example, the target mass of the spleen at age 5 years is computed as:

602

$$m_{\text{Spleen}} = (0.01422)(1{,}500 g) + 50 g = 71.33 g \tag{3.13}$$

603   (57) For regions in Table 3.8 which comprise multiple targets, the blood is split by parenchyma
604   mass fraction across those targets. For example, Table 3.8 has a single entry for the lymphatic
605   nodes, but this blood is split across the extrathoracic, thoracic, and systemic lymph node targets
606   by their respective mass fractions.
607   (58) In the lung regions, the 2.0% nutrient blood is split by mass fraction across the bronchi
608   wall, the bronchiolar wall, and the alveolar interstitium. The pulmonary gas exchange blood
609   (10.5%) is assigned in its entirety to the alveolar interstitium.
610   (59) There are several target regions not specified in Table 3.8. It becomes problematic to use
611   the 'All other tissues' category to assign blood to these regions. First, the total list of target regions
612   remaining does not completely comprise 'All other tissues'. Even if reasonable attempts are made
613   to determine how much tissue mass corresponds to 'All other tissues', practical problems arise
614   such as generating sex-dependent blood mass in tissues for which sex dependency does not exist
615   in the reference model.
616   (60) Instead, an approach was adopted which uses a ratio of blood to lean body mass in the
617   whole-body and applies that to each desired target region not specified in Table 3.8. The method
618   is mathematically summarised in Eq. (3.14).

619

$$m_{\text{blood in tissue}} = (m_{\text{blood}} : m_{\text{tissue}})_{\text{lean}} m_{\text{Tparenchyma}} \tag{3.14}$$

620

621   The ratio of blood to lean body mass is computed using information regarding the blood
622   distribution and the lean tissues masses.

623

$$(m_{\text{blood}} : m_{\text{tissue}})_{\text{lean}} = \frac{m_{\text{blood,wb}}\left(1.00 - f_{\text{blood,fat}} - f_{\text{blood,aorta}} - f_{\text{blood,veins}}\right)}{m_{\text{total body}} - m_{\text{fat}}} \tag{3.15}$$

624

625   In Eq. (3.15) $f_{\text{blood,fat}}$, $f_{\text{blood,aorta}}$, and $f_{\text{blood,veins}}$ are the blood volume fractions in the respective
626   regions. The mass of the total body (Table 2.8) and the mass of fat (page 76) each come from
627   values in *Publication 89*. For example, the blood in the 15-year female breast is computed as:

628

25

$$m_{\text{blood,breast}} = \left(\frac{3{,}500g(1.00 - 0.06608 - 0.060 - 0.18)}{53{,}000g - 14{,}000g}\right) 250g = 15.6g \qquad (3.16)$$

629

3.3. Age-dependent reference masses

(61) The masses of the reference individuals are tabulated by target and source regions. The 43 target regions (41 regions in each sex) consist of those tissues which contribute to effective dose along with a select set of tissues which may also be of interest for different applications. The 79 source regions are regions where biokinetic modelling may assign activity.

3.3.1. Target region masses

(62) Table 3.9 provides the list of target regions, their corresponding abbreviations and information on the source and basis of the mass value. Tables 3.10 through 3.15 provide the reference masses for each of the reference individuals. When applicable, the contribution of blood to a target region's mass is shown.

Table 3.9. Target region names, abbreviations, and origin of reference masses.

Target region	Abbreviation	Origin of parenchyma mass	Origin of blood distribution
Oral mucosa	O-mucosa	Scaled from tongue	Lean body mass ratio[*]
Oesophagus stem cells	Oesophagus	Based on Pub. 100[†]	NA
Stomach stem cells	St-stem	Based on Pub. 100[†]	NA
Small intestine stem cells	SI-stem	Based on Pub. 100[†]	NA
Right colon stem cells	RC-stem	Based on Pub. 100[†]	NA
Left colon stem cells	LC-stem	Based on Pub. 100[†]	NA
Rectosigmoid stem cells	RS-stem	Based on Pub. 100[†]	NA
Anterior nose epithelium	ET1-bas	Pub. 89-Table 5.3[‡]	NA
Extrathoracic airway epithelium	ET2-bas	Pub. 89-Table 5.3[‡]	NA
Extrathoracic lymph nodes	LN-ET	Pub. 89-Table 5.3[‡]	Wayson et al[§]
Bronchi basal layer	Bronchi-bas	Pub. 89-Table 5.3[‡]	NA
Bronchi secretory layer	Bronchi-sec	Pub. 89-Table 5.3[‡]	NA
Bronchiolar secretory layer	Bchiol-sec	Pub. 89-Table 5.3[‡]	NA
Alveolar interstitium	AI	Pub. 89-Table 5.3[‡]	Computed in this work[¶¶]

26

Target region	Abbreviation	Origin of parenchyma mass	Origin of blood distribution
Thoracic lymph nodes	LN-Th	Pub. 89-Table 5.3[‡]	Wayson et al[§]
Red marrow	R-marrow	Pub. 89-Table 2.8[¶]	Wayson et al[§]
Skeletal endosteum	Endost-BS		
Brain	Brain	Pub. 89-Table 2.8[¶]	Wayson et al[§]
Lens of the eye	Eye-lens	Pub. 23, Pub. 143[**]	NA
Pituitary gland	P-gland	Pub. 89-Table 2.8[¶]	Lean body mass ratio[*]
Tongue	Tongue	Pub. 89-Table 2.8[¶]	Lean body mass ratio[*]
Tonsils	Tonsils	Pub. 89-Table 2.8[¶]	Lean body mass ratio[*]
Salivary glands	S-glands	Pub. 89-Table 2.8[¶]	Lean body mass ratio[*]
Thyroid	Thyroid	Pub. 89-Table 2.8[¶]	Wayson et al[§]
Breast	Breast	Pub. 89-Table 2.8[¶] and Pub. 143[§§]	Lean body mass ratio[*]
Thymus	Thymus	Pub. 89-Table 2.8[¶]	Lean body mass ratio[*]
Heart wall	Ht-wall	Pub. 89-Table 2.8[¶]	Wayson et al[§], Pub. 89[¶]
Adrenals	Adrenals	Pub. 89-Table 2.8[¶]	Wayson et al[§]
Liver	Liver	Pub. 89-Table 2.8[¶]	Wayson et al[§]
Pancreas	Pancreas	Pub. 89-Table 2.8[¶]	Wayson et al[§]
Kidneys	Kidneys	Pub. 89-Table 2.8[¶]	Wayson et al[§]
Spleen	Spleen	Pub. 89-Table 2.8[¶]	Wayson et al[§]
Gall bladder wall	GB-wall	Pub. 89-Table 2.8[¶]	Lean body mass ratio[*]
Ureters	Ureters	Pub. 89-Table 2.8[¶]	Lean body mass ratio[*]
Urinary bladder wall	UB-wall	Pub. 89-Table 2.8[¶]	Wayson et al[§]
Ovaries	Ovaries	Pub. 89-Table 2.8[¶]	Wayson et al[§]
Testes	Testes	Pub. 89-Table 2.8[¶]	Wayson et al[§]
Prostate	Prostate	Pub. 89-Table 2.8[¶]	Lean body mass ratio[*]
Uterus	Uterus	Pub. 89-Table 2.8[¶]	Lean body mass ratio[*]
Systemic lymph nodes	LN-Sys	Derived from Pub. 66 and 89[††]	Wayson et al[§]
Skin	Skin	Pub. 89-Table 2.8[¶]	Wayson et al[§]
Adipose	Adipose	Modified from Pub. 89-Table 2.8[♯]	Wayson et al[§]
Muscle	Muscle	Pub. 89-Table 2.8[¶]	Wayson et al[§]

642 [*]Blood component for these tissues computed by using ratio of mass of blood in lean body mass to lean
643 body mass (see explanation in text.)
644 [†]The stylised geometries described in *Publication 100* (ICRP 2006).

27

645 ‡Contained in Table 5.3 of *Publication 89* (ICRP 2002). Newborn values of the bronchi and bronchiole
646 regions computed in this work via the method in *Publication 66*.
647 §Contained in Table 6 of Wayson et al. (2018).
648 ¶Contained in Table 2.8 of *Publication 89* (ICRP 2002)
649 **Publication 23* describes age-dependency for the lens of the eye but does not provide reference values.
650 The phantom mass in *Publication 143* was chosen for the target mass of the lens.
651 ††*Publication 89* (ICRP 2002) describes the age dependency of the total lymph node mass. This information
652 combined with the information in *Publication 66* (ICRP 1994) on the masses of the extrathoracic and
653 thoracic lymph nodes was used to calculate the systemic lymph node mass.
654 #The adipose mass was adjusted from the values in Table 2.8 of *Publication 89* to maintain consistency
655 with the total body mass.
656 §§*Publication 89* does not contain reference masses for the breast at ages 10 years and younger. The phantom
657 masses in *Publication 143* (ICRP 2020b) were adopted at those ages.
658 ¶¶95.1% of the parenchyma lung mass in Table 2.8 from *Publication 89* was used as a starting point for the
659 parenchyma mass of the alveolar tissue. Based on the blood distribution in Wayson et al., a low-energy,
660 limiting SAF for the (AI ← Blood) geometry was computed. This limiting SAF and the alveolar tissue
661 mass inclusive of blood from Table 5 of *Publication 66* (and Table 5.3 of *Publication 89*) to arrive at the
662 mass of blood in AI and the parenchyma mass of AI. The complexity of this calculation is due to Tables
663 2.8 and 5.3 of *Publication 89* containing AI and Lung masses which are not consistent with one another for
664 several ages.
665
666
667

668 Table 3.10. Masses for target regions in the reference newborn (female / male). The target mass
669 is inclusive of blood when applicable.

Target region	Parenchyma mass (g)	Mass of blood (g)	Target mass (g)
O-mucosa	1.608	0.112	1.72
Oesophagus	0.018	NA	0.018
St-stem	0.191	NA	0.191
SI-stem	0.537	NA	0.537
RC-stem	0.280	NA	0.280
LC-stem	0.267	NA	0.267
RS-stem	0.153	NA	0.153
ET1-bas	0.0024	NA	0.0024
ET2-bas	0.053	NA	0.053
LN-ET	0.70	0.023	0.723
Bronch-bas	0.110	NA	0.110
Bronch-sec	0.220	NA	0.220
Bchiol-sec	0.393	NA	0.393
AI	23.0	29.0	52.0
LN-Th	0.70	0.023	0.723
R-marrow	50	15.1	65.1
Endost-BS	34	10.2	44.2
Brain	380	15.7	395.7
Eye-lens	0.13	NA	0.13
P-gland	0.10	0.0068	0.107
Tongue	3.5	0.239	3.74
Tonsils	0.10	0.0068	0.107
S-glands	6.0	0.410	6.41
Thyroid	1.3	0.190	1.49
Breast	0.08	0.0055	0.085
Thymus	13	0.889	13.9
Ht-wall	20	3.16	23.16
Adrenals	6.0	1.2	7.20
Liver	130	37.5	167.5
Pancreas	6.0	1.25	7.25
Kidneys	25	2.04	27.04
Spleen	9.5	4.36	13.86
GB-wall	0.5	0.0342	0.534
Ureters	0.77	0.0526	0.823
UB-wall	4.0	0.0803	4.08
Ovaries	0.30	0.0355	0.336
Testes	0.85	0.0355	0.886
Prostate	0.80	0.0547	0.855
Uterus	4.0	0.273	4.27
LN-Sys	12.9	0.425	13.3
Skin	175	8.90	183.9
Adipose	1016/1019[*]	6.4	1022/1025[*]
Muscle	800	19.33	819.3

670 *The small differences in adipose mass between the female and male result from differences in sex specific
671 tissues (ovaries, prostate, testes, and uterus) and a desire for the total body mass to match the reference total
672 body mass of *Publication 89* which is not sex specific at younger ages.

673
674
675 Table 3.11. Masses for target regions in the reference 1-year old (female / male). The target mass
676 is inclusive of blood when applicable.

Target region	Parenchyma mass (g)	Mass of blood (g)	Target mass (g)
O-mucosa	4.679	0.231	4.910
Oesophagus	0.027	NA	0.027
St-stem	0.231	NA	0.231
SI-stem	0.963	NA	0.963
RC-stem	0.477	NA	0.477
LC-stem	0.420	NA	0.420
RS-stem	0.282	NA	0.282
ET1-bas	0.0041	NA	0.0041
ET2-bas	0.093	NA	0.093
LN-ET	2.1	0.073	2.173
Bronch-bas	0.16	NA	0.16
Bronch-sec	0.31	NA	0.31
Bchiol-sec	0.60	NA	0.60
AI	80.55	69.45	150
LN-Th	2.1	0.073	2.173
R-marrow	150	26.3	176.3
Endost-BS	70	10.9	80.9
Brain	950	28.0	978.0
Eye-lens	0.22	NA	0.22
P-gland	0.15	0.0073	0.157
Tongue	10	0.489	10.49
Tonsils	0.50	0.0244	0.524
S-glands	24	1.174	25.17
Thyroid	1.8	0.168	1.97
Breast	0.43	0.0210	0.451
Thymus	30	1.467	31.5
Ht-wall	50	5.04	55.04
Adrenals	4	0.51	4.51
Liver	330	60.2	390.2
Pancreas	20	2.66	22.66
Kidneys	70	9.32	79.32
Spleen	29	8.35	37.35
GB-wall	1.4	0.0685	1.468
Ureters	2.2	0.1076	2.308
UB-wall	9	0.1155	9.12
Ovaries	0.80	0.0463	0.846
Testes	1.5	0.0463	1.546
Prostate	1.0	0.0489	1.049

Target region	Parenchyma mass (g)	Mass of blood (g)	Target mass (g)
Uterus	1.5	0.073	1.57
LN-Sys	20.8	0.727	21.5
Skin	350	10.95	361
Adipose	4028/4027	26.28	4054/4053
Muscle	1900	29.34	1929.3

677
678
679 Table 3.12. Masses for target regions in the reference 5-year old (female and male). The target
680 mass is inclusive of blood when applicable.

Target region	Parenchyma mass (g)	Mass of blood (g)	Target mass (g)
O-mucosa	8.715	0.615	9.330
Oesophagus	0.043	NA	0.043
St-stem	0.302	NA	0.302
SI-stem	1.586	NA	1.586
RC-stem	0.685	NA	0.685
LC-stem	0.604	NA	0.604
RS-stem	0.401	NA	0.401
ET1-bas	0.0083	NA	0.0083
ET2-bas	0.19	NA	0.19
LN-ET	4.1	0.206	4.306
Bronch-bas	0.23	NA	0.23
Bronch-sec	0.47	NA	0.47
Bchiol-sec	0.95	NA	0.95
AI	117	183	300
LN-Th	4.1	0.206	4.306
R-marrow	340	73.6	413.8
Endost-BS	203	30.6	233.6
Brain	1180/1310	64.7	1245/1375
Eye-lens	0.33	NA	0.33
P-gland	0.25	0.0175	0.268
Tongue	19	1.331	20.33
Tonsils	2	0.1401	2.140
S-glands	34	2.382	36.38
Thyroid	3.4	0.471	3.87
Breast	0.94	0.0659	1.006
Thymus	30	2.102	32.1
Ht-wall	85	12.70	97.70
Adrenals	5	0.95	5.95
Liver	570	154	724
Pancreas	35	6.89	41.89
Kidneys	110	32.39	142.4
Spleen	50	21.33	71.33
GB-wall	2.6	0.1822	2.782
Ureters	4.2	0.2943	4.494
UB-wall	16	0.3041	16.30

Target region	Parenchyma mass (g)	Mass of blood (g)	Target mass (g)
Ovaries	2.0	0.1150	2.115
Testes	1.7	0.1150	1.815
Prostate	1.2	0.0841	1.284
Uterus	3	0.210	3.21
LN-Sys	40.6	2.041	42.6
Skin	570	26.41	596.4
Adipose	5831/5703	60.91	5892/5764
Muscle	5600	128.1	5728

681
682
683　Table 3.13. Masses for target regions in the reference 10-year old (female and male). The target
684　mass is inclusive of blood when applicable.

Target region	Female			Male		
	Parenchyma mass (g)	Mass of blood (g)	Target mass (g)	Parenchyma mass (g)	Mass of blood (g)	Target mass (g)
O-mucosa	14.7	1.0	15.7	14.7	1.0	15.7
Oesophagus	0.063	NA	0.063	0.063	NA	0.063
St-stem	0.366	NA	0.366	0.366	NA	0.366
SI-stem	2.34	NA	2.34	2.34	NA	2.34
RC-stem	0.925	NA	0.925	0.925	NA	0.925
LC-stem	0.822	NA	0.822	0.822	NA	0.822
RS-stem	0.518	NA	0.518	0.518	NA	0.518
ET1-bas	0.013	NA	0.013	0.013	NA	0.013
ET2-bas	0.28	NA	0.28	0.28	NA	0.28
LN-ET	6.8	0.353	7.153	6.8	0.353	7.153
Bronch-bas	0.31	NA	0.31	0.31	NA	0.31
Bronch-sec	0.62	NA	0.62	0.62	NA	0.62
Bchiol-sec	1.3	NA	1.3	1.3	NA	1.3
AI	196	304	500	196	304	500
LN-Th	6.8	0.353	7.153	6.8	0.353	7.153
R-marrow	630	122.9	752.9	630	122.9	752.9
Endost-BS	478	49.4	527.4	478	49.4	527.4
Brain	1220	66.8	1287	1400	66.8	1467
Eye-lens	0.35	NA	0.35	0.35	NA	0.35
P-gland	0.35	0.0242	0.374	0.35	0.0242	0.374
Tongue	32	2.210	34.21	32	2.210	34.21
Tonsils	3.0	0.2072	3.207	3.0	0.2072	3.207
S-glands	44	3.039	47.04	44	3.039	47.04
Thyroid	7.9	1.120	9.02	7.9	1.120	9.02
Breast	7.53	0.5202	8.050	7.12	0.4918	7.612
Thymus	35	2.418	37.42	40	2.763	42.76
Ht-wall	140	21.4	161.4	140	21.4	161.4
Adrenals	7	1.36	8.36	7	1.36	8.36
Liver	830	229.7	1060	830	229.7	1060
Pancreas	60	12.10	72.10	60	12.10	72.10

Target region	Female			Male		
	Parenchyma mass (g)	Mass of blood (g)	Target mass (g)	Parenchyma mass (g)	Mass of blood (g)	Target mass (g)
Kidneys	180	54.28	234.28	180	54.28	234.28
Spleen	80	34.95	114.95	80	34.95	114.95
GB-wall	4.4	0.3039	4.704	4.4	0.3039	4.704
Ureters	7	0.4835	7.484	7	0.4835	7.484
UB-wall	25	0.4866	25.49	25	0.4866	25.49
Ovaries	3.5	0.1785	3.679	NA	NA	NA
Testes	NA	NA	NA	2	0.1785	2.179
Prostate	NA	NA	NA	1.6	0.1105	1.711
Uterus	4	0.276	4.28	NA	NA	NA
LN-Sys	67.3	3.496	70.8	67.3	3.496	70.8
Skin	820	38.92	858.9	820	38.92	858.9
Adipose	9063	103.97	9167	8882	103.97	8986
Muscle	11000	257.7	11258	11000	257.7	11258

685

686

687 Table 3.14. Masses for target regions in the reference 15-year old (female and male). The target
688 mass is inclusive of blood when applicable.

Target region	Female			Male		
	Parenchyma mass (g)	Mass of blood (g)	Target mass (g)	Parenchyma mass (g)	Mass of blood (g)	Target mass (g)
O-mucosa	24.49	1.51	26.00	25.6	1.90	27.5
Oesophagus	0.09	NA	0.09	0.09	NA	0.09
St-stem	0.479	NA	0.479	0.479	NA	0.479
SI-stem	3.512	NA	3.512	3.512	NA	3.512
RC-stem	1.188	NA	1.188	1.188	NA	1.188
LC-stem	1.157	NA	1.157	1.157	NA	1.157
RS-stem	0.699	NA	0.699	0.699	NA	0.699
ET1-bas	0.017	NA	0.017	0.019	NA	0.019
ET2-bas	0.38	NA	0.38	0.42	NA	0.42
LN-ET	11	0.522	11.52	12	0.731	12.73
Bronch-bas	0.38	NA	0.38	0.41	NA	0.41
Bronch-sec	0.76	NA	0.76	0.82	NA	0.82
Bchiol-sec	1.6	NA	1.6	1.8	NA	1.8
AI	311	489	800	297	563	860
LN-Th	11	0.522	11.522	12	0.731	12.73
R-marrow	1000	174.4	1174	1080	232.3	1312
Endost-BS	352	28.5	380.5	395	39.3	434.3
Brain	1300	47.9	1348	1420	75.3	1495
Eye-lens	0.4	NA	0.4	0.49	NA	0.49
P-gland	0.5	0.0311	0.531	0.5	0.037	0.537
Tongue	53	3.301	56.30	56	4.141	60.14
Tonsils	3.0	0.1868	3.187	3	0.2218	3.222

Target region	Female			Male		
	Parenchyma mass (g)	Mass of blood (g)	Target mass (g)	Parenchyma mass (g)	Mass of blood (g)	Target mass (g)
S-glands	65	4.048	69.05	68	5.028	73.03
Thyroid	12	1.497	13.50	12	2.041	14.04
Breast	250	15.57	265.6	15	1.109	16.11
Thymus	30	1.868	31.87	35	2.588	37.6
Ht-wall	220	31.4	251.4	230	39.9	269.9
Adrenals	9	1.47	10.47	10	2.43	12.43
Liver	1300	328.3	1628	1300	409.4	1709.4
Pancreas	100	17.68	117.7	110	26.73	136.7
Kidneys	240	61.71	301.7	250	91.44	341.4
Spleen	130	49.49	179.5	130	68.79	198.8
GB-wall	7.3	0.4546	7.755	7.7	0.5693	8.269
Ureters	12	0.7473	12.75	12	0.8873	12.89
UB-wall	35	0.6187	35.62	40	0.9071	40.91
Ovaries	6	0.3857	6.386	NA	NA	NA
Testes	NA	NA	NA	16	1.037	17.04
Prostate	NA	NA	NA	4.3	0.3179	4.618
Uterus	30	1.868	31.87	NA	NA	NA
LN-Sys	108.8	5.167	114.0	118.7	7.231	125.9
Skin	1700	78.39	1778	2000	103.1	2103
Adipose	17660	231.3	17890	11340	172.9	11510
Muscle	17000	360.6	17360	24000	656.8	24660

689
690
691 Table 3.15. Masses for target regions in the reference adult (female and male). The target mass is
692 inclusive of blood when applicable. Values identical to those in *Publication 133* (ICRP 2016a).

Target region	Female			Male		
	Parenchyma mass (g)	Mass of blood (g)	Target mass (g)	Parenchyma mass (g)	Mass of blood (g)	Target mass (g)
O-mucosa	22.45	NA[*]	22.45	35.8	NA[*]	35.8
Oesophagus	0.088	NA	0.088	0.095	NA	0.095
St-stem	0.616	NA	0.616	0.616	NA	0.616
SI-stem	3.446	NA	3.446	3.711	NA	3.711
RC-stem	1.188	NA	1.188	1.346	NA	1.346
LC-stem	1.157	NA	1.157	1.256	NA	1.256
RS-stem	0.699	NA	0.699	0.759	NA	0.759
ET1-bas	0.017	NA	0.017	0.020	NA	0.020
ET2-bas	0.39	NA	0.39	0.45	NA	0.45
LN-ET	12	0.690	12.69	15	0.942	15.9
Bronch-bas	0.39	NA	0.39	0.43	NA	0.43
Bronch-sec	0.78	NA	0.78	0.86	NA	0.86
Bchiol-sec	1.9	NA	1.9	1.9	NA	1.9

Target region	Female			Male		
	Parenchyma mass (g)	Mass of blood (g)	Target mass (g)	Parenchyma mass (g)	Mass of blood (g)	Target mass (g)
AI	400	504	904	450	650	1100
LN-Th	12	0.690	12.7	15	0.942	15.9
R-marrow	900	164	1064	1170	224	1394
Endost-BS	407	25.3	433	544	35.6	580
Brain	1300	49.2	1349	1450	67.2	1517
Eye-lens	0.4	NA	0.4	0.4	NA	0.4
P-gland	0.6	0.0185	0.618	0.6	0.0281	0.628
Tongue	60	1.85	61.85	73	3.42	76.42
Tonsils	3	0.0923	3.092	3	0.141	3.141
S-glands	70	2.15	72.15	85	3.98	88.98
Thyroid	17	2.46	19.46	20	3.36	23.36
Breast	500	15.4	515.4	25	1.17	26.17
Thymus	20	0.615	20.62	25	1.17	26.17
Ht-wall	250	41	291	330	56	386
Adrenals	13	2.46	15.46	14	3.36	17.36
Liver	1400	410	1810	1800	560	2360
Pancreas	120	24.6	144.6	140	33.6	173.6
Kidneys	275	82.0	357	310	112	422
Spleen	130	57.4	187.4	150	78.4	228.4
GB-wall	8	0.246	8.246	10	0.469	10.47
Ureters	15	0.462	15.46	16	0.750	16.75
UB-wall	40	0.820	40.82	50	1.12	51.12
Ovaries	11	1.64	12.64	NA	NA	NA
Testes	NA	NA	NA	35	2.24	37.24
Prostate	NA	NA	NA	17	0.797	17.8
Uterus	80	2.46	82.46	NA	NA	NA
LN-Sys	119	6.82	126	148	9.32	158
Skin	2300	123	2423	3300	168	3468
Adipose	21410	348.5	21759	17230	280	17510
Muscle	17500	430.5	17931	29000	784	29784

693 *Note that in Tables A.1 and A.2 of *Publication 133* the Oral Mucosa source and target mass did not
694 differ and therefore did not leave room for the mass of blood in the oral mucosa. The SAFs accompanying
695 *Publication 133* did appropriately account for this blood component.

3.3.2. Source region masses (details and origin)

697   (63) Table 3.16 lists the source regions, their abbreviations, and the basis for the values of their
698 mass. It also provides information as to whether the source region is eligible to be part of Other
699 systemic tissue in a biokinetic model. Such tissues are assigned 'Other' compartment activity by
700 mass fraction if they are not explicitly invoked elsewhere in the systemic biokinetic model. Note
701 that although extrathoracic and thoracic lymph node regions are typically invoked in the HRTM
702 model, they will still be considered part of 'Other' if they do not appear in the systemic biokinetic

703 model. Tables 3.17 and 3.18 provide the source region masses for the age-dependent reference
704 individuals.

705

706 Table 3.16. Source region names, abbreviations, and origin of reference masses.

Source region	Abbreviation	Eligible for 'Other'	Origin of mass
Oral cavity	O-cavity	No	No mass
Oral mucosa	O-mucosa	Yes	Scaled from tongue
Teeth surface	Teeth-S	No	No mass
Teeth volume	Teeth-V	Yes	Pub. 89-Table 2.8¶
Tongue	Tongue	No	Pub. 89-Table 2.8¶
Tonsils	Tonsils	Yes	Pub. 89-Table 2.8¶
Slow clearance from oesophagus	Oesophag-s	No	No mass
Fast clearance from oesophagus	Oesophag-f	No	No mass
Oesophagus wall	Oesophag-w	Yes	Pub. 89-Table 2.8¶
Stomach contents	St-cont	No	Pub. 89-Table 2.8¶
Stomach mucosa	St-mucosa	No	Based on Pub. 100†
Stomach wall	St-wall	Yes	Pub. 89-Table 2.8¶
Small intestine contents	SI-cont	No	Pub. 89-Table 2.8¶
Small intestine mucosa	SI-mucosa	No	Based on Pub. 100†
Small intestine wall	SI-wall	Yes	Pub. 89-Table 2.8¶
Small intestine villi	SI-villi	No	Based on Pub. 100†
Right colon contents	RC-cont	No	Pub. 89-Table 2.8¶
Right colon mucosa	RC-mucosa	No	Based on Pub. 100†
Right colon wall	RC-wall	Yes	Pub. 89-Table 2.8¶
Left colon contents	LC-cont	No	Pub. 89-Table 2.8¶
Left colon mucosa	LC-mucosa	No	Based on Pub. 100†
Left colon wall	LC-wall	Yes	Pub. 89-Table 2.8¶
Rectosigmoid colon contents	RS-cont	No	Pub. 89-Table 2.8¶
Rectosigmoid colon mucosa	RS-mucosa	No	Based on Pub. 100†
Rectosigmoid colon wall	RS-wall	Yes	Pub. 89-Table 2.8¶
Nasal vestibule skin surface	ET1-sur	No	No mass
Oropharynx mucous layer	ET2-sur	No	No mass
Oropharynx bound in epithelium	ET2-bnd	No	Based on Pub. 66

Source region	Abbreviation	Eligible for 'Other'	Origin of mass
Oropharynx sequestered in lamina propria	ET2-seq	No	Based on Pub. 66
Extrathoracic lymph nodes	LN-ET	Yes	Pub. 89-Table 5.3[‡]
Bronchi surface transport	Bronchi	No	No mass
Bound in bronchi epithelium	Bronchi-b	No	Based on Pub. 66
Bronchi-sequestered in lamina propria	Bronchi-q	No	Based on Pub. 66
Bronchiole surface transport	Brchiole	No	No mass
Bronchiole-bound in epithelium	Brchiole-b	No	Based on Pub. 66
Bronchiole-sequestered in lamina propria	Brchiole-q	No	Based on Pub. 66
Alveolar interstitium	ALV	No	Pub. 89-Table 5.3[‡,¶]
Thoracic lymph nodes	LN-Th	Yes	Pub. 89-Table 5.3[‡]
Lungs	Lungs	No	Pub. 89-Table 2.8[¶]
Adrenals	Adrenals	Yes	Pub. 89-Table 2.8[¶]
Blood	Blood	No	Pub. 89-Table 2.8[¶]
Cortical bone surface	C-bone-S	No	No mass
Cortical bone volume	C-bone-V	Yes	Pub. 89-Table 2.8[¶]
Trabecular bone surface	T-bone-S	No	No mass
Trabecular bone volume	T-bone-V	Yes	Pub. 89-Table 2.8[¶]
Cortical marrow	C-marrow	No	Pub. 89-Table 2.8[¶]
Trabecular marrow	T-marrow	No	Pub. 89-Table 2.8[¶]
Red marrow	R-marrow	Yes	Pub. 89-Table 2.8[¶]
Yellow marrow	Y-marrow	Yes	Pub. 89-Table 2.8[¶]
Brain	Brain	Yes	Pub. 89-Table 2.8[¶]
Breast	Breast	Yes	Pub. 89-Table 2.8[¶] and Pub. 143[§§]
Lens of the eye	Eye-lens	Yes	Pub. 23, Pub. 143[**]
Gall bladder wall	GB-wall	Yes	Pub. 89-Table 2.8[¶]
Gall bladder contents	GB-cont	No	Pub. 89-Table 2.8[¶]
Heart wall	Ht-wall	Yes	Pub. 89-Table 2.8[¶]
Kidneys	Kidneys	Yes	Pub. 89-Table 2.8[¶]
Liver	Liver	Yes	Pub. 89-Table 2.8[¶]
Systemic lymph nodes	LN-Sys	Yes	Derived from Pub. 66 and 89[††]

Source region	Abbreviation	Eligible for 'Other'	Origin of mass
Ovaries	Ovaries	Yes	Pub. 89-Table 2.8[¶]
Pancreas	Pancreas	Yes	Pub. 89-Table 2.8[¶]
Pituitary gland	P-gland	Yes	Pub. 89-Table 2.8[¶]
Prostate	Prostate	Yes	Pub. 89-Table 2.8[¶]
Salivary glands	S-glands	Yes	Pub. 89-Table 2.8[¶]
Skin	Skin	Yes	Pub. 89-Table 2.8[¶]
Spleen	Spleen	Yes	Pub. 89-Table 2.8[¶]
Testes	Testes	Yes	Pub. 89-Table 2.8[¶]
Thymus	Thymus	Yes	Pub. 89-Table 2.8[¶]
Thyroid	Thyroid	Yes	Pub. 89-Table 2.8[¶]
Ureters	Ureters	Yes	Pub. 89-Table 2.8[¶]
Urinary bladder wall	UB-wall	Yes	Pub. 89-Table 2.8[¶]
Urinary bladder contents	UB-cont	No	Computed for this work
Uterus	Uterus	Yes	Pub. 89-Table 2.8[¶]
Adipose	Adipose	Yes	Modified from Pub. 89-Table 2.8[#]
Cartilage	Cartilage	Yes	Pub. 89-Table 2.8[¶]
Muscle	Muscle	Yes	Pub. 89-Table 2.8[¶]
Nasal vestibule wall	ET1-wall	Yes	Based on Pub. 66
Oropharynx wall	ET2-wall	Yes	Based on Pub. 66
Lung tissue (no blood)	Lung-Tis	Yes	Pub. 89-Table 2.8[¶]
Respiratory tract airways	RT-air	No	No mass

707   [†]The stylised geometries described in *Publication 100* (ICRP 2006).
708   [‡]Contained in Table 5.3 of *Publication 89* (ICRP 2002). Note that the ALV mass is inclusive of blood. See
709   the target mass tables if interested in the parenchyma mass of the alveolar tissue. The lung mass with and
710   without blood in Table 2.8 of *Publication 89* is not consistent with alveolar masses inclusive of blood
711   provided in Table 5 of *Publication 66* and Table 5.3 of *Publication 89*.
712   [§]Contained in Table 6 of Wayson et al. (2018).
713   [¶]Contained in Table 2.8 of *Publication 89* (ICRP 2002)
714   [**]*Publication 23* (ICRP 1975) describes age-dependency for the lens of the eye but does not provide
715   reference values. The phantom mass in *Publication 143* was chosen for the target mass of the lens.
716   [††]*Publication 89* (ICRP 2002) describes the age dependency of the total lymph node mass. This information
717   combined with the information in *Publication 66* (ICRP 1994) on the masses of the extrathoracic and
718   thoracic lymph nodes was used to calculate the systemic lymph node mass.
719   [#]The adipose mass was adjusted from the values in Table 2.8 of *Publication 89* to maintain consistency
720   with the total body mass.
721   [§§]*Publication 89* did not provide breast masses below 15 years, the masses from *Publication 143* (ICRP
722   2020b) have been adopted at ages 10 years and younger.
723
724
725

726 Table 3.17. Masses for source regions in the reference newborn, 1-year old, 5-year old, and 10-year old
727 (female and male).

| Source region | Source region mass (g) (female/male) | | | |
	Newborn	1-y	5-y	10-y
O-cavity	NA	NA	NA	NA
O-mucosa	1.608	4.679	8.715	14.70
Teeth-S	NA	NA	NA	NA
Teeth-V	0.700	5.00	15.0	30.0
Tongue	3.50	10.0	19.0	32.0
Tonsils	0.100	0.500	2.00	3.00
Oesophag-s	NA	NA	NA	NA
Oesophag-f	NA	NA	NA	NA
Oesophag-w	2.00	5.00	10.0	18.0
St-cont	40.0	67.0	83.0	117.0
St-mucosa	1.442	1.744	2.281	2.760
St-wall	7.00	20.0	50.0	85.0
SI-cont	56.0	93.0	117.0	163.0
SI-mucosa	5.332	9.567	15.77	23.29
SI-wall	30.0	85.0	220	370
SI-villi	0.5778	1.637	4.238	7.127
RC-cont	24.0	40.0	50.0	70.0
RC-mucosa	4.158	7.110	10.21	13.80
RC-wall	7.00	20.0	49.0	85.0
LC-cont	12.0	20.0	25.0	35.0
LC-mucosa	3.968	6.237	8.996	12.25
LC-wall	7.00	20.0	49.0	85.0
RS-cont	12.0	20.0	25.0	35.0
RS-mucosa	2.249	4.178	5.938	7.687
RS-wall	3.00	10.0	22.0	40.0
ET1-sur	NA	NA	NA	NA
ET2-sur	NA	NA	NA	NA
ET2-bnd	0.2911	0.5109	1.044	1.538
ET2-seq	0.05305	0.09308	0.1902	0.2802
LN-ET	0.700	2.10	4.10	6.80
Bronchi	NA	NA	NA	NA
Bronchi-b	0.443	0.6390	0.9186	1.238
Bronchi-q	0.0740	0.1080	0.1552	0.2092
Brchiole	NA	NA	NA	NA
Brchiole-b	0.982	1.506	2.384	3.262
Brchiole-q	0.246	0.3854	0.6103	0.8351
ALV	52.0	150	300	500
LN-Th	0.700	2.10	4.10	6.80
Lungs	60.0	150	300	500
Adrenals	6.00	4.00	5.00	7.00
Blood	290	530	1500	2500
C-bone-S	NA	NA	NA	NA
C-bone-V	135	470	1010	1840
T-bone-S	NA	NA	NA	NA
T-bone-V	35.0	120	250	460

Source region	Source region mass (g) (female/male)			
	Newborn	1-y	5-y	10-y
C-marrow	2.818	6.546	30.83	99.51
T-marrow	47.18	163.5	469.2	1160
R-marrow	50.0	150	340	630
Y-marrow	0	20.0	160	630
Brain	380	950	1180/1310	1220/1400
Breast	0.0800	0.430	0.940	7.53/7.12
Eye-lens	0.130	0.220	0.330	0.350
GB-wall	0.500	1.40	2.60	4.40
GB-cont	2.80	8.00	15.0	26.0
Ht-wall	20.0	50.0	85.0	140
Kidneys	25.0	70.0	110	180
Liver	130	330	570	830
LN-Sys	12.9	20.8	40.6	67.3
Ovaries	0.300	0.800	2.00	3.50
Pancreas	6.00	20.0	35.0	60.0
P-gland	0.100	0.150	0.250	0.350
Prostate	0.800	1.00	1.20	1.60
S-glands	6.00	24.0	34.0	44.0
Skin	175	350	570	820
Spleen	9.50	29.0	50.0	80.0
Testes	0.850	1.50	1.70	2.00
Thymus	13.0	30.0	30.0	35.0/40.0
Thyroid	1.30	1.80	3.40	7.90
Ureters	0.770	2.20	4.20	7.00
UB-wall	4.00	9.00	16.0	25.0
UB-cont	15.0	25.0	65.0	75.0
Uterus	4.00	1.50	3.00	4.00
Adipose	1016/1019	4028/4027	5831/5703	9063/8882
Cartilage	130	360	600	820
Muscle	800	1900	5600	11000
ET1-wall	0.3443	0.6041	1.234	1.819
ET2-wall	0.3443	0.6041	1.234	1.819
Lung-Tis	26.79	78.26	150.1	243.8
RT-air	NA	NA	NA	NA

728
729
730 Table 3.18. Masses for source regions in the reference 15-year-old and adult (female and male).

Source region	Source region mass (g)			
	15-year female	15-year male	Adult female	Adult male
O-cavity	NA	NA	NA	NA
O-mucosa	24.49	25.60	22.45	35.83
Teeth-S	NA	NA	NA	NA
Teeth-V	35.0	45.0	40.0	50.0
Tongue	53.0	56.0	60.0	73.0
Tonsils	3.00	3.00	3.00	3.00
Oesophag-s	NA	NA	NA	NA
Oesophag-f	NA	NA	NA	NA

Source region	Source region mass (g)			
	15-year female	15-year male	Adult female	Adult male
Oesophag-w	30.0	30.0	35.0	40.0
St-cont	200	200	230	250
St-mucosa	3.612	3.612	4.639	4.639
St-wall	120	120	140	150
SI-cont	280	280	280	350
SI-mucosa	34.98	34.98	34.32	36.96
SI-wall	520	520	600	650
SI-villi	10.02	10.02	12.52	12.52
RC-cont	120	120	160	150
RC-mucosa	17.73	17.73	17.73	20.10
RC-wall	122	122	145	150
LC-cont	60.0	60.0	80.0	75.0
LC-mucosa	17.26	17.26	17.26	18.75
LC-wall	122	122	145	150
RS-cont	60.0	60.0	80.0	75.0
RS-mucosa	10.39	10.39	10.39	11.28
RS-wall	56.0	56.0	70.0	70.0
ET1-sur	NA	NA	NA	NA
ET2-sur	NA	NA	NA	NA
ET2-bnd	2.087	2.307	2.137	2.472
ET2-seq	0.3803	0.4204	0.3894	0.4504
LN-ET	11.0	12.0	12.0	15.0
Bronchi	NA	NA	NA	NA
Bronchi-b	1.518	1.638	1.552	1.727
Bronchi-q	0.2564	0.2767	0.2622	0.2918
Brchiole	NA	NA	NA	NA
Brchiole-b	4.015	4.517	4.703	4.891
Brchiole-q	1.028	1.156	1.204	1.252
ALV	800	860	900	1100
LN-Th	11.0	12.0	12.0	15.0
Lungs	750	900	950	1200
Adrenals	9.00	10.0	13.0	14.0
Blood	3500	4800	4100	5600
C-bone-S	NA	NA	NA	NA
C-bone-V	2960	3240	3200	4400
T-bone-S	NA	NA	NA	NA
T-bone-V	740	810	800	1100
C-marrow	158.5	201.5	258.0	279.0
T-marrow	2222	2359	2442	3371
R-marrow	1000	1080	900	1170
Y-marrow	1380	1480	1800	2480
Brain	1300	1420	1300	1450
Breast	250	15.0	500	25.0
Eye-lens	0.400	0.490	0.400	0.400
GB-wall	7.30	7.70	8.00	10.0
GB-cont	42.0	45.0	48.0	58.0
Ht-wall	220	230	250	330
Kidneys	240	250	275	310

Source region	Source region mass (g)			
	15-year female	15-year male	Adult female	Adult male
Liver	1300	1300	1400	1800
LN-Sys	108.8	118.7	118.7	148.4
Ovaries	6.00	NA	11.0	NA
Pancreas	100	110	120	140
P-gland	0.500	0.500	0.600	0.600
Prostate	NA	4.30	NA	17.0
S-glands	65.0	68.0	70.0	85.0
Skin	1700	2000	2300	3300
Spleen	130	130	130	150
Testes	NA	16.0	NA	35.0
Thymus	30.0	35.0	20.0	25.0
Thyroid	12.0	12.0	17.0	20.0
Ureters	12.0	12.0	15.0	16.0
UB-wall	35.0	40.0	40.0	50.0
UB-cont	85.0	85.0	200	200
Uterus	30.0	NA	80.0	NA
Adipose	17660	11340	21410	17230
Cartilage	920	1140	900	1100
Muscle	17000	24000	17500	29000
ET1-wall	2.468	2.728	2.526	2.923
ET2-wall	2.468	2.728	2.526	2.923
Lung-Tis	379.7	409.3	420.0	500.0
RT-air	NA	NA	NA	NA

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732

733 **4. MODELS AND METHODS FOR ENERGY ABSORPTION**
734 **COMPUTATION**

735

736   (64) To compute SAFs, the absorbed fraction requires the computation of the energy absorption
737 in each target per energy emitted from each source region. This computation is performed in a
738 computational model.

739   (65) For a large number of source-target geometries, the computational models are the reference
740 voxel phantoms provided in *Publications 110* and *143 (ICRP 2009, 2020b)*. But there are many
741 smaller regions where a finer, detailed model is required. These include the alimentary tract, the
742 respiratory tract, and the skeleton. The following sections describe the models and the methods
743 used to compute specific absorbed fractions in those models.

744 ## 4.1. Reference voxel phantoms

745 ### 4.1.1. Summary and definition

746   (66) The reference voxel phantoms for the adult are found in *Publication 110* and were adjusted
747 to conform with reference parameters from individuals of similar size (Zankl and Wittmann 2001;
748 Zankl 2005). The development of the phantoms is detailed in *Publication 110* and the use of the
749 phantom to compute SAFs is described in detail in *Publication 133*. Since the SAFs in *Publication*
750 *133* are adopted as published for this work, the focus in this section will be on the use of the
751 *Publication 143* phantoms to compute SAFs for the paediatric reference individuals.
752   (67) The paediatric reference computational phantoms were based on a series of phantoms
753 developed at the University of Florida and the US National Cancer Institute (Lee et al. 2010). The
754 details of the adjustments made to the phantoms are described in *Publication 143*. The voxelised
755 phantoms are depicted in Fig. 4.1.
756   (68) While the masses and sizes of the *Publication 143* phantoms are unique, they were
757 developed to have consistent descriptors as those in *Publication 110* (e.g. organs, organ ID
758 numbers, blood contribution to elemental compositions). Body morphometry of the *Publication*
759 *143* phantoms were based on values provided in *Publication 89*. The phantoms are based on
760 medical image data of real individuals consistent with the reference anatomical information in
761 *Publication 89*.
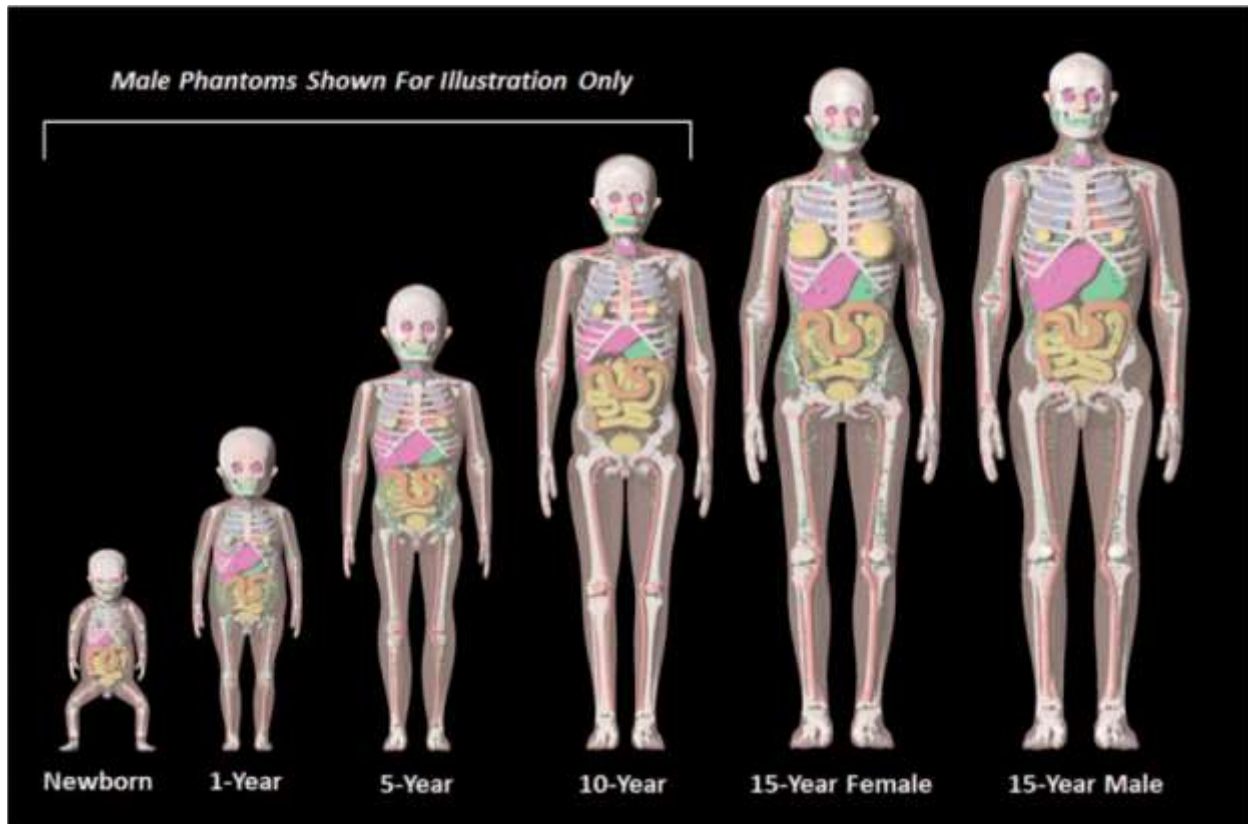
Fig. 4.1. ICRP series of reference paediatric voxel computational phantoms from *Publication 143*.

4.1.2. Photons

(69) Schwarz et al. (2021b) contains the details for the computation of photon SAFs in the reference paediatric phantoms of *Publication 143*. Monte Carlo photon radiation transport simulations were performed using MCNPX v2.7 (Pelowitz 2011) in each paediatric reference phantom. In each phantom, 60 tissues served as source and/or target regions. When a desired tissue region did not exist in the reference voxel phantom, surrogate tissues were used to represent the desired tissue. For example, the reference phantoms do not model the thin stem cell target regions in the alimentary tract. The entire stomach wall is thus treated as a surrogate for the stomach stem target.

(70) Monoenergetic photon emissions were simulated from source regions across a logarithmic energy grid from 10 keV to 10 MeV. For non-skeletal source regions, all voxels comprising a source region were uniformly sampled. For skeletal source regions, non-uniform spatial sampling was applied within the various tissues of the paediatric skeleton. As with the *Publication 110* adult phantoms, each of the *Publication 143* phantoms' skeletal sites may be composed of both spongiosa (representing a mixture of marrow cavities and bone trabeculae) and cortical bone (the bone cortex). The spongiosa represents four source regions – active marrow (red marrow), inactive marrow (yellow marrow), trabecular bone surface, and trabecular bone volume. Spongiosa regions exist in bones of both the axial and appendicular skeleton. The cortical bone surface and cortical bone volume source regions are simulated as emissions from cortical bone voxels. A table in Schwarz et al. (2021b) contains the fractional distribution of the skeletal tissue regions based on previously published skeletal tissue models (Pafundi et al. 2010; Wayson 2012).

785   (71) Energy absorption in red marrow and the bone endosteum were computed for photons by
786   coupling energy-dependent fluence-to-absorbed dose response functions (Wayson 2012) to
787   energy-dependent photon fluences scored in the spongiosa and medullary cavities of the long
788   bones. The response functions were derived as described in Johnson et al. (2011). The calculation
789   of the specific absorbed fraction, Φ, to red marrow, RM, and the bone endosteum target, BS (short
790   for bone surface), from photon emission in a source region, r_S, are given by Eqs. (4.1) and (4.2).
791

$$\Phi\left(\text{R-marrow} \leftarrow r_S, E_0\right) = \frac{1}{E_0} \sum_x f_{\text{RM,x}} \sum_i \text{DRF}\left(\text{RM}, E_i, x\right) \Phi_{\text{ph}}\left(\text{Sp/MC} \leftarrow r_S, E_i, x\right) \quad (4.1)$$

$$\Phi\left(\text{Endost-BS} \leftarrow r_S, E_0\right) = \frac{1}{E_0} \sum_x f_{\text{BS,x}} \sum_i \text{DRF}\left(\text{BS}, E_i, x\right) \Phi_{\text{ph}}\left(\text{Sp/MC} \leftarrow r_S, E_i, x\right) \quad (4.2)$$

792

793   (72) The emitted photon energy is E_0 and $\Phi_{\text{ph}}\left(\text{Sp/MC} \leftarrow r_S, E_i, x\right)$ is the scored photon fluence
794   within the spongiosa (Sp) or medullary cavity (MC) region of bone site x at photon energy E_i. The
795   skeletal dose response functions, $\text{DRF}\left(\text{RM}, E_i, x\right)$ and $\text{DRF}\left(\text{BS}, E_i, x\right)$, provide the absorbed
796   dose per unit photon fluence for red marrow and bone endosteum targets, respectively, at each
797   photon energy and within each bone site. The fractional masses of red marrow and bone endosteum
798   within each bone site are provided by f. Tabulated values for the dose response functions and the
799   fractional masses are provided in the electronic download which accompanies this publication and
800   are described in Annex A.
801   (73) The inclusion of a blood source region in the latest ICRP biokinetic models necessitates
802   computation of SAFs for emissions from a blood source distributed appropriately across the
803   reference voxel phantoms. Source regions for a blood source should include blood in large vessels,
804   heart contents, and blood perfusing tissue. For the latter region, weighting of all blood-containing
805   tissue source region SAFs can be used to compute a blood SAF as detailed in Eq. (4.3),
806

$$\Phi\left(r_T \leftarrow \text{Blood}, E_0\right) = \sum_S f_{\text{Blood,S}} \Phi\left(r_T \leftarrow r_S, E_0\right) \quad (4.3)$$

807   where $f_{\text{Blood,S}}$ is the fraction of the body's blood assigned in a source region and Φ is the photon
808   SAF for a given source/target combination. The fractional blood distribution is published in
809   Wayson et al (2018). Further details on the application of this blood distribution to the phantoms
810   are described in Schwarz et al (2021b).
811   (74) For those crossfire geometries at lower energies when relative error in energy deposition
812   tallies exceed 5% (photons of energies at or below 30 keV) data smoothing was performed. At the
813   lowest energies, log-log extrapolation to theoretical zero-energy limiting values (see section 5.2)
814   was performed. Details of the smoothing methods and when it was applied in each phantom are
815   found in Schwarz et al (2021b)

4.1.3. Electrons

817   (75) Schwarz et al. (2021a) contains the details for the computation of electron SAFs in the
818   reference paediatric phantoms. Until *Publication 133* for the adult and this publication for
819   paediatric individuals, electron absorbed fractions were generally treated as either unity for self-

45

820   irradiation geometries or zero for crossfire geometries. In *Publication 133* and in this work, Monte
821   Carlo transport of electrons in the reference phantoms allows for non-unity, non-zero absorbed
822   fractions which vary with electron energy. Emitted electron energy is allowed to escape the source
823   region either in the form of electron kinetic energy or via bremsstrahlung x-rays resulting from
824   electron radiative energy losses.

825   (76) The same logarithmic energy grid used for photons is used for electron SAFs. Collisional
826   and radiative components of the electron SAFs are computed independently with the radiative
827   contribution utilizing previously computed photon SAFs (Wayson et al. 2012; Schwarz et al.
828   2021a). Monte Carlo simulations of the electron transport in the phantoms were performed using
829   MCNPX v2.7 (Pelowitz 2011). The description of sampling source regions and computing energy
830   absorption in target regions are the same as those described in the previous section for photons.

831   (77) Schwarz et al (2021a) computed collisional electron energy absorption during the electron
832   Monte Carlo transport. When a photon associated with bremsstrahlung x-ray production was
833   created, its energy and source region was scored to create an energy distribution in each region.
834   This distribution was then subsequently coupled to photon SAFs to compute the SAFs associated
835   with radiative losses. The collisional and radiative SAFs were then summed to arrive at the total
836   electron SAFs presented in this work. The radiative component of the electron SAF was computed
837   as:

$$\Phi_R\left(r_T \leftarrow r_S, E_0\right) = \frac{1}{N_e E_0^e} \sum_i E_i^P\ \Phi^P\left(r_T \leftarrow r_S, E_i^P\right) \tag{4.4}$$

838   where $\Phi^P\left(r_T \leftarrow r_S, E_i^P\right)$ is the photon SAF for the source/target pair indexed to the x-ray photon
839   energy E_i^P. The denominator is the product of the number of electrons simulated, N_e, and the
840   emitted electron energy, E_0^e. This approach necessarily presumes that all bremsstrahlung x-rays are
841   created interior to the source region, thus neglecting cases where the x-ray was generated by an
842   electron which had previously exited the source region boundary. However, in a study by Wayson
843   et al. (2012) using a University of Florida newborn phantom, it was shown that this two-stage
844   approach to computing the electron SAF was statistically comparable to that using full electron
845   transport with explicit bremsstrahlung x-ray production and transport.

846   (78) The reference phantoms were not used to derive SAFs for electrons emitted from within
847   skeletal tissues irradiating skeletal targets. The models used for these intra-skeletal geometries are
848   described in section 4.4.2. For electrons emitted from outside the skeleton, the collisional
849   component of the SAF to skeletal targets $\Phi_C\left(\text{R-marrow} \leftarrow r_S, E_0\right)$ was computed as shown in Eqs.
850   (4.5) and (4.6). The fraction of red marrow (or bone endosteum), $f_{RM,x}$ in each skeletal site, x, is
851   found in Schwarz et al (2021b). The energy deposited in the spongiosa or medullary cavity region
852   for each skeletal site is E_x.

$$\Phi_C\left(\text{R-marrow} \leftarrow r_S, E_0\right) = \frac{1}{E_0} \sum_x f_{RM,x}\left(\frac{E_x}{m_{RM,x}}\right) \tag{4.5}$$

$$\Phi_C\left(\text{Endost-BS} \leftarrow r_S, E_0\right) = \frac{1}{E_0} \sum_x f_{BS,x}\left(\frac{E_x}{m_{BS,x}}\right) \tag{4.6}$$

853
854   (79) Data smoothing of electron SAFs was found to be unnecessary since the collisional
855   component of the electron SAF had very small statistical errors and the radiative component

856 utilised photon SAFs which had already been smoothed where necessary. Low energy
857 interpolation to theoretical zero-energy SAFs was performed in the same manner (log-log) as
858 described previously for photons.

859 ### 4.1.4. Neutrons from spontaneous fission

860 (80) Griffin et al. (2022) contains the details for the computation of SAFs for fission-spectrum
861 neutrons in the reference paediatric phantoms. Neutron SAFs in this publication address 28
862 radionuclides which undergo spontaneous fission with a branching fraction greater than 1×10^{-9}
863 per nuclear transformation (ICRP 2008a). Unlike the other SAFs in this publication, neutron SAFs
864 are computed and tabulated in a manner specific to the radionuclide rather than specific to a grid
865 of monoenergetic emissions. SAFs were calculated for ^{252}Cf using MCNP6 (version 6.1) (Pelowitz
866 2013) in major source regions of the reference voxel phantoms; in other source regions, ^{252}Cf SAFs
867 were derived using a point-kernel approach. For the remaining 27 radionuclides, the SAFs for ^{252}Cf
868 were scaled using normalization factors to account for difference in soft tissue kerma and the
869 average energy of an emitted neutron.
870 (81) Table 4.1 summarises the decay data information for the selected radionuclides (ICRP
871 2008a). The spontaneous fission branching fraction ranges from 1.37×10^{-9} (^{236}Pu) to 0.997 (^{254}Cf)
872 per nuclear transformation. The average number of neutrons emitted per fission ranges from 2.01
873 (^{238}U) to 4.01 (^{256}Fm) per fission. The average emitted neutron energy per fission ranges from 3.39
874 (^{238}U) to 8.99 (^{254}Cf) MeV. Note the energy associated with fission fragments greatly exceeds that
875 of the neutrons. For example, the energy of the ^{256}Fm fission fragments is 194.56 MeV. These
876 fragments are assumed to have the same SAF as a 2.0 MeV alpha particle (local absorption).
877 (82) The neutron SAFs are tabulated by radionuclide and address the energy spectrum of the
878 fission neutrons. Since the neutron radiation weighting factors in *Publication 103* (ICRP 2007) are
879 energy-dependent, radiation weighting factors for neutrons from nuclides undergoing spontaneous
880 fission are needed which are nuclide-specific and spectrum-weighted. Nuclide-specific radiation
881 weighting factors were derived assuming the neutron radiation weighting factor expressions in
882 Table 2.3 and the Watt neutron fission spectra defined in *Publication 107*. The resultant spectrum-
883 weighted neutron radiation weighting factors are provided in Table 4.1.
884 (83) The right most column of Table 4.1 lists the nuclide specific normalization factor applied
885 to ^{252}Cf SAF values, which are independent of age. This factor accounts for the difference in soft
886 tissue kerma for the spontaneous fission neutron spectrum of the nuclides relative to that of ^{252}Cf.
887 Figure 4.2 shows the dependence of the kerma coefficient as a function of neutron energy. The
888 data of Fig. 4.2 was integrated over the Watt spectra and the resultant value normalised to that for
889 ^{252}Cf. This factor also accounts for the difference in the average energy of an emitted neutron from
890 the nuclide relative to that of ^{252}Cf. The radionuclide normalization factor ranges from 0.981
891 (^{240}Cm) to 1.198 (^{238}U).
892
893

894 Table 4.1. Properties of spontaneous fission emitting radionuclides

Radionuclide	Half-life	Fission probability per nuclear transformation	Mean neutrons emitted per fission	Mean neutron energy per fission (MeV)	Spectrum-weighted radiation weighting factor	Radionuclide normalization factor
^{238}U	4.468×10^9 y	5.45×10^{-7}	2.01	3.39	17.49	1.198
^{236}Pu	2.858 y	1.37×10^{-9}	2.13	4.77	16.67	1.017
^{238}Pu	87.7 y	1.85×10^{-9}	2.22	4.49	16.99	1.080
^{240}Pu	6564 y	5.75×10^{-8}	2.16	4.18	17.12	1.108
^{242}Pu	3.75×10^5 y	5.54×10^{-6}	2.15	4.22	17.07	1.099
^{244}Pu	8.00×10^7 y	1.21×10^{-3}	2.30	4.06	17.37	1.168
^{240}Cm	27 d	3.90×10^{-8}	2.39	5.69	16.47	0.981
^{242}Cm	162.8 d	6.37×10^{-8}	2.52	5.28	16.88	1.058
^{244}Cm	18.1 y	1.371×10^{-6}	2.69	5.68	16.85	1.053
^{245}Cm	8.50×10^3 y	6.10×10^{-9}	2.87	6.09	16.84	1.050
^{246}Cm	4.76×10^3 y	2.63×10^{-4}	3.18	6.57	16.92	1.066
^{248}Cm	3.84×10^5 y	8.39×10^{-2}	3.11	6.08	17.09	1.102
^{250}Cm	8300 y	7.40×10^{-1}	3.31	6.07	17.27	1.142
^{246}Cf	35.7 h	2.50×10^{-6}	3.10	7.16	16.57	0.999
^{248}C	334 d	2.90×10^{-5}	3.34	7.73	16.56	0.997
^{249}C	351 y	5.02×10^{-9}	3.41	7.88	16.57	0.999
^{250}Cf	13.08 y	7.70×10^{-4}	3.53	8.15	16.57	0.999
^{252}C	2.645 y	3.092×10^{-2}	3.765	8.68	16.57	1.000
^{254}Cf	60.5 d	9.969×10^{-1}	3.89	8.99	16.57	0.999
^{253}Es	20.47 d	8.90×10^{-8}	3.93	7.87	17.02	1.087
^{254}Es	275.7 d	3.00×10^{-8}	3.95	7.91	17.02	1.087
^{254m}E	39.3 h	4.50×10^{-4}	3.95	7.91	17.02	1.087
^{255}Es	39.8 d	4.50×10^{-5}	3.97	7.95	17.02	1.087
^{252}Fm	25.39 h	2.30×10^{-5}	3.90	7.81	17.02	1.087
^{254}F	3.240 h	5.92×10^{-4}	3.96	7.93	17.02	1.087
^{255}Fm	20.07 h	2.30×10^{-7}	3.73	7.47	17.02	1.087
^{256}Fm	157.6 m	9.19×10^{-1}	4.01	8.03	17.02	1.087
^{257}Fm	100.5 d	2.10×10^{-3}	3.85	7.71	17.02	1.087

895
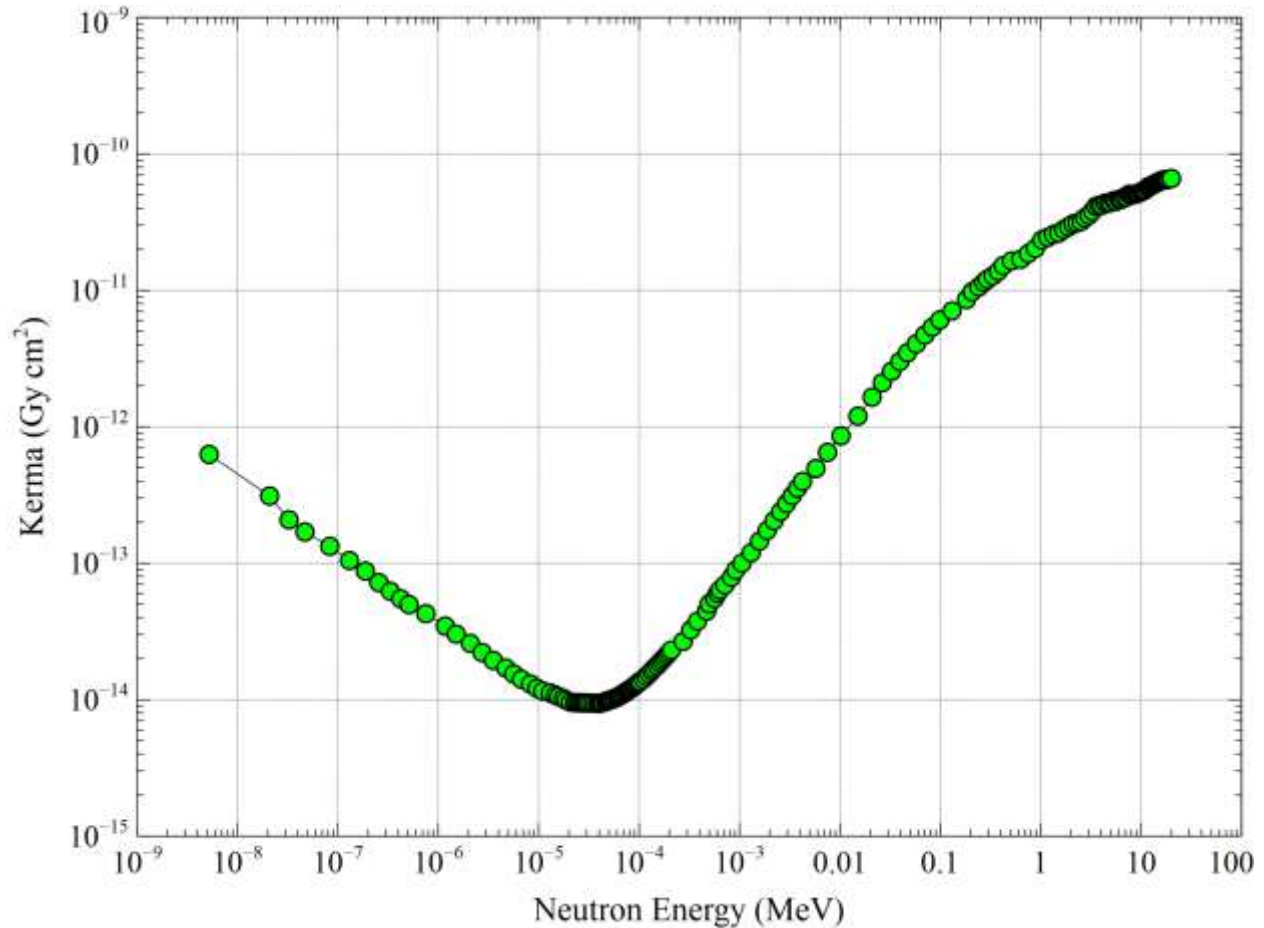
896
897 Fig. 4.2. Neutron kerma coefficient (Gy cm^2) in soft tissue as a function of neutron energy
898 (Howerton 1986).

4.1.5. Alpha particles

900 (84) Unlike electron transport simulations in the reference phantoms, alpha particle transport
901 simulations are unnecessary due to the short range of the alpha particles compared to the size of
902 the source regions. For such geometries, the alpha absorbed fraction is set to unity for self-
903 irradiation geometries and zero for non-overlapping source-target geometries (crossfire
904 geometries.) The resulting alpha SAF for the self-irradiation geometries is simply the inverse of
905 the target region mass. These values are applied at all alpha particle energies (up to 12 MeV.) The
906 kinetic energy of the recoiling nucleus, typically about 2% of alpha particle energy, is assumed to
907 inherit the SAF of a 2.0 MeV alpha particle (local absorption.)

4.2. Alimentary tract

4.2.1. Summary and definition

910 (85) The computational models used to compute SAFs within the alimentary tract are based on
911 the geometrical definitions provided in Section 7 of *Publication 100* (ICRP 2006). For each region

912 in the alimentary tract, information is provided on the simplified geometrical shape and the sizes
913 of these regions. Tables 3.6 and 3.7 summarise some of this information for the various target
914 regions. Similar information is provided in *Publication 100* which define the location and size of
915 various source regions.

916 **4.2.2. Electrons and Alphas**

917 (86) Annex F of *Publication 100* provided electron SAF values based upon Monte Carlo
918 radiation transport simulation in the geometrical models. Similar simulations were not provided
919 for alpha particles. For *Publication 133*, new radiation transport simulations were performed for
920 both electron and alpha particles using the geometries from *Publication 100* with one modelling
921 improvement made to the small intestine. Rather than modelling the small intestine as a single
922 cylinder, the cylinders were stacked in a hexagonal array to allow for energy deposition across one
923 segment of the small intestine to another, nearby. Figure 4.3 depicts the geometry used for the
924 small intestine.

925
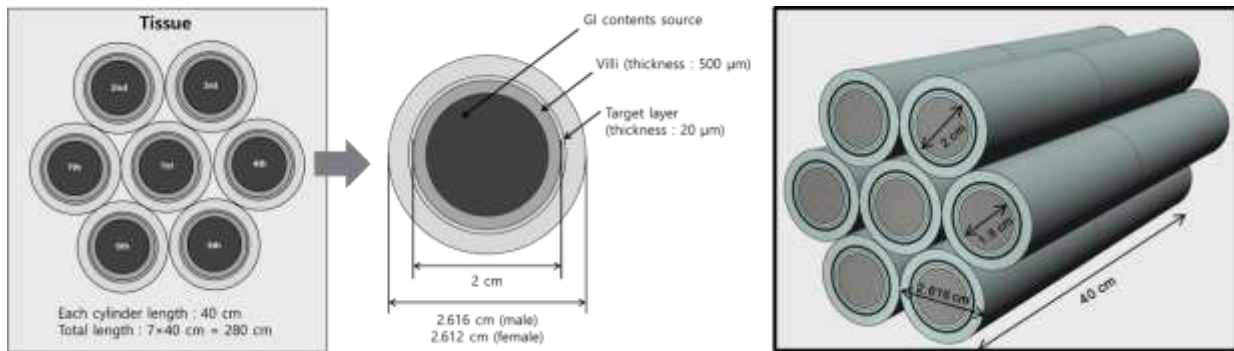
926
927 Fig. 4.3. Schematic of the folded small intestine model used to allow for electron crossfire.
928
929 (87) The same approach used in *Publication 133* has been extended in this work using the age-
930 specific geometry information provided in *Publication 100* for both electrons (up to 10 MeV) and
931 alpha particles (up to 12 MeV).

932 **4.2.3. Photons and Neutrons**

933 (88) For photons and neutrons, surrogate tissues in the reference phantom were used to
934 represent the small source and target regions in the alimentary tract. For example, the SAF to
935 desired stem cell targets is considered to be the same as the SAF to the encompassing,
936 corresponding wall region. Similarly, a photon or neutron source emanating from an alimentary
937 mucosal region is treated as originating from the wall in the reference voxel phantom.

938 **4.3. Respiratory tract**

939 **4.3.1. Summary and definition**

940 (89) *Publication 66* (ICRP 1994) contains information on the morphometrical model used to
941 define computational models for regions inside the respiratory tract. While the publication contains

942 some information on age and sex dependency, for dosimetric modelling the cross-sectional
943 dimensions of the airway regions (airway and wall thicknesses) have been treated as independent
944 of age and sex. Thus, the absorbed fractions computed for the adults are applied at all younger
945 ages. The SAF then changes by the mass of the target region which is dependent on age and sex.

4.3.2. Electrons and Alphas

947 (90) Section 5 of *Publication 133* describes the adoption of respiratory tract SAFs previously
948 provided in *Publication 66* in Annexe H. In the first part of the OIR Series, *Publication 130* (ICRP
949 2015), revisions were made to the respiratory tract model. The original HRTM included particle-
950 size-dependent slow clearance compartments which were eliminated in the revision. The revised
951 source region is taken to be uniformly distributed throughout both the gel and sol layers of
952 *Publication 66*. The weights for the relative thickness of the gel and sol are 5/11 and 6/11,
953 respectively for the bronchial region and 1/3 and 2/3, respectively for the bronchiolar region.
954 (91) *Publication 133* also describes the addition of new electron SAFs for geometries based on
955 radiation transport in the reference voxel phantoms. This was used for alveolar interstitial and
956 extrathoracic lymph node source regions. Alpha SAFs were not updated in this manner but were
957 instead adopted as they appear in *Publication 66*.

4.3.3. Photons and Neutrons

959 (92) For photons and neutrons, surrogate tissues in the reference phantom were used to
960 represent the small source and target regions in the respiratory tract. For example, the SAFs to
961 secretory targets in the bronchi were considered to be the same as the SAFs to the bronchi wall
962 region. Similarly, a photon or neutron source emanating from the alveolar interstitial is treated as
963 coming from the whole lung in the reference voxel phantom.

4.4. Skeleton

4.4.1. Summary and definition

966 (93) *Publication 11* (ICRP 1968) defined three cellular regions at risk for radiogenic damage
967 within the skeleton: cells among the osteogenic cells on bone surfaces, haematopoietic marrow,
968 and certain epithelial cells close to bone surfaces. The same publication defined the dose to the
969 latter category as averaged over the region "…from 5 to 10 µm from the trabecular surface."
970 *Publication 26* (ICRP 1977) includes a recommendation that the "…dose equivalent in bone
971 should apply to the endosteal cells and cells on bone surfaces, and should be calculated as an
972 average over tissue up to a distance of 10 µm from the relevant bone surfaces." *Publication 30*
973 (ICRP 1979) uses the 10 µm recommendation from *Publication 26*.
974 (94) More recently, studies have shown that the cells at risk for bone cancer induction are
975 localised up to 50 µm from trabecular and interior cortical bone surfaces (Gossner et al. 2000;
976 Gossner 2003; Bolch et al. 2007). In this work and in *Publication 133*, the bone endosteum target
977 is considered to be all marrow tissue within 50 µm of a trabecular surface or interior cortical bone
978 surface along the shafts of the long bones.
979 (95) Data suggest haematopoietic stem cells are found preferentially near trabecular bone
980 surfaces (Watchman; et al. 2007; Bourke et al. 2009). Nevertheless, in this work as in *Publication*

51

981 *133*, dosimetric modelling treats the cells as uniformly distributed among the marrow spaces. The
982 models used do explicitly treat red and yellow marrow as separate, interspersed regions within the
983 marrow spaces.

984 (96) *Publication 20* (ICRP 1973) describes the basis for the definition of skeletal source
985 regions. Rowland (1966) describes rapidly-exchangeable calcium of bone as located only at bone
986 surfaces which include cortical and trabecular endosteum, periosteum, and the surfaces of
987 Haversian and Volkmann canals. "The calcium which lies within less than one micron from a bone
988 surface was found to be sufficient to account for the size and location of the observed exchangeable
989 pool" (ICRP 1973). *Publication 20* also describes the splitting of activity in the bone between
990 cortical and trabecular regions of the skeleton as being split by the fraction of cortical/trabecular
991 bone in the whole-body skeleton (80% / 20%). This value was later affirmed in *Publication 70*
992 (ICRP 1995b).

993 (97) For the dosimetry in *Publication 30*, as well as the dosimetry here, radionuclides assumed
994 to be on bone surfaces are modelled as uniformly spread in an infinitely thin layer over the relevant
995 surfaces of bone. Importantly, *Publication 30* states "This assumption will result in an over-
996 estimate of the true committed dose equivalents received by bone surface cells and active bone
997 marrow because it disregards burial of radioactive deposits by the deposition of new bone
998 mineral."

999 (98) The absorbed fraction of alpha particle energy emitted from skeletal regions was described
1000 in *Publication 30*. These values were used in subsequent ICRP dosimetry calculations. Several
1001 studies have found energy dependency in intraskeletal absorbed fractions for electrons (Spiers
1002 1970; Eckerman et al. 1985; Bouchet et al. 1999; Eckerman and Stabin 2000; Jokisch et al. 2001;
1003 Patton et al. 2002; Shah et al. 2005; Kramer et al. 2012; Dant et al. 2013; Gao et al. 2017; Degteva
1004 et al. 2021) and alpha particles (Thorne 1976; Watchman et al. 2005; Hunt et al. 2007; Watchman
1005 and Bolch 2009). *Publication 106* (ICRP 2008b) represented the first departure from the electron
1006 absorbed fraction values of *Publication 30* and shown in Table 4.2. *Publication 106* used values
1007 for the adult from Stabin and Siegel (2003) which were based on work by Eckerman and Stabin
1008 (2000) and Bouchet et al. (2000) and was described in Stabin et al (2002). In *Publication 30*, the
1009 reference target masses for the red marrow and bone endosteum were 1.5 kg and 0.12 kg,
1010 respectively.

1011
1012 Table 4.2. Skeletal absorbed fractions in *Publication 30* (ICRP 1979) for the adult.

Radiation type	Target ← Source	Absorbed Fraction	Based on
Alpha particles	Endosteum ← Trab. bone volume	0.025	(Mays and Sears 1962; Thorne 1977)
	Endosteum ← Cortical bone-volume	0.010	(Spiers 1974)
	Red marrow ← Trab. bone volume	0.050	(Mays and Sears 1962; Thorne 1977)
	Red marrow ← Cortical bone volume	0.0	(Whitwell and Spiers 1976)
	Endosteum ← Trab. bone surface	0.25	(Mays and Sears 1962; Thorne 1977)

Radiation type	Target ← Source	Absorbed Fraction	Based on
	Endosteum ← Cortical bone surface	0.25	(Whitwell and Spiers 1976; Thorne 1977)
	Red marrow ← Trab. bone surface	0.50	Geometrical assumption
	Red marrow ← Cortical bone surface	0.0	Negligible compared to Trab. bone surface contribution
Electrons	Endosteum ← Trab. bone volume	0.025	(Spiers 1968, 1969, 1974; Whitwell and Spiers 1976)
	Endosteum ← Cortical bone-volume	0.015	
	Red marrow ← Trab. bone volume	0.35	
	Red marrow ← Cortical bone volume	0.0	
	Endosteum ← Trab. bone surface	0.25 E < 0.2 MeV 0.025 E ≥ 0.2 MeV	
	Endosteum ← Cortical bone surface	0.25 E < 0.2 MeV 0.015 E ≥ 0.2 MeV	
	Red marrow ← Trab. bone surface	0.50	
	Red marrow ← Cortical bone surface	0.0	

1013
1014   (99) Marrow cellularity is defined as the fraction of bone marrow volume that is
1015 haematopoietically active. Cellularity varies by location in the skeleton. Cellularity is also known
1016 to vary by age. In this work, reference values for marrow cellularity have been adopted from Table
1017 41 of *Publication 70* (ICRP 1995b). The data is based largely on a review performed by Cristy
1018 (1981) of various studies of active marrow distribution. Fig. 4.4 contains a plot of these reference
1019 cellularities and how they vary by skeletal site and age.
1020
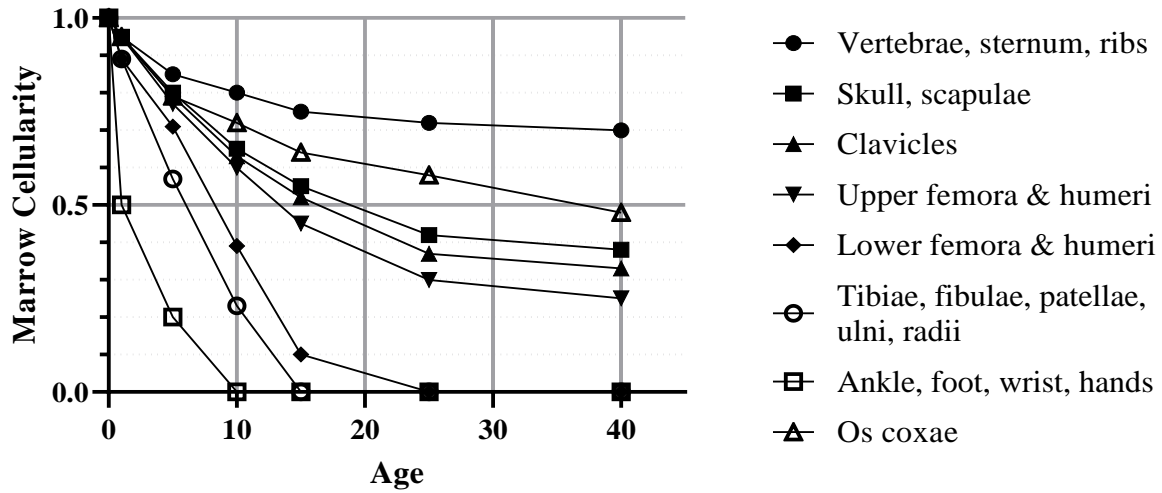
1021
1022   Fig. 4.4. Reference marrow cellularity of *Publication 70* (ICRP 1995b) by skeletal site and age.

1023   **4.4.2. Electrons**

1024   (100) Since the microstructure of the skeleton cannot be modelled in the reference voxel
1025   phantoms, separate image-based voxel models of human skeletal microstructure have been used
1026   to compute absorbed fractions in the adult (Hough et al. 2011; O'Reilly et al. 2016) and paediatric
1027   individuals (Pafundi et al. 2010).
1028   (101) Intraskeletal electron SAFs in this work are taken from those developed in Pafundi (2009)
1029   and are given as a function of reference age with no differentiation by sex. As described in Pafundi
1030   et al. (Pafundi et al. 2009; Pafundi et al. 2010), electron SAFs were computed following paired-
1031   image radiation transport simulation within CT-based images of whole bone and microCT images
1032   of spongiosa cores acquired in 5 skeletal sites within two female newborns at autopsy. The bone
1033   sites were the sternum, occipital bone, ribs, thoracic vertebrae, and lumbar vertebrae. SAF values
1034   at bone sites for which a 3D voxelised model was not available were estimated using weighting
1035   schemes originally proposed by Whitwell (1973). For the 15-year model, intraskeletal electron
1036   SAFs were based upon paired-image radiation transport simulations within CT and microCT
1037   images of some 26 skeletal sites across both the axial and appendicular skeleton of an 18-year
1038   male cadaver. Methods applied to this model were identical to those described in both Hough et
1039   al. (2011) and O'Reilly et al. (2016) for the UF reference adult male and adult female, respectively.
1040   (102) As physical samples of trabecular spongiosa were not available to perform 3D electron
1041   transport in the skeletons of the 1-year, 5-year, and 10-year reference children, an alternative
1042   approach was taken. Macroscale electron transport was first performed within the skeletal sites of
1043   the reference phantoms at these three ages to compute sources in the cortical bone, trabecular
1044   spongiosa, and medullary cavities of the long bones. Next, microscale electron transport was
1045   performed for the 1-year and 10-year reference children using optical pathlength distributions
1046   originally reported in Beddoe et al. (1976) for a 1.7-year and 9-year child in simulated 3D
1047   geometries as described by Watchman et al. (2005). Pathlength distributions within the 5-year
1048   model were established as age-interpolated values between the 1.7-year and 9-year datasets.
1049   (103) Figure 4.5 plots the electron SAFs in this work along with those for the adult from
1050   *Publications 30, 106,* and *133*. The SAF to the bone surface target is significantly smaller than
1051   values used in *Publications 30* and *133* due to the previously mentioned change in the target
1052   thickness from 10 µm to 50 µm. A significant difference in the definition of the cortical bone
1053   source is observed in Figure 4.5b. In the present work for electrons, the cortical bone surface was
1054   modelled as consisting of Haversian canals within the bone cortex and the endosteal surface of
1055   cortical bone of the long bone shafts. Since Haversian canals exist throughout the cortical bone
1056   volume, the electron SAFs for cortical bone surfaces are assumed to be identical to those of the
1057   cortical bone volume.
1058
1059
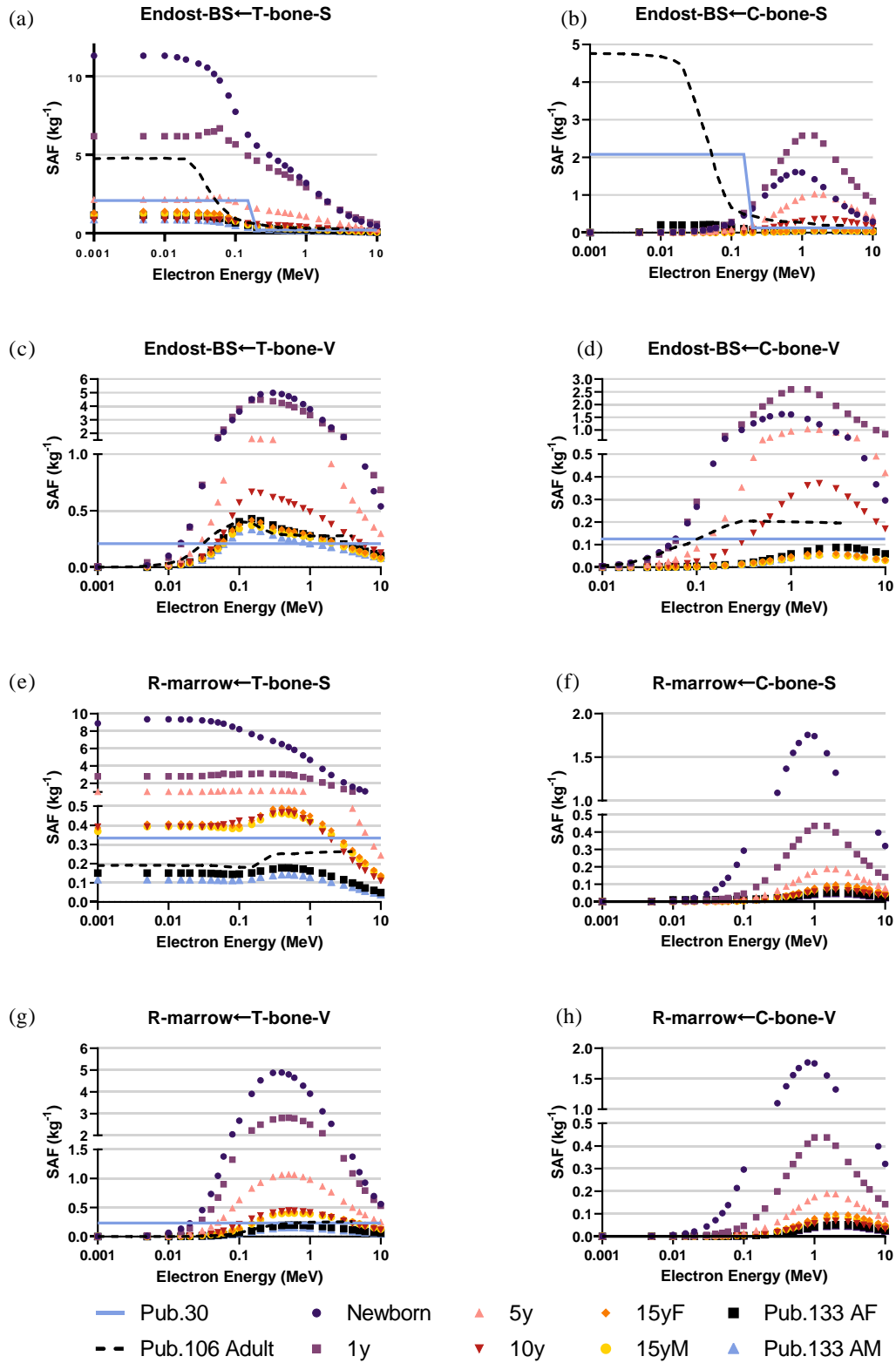
1060
1061 Fig. 4.5 Intraskeletal electron SAFs for each reference individual. The plots also show adult SAF
1062 values from *Publications 30* and *106*.

1063
1064   (104) The intraskeletal electron SAFs for emissions from the red marrow are shown in Figure
1065   4.6. The red marrow self-irradiation geometry was treated as independent of energy in *Publication*
1066   *30*. The current models now account for energy-dependent loss to surrounding yellow marrow and
1067   bone. The age-dependency accounts for the variation in marrow cellularity with age.
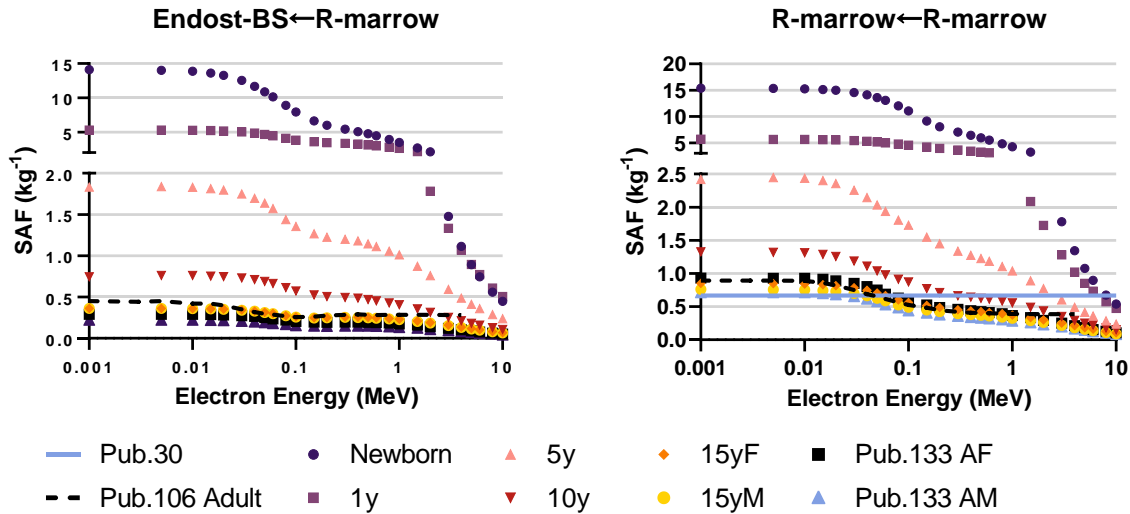
1068
1069   Fig. 4.6. Intraskeletal electron SAFs for each reference individual for emission from the red
1070   marrow.

1071   **4.4.3. Alphas**

1072   (105) Intraskeletal alpha-particle SAFs for the adults were computed using both Monte Carlo
1073   and range-energy type calculations as described in *Publication 133*. Results using similar methods
1074   were not available for alpha particles in the paediatric skeleton. One approach for obtaining
1075   paediatric SAFs would be to scale the adult SAFs by the target mass. However, the significant
1076   changes in the skeletal structures and marrow cellularity with age make this problematic. Instead,
1077   an approach was adopted which uses electron SAFs for similarly ranged alpha particles. The
1078   method has the benefit of using electron SAF data which accounts for age-dependent changes in
1079   the skeleton. The weakness of the method is that the stopping power is not the same for similarly
1080   ranged alpha particles and electrons.
1081   (106) Figure 4.7 plots the energy of alpha particles and electrons versus their range in red
1082   marrow. Each set of data has been fit to obtain empirical power functions relating range and energy
1083   for each radiation type. Equations (4.7) and (4.8) give an empirical range-energy equation for each
1084   radiation in red marrow, where *E* is the energy in MeV of the given radiation type and *R* is the
1085   linear range in units of cm.
1086

$$E_{\text{alpha,RM}} = 210 R^{0.6678} \tag{4.7}$$

$$E_{\text{electron,RM}} = 1.197 R^{0.5757} \tag{4.8}$$

1087
1088   (107) Combining Eqs. (4.7) and (4.8) and eliminating the range gives Eq. (4.9) which provides
1089   the energy of an electron with equivalent range in red marrow to that of an alpha particle of given

57

1090 energy. Equation (4.9) is used to obtain electron energies with equivalent ranges to each desired
1091 alpha energy on the SAF grid. The SAF is then obtained by interpolating the skeletal electron
1092 SAFs.

$$E_{\text{electron,RM}} = 1.197\left(\frac{E_{\text{alpha,RM}}}{210}\right)^{0.862} \tag{4.9}$$

1093 (108) Equation (4.9) was used to obtain alpha SAFs for emissions from all marrow regions and
1094 bone surfaces since the energy absorption is occurring on the soft tissue side of the bone-marrow
1095 surface plane. An exception was made for the red marrow self-irradiation geometry. For this
1096 geometry adult SAF values were scaled by target mass to the younger ages to preserve consistency
1097 of shape of the SAF curve.
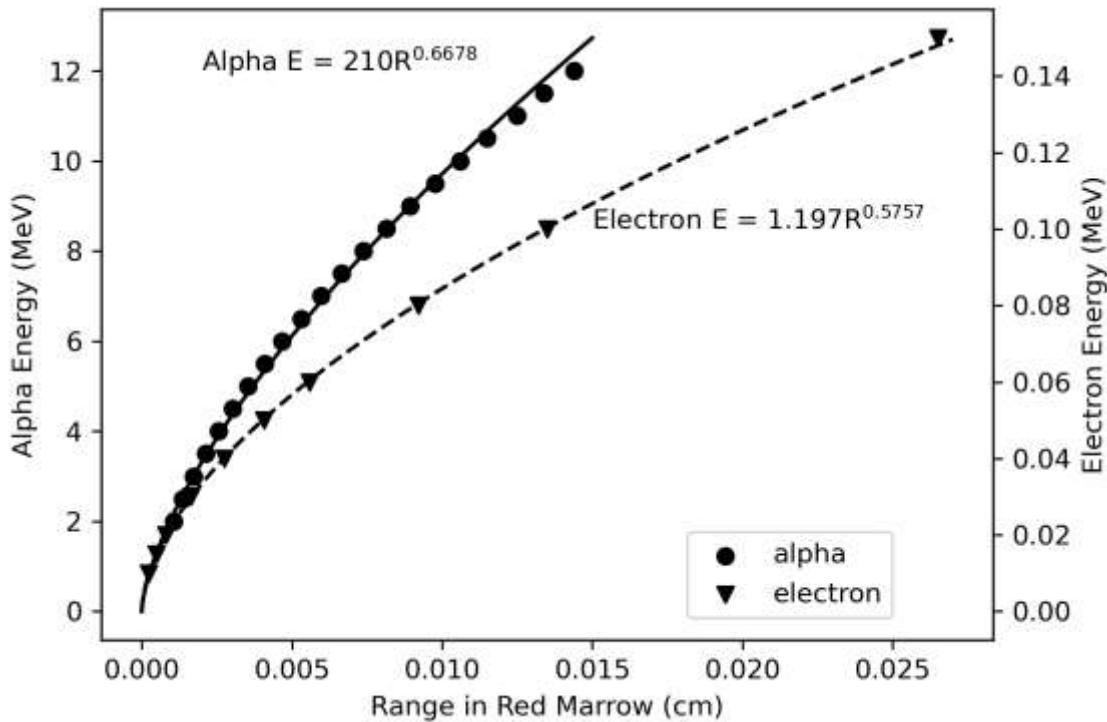
1098
1099 Fig. 4.7 Energy versus range in red marrow for alpha particles and electrons.
1100
1101 (109) Figure 4.8 shows the ranges of alpha particles and electrons in bone. Equations (4.10) and
1102 (4.11) show empirical relationships between energy and range. Combining these equations and
1103 eliminating the range gives Eq. (4.12) which relates the alpha energy to the electron energy which
1104 would yield the same range in bone. This equation was used to find interpolated SAFs for
1105 emissions from the trabecular bone volume. Note that alpha particles emitted from the cortical
1106 bone volume are considered to have absorbed fractions of zero at all alpha energies.
1107

$$E_{\text{alpha,bone}} = 259R^{0.6617} \tag{4.10}$$

$$E_{\text{electron,bone}} = 1.504R^{0.5777} \tag{4.11}$$

$$E_{\text{electron,bone}} = 1.504\left(\frac{E_{\text{alpha,bone}}}{259}\right)^{0.873} \tag{4.12}$$

1108
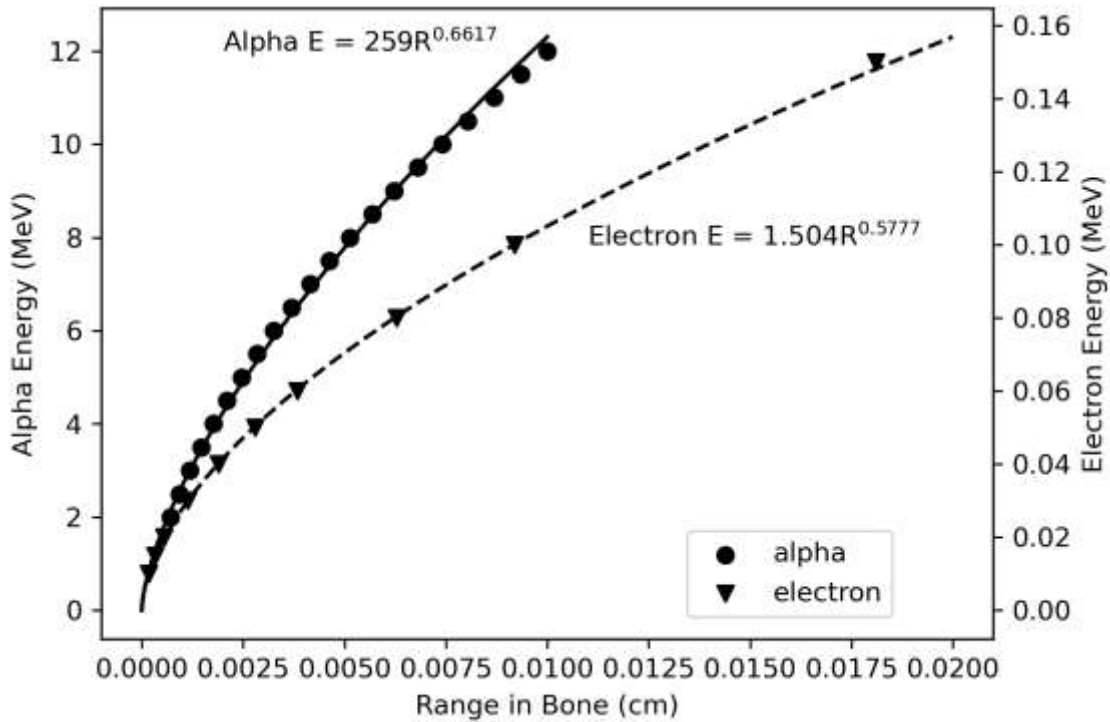
1109
1110   Fig. 4.8 Energy versus range in bone for alpha particles and electrons.
1111
1112   (110) The intraskeletal alpha-particle SAFs are shown in Fig. 4.9. As with electrons, significant
1113   differences are seen resulting from the change in the modelling definition to a 50 µm endosteum
1114   target. For alpha emissions in red marrow, energy loss to surrounding yellow marrow and bone is
1115   less significant but does still show an energy dependency. Fig. 4.10 displays values of the SAF for
1116   a red marrow source of alpha particles.
1117
1118
1119
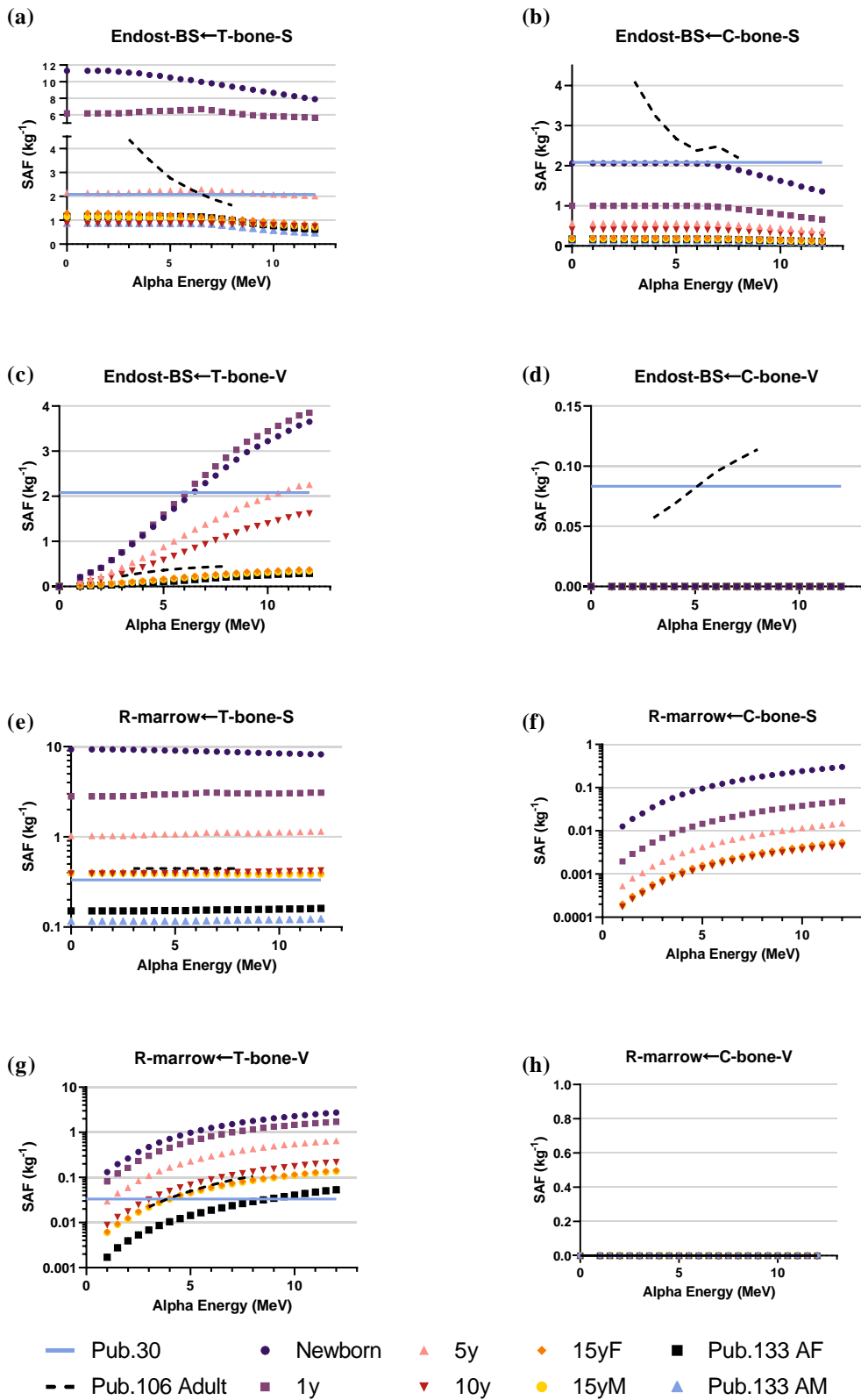
1120
1121 Fig. 4.9 Intraskeletal alpha-particle SAFs from bone source regions. Note that y-axis scales are
1122 varied to improve visualization.
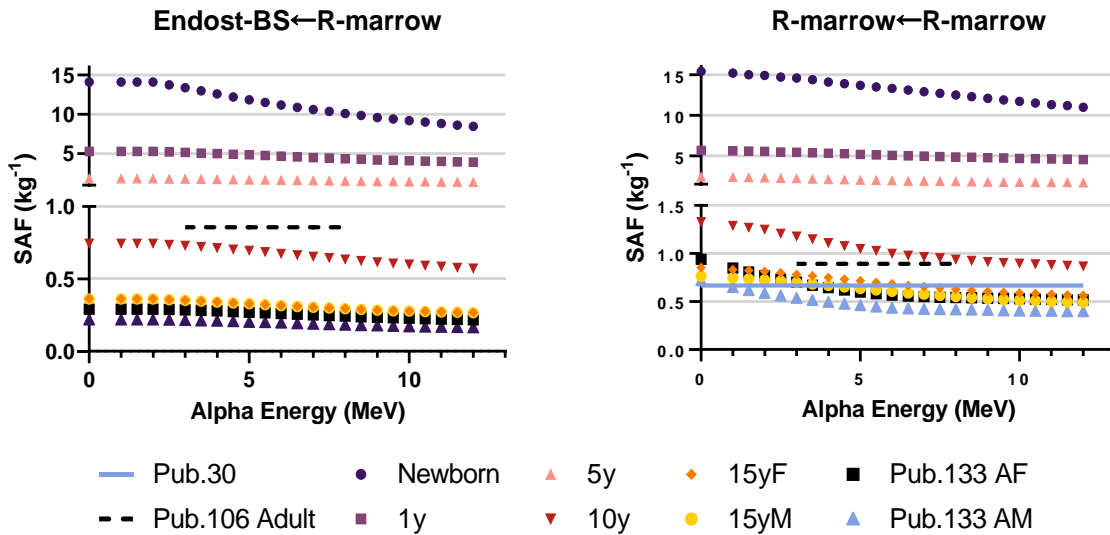
1123
1124 Fig. 4.10. Skeletal SAFs for alpha-particles emitted from the red (active) marrow.
1125

1126 **4.4.4. Photons and Neutrons**

1127   (111) SAFs to the skeletal targets for both intra-skeletal and extra-skeletal photon sources were
1128 computed by coupling (1) Monte Carlo derived energy/bone-dependent volumetric photon
1129 fluences scored within regions of trabecular spongiosa and long-bone medullary marrow cavities
1130 and (2) energy/bone site-dependent fluence-to-dose response functions for red marrow and
1131 endosteum. Adult skeletal dose-response functions (ICRP 2010, 2016a) were originally computed
1132 in Wayson (2012) using the electron SAFs and skeletal tissue masses given in Pafundi (2009) via
1133 the methods of Johnson et al. (2011) established for adult photon skeletal dosimetry and used as
1134 described here in Eqs. (4.1) and (4.2). Age-dependent photon skeletal dose-response functions
1135 were used in the computation of photon SAFs.
1136   (112) In *Publication 133*, SAFs to skeletal targets (red marrow and endosteum) for neutrons
1137 from spontaneous fission sources were computed by coupling Monte Carlo derived neutron
1138 fluences to neutron fluence-to-dose response functions (Bahadori et al. 2011). Similarly, neutron-
1139 induced photon fluences, from (n, γ) reactions, were coupled to adult photon fluence-to-dose
1140 response functions (Eckerman et al. 2008; Johnson 2011). For the reference paediatric individuals,
1141 the age-dependent photon fluence-to-dose response functions were coupled to the neutron-induced
1142 photon fluences from (n, γ) reactions. Fluence-to-dose response functions for neutron fluences in
1143 paediatric individuals were not available, so those derived for the adult male were used instead.
1144

1145   **5. SPECIFIC ABSORBED FRACTION CALCULATION AND**
1146   **TABULATION**

1147
1148   (114) As described by Equation (2.14) the SAF is determined by taking the fraction of emitted
1149   energy within a source region which is absorbed in a target region and dividing by the mass of the
1150   target region. Section 4 described the computational methods and models used to arrive at the
1151   absorbed fraction for each source-target combination. Division by the target mass is then
1152   performed to provide a SAF. This section describes what adjustments, if any, are made to SAFs
1153   computed in models. It also describes methods for quality assurance in this large data set.

1154   ## 5.1. Scaling SAFs to reference mass

1155   (115) While the computational models detailed in Section 4 were designed based on the
1156   definitions of the reference individuals of Section 3, the target mass used to compute a SAF in a
1157   given model is not always consistent with the reference target mass. In such cases, adjustment of
1158   the model-derived SAFs needs to be considered to arrive at the reference SAFs.
1159   (116) The need to consider scaling SAFs from a model or phantom to conform to another
1160   individual, whether it be a reference individual, a specific worker, a member of the public, or a
1161   medical patient is not new or unique to this effort. W.S. Snyder (1970) wrote about this need in
1162   what he described as a "preliminary" discussion which he hoped would spur further study. Snyder
1163   proposed a scaling for photon absorbed fractions in self-irradiation geometries which was
1164   proportional to the cube root of the mass of the source (and target) region. Snyder found that the
1165   proportionality worked well over the region where Compton scattering predominates. Snyder
1166   wrote:

1167
1168   "Clearly, this rule fails badly for photons of energy below 50 keV, and in these cases the
1169   AF [absorbed fraction] is greater than 0.5. Perhaps this reveals at once the limitations of
1170   this principle – namely, the organ must be small in relation to the mean free path of the
1171   photons that buildup is not an important contribution to the dose or to AF, and thus the
1172   principle does not hold for low energies. Clearly, for low photon energies such that the
1173   AF is approximately 1, the AF cannot continue to increase with the cube root of the mass
1174   as the mass of the organ is increased. Thus, the principle should be applied only for the
1175   energy region where Compton scattering predominates and then only when the AF is well
1176   below 1, say, ≤ 0.5. But for many body organs and for a range of photon energies from,
1177   say, 0.2 to 2 MeV, the principle seems to hold fairly well…"

1178
1179   "It should be understood that no claim to a high degree of accuracy is made for these
1180   methods; indeed, quite the reverse. It is evident that only a rough approximation to the
1181   dose is given."

1182
1183   (117) In MIRD Pamphlet 11 (Snyder et al. 1975), the MIRD Committee presented the
1184   proportionality above in terms of the SAF or absorbed dose as being equivalently proportional to
1185   the inverse of the mass to the 2/3 power. Again, the proportionality was qualified as being useful
1186   for photons "…with energies above 100 keV."

1187
1188   "Since dose from electrons scales with the inverse first power of the mass, if one assumes
1189   complete absorption of energy, scaling is no longer simple; the photon dose changes with
1190   one power of the mass and the electron dose changes with another. In fact, there seems to
1191   be no simple scaling procedure which is approximately correct for all energies of particles
1192   and masses of organs."
1193
1194   (118) Adams (1981) described using linear mass scaling for photon energies less than 30 keV
1195 and the inverse 2/3 power scaling for energies above 30 keV. Petoussi-Henss et al. (2007) found
1196 that photon self-dose SAFs vary with the inverse 2/3 power of mass for energies above 100 keV
1197 "…and for organs that are not extended." Wayson and Bolch (2018) performed Monte Carlo
1198 radiation transport in spheres of varying sizes for photons and electrons. For photon self-dose they
1199 found mass proportionality which varies from the inverse first power (at around 10 keV) to the
1200 inverse 2/3 power (100 keV) and smaller when photon energy exceeds 1 MeV. For electrons, the
1201 same study found the SAF was proportional to the inverse of the mass for all energies up to around
1202 1 MeV.

1203 **5.1.1.   Self-irradiation geometries**

1204   (119) Self-irradiation geometries are defined here as any in which the low energy SAF is non-
1205 zero. These include source and target region being identical, but also include overlapping source
1206 and target regions.
1207   (120) The low energy self-irradiation SAF is often the most important SAF in internal dose
1208 coefficient calculations. A non-energy-dependent 2/3 power scaling approach would perturb the
1209 low energy value. While an energy-dependent scaling such as described by Wayson and Bolch
1210 may improve photon SAFs above 100 keV, in this work the simpler linear mass scaling described
1211 in Eq. (5.1) was used for alphas, electrons, and photons.
1212

$$\Phi_{\text{reference}}(r_\text{T} \leftarrow r_\text{S}, E) = \frac{m_{\text{T,phantom}}}{m_{\text{T,reference}}} \Phi_{\text{phantom}}(r_\text{T} \leftarrow r_\text{S}, E) \qquad (5.1)$$

1213
1214 where $m_{\text{T,phantom}}$ is the mass of the target region in the phantom or model used for the radiation
1215 transport calculations and $m_{\text{T,reference}}$ is the mass of the target regions provided in Tables 3.10
1216 through 3.15. This approach essentially treats the self-irradiation absorbed fraction in the phantom
1217 as equivalent to the absorbed fraction in the reference individual.

1218 **5.1.2.   Crossfire irradiation geometries**

1219   (121) Crossfire geometries are defined here as any in which the low energy SAF is zero. MIRD
1220 Pamphlet 11 (Snyder et al. 1975), Petoussi-Henss et al. (2007), and Wayson and Bolch (2018) all
1221 provide evidence that scaling is not required for these geometries. Therefore, crossfire geometry
1222 SAFs computed in the phantoms and models are adopted for the reference individuals.

1223 ## 5.2. Low energy, limiting SAF values

1224   (122) As the kinetic energy of any radiation approaches zero, the SAF approaches a value which
1225 can be theoretically computed. The equations for the limiting values were provided in section 7 of
1226 *Publication 133* (ICRP 2016a) and are summarised below. As in *Publication 133*, the SAFs
1227 include tabulated SAFs for zero energy emissions of alphas, electrons, and photons. In addition to
1228 their usefulness in low energy SAF interpolation, these theoretical, limiting SAF values were used
1229 to confirm the correctness of the SAFs computed in various models.

1230 ### 5.2.1. Whole-body geometries

1231   (123) If the source and target regions are non-overlapping with any distance between them, the
1232 low energy absorbed fraction, and therefore the SAF approaches zero. If the definition of the
1233 source and target consist of the same volume, the low energy absorbed fraction approaches unity
1234 and the SAF is the inverse of the target mass as shown in Eq. (5.2).
1235

$$\lim_{E \to 0} \Phi(r_T \leftarrow r_S, E) = \begin{cases} \dfrac{1}{m_T}, & \text{if } r_S = r_T \\ 0, & \text{if } r_S \neq r_T \end{cases} \tag{5.2}$$

1236

1237 ### 5.2.2. Alimentary tract geometries

1238   (124) As described in section 4.2, the walls of the alimentary tract contain several source and
1239 target regions which partially overlap. The low energy absorbed fraction in such regions is given
1240 by the fraction of the source region's volume which is designated as a target region. Since the mass
1241 density is the same throughout the regions, the volume ratio is equivalent to the mass ratio. If the
1242 target region is completely within the source region, as is the case for the alimentary stem cell
1243 targets for wall and mucosa source regions, the mass of the target cancels out in the SAF as shown
1244 in Eq. (5.3). Note that the mass of the wall (or mucosa) in the denominator of Eq. (5.3) should
1245 include the mass of blood in that region.

$$\lim_{E \to 0} \Phi(\text{HATM}_{\text{stem}} \leftarrow \text{HATM}_{\text{wall}}, E) = \frac{\frac{V_{\text{stem}}}{V_{\text{wall}}}}{m_{\text{stem}}} = \frac{\frac{m_{\text{stem}}}{m_{\text{wall}}}}{m_{\text{stem}}} = \frac{1}{m_{\text{wall}}} \tag{5.3}$$

1246
1247   (125) All remaining source regions in the alimentary tract do not overlap with the target and
1248 therefore give a low energy SAF of zero. These source regions include: the slow and fast clearance
1249 regions in the oesophagus, the alimentary tract contents, and the villi in the small intestines.

1250 ### 5.2.3. Respiratory tract geometries

1251   (126) In the respiratory tract the target regions are basal cells in the extrathoracic tissues (ET1
1252 and ET2) and the bronchi of the lungs, secretory and basal cells in the bronchi, and secretory cells
1253 in the bronchioles, and the alveolar interstitium. Source regions which do not overlap with these
1254 targets and therefore give a low energy SAF of zero are the mucosal surfaces of the extrathoracic
1255 regions (ET1-sur, ET2-sur), the sequestered regions of the posterior nasal passage, larynx,

1256   pharynx, and mouth (ET2-seq), the bronchi and bronchioles (bronchi-q and brchiole-q), surface
1257   transport in the bronchi and bronchioles (bronchi, brchiole), and the airways (RT-air).
1258   (127) All other source regions (walls and bound regions) in the respiratory tract overlap with
1259   the target regions, and therefore the same relationship described in Eq. (5.3) applies to these
1260   geometries. The low energy SAF will approach the inverse of the mass of the source region
1261   inclusive of any blood in the source region.

1262   **5.2.4. Skeletal geometries**

1263   (128) Within the skeleton, the two target regions are the red (active) marrow and the bone
1264   endosteum. The latter is defined as a 50-µm thick region of soft tissue adjacent to the interior bone
1265   surface (Bolch et al. 2007). Source regions within the skeleton include bone marrow, cortical and
1266   trabecular bone volumes and surfaces. The bone surface sources are mathematically defined as a
1267   two-dimensional, non-volumetric interface between the bone and marrow cavity.
1268   (129) The marrow source regions are divided as either red and yellow marrow or as trabecular
1269   and cortical marrow. The trabecular and cortical marrow consists of a mixture of red and yellow
1270   marrow in varying proportion with age depending on the skeletal site-specific marrow cellularity.
1271   The trabecular and cortical marrow source regions are called for in the systemic biokinetic models
1272   of many of the actinides and lanthanides (ICRP 2017, 2019). In this work, the SAFs were computed
1273   using models with red and yellow marrow regions. Cortical and trabecular SAFs were computed
1274   later using skeletal site specific SAFs of the red and yellow marrow regions and information on
1275   marrow cellularity. The need for two different source region treatments for the marrow space
1276   results from systemic biokinetic modelling. When the cortical/trabecular treatment is not
1277   specifically invoked by a systemic biokinetic model, the red/yellow treatment should be used as
1278   the default marrow treatment.
1279   (130) For source material in the marrow space irradiating the bone endosteum target, the
1280   regions overlap and similarly to Eq. (5.3), the low energy absorbed fraction can be found by the
1281   volume ratio. The resulting SAF is shown in Eq. (5.4), where m_{Marrow} is the mass of the entire
1282   marrow space.
1283

$$\lim_{E \to 0} \Phi(\text{Endost-BS} \leftarrow \text{Marrow}, E) = \frac{\frac{V_{\text{Endost-BS}}}{V_{\text{Marrow}}}}{m_{\text{Endost-BS}}} = \frac{\frac{m_{\text{Endost-BS}}}{m_{\text{Marrow}}}}{m_{\text{Endost-BS}}} = \frac{1}{m_{\text{Marrow}}} \qquad (5.4)$$

1284
1285   (131) For source material on the trabecular bone surface irradiating the bone surface, the low
1286   energy absorbed fraction is one-half. The low energy SAF is given in Eq. (5.5).
1287

$$\lim_{E \to 0} \Phi(\text{Endost-BS} \leftarrow \text{T-bone-S}, E) = \frac{^1/_2}{m_{\text{Endost-BS}}} = \frac{1}{2m_{\text{Endost-BS}}} \qquad (5.5)$$

1288
1289   (132) The low energy SAF for activity on the trabecular bone surface irradiating the red marrow
1290   is more complex. For a given skeletal site, i, with known red marrow cellularity, c_i (fraction of
1291   marrow which is active), Eq. (5.6) can be used to find a limiting SAF. Since the cellularity varies
1292   across different skeletal sites, the limiting value for each site must be summed using source
1293   weighting to obtain a skeletal averaged low energy SAF.
1294

$$\lim_{E \to 0} \Phi_i(\text{R-marrow} \leftarrow \text{T-bone-S}, E) = \frac{c_i/2}{m_{\text{Endost-BS},i}} = \frac{c_i}{2m_{\text{Endost-BS},i}}$$

$$\lim_{E \to 0} \Phi_{\text{skeleton}}(\text{R-marrow} \leftarrow \text{T-bone-S}, E) = \sum_i \frac{SA_{\text{BS},i}}{SA_{\text{BS,skeleton}}} \frac{c_i}{2m_{\text{Endost-BS},i}} \tag{5.6}$$

1295

5.2.5. Blood source geometries

1296

1297 (133) The blood source in the SAF represents blood distributed throughout the entire body. The
1298 blood SAFs give the fractional energy absorption to targets resulting from nuclear transformations
1299 taking place in large arteries and veins as well as those taking place in blood which has perfused
1300 tissue. As given in *Publication 133*, the low energy limiting SAF for source material in the blood
1301 irradiating a given target region is:

$$\lim_{E \to 0} \Phi(r_{\text{T}} \leftarrow \text{Blood}, E) = \frac{f_{r_{\text{T}}}}{m_{\text{T}}} \tag{5.2}$$

1302
1303 where $f_{r_{\text{T}}}$ is the fraction of the body's blood in region r_{T} as described in Table 3.3.

5.2.6. Low-energy extrapolation

1304

1305 (134) As was performed in *Publication 133* (ICRP 2016a), when the low energy limiting SAF
1306 is non-zero, log-log interpolation was performed for SAF values at energies smaller than those
1307 reliably provided by the radiation transport calculations. For the sake of the log-log interpolation,
1308 zero energy is treated as having a value of 10^{-3} keV and, if the low energy limiting SAF is zero it
1309 is treated as having a value of 10^{-12} kg^{-1}.
1310 (135) Schwarz et al (2021a) describe how interpolations were performed for electrons with
1311 kinetic energies less than 10 keV. For photons, the energy used for interpolation would vary
1312 between 10 and 30 keV depending on the source-target geometry and the energy-dependent shape
1313 of the SAF curve (Schwarz et al. 2021b).

5.3. Quality checks on SAF values

1314

1315 (136) The set of paediatric SAFs for ICRP reference individuals represents a large data set.
1316 Quality checks were performed on this data at multiple stages. Use of version control repositories
1317 allowed for tracking of edits and changes to the data set during development. The theoretical low
1318 energy limiting SAF values described earlier in this section were computed and compared to data
1319 sets. Visualizations of data sets were also reviewed for expected trends and relationships. For
1320 example, since most target masses increase with increasing age, SAFs generally decrease with
1321 increasing age. Additionally, some geometries within a system create logical relationships between
1322 source/target combinations. The following examples provide a look at some of the quality checks.
1323 (137) Another important tool for checking the quality of SAFs is the calculation and evaluation
1324 of the associated organ and tissue dose coefficients. Preliminary SAFs were distributed to multiple
1325 users with codes used for computing internal dose coefficients. The resulting equivalent and
1326 effective dose coefficients were studied to look for anomalous results. Dose coefficients can be
1327 compared to past dose coefficients with changes needing to be explained either by something in

1328   the biokinetics or in the energy absorption term. One particularly valuable case is to look at
1329   equivalent dose coefficients resulting from the ingestion of tritiated water. Water distributes fairly
1330   uniformly throughout soft tissue. The low energy, pure beta emission associated with tritium
1331   means uniform equivalent dose coefficients should result across all soft tissue targets.

1332   **5.3.1.   Limiting value checks across radiation types**

1333   (138)   The theoretical low energy limiting SAF values provided in section 5.1 are a useful tool
1334   for checking the quality of SAF data. These values were computed based on the reference masses
1335   in section 3 and compared to SAF data. Since these values are independent of radiation type, plots
1336   were created for a given geometry with alpha, electron, and photon SAFs on the same plot and
1337   reviewed for SAF convergence to the limiting value at low energy.
1338   (139)   Figures 5.1 through 5.3 provide three examples of such plots. Self-irradiation of the 15y
1339   female liver is shown in Fig. 5.1. Using Eq. (5.2) with the target mass for the 15y female liver of
1340   1.628 kg from Table 3.14 yields a theoretical low-energy SAF of 0.614 kg^{-1}. This value matches
1341   the data in Fig. 5.1. Note that theoretical low energy limiting SAFs are generally checked
1342   numerically within the SAF files. Calculated similarly, the theoretical low energy SAF for self-
1343   irradiation of the newborn female brain (Fig. 5.2) is 2.527 kg^{-1}.
1344   (140) Equation (5.7) was used to compute the theoretical low energy limiting SAF for the blood
1345   irradiating the alveolar target in a 10y male. As described in section 3.2, the alveolar interstitium
1346   (AI) target receives all of the pulmonary gas exchange blood and a portion of the pulmonary
1347   nutrient blood. Performing the mass splitting of the nutrient blood results in 12.2% of the body's
1348   blood being assigned to the AI target. Using the AI target mass of 500 g (Table 3.13) results in a
1349   low energy SAF of 0.243 kg^{-1}. Figure 5.3 contains this data, although because the x-axis is log-
1350   scale the low energy limiting SAF has not yet reached convergence at 1 keV. Instead, it does so
1351   at the zero energy point in the data files.
1352
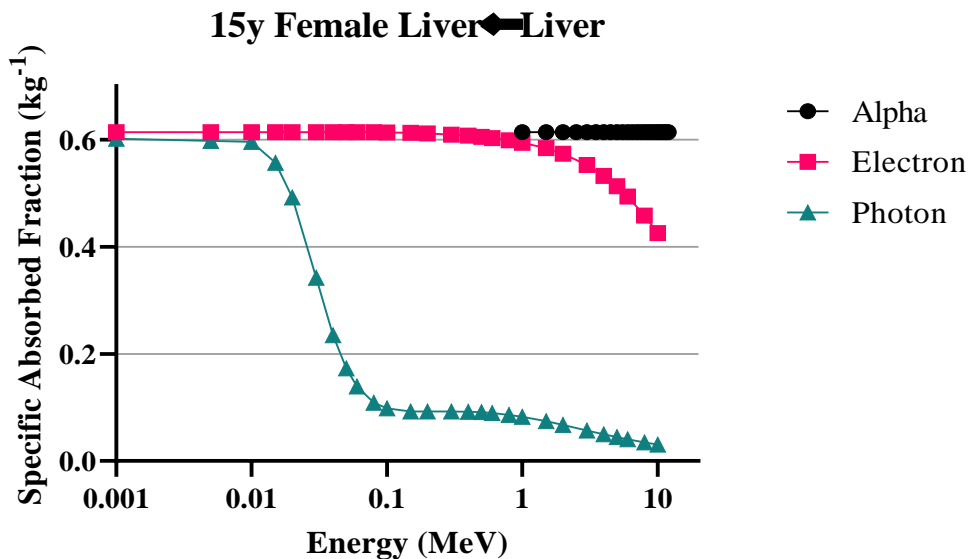
1353
1354   Fig. 5.1. Liver self-irradiation SAFs in the 15-year female for alphas, electrons, and photons.
1355

0y Female Brain◆Brain
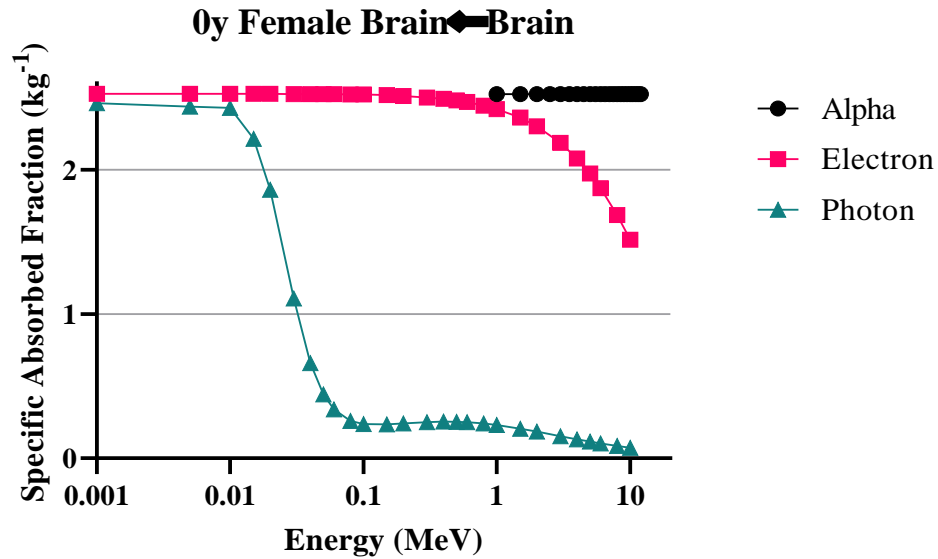
1356
1357 Fig. 5.2. Brain self-irradiation SAFs in the newborn female for alphas, electrons, and photons.
1358

10y Male AI◆Blood
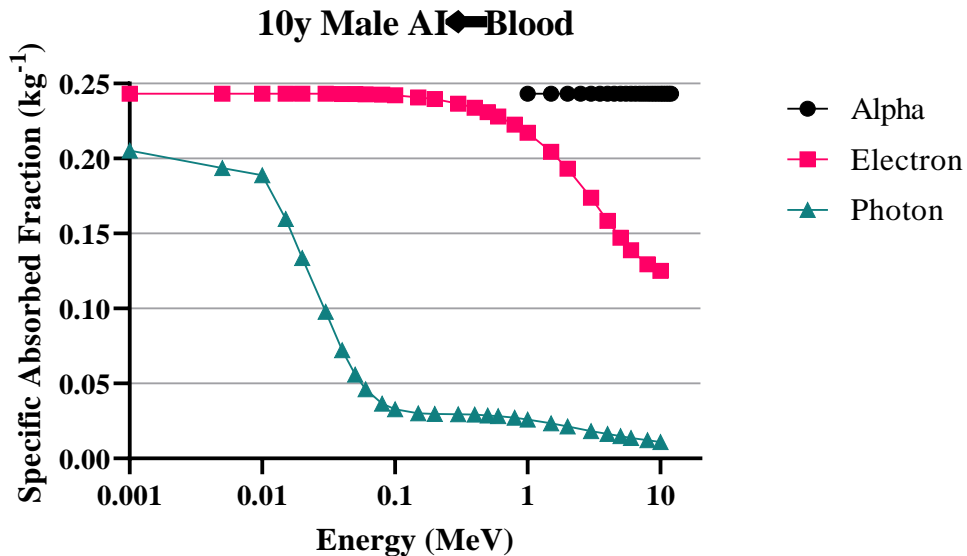
1359
1360 Fig. 5.3. SAFs for emissions from the blood irradiating the alveolar interstitium in the 10-year
1361 male for alphas, electrons, and photons.
1362

1363 **5.3.2. Age-dependency**

1364 (141) Age dependency of SAFs is inversely proportional to the mass of the target when the
1365 absorbed fraction is at or near unity. This is particularly true for alpha particles and low energy
1366 electrons. Figure 5.4 shows self-irradiation of the female breast for alpha particles and the expected
1367 relationship between ages is observed. Figure 5.5 shows a partial, self-irradiation as the right colon
1368 stem cell target comprises a portion of the right colon wall. At sufficient electron energies, the

1369   SAF drops from its low energy value and the difference between ages decreases. Figure 5.6 is
1370   photon self-irradiation of the skin and displays the expected age dependency.
1371   (142) Figure 5.7 is an example of a result where a small inconsistency can be observed between
1372   the data for the adult and the paediatric individuals. The adrenals are located in close proximity to
1373   the kidneys. Around 200 keV the electron SAF for the adult begins to increase away from zero
1374   while the SAF for younger individuals remains near zero. In the voxel phantom for the adult, the
1375   adrenals are located closer to the kidneys than in the paediatric voxel phantoms, in fact some
1376   adrenal voxels are located adjacent to kidney voxels in the adult reference voxel phantoms. The
1377   SAF for the adult also peaks at a lower energy than it does for every other phantom except for the
1378   newborn which is consistent with the adrenals being slightly further away in the paediatric
1379   phantoms than they are in the adult phantom. This does not necessarily speak to a problem with
1380   any of the plotted SAFs, particularly when one considers the small differences in the SAFs and the
1381   consistency of the shape amongst the individuals. It simply reflects a modelling difference which
1382   may reflect anatomical reality or biological variability.
1383   (143) Figure 5.8 shows SAFs for photons emitted from the cortical bone volume irradiating the
1384   thyroid. Consistency of shape is again observed, and the expected age dependency is observed.
1385
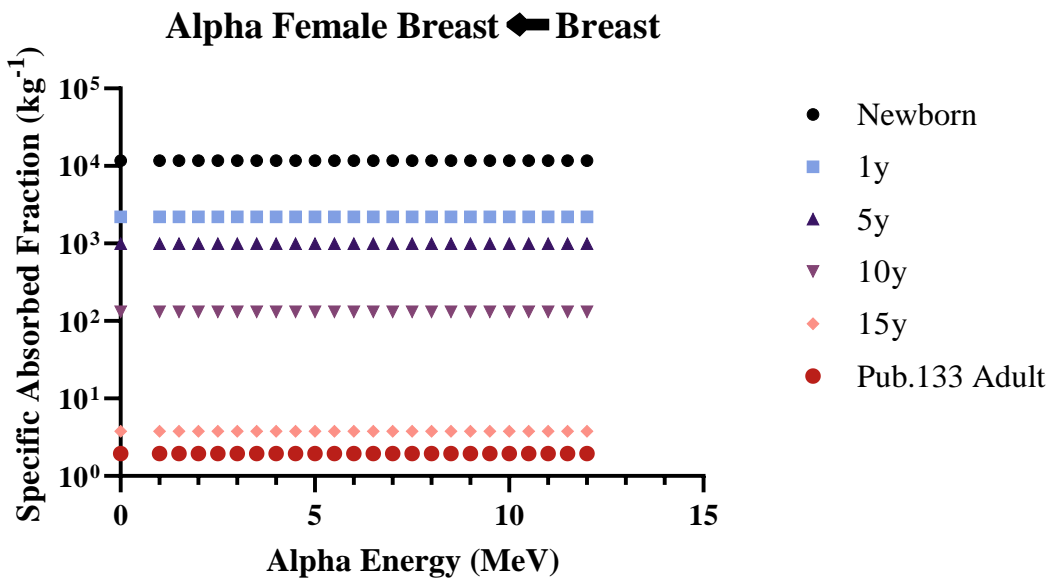
1386
1387   Fig. 5.4. Breast self-irradiation SAFs for alpha particles in each reference female.
1388
1389
1390

Electron Male Right Colon Stem ⬅ Wall
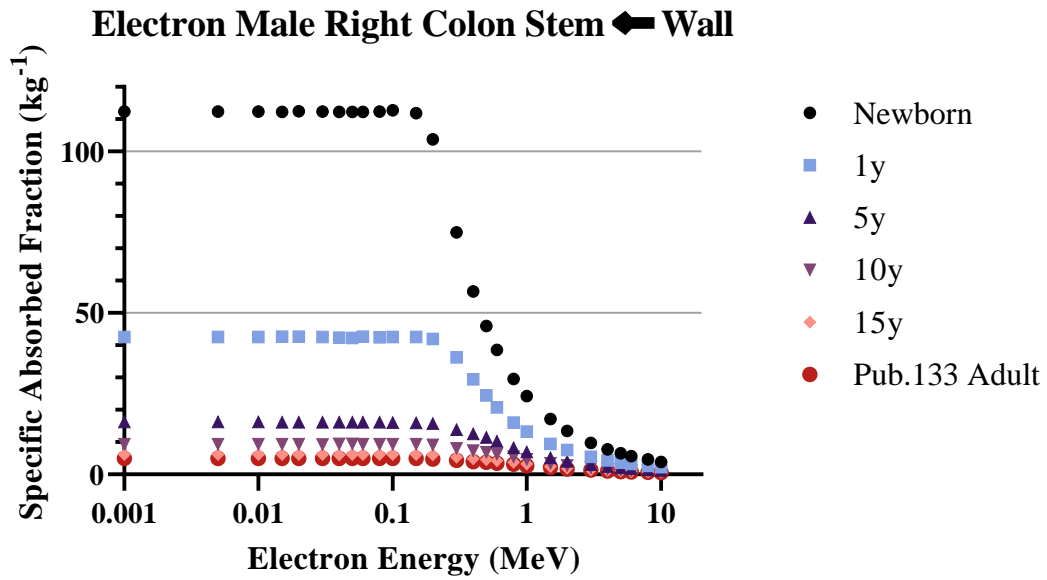
1391
1392 Fig. 5.5. Electron self-irradiation SAFs for the right colon stem cell target irradiated from the
1393 right colon wall in each reference male.
1394

Photon Female Skin ⬅ Skin
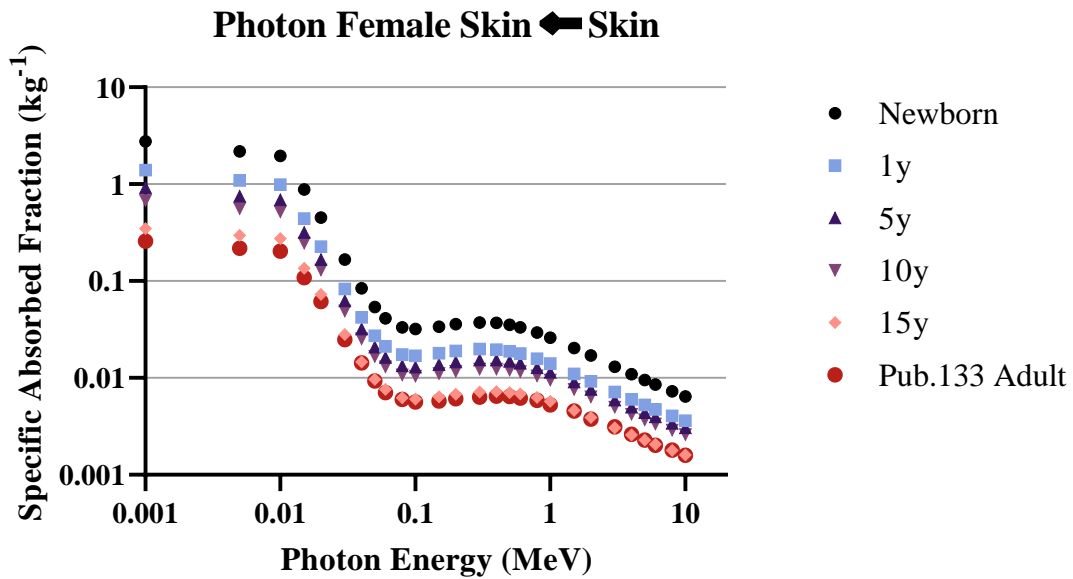
1395
1396 Fig. 5.6. Skin self-irradiation SAFs for photons in each reference female.
1397
1398
1399

1412   increases the trabecular bone volume source is the first of the bone sources to depart from zero due
1413   to the smaller size of trabecular bone and being surrounded by marrow. Cortical bone is generally
1414   thicker and has marrow located on only the interior side of the source region. Finally, as electron
1415   energy continues to increase the expected convergence of the SAFs is observed. At high energies
1416   (long ranges) the medium of origin of the electron becomes irrelevant.
1417   (145) Figure 5.10 displays SAFs in the 15y female bone endosteum target for electrons emitted
1418   from varying skeletal source regions. Since the trabecular bone surface is adjacent to the bone
1419   endosteum emissions from that surface produce the highest SAF at low energies. The marrow
1420   source regions give non-zero low energy SAFs since the bone endosteum target consists of marrow
1421   space adjacent to the surface. Similar trends as those described in the previous paragraph are
1422   observed for intermediate and high energy electrons.
1423
1424

Electrons in Newborn, Target = Red Marrow
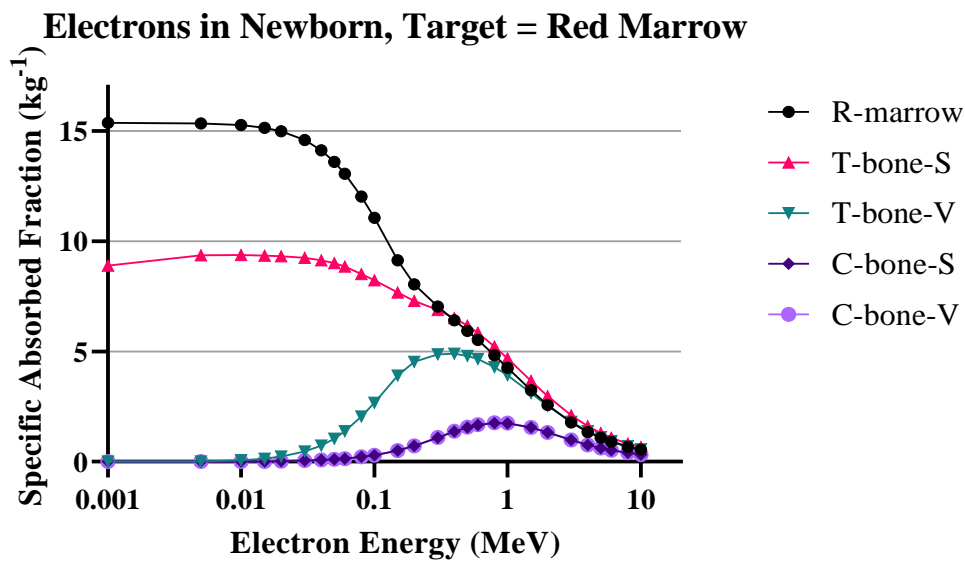
1425
1426
1427   Fig. 5.9. Newborn SAFs for electrons emitted from various skeletal source regions irradiating the
1428   red marrow.
1429
1430

Electrons in 15y Female, Target = Endost-BS
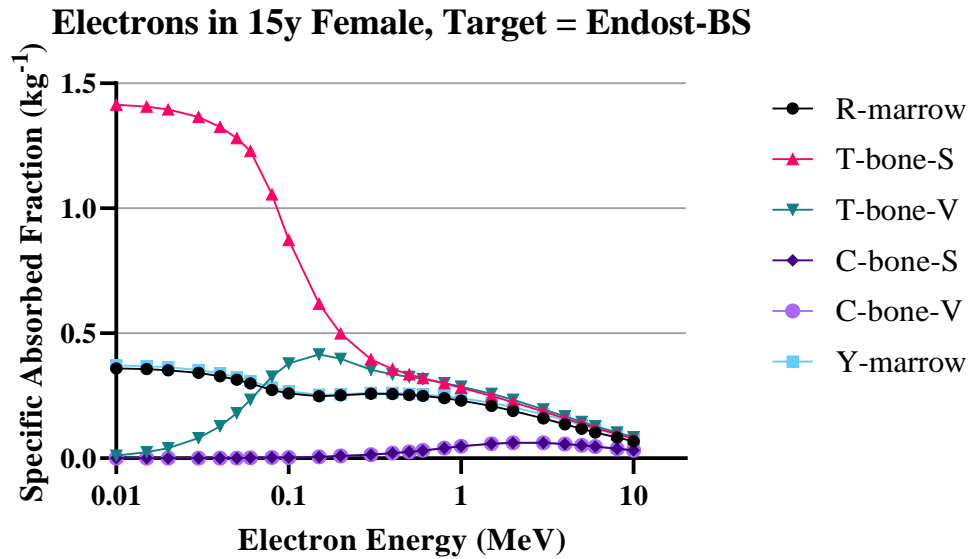
1431
1432 Fig. 5.10. 15-year female SAFs for electrons emitted from various skeletal source regions
1433 irradiating the bone endosteum.
1434
1435   (146) Figure 5.11 is a plot of SAFs for electrons emitted from various small intestine source
1436 regions irradiating the 10y male small intestine stem cell target. The stem cell target layer is
1437 contained within the mucosa and the mucosa is enveloped by the wall. The expected non-zero SAF
1438 is observed for both geometries with the mucosa source producing a larger SAF owing to its
1439 smaller size compared to the wall. Since the villi are closer in proximity to the stem cell target than
1440 the contents, the SAF increases away from zero at a lower electron energy for emissions from the
1441 villi. Finally, as with the skeletal geometries at high energies the SAFs converge as the location of
1442 the emission becomes less important.
1443   (147) Figure 5.12 is a plot of SAFs for electrons emitted from lung source regions irradiating
1444 the bronchiole secretory cell target. Source material bound in the bronchiolar epithelium (Brchiole-
1445 b) overlaps with the target region and therefore has a non-zero low energy SAF. The surface
1446 transport region (Brchiole) is the next closest source region to the target followed closely by
1447 material sequestered in the lamina propria (Brchiole-q) so the SAF for electrons emitted from those
1448 two regions rise away from zero at similar energies. The alveolar source region is further away,
1449 but in still close proximity to the bronchiole target tissue. Similar to the other geometries discussed
1450 in this section, at high energies the SAFs converge.
1451
1452

Electrons in 10y Male, Target = SI-stem
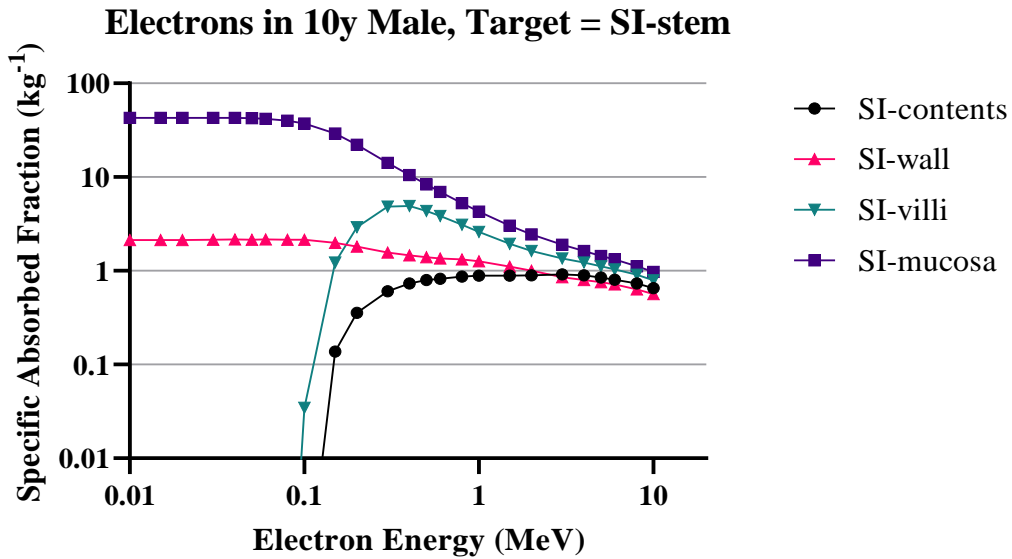
1453
1454 Fig. 5.11. 10-year male SAFs for electrons emitted from various small intestine source regions
1455 irradiating the small intestine stem cell target.
1456
1457

Electrons in 5y Female, Target = Brchiole-sec
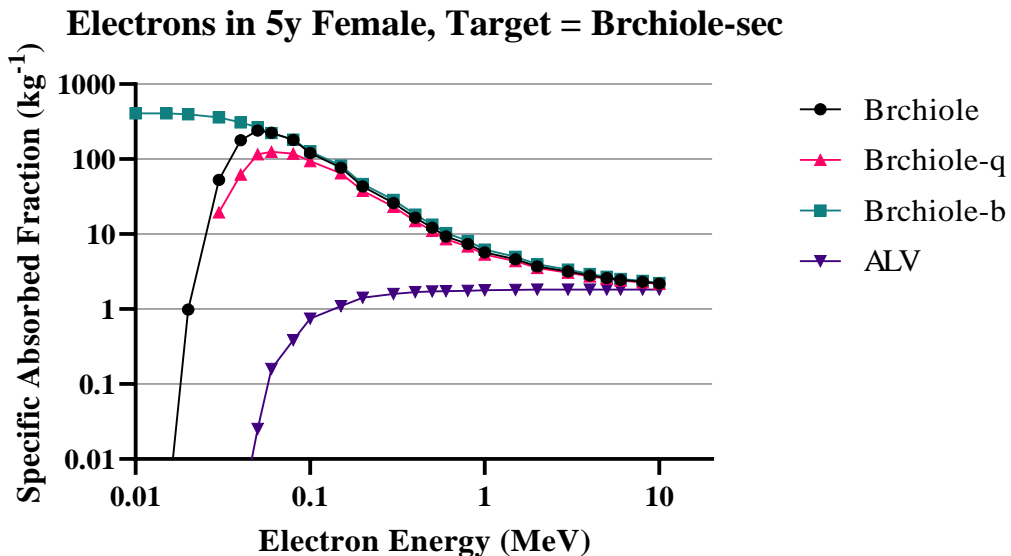
1458
1459 Fig. 5.12. 5-year female SAFs for electrons emitted from various lung source regions irradiating
1460 the bronchiolar secretory cell target.
1461

1462 **5.4. Plots of example SAFs**

1463 (148) The plots in this section contain additional examples of SAFs plotted for all reference
1464 ages. Figures 5.13 through 5.16 are examples of alpha particle SAFs, all of which result from

1465   absorbed fractions of unity which are independent of alpha energy. Differences, therefore, are
1466   solely the result of differences in target masses.
1467

Alpha F Liver ⬅ Liver
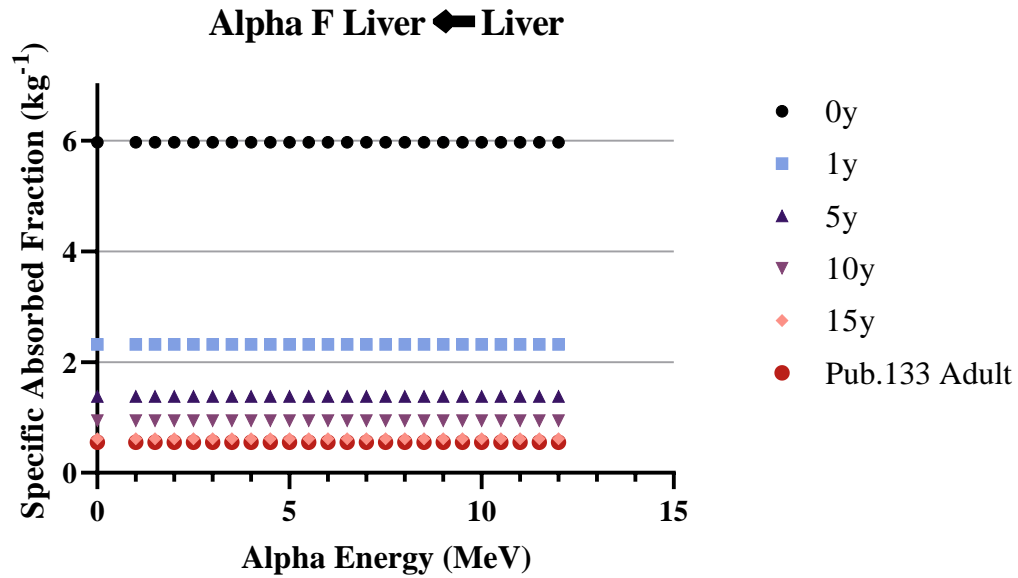
1468
1469   Fig. 5.13. Liver self-irradiation alpha particle SAFs in the reference females.
1470
1471

Alpha M R-marrow ⬅ Blood
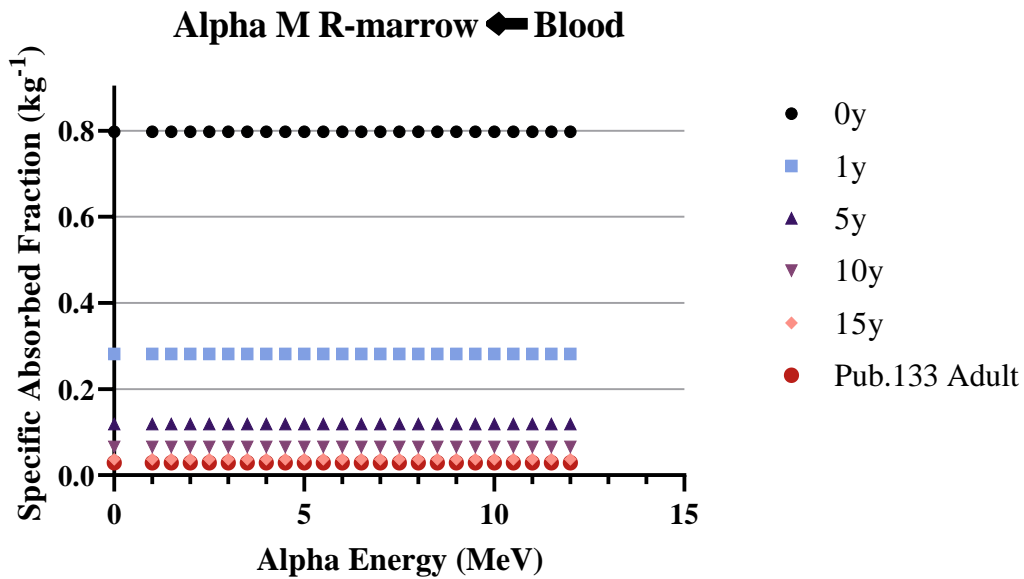
1472
1473   Fig. 5.14. Alpha particle SAFs to the red marrow for emissions from the blood in the reference
1474   males.
1475
1476
1477

Alpha F Thyroid ⬅ Thyroid
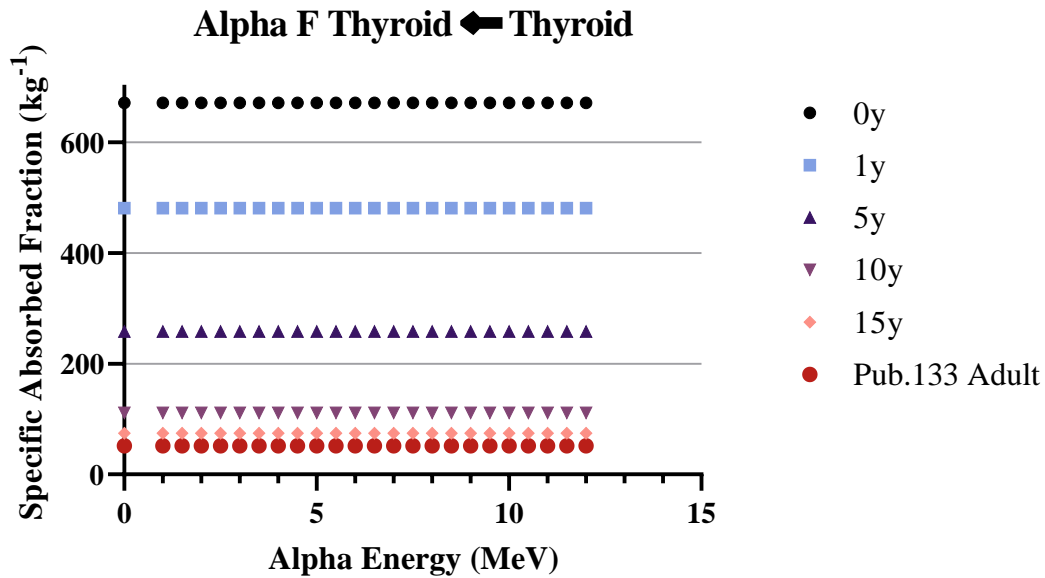
1478
1479 Fig. 5.15. Alpha particle SAFs for thyroid self-irradiation in the reference females.
1480

Alpha M S-glands ⬅ S-glands
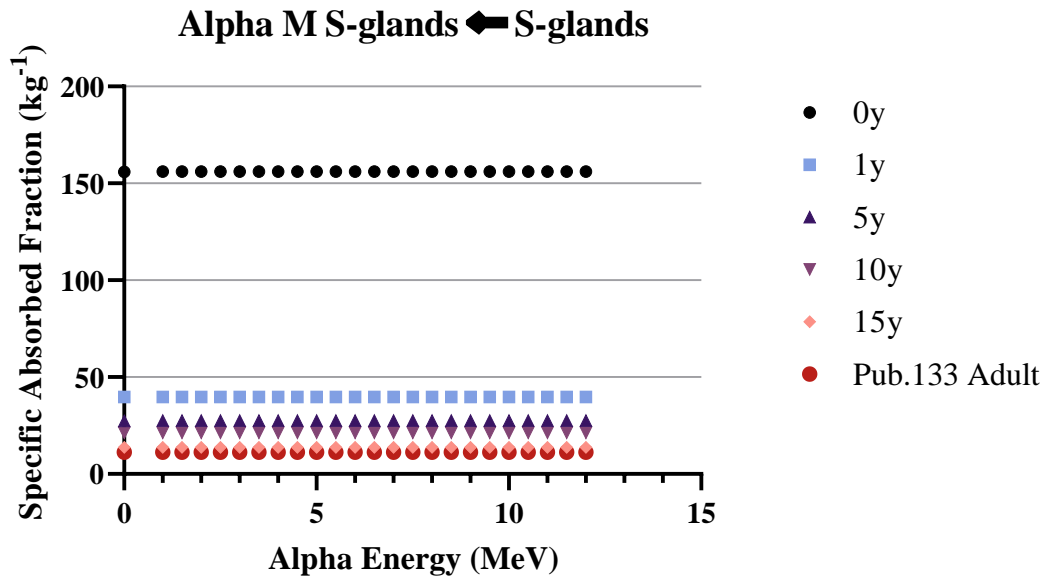
1481
1482 Fig. 5.16. Alpha particle SAFs for salivary glands self-irradiation in the reference males.
1483
1484   (149) Figures 5.17 through 5.20 are examples of electron SAFs. Figure 5.17 shows electron
1485 SAFs for self-irradiation of the female breast. Figure 5.18 has electron SAFs in the male for
1486 irradiation of the bronchi basal target from source bound in the bronchi epithelium. Figure 5.19
1487 shows the irradiation of the stomach stem cell target by electrons originating in the stomach
1488 contents.
1489   (150) Figure 5.20 contains SAFs for electrons emitted from the blood irradiating the AI target.
1490 The expected age dependency based on varying target mass is observed. At the highest electron
1491 energies, a surprising peak is seen in the newborn SAFs. Further exploration of the source SAFs

76

1492 reveals this is coming from the collisional component of the electron SAF and not the radiative
1493 component. The target in this case is the lung located somewhat centrally in the trunk of the body.
1494 The source is blood both within the lung (driving the SAF at low and moderate energies) but also
1495 blood in tissues neighbouring the lung. It is thought that the peak results from electrons from these
1496 neighbouring tissues (e.g. heart) being able to reach the lung target. This effect is observed in the
1497 newborn and not the older phantoms due to the smaller size and proximity of all organs in the
1498 newborn.
1499
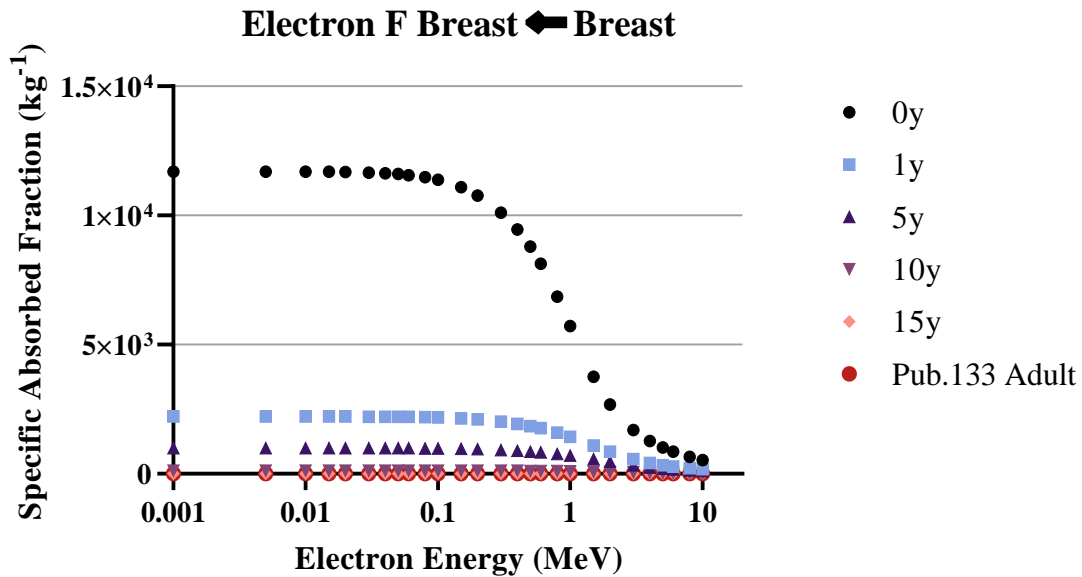
1500
1501 Fig. 5.17. Electron SAFs for breast self-irradiation in the reference females.
1502
1503
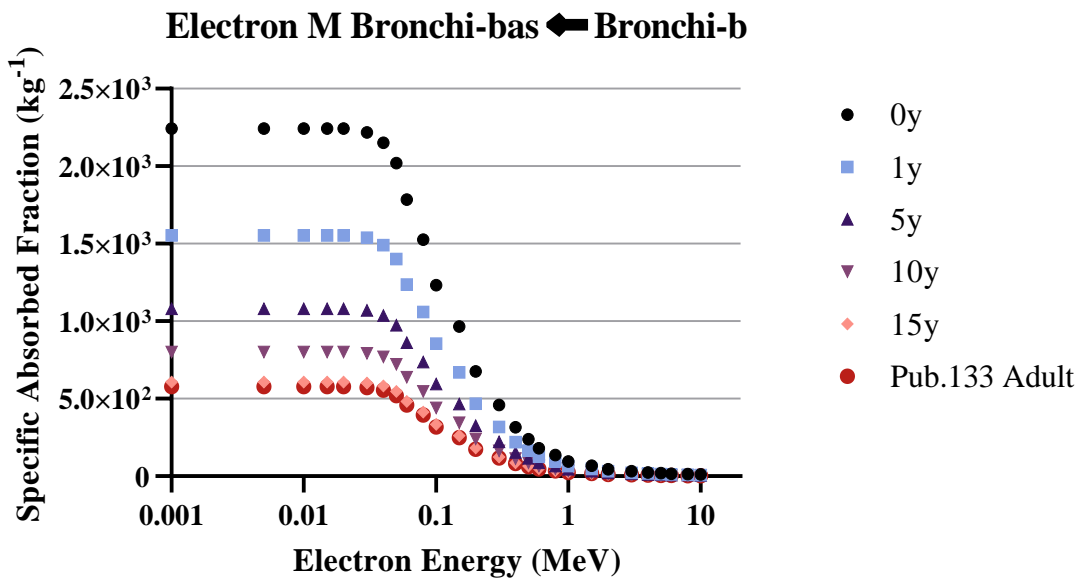
1504

1505 Fig. 5.18. Electron SAFs for emissions from the bound bronchi epithelium irradiating the bronchi
1506 basal layer in the reference males.
1507

Electron M St-stem ⬅ St-cont
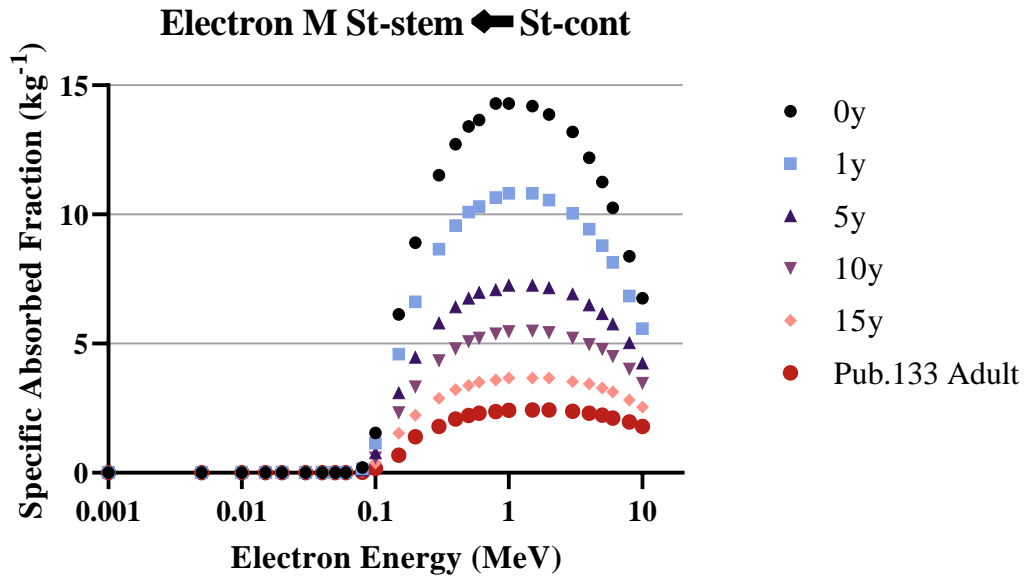
1508
1509 Fig. 5.19. Electron SAFs for emissions from the stomach contents irradiating the stomach stem
1510 cell layer in the reference males.
1511
1512

Electron F AI ⬅ Blood
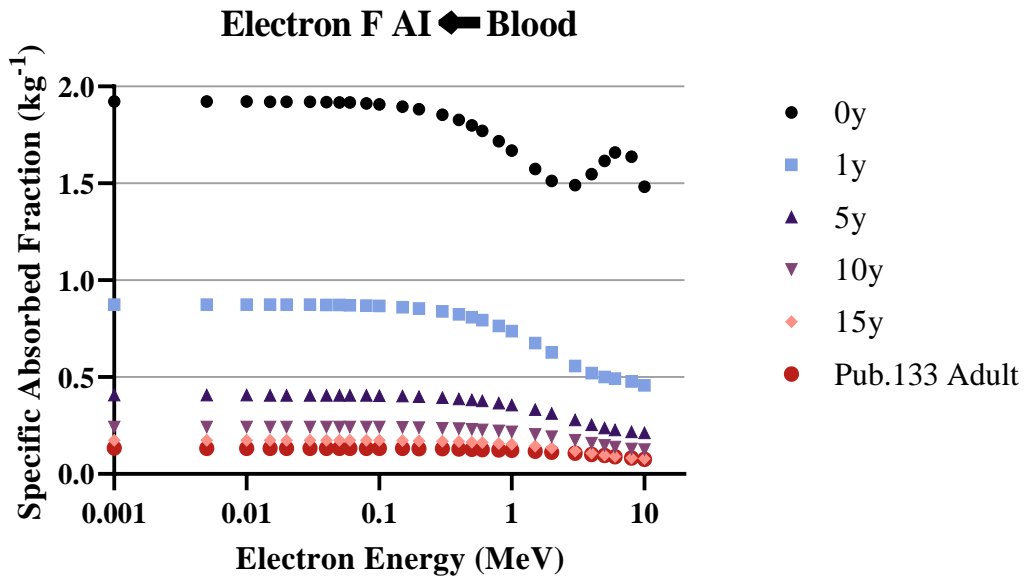
1513
1514 Fig. 5.20. Electron SAFs for emissions from the blood irradiating the alveolar interstitial target in
1515 the reference females.
1516
1517
1518

1519
1520
1521
1522   (151) Figures 5.21 through 5.24 are examples of photon SAFs. In all cases the expected age
1523   dependency is observed.
1524
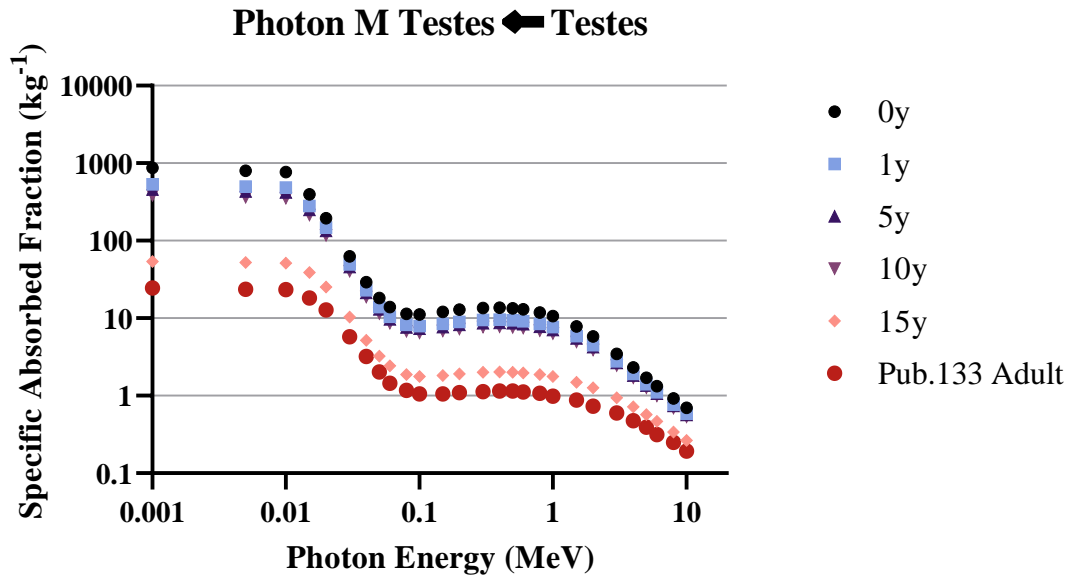
Photon M Testes ⬅ Testes

1525
1526   Fig. 5.21. Photon SAFs for testes self-irradiation in the reference males.
1527
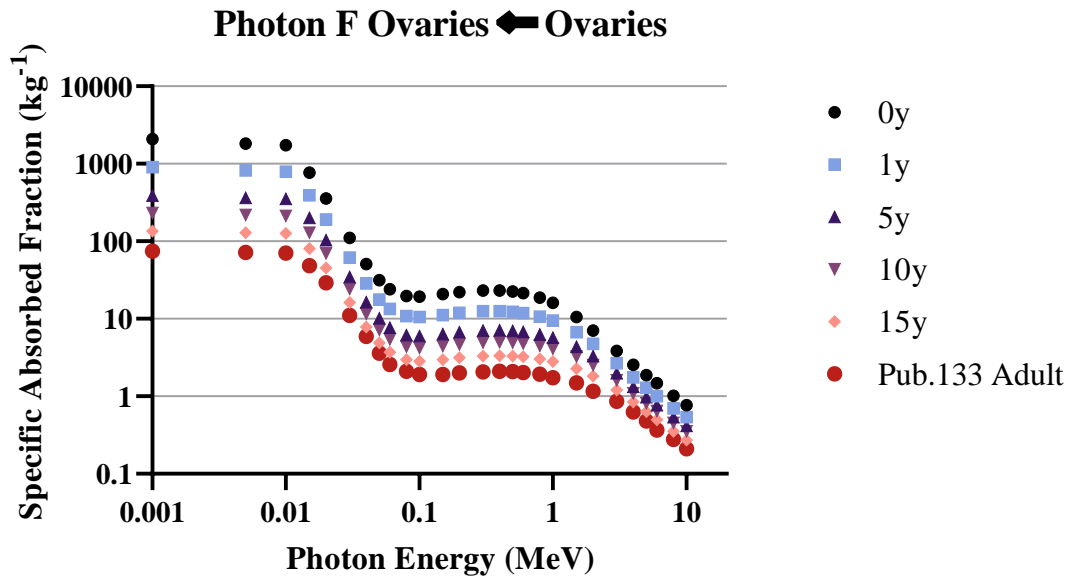
Photon F Ovaries ⬅ Ovaries

1528
1529   Fig. 5.22. Photon SAFs for ovaries self-irradiation in the reference females.
1530
1531
1532

Photon M UB-wall ⬅ UB-cont
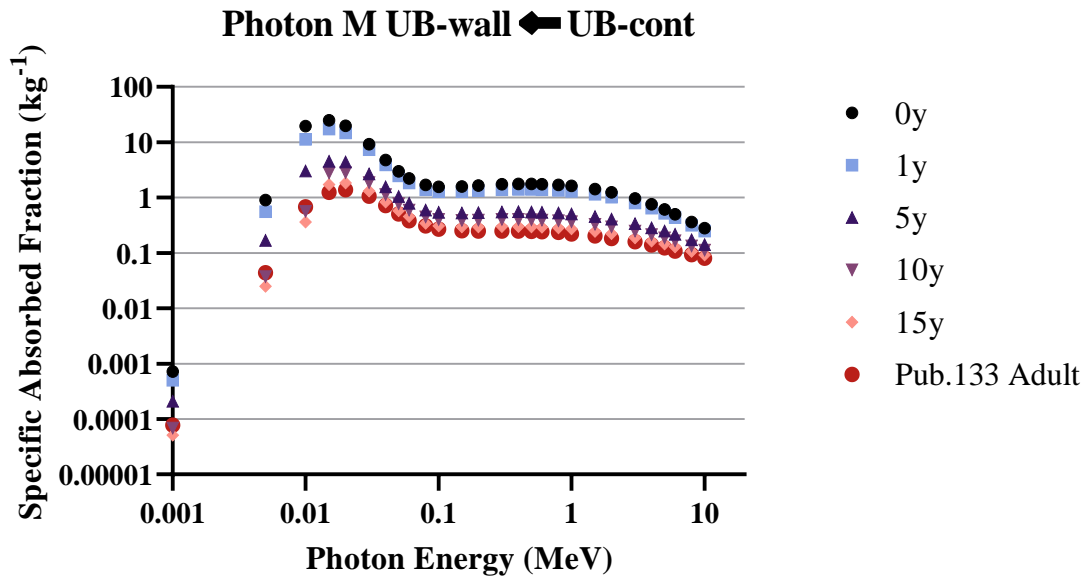
1533
1534 Fig. 5.23. Photon SAFs for emissions from the urinary bladder contents irradiating the urinary
1535 bladder wall in the reference males.
1536
1537

Photon F Oesophagus ⬅ Oesophag-s
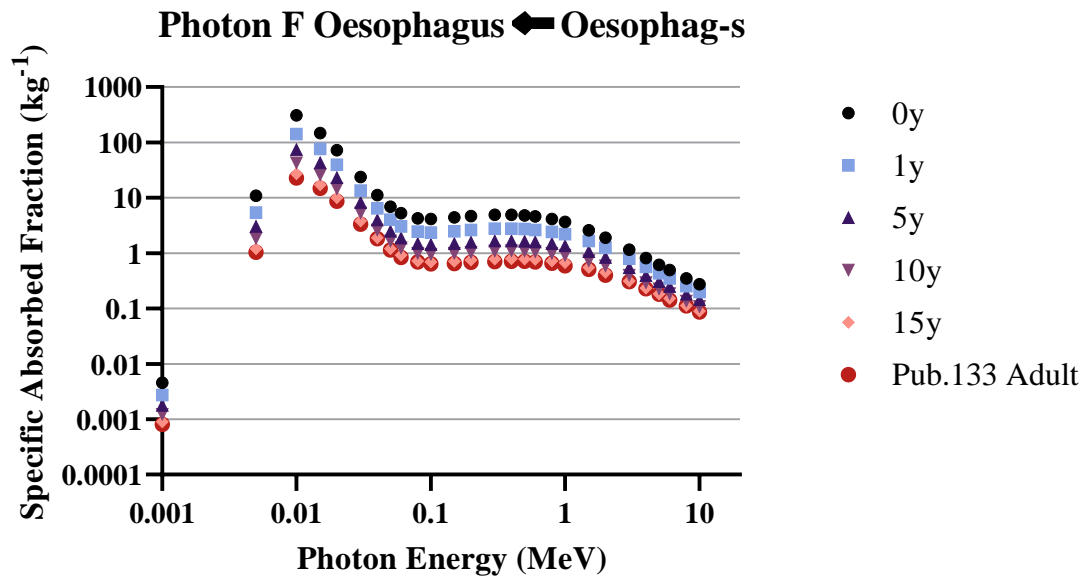
1538
1539 Fig. 5.24. Photon SAFs for emissions from the oesophagus contents irradiating the oesophagus
1540 stem cell target in the reference females.
1541
1542
1543
1544
1545
1546

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ANNEX A. DESCRIPTION OF ELECTRONIC FILES

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1722

1723 (A 1) Electronic files containing SAFs, source and target region masses, and skeletal photon
1724 dose response functions are available for download at www.icrp.org as a supplement to this
1725 publication. The SAF and mass files use the abbreviations provided in Tables 3.9 and 3.16.

1726 (A 2) The SAF filenames are provided in Table A.1. Source region masses for the female are
1727 found in Sregions_Female.ndx and for the male in Sregions_Male.ndx. Target region masses are
1728 found in Torgans_Female.ndx and Torgans_Male.ndx.

1729

1730 Table A.1. Filenames for specific absorbed fraction tables

Reference Individual	Photons	Electrons	Alpha particles	Neutrons
Newborn female	rcp-00F_photon.SAF	rcp-00F_electron.SAF	rcp-00F_alpha.SAF	rcp-00F_neutron.SAF
Newborn male	rcp-00M_photon.SAF	rcp-00M_electron.SAF	rcp-00M_alpha.SAF	rcp-00M_neutron.SAF
1y female	rcp-01F_photon.SAF	rcp-01F_electron.SAF	rcp-01F_alpha.SAF	rcp-01F_neutron.SAF
1y male	rcp-01M_photon.SAF	rcp-01M_electron.SAF	rcp-01M_alpha.SAF	rcp-01M_neutron.SAF
5y female	rcp-05F_photon.SAF	rcp-05F_electron.SAF	rcp-05F_alpha.SAF	rcp-05F_neutron.SAF
5y male	rcp-05M_photon.SAF	rcp-05M_electron.SAF	rcp-05M_alpha.SAF	rcp-05M_neutron.SAF
10y female	rcp-10F_photon.SAF	rcp-10F_electron.SAF	rcp-10F_alpha.SAF	rcp-10F_neutron.SAF
10y male	rcp-10M_photon.SAF	rcp-10M_electron.SAF	rcp-10M_alpha.SAF	rcp-10M_neutron.SAF
15y female	rcp-15F_photon.SAF	rcp-15F_electron.SAF	rcp-15F_alpha.SAF	rcp-15F_neutron.SAF
15y male	rcp-15M_photon.SAF	rcp-15M_electron.SAF	rcp-15M_alpha.SAF	rcp-15M_neutron.SAF
Adult female	rcp-af_photon.SAF	rcp-af_electron.SAF	rcp-af_alpha.SAF	rcp-af_neutron.SAF
Adult male	rcp-am_photon.SAF	rcp-am_electron.SAF	rcp-am_alpha.SAF	rcp-am_neutron.SAF

1731

1732 (A 3) Each of the SAF files has five header rows with the sixth row containing SAFs for the
1733 first described source/target geometry. Annex B of *Publication 133* details the manner of access
1734 to the files. There are a total of 43 target regions and 79 source regions resulting in 3,402 rows of
1735 SAFs in each file. Each row in the file contains 315 (photons and electrons) or 270 (alphas)
1736 characters. The difference in characters results from photon and electron SAFs being tabulated for
1737 28 energies while the alpha SAFs are tabulated for 24 energies. These energies appear in units of
1738 MeV in the fourth row of each file.

1739 (A 4) The last two columns in each SAF file contain the Ecutoff and ID. The Ecutoff value is
1740 the kinetic energy of the lowest energy radiation for that geometry which contains a non-zero value
1741 for the SAF. If all SAFs for that geometry are non-zero, the Ecutoff is zero. The ID is the index
1742 (integer location) of the Ecutoff value. If the Ecutoff for a particular geometry (row) was 0.010
1743 MeV, which is the fourth energy on the electron energy grid, the ID would be 4.

1744 (A 5) Neutron SAFs are structured differently since they are weighted for each radionuclide's
1745 spontaneous fission spectrum. The fourth row of each neutron SAF file contains the spectrum-
1746 weighted neutron radiation weighting factor which should be applied if computing equivalent and
1747 effective dose. Twenty-eight radionuclides are listed in each file and are: ^{238}U, ^{236}Pu, ^{238}Pu, ^{240}Pu,
1748 ^{242}Pu, ^{244}Pu, ^{240}Cm, ^{242}Cm, ^{244}Cm, ^{245}Cm, ^{246}Cm, ^{248}Cm, ^{250}Cm, ^{246}Cf, ^{248}Cf, ^{249}Cf, ^{250}Cf, ^{252}Cf,
1749 ^{254}Cf, ^{253}Es, ^{254}Es, ^{254m}Es, ^{255}Es, ^{252}Fm, ^{254}Fm, ^{255}Fm, ^{256}Fm, and ^{257}Fm.

1750 (A 6) The date of last revision to each SAF and mass file is listed on the far right of the first
1751 row. Note that dates may not be consistent across all files as revisions occur for some files without
1752 affecting other files.

1753   (A 7) The skeletal photon dose response functions have been described in sections 4.1.2 and
1754 4.4.4. They are provided and have a filename photon_drf.xls. Note that the dose response functions
1755 used in this work to compute photon SAFs were an earlier version (up to date at the time the SAFs
1756 were computed). The values of the skeletal photon dose response functions provided here have
1757 been recently revised and refined by the members of ICRP Task Group 113 in their work on
1758 reference dose coefficients for radiological imaging exams using the *Publication 110* adult and
1759 *Publication 143* paediatric reference voxel phantoms.
1760

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