A model for estimating radiation doses and population cancer risk in Sweden after the Chernobyl Nuclear Power Plant accident in 1986

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DOI: 10.33063/diva-544175
ISBN: 978-91-506-3083-1
January 20, 2025

Contents

1 Introduction

The accident at the Chernobyl Nuclear Power Plant (NPP) occurred on 26 April 1986 at 1.24 a.m (local time). A large amount of radioactive material was released into the atmosphere. The radioactive cloud reached Sweden on 27 April at 7 p.m. with a subsequent deposition on the ground during a heavy rainfall, mainly on the coastal area north of Stockholm, 28 to 29 April 1986. In this report we use only data from open sources from the population register at Statistics Sweden in combination with an updated method of organ absorbed dose assessment described by Tondel et al. (2023a). This method was applied in an epidemiological study using a closed cohort of the population living in the 9 most northern counties of Sweden by Tondel et al. (2023b). The current study is now extended to include the total annual Swedish population with future projections given by Statistics Sweden for the time period 1986 to 2036. The absorbed organ doses in this updated manual are calculated using the same method as described in the previous report (Tondel et al., 2023a). In addition, we have included calculations of Lifetime attributable risk (LAR) with a method proposed by Environmental Protection Agency (EPA, 2011) and also estimated effective dose and collective dose suggested by International Commission of Radiological Protection (ICRP, 2007). LAR has never been calculated in Sweden after the Chernobyl NPP accident and the most recent collective dose estimate is from Mattsson and Moberg (1991). It is now possible for more precise estimates of collective dose after extended aerial measurements on ^{137}Cs deposition and additional data from whole body counter measurements. The organ dose coefficients for both internal and external effective dose have previously been published by Rääf et al. (2020), but have now been updated by data from Isaksson et al. (2021) and ICRP (2020). To enable calculation of effective dose and LAR we have updated the package `absorbedDose` in the statistical software R (R Core Team, 2022) which is available for download from https://github.com/absorbedDose/absorbedDose.

2 Population

In this study we use the total annual Swedish population in the time period 1986–2036. For years 1986–2023 we have exact data from Statistics Sweden as of 2024, and the years 2024–2036 are based on the population forecast done by Statistics Sweden. For each year, there is a number of citizens in each municipality (290 municipalities) categorised by sex (male, female) and by age (0, 1, 2, ..., 99, 100+ years).

The data on the population statistics is downloaded on August 12, 2024 from the webpage of Statistics Sweden using the Application Programming Interface (API) with the R package `pxweb` (Magnusson et al., 2019). The data for the period 1985 – 2023 is extracted from the table "Population by region, marital status, age and sex. Year 1968 – 2023" (Statistics Sweden, 2024b). The data for population forecast is extracted from the table "Population by region, born in Sweden/foreign born, age and sex. Year 2024 – 2070" (Statistics Sweden, 2024a).

The number of citizens per county and sex is presented in Figure 1 and Figure 2.

Figure 1. Population in Sweden per sex and year.

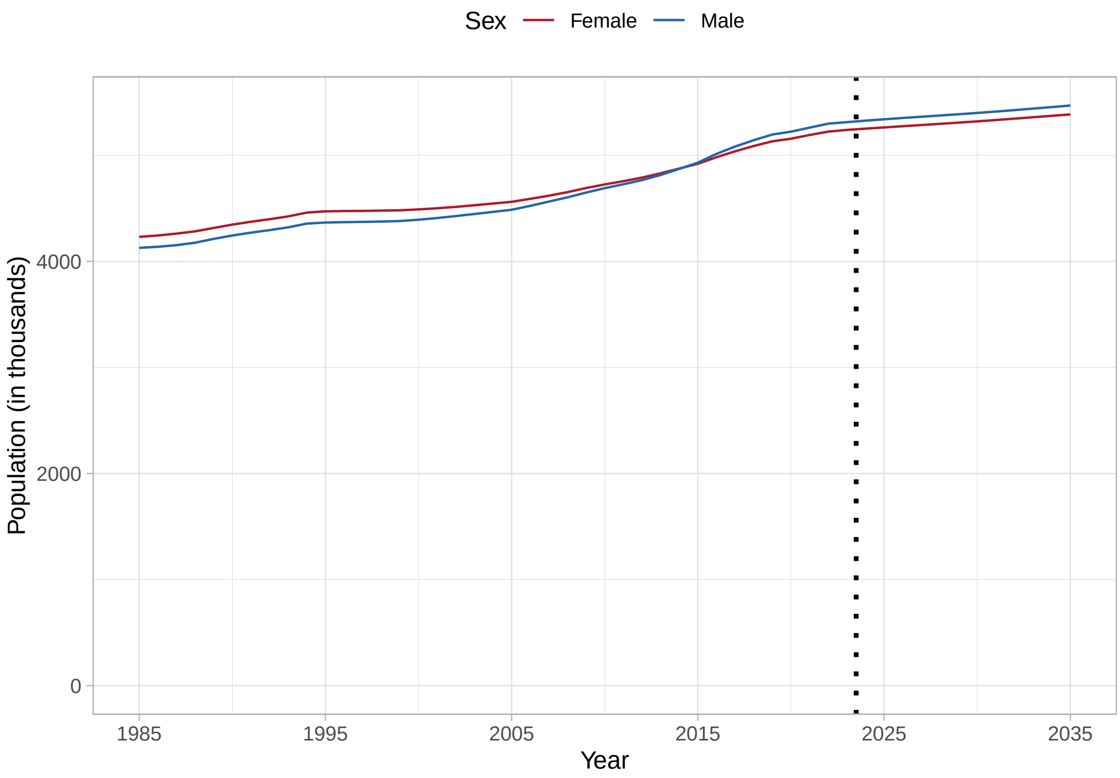
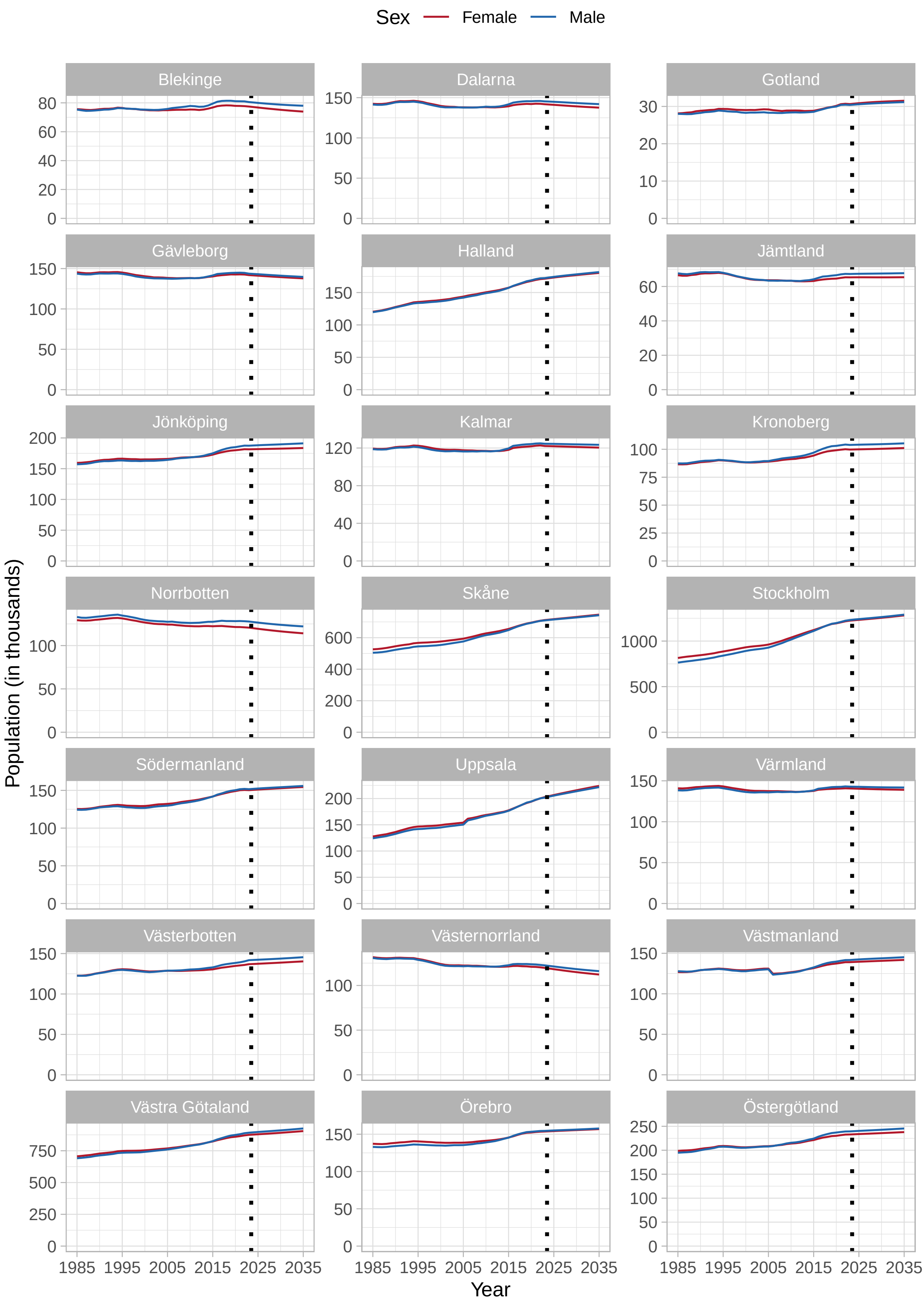


Figure 2. Population in each county per sex and year.



3 Proportion of hunter households

In the model estimating the organ absorbed dose, hunters and members of hunter households assume to have higher internal absorbed doses. The rationale for this categorization is that households (including females and children) with at least one family member who hunts tend to consume more game than other families, hence will regularly be exposed to a diet containing higher concentrations of ^{137}Cs (Ågren, 1998).

To approximate the number of hunters in the Swedish population, we use the number of male hunters in 1986. The number of male hunters per municipality in 9 counties were obtained from a register of licence holders of hunting weapons (Tondel et al., 2022) and the proportion of hunters in these municipalities was calculated. For the remaining 12 counties in Sweden, the proportion of male hunters was calculated as the number of male hunters living in these 12 counties divided by the total number of male population older than 18 in 1986 in these 12 counties. There were 55 678 hunters and 2 336 883 male adults, which gives 2.38% hunters.

The same hunter proportion is applied for male, female and children, for all age categories, and for every year in the calculations. The proportions per municipality are presented in Table 8.

4 A model for estimating the organ absorbed dose

The following model for calculating the organ absorbed dose is described in Tondel et al. (2023a). However, we repeat the equations in this section for ease of reading.

The following coefficients are changed comparing to the Tondel et al. (2023a).
External dose:

- A_{esd} for ^{137}Cs (kBq/m^2) was previously specific to the person's address, but now the value is per municipality ($A_{\text{esd,municip}}$).
- Values of $k_{\text{SEQ, organ,sex,ext}}$ and $k_{\text{organ,sex}}$ polynomial coefficients are updated because dose coefficients for external exposure is now retrieved from ICRP, 2020.
- Value of $f_{\text{shield,snow,county}}$ was changed for Blekinge county from 0.9 to 0.97.

Internal dose:

- Coefficients $\epsilon_{\text{Cs-137,organ,sex}}$ and $\epsilon_{\text{Cs-134,organ,sex}}$ for colon are updated since ICRP-weighting is used for the parts of the colon.

Inhalation absorbed dose from ^{131}I:

- Values of $E_{\text{inh,county}}$ were updated.

Cancer sites/tissues:

- The tables with coefficients per organ include only cancer sites/tissues contributing to the effective dose and those that have assigned LAR-coefficients.

4.1 Total absorbed dose

The exposure to the thyroid from the Chernobyl fallout is here described separately from the total absorbed dose to the other organs. The reason is that there are two additional exposure pathways to the thyroid compared with the other organs. The contribution to the absorbed dose to thyroid in time period t_i to t_{i+1}, $D_{\text{tot,Thyroid}}(t_i, t_{i+1})$, can be divided into four components,

$$\begin{aligned} D_{\text{tot,Thyroid}}(t_i, t_{i+1}) &= D_{\text{ext,Thyroid}}(t_i, t_{i+1}) + D_{\text{ing,Thyroid}}(t_i, t_{i+1}) \\ &\quad + D_{\text{milk,Thyroid}}(t_i, t_{i+1}) + D_{\text{inh,Thyroid}}(t_i, t_{i+1}), \end{aligned}$$

that is, the combined external exposure from ^{134}Cs, ^{137}Cs and short-lived nuclides on the ground ($D_{\text{ext,Thyroid}}$), the ingestion of ^{134}Cs, ^{137}Cs ($D_{\text{ing,Thyroid}}$), the ingestion of ^{131}I via milk ($D_{\text{milk,Thyroid}}$), and the inhalation of airborne ^{131}I ($D_{\text{inh,Thyroid}}$).

For the remaining organs, the absorbed dose in time period t_i to t_{i+1}, $D_{\text{tot,organ}}(t_i, t_{i+1})$, includes only the first two components above,

$$D_{\text{tot,organ}}(t_i, t_{i+1}) = D_{\text{ext,organ}}(t_i, t_{i+1}) + D_{\text{ing,organ}}(t_i, t_{i+1}).$$

The models for these two dose components are described in Subsection 4.2 and Subsection 4.3.

The internal dose to thyroid via ^{131}I in dairy milk ingestion and the inhalation dose from ^{131}I contribute to the total absorbed dose only in the first 50 days (0.14 year) after April 28, 1986. That is, these doses are 0 if the time period starts after June 17, 1986. The models for these dose components are described in Subsection 4.4 and Subsection 4.5.

4.2 External absorbed dose

The dose from external gamma radiation exposure of a specific organ can be estimated as

$$D_{\text{ext,organ}}(t_i, t_{i+1}) = A_{\text{esd,municip}} \cdot d_{\text{Cs}} \cdot \phi_{\text{Kerma/H}} \cdot f_{\text{shield,snow,county}} \cdot k_{\text{SEQ, organ,sex,ext}} \cdot (f_{\text{out}} + (1 - f_{\text{out}}) \cdot f_{\text{shield,municip}}) \cdot \int_{t_i}^{t_{i+1}} k_{\text{organ,sex}}(\text{age}(t)) \cdot r(t)\ \text{d}t,$$

with the parameters as in Table 1.

For adults (age $\geq$ 20) $k_{\text{organ,sex}}(\text{age}(t))$ is a constant and the integral can be calculated as follows

$$\begin{aligned}\int_{t_i}^{t_{i+1}} & k_{\text{organ,sex}}(\text{age}(t)) \cdot r(t)\ \text{d}t \\ &= \int_{t_i}^{t_{i+1}} k_{\text{organ,sex}}(\text{age}(t)) \cdot \left(0.96e^{-36.89t} + 0.10823e^{-2.447t} + 0.0796e^{-0.6684t} + 0.0314e^{-0.125646t}\right)\ \text{d}t \\ &= k_{\text{organ,sex}}(\text{adult}) \left(-\frac{0.96}{36.89}e^{-36.89t} - \frac{0.10823}{2.447}e^{-2.447t} - \frac{0.0796}{0.6684}e^{-0.6684t} - \frac{0.0314}{0.125646}e^{-0.125646t}\right)\Bigg|_{t_i}^{t_{i+1}}.\end{aligned}$$

When age < 20, the function $k_{\text{organ,sex}}(\text{age}(t))$ is a 2$^{\text{nd}}$ or 3$^{\text{rd}}$ degree polynomial, depending on organ (See Table 9 and 10 for coefficient values). In this case, the integral above can also be calculated explicitly but the expression is not presented here for brevity.

Table 1. Parameters used in the model for the external dose.

Parameter	Unit	Value
$A_{\text{esd,municip}}$	kBq/m^2	^{137}Cs, see Table 8
d_{Cs}	(mSv/y)/(kBq/m^2)	1.016856
$\phi_{\text{Kerma/H}}$	mGy/mSv	0.83 (The ratio between air kerma and ambient dose equivalent for 600 keV photons taken from Portal et al. (1992).)
$f_{\text{shield,snow,county}}$	—	see Table 7
$k_{\text{SEQ, organ,sex,ext}}$	—	see Table 9 and 10
f_{out}	—	0.2
$f_{\text{shield,municip}}$	—	see Table 8
$k_{\text{organ,sex}}(\text{age}(t))$	—	1 for age(t_i) $\geq$ 20 polynomial of the form $a_0+a_1\cdot\text{age}+a_2\cdot\text{age}^2+a_3\cdot\text{age}^3$ for age(t_i) < 20, coefficients depend on the sex and organ (see Table 9 and 10 for coefficients, Subsection A.2.1 for figures)
$r(t)$	—	$0.96e^{-36.89t} + 0.10823e^{-2.447t} + 0.0796e^{-0.6684t} + 0.0314e^{-0.125646t}$

4.3 Internal absorbed dose

The internal dose from the ingestion component of a specific organ is estimated as

$$
\begin{aligned}
D_{\text{ing,organ}}(t_i, t_{i+1}) = {} & A_{\text{esd,county}} \cdot T_{\text{ag,max,Cs}} \cdot S_{\text{aliment}} \cdot \int_{t_i}^{t_{i+1}} \left(1 - e^{\frac{-\ln(2)}{t_1} t}\right) \cdot \left(c_1 \cdot e^{\frac{-\ln(2)}{t_2} t} + c_2 \cdot e^{\frac{-\ln(2)}{t_3} t}\right) \\
& \cdot f_{\text{sex}}(\text{age}(t)) \cdot \left(\epsilon_{\text{Cs-137,organ,sex}} \cdot w_{\text{sex}}(\text{age}(t)) \cdot \left(\frac{w_{\text{sex}}(\text{age}(t))}{w_{\text{adult,sex}}}\right)^{-0.889}\right. \\
& \left. + FR \cdot \epsilon_{\text{Cs-134,organ,sex}} \cdot w_{\text{sex}}(\text{age}(t)) \cdot \left(\frac{w_{\text{sex}}(\text{age}(t))}{w_{\text{adult,sex}}}\right)^{-0.812} \cdot e^{-\left(\frac{\ln(2)}{T_{\frac{1}{2}\text{Cs-134}}} - \frac{\ln(2)}{T_{\frac{1}{2}\text{Cs-137}}}\right) t}\right) \mathrm{d}t \\
\approx {} & A_{\text{esd,county}} \cdot T_{\text{ag,max,Cs}} \cdot S_{\text{aliment}} \cdot f_{\text{sex}}\left(\text{age}\left(\frac{t_i + t_{i+1}}{2}\right)\right) \\
& \cdot \left(\epsilon_{\text{Cs-137,organ,sex}} \cdot w_{\text{adult,sex}}^{0.889} \cdot w_{\text{sex}}\left(\text{age}\left(\frac{t_i + t_{i+1}}{2}\right)\right)^{0.111}\right. \\
& \cdot \int_{t_i}^{t_{i+1}} \left(1 - e^{\frac{-\ln(2)}{t_1} t}\right) \cdot \left(c_1 \cdot e^{\frac{-\ln(2)}{t_2} t} + c_2 \cdot e^{\frac{-\ln(2)}{t_3} t}\right) \mathrm{d}t \\
& + FR \cdot \epsilon_{\text{Cs-134,organ,sex}} \cdot w_{\text{adult,sex}}^{0.812} \cdot w_{\text{sex}}\left(\text{age}\left(\frac{t_i + t_{i+1}}{2}\right)\right)^{0.188} \\
& \left. \cdot \int_{t_i}^{t_{i+1}} \left(1 - e^{\frac{-\ln(2)}{t_1} t}\right) \cdot \left(c_1 \cdot e^{\frac{-\ln(2)}{t_2} t} + c_2 \cdot e^{\frac{-\ln(2)}{t_3} t}\right) \cdot e^{-\left(\frac{\ln(2)}{T_{\frac{1}{2}\text{Cs-134}}} - \frac{\ln(2)}{T_{\frac{1}{2}\text{Cs-137}}}\right) t} \mathrm{d}t\right).
\end{aligned}
$$

The last two integrals above can be rewritten in the same form and calculated as

$$
\int_{t_i}^{t_{i+1}} a_1 \cdot e^{b_1 t} + a_2 \cdot e^{b_2 t} - a_3 \cdot e^{b_3 t} - a_4 \cdot e^{b_4 t} \, \mathrm{d}t = \left(\frac{a_1}{b_1} \cdot e^{b_1 t} + \frac{a_2}{b_2} \cdot e^{b_2 t} - \frac{a_3}{b_3} \cdot e^{b_3 t} - \frac{a_4}{b_4} \cdot e^{b_4 t}\right) \Bigg|_{t_i}^{t_{i+1}}.
$$

The coefficients of the integrals are listed in Table 2.

The description of parameters used to calculate the internal dose is given in Table 3.

The functions $\left(\frac{w_{\text{sex}}(\text{age}(t))}{w_{\text{adult,sex}}}\right)^{-0.889}$ and $\left(\frac{w_{\text{sex}}(\text{age}(t))}{w_{\text{adult,sex}}}\right)^{-0.812}$ are introduced here to accommodate the decreasing organ specific internal dose coefficients for children with their smaller body size, since for a given body concentration a larger fraction of the emitted gamma radiation will escape the organs of a smaller body. These functions are needed because the dose coefficients from Isaksson et al. (2021), $\epsilon_{\text{Cs-137,organ,sex}}$ and $\epsilon_{\text{Cs-134,organ,sex}}$, only refer to adult males and females. The functions are derived from a mathematical fit presented by Falk et al. (1991).

Table 2. Coefficients in the remaining integrals for the ^{137}Cs and ^{134}Cs contributions. The half-life for ^{137}Cs appears in the coefficient for ^{134}Cs since the change of the isotopic ratio, FR, with time is affected by the half-life of both isotopes. See Table 3 for values of c_1, c_2, t_1, t_2, t_3, $T_{\frac{1}{2}\text{Cs}-134}$, $T_{\frac{1}{2}\text{Cs}-137}$.

Coefficient	^{137}Cs	^{134}Cs	Unit
a_1	c_1	c_1	—
b_1	$-\frac{\ln(2)}{t_2}$	$-\left(\frac{\ln(2)}{t_2} + \frac{\ln(2)}{T_{\frac{1}{2}\text{Cs}-134}} - \frac{\ln(2)}{T_{\frac{1}{2}\text{Cs}-137}}\right)$	y^{-1}
a_2	c_2	c_2	—
b_2	$-\frac{\ln(2)}{t_3}$	$-\left(\frac{\ln(2)}{t_3} + \frac{\ln(2)}{T_{\frac{1}{2}\text{Cs}-134}} - \frac{\ln(2)}{T_{\frac{1}{2}\text{Cs}-137}}\right)$	y^{-1}
a_3	c_1	c_1	—
b_3	$-\left(\frac{\ln(2)}{t_1} + \frac{\ln(2)}{t_2}\right)$	$-\left(\frac{\ln(2)}{t_1} + \frac{\ln(2)}{t_2} + \frac{\ln(2)}{T_{\frac{1}{2}\text{Cs}-134}} - \frac{\ln(2)}{T_{\frac{1}{2}\text{Cs}-137}}\right)$	y^{-1}
a_4	c_2	c_2	—
b_4	$-\left(\frac{\ln(2)}{t_1} + \frac{\ln(2)}{t_3}\right)$	$-\left(\frac{\ln(2)}{t_1} + \frac{\ln(2)}{t_3} + \frac{\ln(2)}{T_{\frac{1}{2}\text{Cs}-134}} - \frac{\ln(2)}{T_{\frac{1}{2}\text{Cs}-137}}\right)$	y^{-1}

Table 3. Parameters used in the model for the internal dose from the ingestion.

Parameter	Unit	Value
$A_{\text{esd,county}}$	kBq/m^2	^{137}Cs, see Table 7
$T_{\text{ag,max,Cs}}$	$(\text{Bq/kg})/(\text{kBq/m}^2)$	11 for non-hunter household 29.3 for hunter households
S_{aliment}	—	1 (a factor describing the effects of countermeasures to reduce the transfer to humans of radionuclides through foodstuff. In Sweden 1.0 after Chernobyl.)
t_1	y	1 for non-hunter household 1.1 for hunter households
c_1	—	1 for non-hunter household 0.9 for hunter households
t_2	y	0.75 for non-hunter household 1.2 for hunter households
c_2	—	0.1 for non-hunter household 0.11 for hunter households
t_3	y	15 for non-hunter household 30 for hunter households
$f_{\text{sex}}(\text{age}(t))$	—	0.61 for women ($\text{age}(t) \geq 20$), 1 for men ($\text{age}(t) \geq 20$) and children ($\text{age}(t) < 20$)
$\epsilon_{\text{Cs-137,organ,sex}}$	mGy/(Bq y)	see Table 11 for coefficients in Gy/(Bq s), multiplied by $3600 \cdot 24 \cdot 365.25 \cdot 1000$ to convert to mGy/(Bq y)
$\epsilon_{\text{Cs-134,organ,sex}}$	mGy/(Bq y)	see Table 11 for coefficients in Gy/(Bq s), multiplied by $3600 \cdot 24 \cdot 365.25 \cdot 1000$ to convert to mGy/(Bq y)
FR	—	0.56
$w_{\text{adult,sex}}$	kg	78 for men, 63 for women
$w_{\text{sex}}(\text{age}(t))$	kg	78 for men ($\text{age}(t) \geq 20$), 63 for women ($\text{age}(t) \geq 20$), $-0.0000021 \cdot \text{age}^6 + 0.0002623 \cdot \text{age}^5 - 0.011799 \cdot \text{age}^4 + 0.2305 \cdot \text{age}^3 - 1.8759 \cdot \text{age}^2 + 8.0766 \cdot \text{age} + 3.8872$ for male children ($\text{age}(t) < 20$), $-0.0000057 \cdot \text{age}^6 + 0.000552 \cdot \text{age}^5 - 0.0199 \cdot \text{age}^4 + 0.3191 \cdot \text{age}^3 - 2.1579 \cdot \text{age}^2 + 7.4423 \cdot \text{age} + 3.9529$ for female children ($\text{age}(t) < 20$) (see Figure A.2.2)
$T_{\frac{1}{2}\text{Cs-134}}$	y	2.06
$T_{\frac{1}{2}\text{Cs-137}}$	y	30.2

4.4 Internal absorbed dose via ^{131}I in dairy milk

The internal dose via ^{131}I in dairy milk ingestion, during the first 50 days after the accident, is calculated only for the organ thyroid. For the other organs the absorbed dose from ^{131}I is assumed to be 0.

The absorbed dose to the thyroid from the intake of dairy milk is estimated as

$$D_{\text{milk,Thyroid}}(0, 0.14) = c_{\text{milk,county}} \cdot k_{\text{delay}} \cdot a\left(\text{age}(0.07)\right) \cdot d_{\text{ing}}\left(\text{age}(0.07)\right),$$

with the parameters as in Table 4.

Table 4. Parameters used in the model for the internal dose from ^{131}I via dairy milk ingestion.

Parameter	Unit	Value
$c_{\text{milk,county}}$	Bq d/kg	time-integrated ^{131}I activity concentration in milk, see Table 7
k_{delay}	—	0.74, accounts for the decay of ^{131}I between reported concentrations in dairy milk and the time when consumers ingest the fresh milk, assumed being about 3 days (Rääf et al., 2019)
age(0.07)	y	age at 25 days (0.07 years)
$a(\text{age}(t))$	kg/d	$0.75 \cdot 0.3 = 0.225$ when $\text{age}(t) < 1$, $0.00002 \cdot \text{age}^3 - 0.0017 \cdot \text{age}^2 + 0.04 \cdot \text{age} + 0.102$ when $1 \leq \text{age}(t) < 20$, 0.41 when $\text{age}(t) \geq 20$
$d_{\text{ing}}(\text{age}(t))$	mGy/Bq	$(4.0459 - 0.718272 \cdot \text{age} + 0.072904 \cdot \text{age}^2 - 0.00441 \cdot \text{age}^3 + 0.0001524 \cdot \text{age}^4 - 0.000002717 \cdot \text{age}^5 + 1.93 \cdot 10^{-8} \cdot \text{age}^6)/1000$ when $\text{age}(t) < 20$, 0.00043 when $\text{age}(t) \geq 20$ (no sex difference assumed)

4.5 Inhalation absorbed dose from ^{131}I

The inhalation dose from ^{131}I, during the first 50 days after the accident, is calculated only for the organ thyroid. For the other organs the absorbed dose from ^{131}I is assumed to be 0.

The absorbed dose to thyroid from the inhalation is estimated as

$$D_{\text{inh,Thyroid}}(0, 0.14) = E_{\text{inh,county}} \cdot F\left(\text{age}(0.07)\right) \cdot k_{\text{thy/E}} \cdot 10^{-3},$$

with parameters as in Table 5.

Table 5. Parameters used in the model for the inhalation dose.

Parameter	Unit	Value
$E_{\text{inh,county}}$	μSv	see Table 7
age(0.07)	y	age at 25 days (0.07 years)
$F(\text{age}(t))$	—	$1.7245 + 0.7869 \cdot \text{age} - 0.1976 \cdot \text{age}^2 + 0.02309 \cdot \text{age}^3 - 0.0015207 \cdot \text{age}^4 + 0.0000521 \cdot \text{age}^5 - 0.0000007097 \cdot \text{age}^6$ when $\text{age}(t) < 20$, 1 when $\text{age}(t) \geq 20$
$k_{\text{thy/E}}$	mGy/mSv	20

5 Organ absorbed dose to the Swedish population

For each year, we had the population registered in Sweden on December 31 that year. We assumed that this population is valid between July 01 that year and June 30 next year.

We calculated the absorbed dose between April 28, 1986 and April 27, 2036, divided in by years in the following time periods: April 28, 1986 – June 30, 1986, thereafter between July 01 and June 30 next year for years from 1986 until 2035, and July 01, 2035 – April 27, 2036.

We first calculated the organ specific external, internal and total absorbed dose for one male and one female representative from each municipality, from each 1-year age category, and from hunter or non-hunter household. The equations used for calculating the absorbed dose is described in detail in Section 4.

Then the sex, age and organ specific dose from all considered exposure pathways was multiplied by the number of individuals in each population category for a given municipality, as follows:

$$D_{\text{pop,municip,age,M}}(t_i, t_{i+1}) = n_{\text{municip,age,M}} \cdot [(1 - p_{\text{municip,hunters}}) \cdot D_{\text{municip,age,M,non-hunter}}(t_i, t_{i+1}) + p_{\text{municip,hunters}} \cdot D_{\text{municip,age,M,hunter}}(t_i, t_{i+1})],$$

$$D_{\text{pop,municip,age,F}}(t_i, t_{i+1}) = n_{\text{municip,age,F}} \cdot [(1 - p_{\text{municip,hunters}}) \cdot D_{\text{municip,age,F,non-hunter}}(t_i, t_{i+1}) + p_{\text{municip,hunters}} \cdot D_{\text{municip,age F,hunter}}(t_i, t_{i+1})],$$

where n is the municipality population in the time period (t_i, t_{i+1}) of a 1-year age category and p is proportion of hunter households in the municipality (see Section 3 and Table 8). The population summed absorbed dose of specific organ of male Swedish population in all 290 municipalities for the time period was then calculated as

$$D_{\text{pop,Sweden,M}}(t_i, t_{i+1}) = \sum_{\text{municip}=1}^{290} \sum_{\text{age}=0}^{100} D_{\text{pop,municip,age,M}}(t_i, t_{i+1}),$$

and of female Swedish population as

$$D_{\text{pop,Sweden,F}}(t_i, t_{i+1}) = \sum_{\text{municip}=1}^{290} \sum_{\text{age}=0}^{100} D_{\text{pop,municip,age,F}}(t_i, t_{i+1}).$$

6 Lifetime attributable cancer risk (LAR)

LAR at a certain 1-year age group was obtained by multiplying the absorbed dose to a specific organ with the corresponding sex-specific LAR coefficient for cancer incidence in that organ and the age at the time of exposure. The LAR coefficients are presented in Table 12 and 13. LAR coefficients for age groups, not in the tables, were estimated with linear interpolation, as illustrated in the figures in Subsection A.4.2. In the calculations, we used the coefficients for the age in the middle of the time interval (t_i, t_{i+1}).

The estimated number of attributable cancer cases (AC) in a specific calendar year from the Chernobyl fallout for each municipality was calculated using the organ absorbed doses that year in each 1-year age category, the number of individuals in that municipality by age and the age- and cancer site-specific LAR:s. The cumulative number of AC to a specific cancer site in the Swedish population was obtained by summing the number of AC over all age categories and municipalities.

$$AC_{\text{Sweden,M}}(t_i, t_{i+1}) = \sum_{\text{municip}=1}^{290} \sum_{\text{age}=0}^{100} D_{\text{pop,municip,age,M}}(t_i, t_{i+1}) \cdot LAR_{\text{age,M}} \cdot 10^{-7},$$

and

$$AC_{\text{Sweden,F}}(t_i, t_{i+1}) = \sum_{\text{municip}=1}^{290} \sum_{\text{age}=0}^{100} D_{\text{pop,municip,age,F}}(t_i, t_{i+1}) \cdot LAR_{\text{age,F}} \cdot 10^{-7}.$$

The factor 10^{-7} converts number of cases per 10000 individuals per Gy organ specific absorbed dose into number of cancer cases induced per unit absorbed dose in mGy since LAR coefficient taken from EPA (2011) are expressed in the former unit (i.e. cases per 10000 person Gy).

7 Effective dose

Since the radiation weighting factor for beta and gamma radiation is unity, and all considered exposure pathways in this study only involves these two types of radiation, the effective dose E was calculated as:

$$E_{\text{tot}}(t_i, t_{i+1}) = \sum_{\text{all tissues}} w_T \cdot D_{\text{ext,tissue}}(t_i, t_{i+1}) + \sum_{\text{all tissues}} w_T \cdot D_{\text{ing,tissue}}(t_i, t_{i+1}) + 0.04 \cdot D_{\text{milk,Thyroid}}(t_i, t_{i+1}) + 0.04 \cdot D_{\text{inh,Thyroid}}(t_i, t_{i+1}).$$

The list of tissues included in the calculation of the effective external and internal dose components, and coefficients used in the calculations are listed in Table 9, 10 and 11. Tissue weighting factors w_T, as in ICRP (2007), are given in Table 6. The internal dose via dairy milk and the inhalation contribute only for Thyroid which has weight 0.04.

Table 6. Tissue weighting factors according to ICRP 103 (ICRP, 2007).

Tissue	Tissue weighting factor w_T	$\sum w_T$
breast, colon, lung, red active marrow, remainder[1], stomach	0.12	0.72
gonads (ovaries, testes)	0.08	0.08
liver, oesophagus, thyroid, urinary bladder	0.04	0.16
bone surface, brain, salivary glands, skin	0.01	0.04
	Total	1.00

[1]Remaining tissues: adrenals, ET, gall bladder, heart, kidneys, lymph, muscle, oral mucosa, pancreas, prostate (♂), small intestine, spleen, thymus, uterus/cervix (♀).

The effective dose E to a reference person of a certain age in a municipality was calculated as

$$\begin{aligned} E_{\text{municip,age}}(t_i, t_{i+1}) = [&n_{\text{municip,age,M}} \cdot [(1 - p_{\text{municip, hunters}}) \cdot E_{\text{tot,municip,age,M,non-hunter}}(t_i, t_{i+1}) \\ &+ p_{\text{municip,hunters}} \cdot E_{\text{municip,age,M,hunter}}(t_i, t_{i+1})] \\ &+ n_{\text{municip,age,F}} \cdot [(1 - p_{\text{municip,hunters}}) \cdot E_{\text{tot,municip,age,F,non-hunter}}(t_i, t_{i+1}) \\ &+ p_{\text{municip,hunters}} \cdot E_{\text{municip,age,F,hunter}}(t_i, t_{i+1})]]/(n_{\text{municip,age,M}} + n_{\text{municip,age,F}}), \end{aligned}$$

where n is the municipality population in the time period (t_i, t_{i+1}) of a specific 1-year age category and p is proportion of hunter households in the municipality (see Section 3 and Table 8). The weighted mean was used in order to take into account that the number of males and females in each municipality was not equal.

The annual collective effective dose in Sweden, S, was calculated as E times the number of individuals in the age category in the municipality, summed over all age categories and all municipalities,

$$S(t_i, t_{i+1}) = \sum_{\text{municip}=1}^{290} \sum_{\text{age}=0}^{100} n_{\text{municip,age}} \cdot E_{\text{municip,age}}(t_i, t_{i+1}).$$

8 R package `absorbedDose`

The R package absorbedDose was developed to calculate the organ absorbed dose to an individual using the model described in Section 4 (Tondel et al., 2023a). The package was updated to enable the calculation of the number of attributable cancer cases and the effective dose. The number of AC, as described in Section 6, can be calculated using the functions `LAR` and `dose_collective`. The effective dose, as described in Section 7, can be calculated with the function `dose_effective`. Additionally, the data sets containing coefficients per county, municipality, tissue/organ, and LAR coefficients presented in the Appendix, and tissue weighting factors presented in Table 6 were added.

The R package `absorbedDose` can be download from https://github.com/absorbedDose/absorbedDose.

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A Appendix

A.1 Coefficients per county, municipality and organ

A.1.1 Coefficients per county

Table 7. $A_{\mathrm{esd,county}}$, $f_{\mathrm{shield,snow,county}}$, $c_{\mathrm{milk,county}}$ and $E_{\mathrm{inh,county}}$ values per county. Values $A_{\mathrm{esd,county}}$ are taken from Byström (2000) and Tondel et al. (2022). Values $f_{\mathrm{shield,snow,county}}$ are taken from Finck (1992). Values $c_{\mathrm{milk,county}}$ are time-integrated activity concentrations in milk. Values $c_{\mathrm{milk,county}}$ and $E_{\mathrm{inh,county}}$ are derived from Rääf et al. (2019).

County code		^{137}Cs $A_{\mathrm{esd,county}}$ kBq/m^2	– $f_{\mathrm{shield,snow,county}}$ —	^{131}I $c_{\mathrm{milk,county}}$ Bq d/kg	^{131}I $E_{\mathrm{inh,county}}$ μSv
1	Stockholm	2.579	0.90	398	16.00
3	Uppsala	15.183	0.90	302	16.00
4	Södermanland	5.043	0.90	449	16.00
5	Östergötland	2.184	0.90	141	11.60
6	Jönköping	1.747	0.90	160	3.40
7	Kronoberg	1.613	0.90	160	7.20
8	Kalmar	2.054	0.90	160	11.60
9	Gotland	3.140	0.97	1721	16.00
10	Blekinge	1.964	0.97	160	7.20
12	Skåne	1.760	0.97	160	7.20
13	Halland	1.792	0.97	141	5.30
14	Västra Götaland	1.873	0.97	141	3.40
17	Värmland	2.042	0.85	100	3.40
18	Örebro	1.931	0.90	141	3.40
19	Västmanland	10.897	0.90	224	16.00
20	Dalarna	2.448	0.85	100	10.06
21	Gävleborg	13.112	0.85	311	4.12
22	Västernorrland	27.872	0.84	356	1.90
23	Jämtland	6.352	0.84	91	4.12
24	Västerbotten	14.361	0.84	181	1.90
25	Norrbotten	2.054	0.81	329	1.17

A.1.2 Coefficients per municipality

Shielding factors for dwellings, $f_{\text{shield,municip}}$, were calculated for each municipality, based on the distribution of multi-storey houses and one-family houses in each municipality. For these types of dwellings, shielding factors were taken from Finck (1992), where multi-storey houses are assigned a shielding factor of $f_{\text{M}} = 0.04$ and one-family houses are assigned a shielding factor of $f_0 = 0.38$. For each municipality, the number of multi-storey houses, N_{M}, and one-family houses, N_0, respectively, in year 1990 were retrieved from Statistics Sweden (2021) and a weighted shielding factor was calculated as $(N_{\text{M}} \cdot f_{\text{M}} + N_0 \cdot f_0)/(N_{\text{M}} + N_0)$.

Table 8. $A_{\text{esd,municip}}$, $f_{\text{shield,municip}}$ and proportion of hunter households per municipality.

Municipality code	Municipality name	County code	^{137}Cs $A_{\text{esd,municip}}$ kBq/m^2	$f_{\text{shield,municip}}$ —	Hunter %
114	Upplands Väsby	1	1.939	0.164	2.38
115	Vallentuna	1	1.680	0.272	2.38
117	Österåker	1	1.992	0.288	2.38
120	Värmdö	1	2.033	0.269	2.38
123	Järfälla	1	1.956	0.174	2.38
125	Ekerö	1	2.424	0.320	2.38
126	Huddinge	1	2.233	0.185	2.38
127	Botkyrka	1	1.877	0.154	2.38
128	Salem	1	1.722	0.253	2.38
136	Haninge	1	1.845	0.172	2.38
138	Tyresö	1	2.027	0.206	2.38
139	Upplands-Bro	1	7.261	0.185	2.38
140	Nykvarn	1	3.003	0.276	2.38
160	Täby	1	1.509	0.219	2.38
162	Danderyd	1	1.773	0.231	2.38
163	Sollentuna	1	1.849	0.203	2.38
180	Stockholm	1	1.755	0.077	2.38
181	Södertälje	1	2.212	0.134	2.38
182	Nacka	1	2.175	0.177	2.38
183	Sundbyberg	1	1.584	0.057	2.38
184	Solna	1	2.359	0.050	2.38
186	Lidingö	1	2.177	0.163	2.38
187	Vaxholm	1	2.137	0.230	2.38
188	Norrtälje	1	2.725	0.243	2.38
191	Sigtuna	1	5.002	0.168	2.38
192	Nynäshamn	1	1.921	0.196	2.38
305	Håbo	3	20.993	0.309	2.38
319	Älvkarleby	3	37.889	0.252	3.14
330	Knivsta	3	13.557	0.283	2.36
331	Heby	19	31.384	0.300	5.93
360	Tierp	3	19.800	0.260	5.80
380	Uppsala	3	13.557	0.148	2.36
381	Enköping	3	18.563	0.227	3.87
382	Östhammar	3	7.026	0.266	6.67
428	Vingåker	4	2.415	0.245	3.82
461	Gnesta	4	3.826	0.266	2.86
480	Nyköping	4	2.616	0.183	2.86
481	Oxelösund	4	2.303	0.175	2.39
482	Flen	4	6.767	0.225	3.60
483	Katrineholm	4	3.939	0.184	2.58
484	Eskilstuna	4	6.691	0.161	1.59
486	Strängnäs	4	10.136	0.220	2.98
488	Trosa	4	2.192	0.277	2.86

Table 8. *(continued)*

Municipality code	Municipality name	County code	^{137}Cs $A_{\text{esd,municip}}$	$f_{\text{shield,municip}}$	Hunter
			kBq/m^2	—	%
509	Ödeshög	5	1.933	0.307	2.38
512	Ydre	5	2.356	0.331	2.38
513	Kinda	5	2.013	0.280	2.38
560	Boxholm	5	2.209	0.251	2.38
561	Åtvidaberg	5	2.242	0.254	2.38
562	Finspång	5	2.056	0.207	2.38
563	Valdemarsvik	5	2.537	0.262	2.38
580	Linköping	5	1.922	0.158	2.38
581	Norrköping	5	2.606	0.156	2.38
582	Söderköping	5	2.826	0.260	2.38
583	Motala	5	1.785	0.219	2.38
584	Vadstena	5	1.519	0.245	2.38
586	Mjölby	5	1.887	0.219	2.38
604	Aneby	6	2.170	0.295	2.38
617	Gnosjö	6	1.454	0.283	2.38
642	Mullsjö	6	1.698	0.334	2.38
643	Habo	6	1.362	0.320	2.38
662	Gislaved	6	1.338	0.280	2.38
665	Vaggeryd	6	1.890	0.294	2.38
680	Jönköping	6	1.654	0.191	2.38
682	Nässjö	6	1.960	0.221	2.38
683	Värnamo	6	1.479	0.260	2.38
684	Sävsjö	6	1.812	0.287	2.38
685	Vetlanda	6	1.795	0.270	2.38
686	Eksjö	6	2.182	0.242	2.38
687	Tranås	6	2.217	0.198	2.38
760	Uppvidinge	7	1.849	0.297	2.38
761	Lessebo	7	1.893	0.290	2.38
763	Tingsryd	7	1.784	0.312	2.38
764	Alvesta	7	1.678	0.290	2.38
765	Älmhult	7	1.454	0.282	2.38
767	Markaryd	7	1.239	0.281	2.38
780	Växjö	7	1.832	0.221	2.38
781	Ljungby	7	1.232	0.264	2.38
821	Högsby	8	1.960	0.321	2.38
834	Torsås	8	1.922	0.329	2.38
840	Mörbylånga	8	2.364	0.335	2.38
860	Hultsfred	8	2.189	0.276	2.38
861	Mönsterås	8	2.070	0.283	2.38
862	Emmaboda	8	1.774	0.299	2.38
880	Kalmar	8	1.712	0.194	2.38
881	Nybro	8	1.840	0.253	2.38
882	Oskarshamn	8	1.811	0.218	2.38

Table 8. *(continued)*

Municipality code	Municipality name	County code	^{137}Cs $A_{\mathrm{esd,municip}}$	$f_{\mathrm{shield,municip}}$	Hunter
			kBq/m^2	—	%
883	Västervik	8	2.398	0.226	2.38
884	Vimmerby	8	2.257	0.267	2.38
885	Borgholm	8	1.925	0.325	2.38
980	Gotland	9	3.140	0.272	2.38
1060	Olofström	10	1.655	0.259	2.38
1080	Karlskrona	10	2.056	0.217	2.38
1081	Ronneby	10	2.048	0.265	2.38
1082	Karlshamn	10	1.978	0.234	2.38
1083	Sölvesborg	10	1.685	0.290	2.38
1214	Svalöv	12	2.249	0.310	2.38
1230	Staffanstorp	12	1.788	0.314	2.38
1231	Burlöv	12	1.791	0.174	2.38
1233	Vellinge	12	1.577	0.337	2.38
1256	Östra Göinge	12	1.613	0.287	2.38
1257	Örkelljunga	12	1.741	0.294	2.38
1260	Bjuv	12	2.424	0.281	2.38
1261	Kävlinge	12	2.062	0.301	2.38
1262	Lomma	12	1.929	0.300	2.38
1263	Svedala	12	1.668	0.306	2.38
1264	Skurup	12	1.319	0.316	2.38
1265	Sjöbo	12	1.602	0.317	2.38
1266	Hörby	12	1.640	0.297	2.38
1267	Höör	12	1.723	0.306	2.38
1270	Tomelilla	12	1.503	0.298	2.38
1272	Bromölla	12	1.600	0.296	2.38
1273	Osby	12	1.583	0.277	2.38
1275	Perstorp	12	1.900	0.225	2.38
1276	Klippan	12	2.130	0.259	2.38
1277	Åstorp	12	2.523	0.272	2.38
1278	Båstad	12	2.519	0.313	2.38
1280	Malmö	12	1.611	0.100	2.38
1281	Lund	12	1.883	0.166	2.38
1282	Landskrona	12	2.114	0.163	2.38
1283	Helsingborg	12	2.415	0.153	2.38
1284	Höganäs	12	2.620	0.298	2.38
1285	Eslöv	12	1.891	0.244	2.38
1286	Ystad	12	1.294	0.228	2.38
1287	Trelleborg	12	1.393	0.229	2.38
1290	Kristianstad	12	1.531	0.239	2.38
1291	Simrishamn	12	1.417	0.280	2.38
1292	Ängelholm	12	2.366	0.248	2.38
1293	Hässleholm	12	1.612	0.262	2.38
1315	Hylte	13	1.417	0.309	2.38

Table 8. *(continued)*

Municipality code	Municipality name	County code	^{137}Cs $A_{\mathrm{esd,municip}}$ kBq/m^2	$f_{\mathrm{shield,municip}}$ —	Hunter %
1380	Halmstad	13	1.743	0.218	2.38
1381	Laholm	13	1.554	0.321	2.38
1382	Falkenberg	13	1.685	0.281	2.38
1383	Varberg	13	2.186	0.233	2.38
1384	Kungsbacka	13	2.436	0.312	2.38
1401	Härryda	14	2.106	0.295	2.38
1402	Partille	14	2.363	0.220	2.38
1407	Öckerö	14	2.424	0.367	2.38
1415	Stenungsund	14	2.335	0.270	2.38
1419	Tjörn	14	2.454	0.351	2.38
1421	Orust	14	2.603	0.331	2.38
1427	Sotenäs	14	2.731	0.315	2.38
1430	Munkedal	14	2.304	0.303	2.38
1435	Tanum	14	2.145	0.317	2.38
1438	Dals-Ed	14	2.715	0.307	2.38
1439	Färgelanda	14	2.586	0.337	2.38
1440	Ale	14	1.948	0.256	2.38
1441	Lerum	14	1.866	0.309	2.38
1442	Vårgårda	14	1.647	0.299	2.38
1443	Bollebygd	14	1.974	0.317	2.38
1444	Grästorp	14	1.273	0.320	2.38
1445	Essunga	14	1.428	0.325	2.38
1446	Karlsborg	14	1.542	0.257	2.38
1447	Gullspång	14	1.797	0.286	2.38
1452	Tranemo	14	1.546	0.301	2.38
1460	Bengtsfors	14	2.389	0.272	2.38
1461	Mellerud	14	2.007	0.296	2.38
1462	Lilla Edet	14	2.058	0.301	2.38
1463	Mark	14	2.036	0.290	2.38
1465	Svenljunga	14	1.545	0.323	2.38
1466	Herrljunga	14	1.550	0.312	2.38
1470	Vara	14	1.169	0.319	2.38
1471	Götene	14	1.059	0.301	2.38
1472	Tibro	14	1.481	0.254	2.38
1473	Töreboda	14	1.339	0.278	2.38
1480	Göteborg	14	2.310	0.110	2.38
1481	Mölndal	14	2.259	0.198	2.38
1482	Kungälv	14	2.292	0.249	2.38
1484	Lysekil	14	2.766	0.244	2.38
1485	Uddevalla	14	2.424	0.191	2.38
1486	Strömstad	14	3.010	0.256	2.38
1487	Vänersborg	14	1.982	0.225	2.38
1488	Trollhättan	14	1.860	0.183	2.38

Table 8. *(continued)*

Municipality code	Municipality name	County code	^{137}Cs $A_{\mathrm{esd,municip}}$	$f_{\mathrm{shield,municip}}$	Hunter
			kBq/m^2	—	%
1489	Alingsås	14	1.692	0.241	2.38
1490	Borås	14	1.842	0.173	2.38
1491	Ulricehamn	14	1.630	0.279	2.38
1492	Åmål	14	2.242	0.242	2.38
1493	Mariestad	14	1.151	0.233	2.38
1494	Lidköping	14	0.991	0.224	2.38
1495	Skara	14	1.228	0.222	2.38
1496	Skövde	14	1.257	0.203	2.38
1497	Hjo	14	1.859	0.270	2.38
1498	Tidaholm	14	1.930	0.252	2.38
1499	Falköping	14	1.611	0.233	2.38
1715	Kil	17	1.957	0.278	2.38
1730	Eda	17	1.889	0.293	2.38
1737	Torsby	17	2.121	0.307	2.38
1760	Storfors	17	2.481	0.271	2.38
1761	Hammarö	17	1.417	0.253	2.38
1762	Munkfors	17	1.733	0.249	2.38
1763	Forshaga	17	1.815	0.287	2.38
1764	Grums	17	1.956	0.257	2.38
1765	Årjäng	17	2.257	0.292	2.38
1766	Sunne	17	1.879	0.309	2.38
1780	Karlstad	17	1.859	0.171	2.38
1781	Kristinehamn	17	2.094	0.201	2.38
1782	Filipstad	17	2.183	0.221	2.38
1783	Hagfors	17	2.085	0.255	2.38
1784	Arvika	17	1.933	0.246	2.38
1785	Säffle	17	1.880	0.255	2.38
1814	Lekeberg	18	1.910	0.330	2.38
1860	Laxå	18	1.797	0.215	2.38
1861	Hallsberg	18	1.867	0.250	2.38
1862	Degerfors	18	1.928	0.240	2.38
1863	Hällefors	18	2.241	0.217	2.38
1864	Ljusnarsberg	18	1.957	0.247	2.38
1880	Örebro	18	1.780	0.161	2.38
1881	Kumla	18	1.753	0.241	2.38
1882	Askersund	18	1.789	0.264	2.38
1883	Karlskoga	18	2.156	0.184	2.38
1884	Nora	18	2.024	0.273	2.38
1885	Lindesberg	18	1.933	0.259	2.38
1904	Skinnskatteberg	19	2.083	0.267	5.60
1907	Surahammar	19	2.556	0.248	2.36
1960	Kungsör	19	3.107	0.253	2.91
1961	Hallstahammar	19	4.420	0.204	1.97

Table 8. *(continued)*

Municipality code	Municipality name	County code	^{137}Cs $A_{\text{esd,municip}}$	$f_{\text{shield,municip}}$	Hunter
			kBq/m^2	—	%
1962	Norberg	19	2.107	0.231	3.77
1980	Västerås	19	10.824	0.162	1.45
1981	Sala	19	12.241	0.251	4.44
1982	Fagersta	19	1.737	0.164	2.25
1983	Köping	19	2.588	0.175	2.69
1984	Arboga	19	2.148	0.199	2.68
2021	Vansbro	20	1.819	0.303	7.94
2023	Malung-Sälen	20	2.228	0.302	8.80
2026	Gagnef	20	2.181	0.353	7.31
2029	Leksand	20	2.455	0.298	6.02
2031	Rättvik	20	2.690	0.284	5.63
2034	Orsa	20	2.382	0.276	8.21
2039	Älvdalen	20	2.510	0.318	10.13
2061	Smedjebacken	20	2.238	0.248	4.03
2062	Mora	20	2.312	0.289	6.34
2080	Falun	20	2.841	0.216	4.28
2081	Borlänge	20	2.240	0.202	2.79
2082	Säter	20	2.023	0.262	4.98
2083	Hedemora	20	2.146	0.240	4.27
2084	Avesta	20	6.268	0.201	2.94
2085	Ludvika	20	2.016	0.198	3.20
2101	Ockelbo	21	8.167	0.301	7.46
2104	Hofors	21	5.216	0.205	3.04
2121	Ovanåker	21	3.148	0.267	7.84
2132	Nordanstig	21	23.237	0.290	6.38
2161	Ljusdal	21	3.880	0.256	7.75
2180	Gävle	21	49.720	0.186	2.50
2181	Sandviken	21	17.258	0.205	2.91
2182	Söderhamn	21	14.637	0.216	4.10
2183	Bollnäs	21	5.670	0.236	5.23
2184	Hudiksvall	21	17.373	0.225	5.11
2260	Ånge	22	6.550	0.266	8.03
2262	Timrå	22	37.096	0.226	4.14
2280	Härnösand	22	45.605	0.211	4.23
2281	Sundsvall	22	19.865	0.188	3.69
2282	Kramfors	22	34.127	0.269	4.62
2283	Sollefteå	22	32.110	0.265	6.69
2284	Örnsköldsvik	22	32.733	0.262	4.98
2303	Ragunda	23	18.782	0.304	7.97
2305	Bräcke	23	7.213	0.286	7.76
2309	Krokom	23	5.725	0.299	8.26
2313	Strömsund	23	10.631	0.281	8.98
2321	Åre	23	5.416	0.264	7.55

Table 8. *(continued)*

Municipality code	Municipality name	County code	^{137}Cs $A_{\mathrm{esd,municip}}$	$f_{\mathrm{shield,municip}}$	Hunter
			kBq/m^2	—	%
2326	Berg	23	2.983	0.334	7.16
2361	Härjedalen	23	2.483	0.308	9.03
2380	Östersund	23	3.995	0.156	5.12
2401	Nordmaling	24	28.631	0.310	7.84
2403	Bjurholm	24	23.759	0.335	8.64
2404	Vindeln	24	14.483	0.315	9.36
2409	Robertsfors	24	12.186	0.321	7.71
2417	Norsjö	24	5.487	0.302	14.25
2418	Malå	24	4.311	0.302	13.44
2421	Storuman	24	11.332	0.296	13.36
2422	Sorsele	24	6.919	0.308	13.34
2425	Dorotea	24	15.773	0.273	10.84
2460	Vännäs	24	17.939	0.271	5.58
2462	Vilhelmina	24	25.123	0.272	12.10
2463	Åsele	24	25.562	0.276	11.79
2480	Umeå	24	18.657	0.186	4.67
2481	Lycksele	24	14.951	0.236	10.04
2482	Skellefteå	24	3.805	0.237	6.94
2505	Arvidsjaur	25	2.112	0.265	13.00
2506	Arjeplog	25	2.705	0.283	14.46
2510	Jokkmokk	25	2.301	0.288	12.06
2513	Överkalix	25	2.529	0.312	11.36
2514	Kalix	25	1.797	0.285	9.03
2518	Övertorneå	25	2.066	0.311	9.15
2521	Pajala	25	1.549	0.312	11.51
2523	Gällivare	25	2.018	0.205	9.20
2560	Älvsbyn	25	1.731	0.279	8.68
2580	Luleå	25	1.545	0.179	5.75
2581	Piteå	25	1.525	0.253	6.68
2582	Boden	25	1.893	0.215	7.61
2583	Haparanda	25	1.801	0.251	5.74
2584	Kiruna	25	1.768	0.182	9.53

A.1.3 Coefficients per tissue/organ

Table 9. Coefficients in the model for computation of external dose to tissue/organs for males included in the calculation of i) Lifetime attributable risk (EPA, 2011) and ii) effective dose (ICRP, 2007). The coefficients are derived from listed organ coefficients in ICRP (2020). The coefficients for Remainder are calculated from the coefficients for the remaining organs, as described in Subsection A.3.

Organ included and defined in ICRP 144	EPA cancer site[a]	ICRP risk organ[b]	$k_{\text{SEQ,organ,ext}}$	a_0	a_1	a_2	a_3
Adipose	Residual	Not defined	—	—	—	—	—
Adrenals	Residual	Remainder	0.735	1.36	-0.0291	5.58×10^{-4}	0
Brain	Residual	Brain	0.826	1.21	-0.0272	8.32×10^{-4}	0
Breast	Residual	Breast	0.845	1.29	-0.0458	2.82×10^{-3}	-6.3×10^{-5}
Bronch-bas Bronch-sec Bchiol-sec AI	Lung	Lung	0.741	1.43	-0.0415	1.01×10^{-3}	0
Endost-BS (Skeletal endosteum)	Bone	Bone surface	0.923	1.10	-0.0102	2.54×10^{-4}	0
ET1-bas ET2-bas	Residual Residual	Remainder	0.865	1.22	-0.0223	5.68×10^{-4}	0
Eye-lens	Residual	Not defined	—	—	—	—	—
GB-wall	Residual	Remainder	0.715	1.42	-0.0273	3.23×10^{-4}	0
Ht-wall	Residual	Remainder	0.715	1.50	-0.0613	1.80×10^{-3}	0
Kidneys	Kidneys	Remainder	0.735	1.50	-0.0440	9.51×10^{-4}	0
Liver	Liver	Liver	0.722	1.39	-0.0315	5.91×10^{-4}	0
LN-ET LN-Sys LN-Th	Residual	Remainder	0.767	1.48	-0.0393	7.64×10^{-4}	0
Muscle	Residual	Remainder	0.891	1.34	-0.0303	6.58×10^{-4}	0
O-mucosa	Residual	Remainder	0.832	1.31	-0.0248	4.65×10^{-4}	0
Oesophagus	Residual	Oesophagus	0.715	1.51	-0.0603	1.74×10^{-3}	0
Ovaries	Not defined	Not defined	—	—	—	—	—
P-gland	Residual	Not defined	—	—	—	—	—
Pancreas	Residual	Remainder	0.702	1.53	-0.0475	1.04×10^{-3}	0
Prostate	Prostate	Remainder	0.767	1.51	-0.0268	6.61×10^{-5}	0
R-marrow	Leukemia	Red marrow	0.748	1.34	-0.0203	1.54×10^{-4}	0
RC-stem LC-stem RS-stem	Colon	Colon	0.767	1.38	-0.0218	1.40×10^{-4}	0
S-glands	Residual	Salivary glands	0.878	1.29	-0.0327	9.16×10^{-4}	0
SI-stem	Residual	Remainder	0.735	1.42	-0.0266	2.76×10^{-4}	0
Skin	Skin	Skin	0.956	1.21	-0.0208	5.12×10^{-4}	0
Spleen	Residual	Remainder	0.735	1.42	-0.0316	5.34×10^{-4}	0

[a]Organ/tissues included by EPA (2011) that are used for computation of lifetime attributable risk (LAR).

[b]Organ/tissues included by ICRP that are used for computation of organ absorbed dose and effective dose.

[1]Represented by coefficients for Colon.

[2]Calculated from the remaining organs as described in Subsection A.3.

Table 9. *(continued)*

Organ included and defined in ICRP 144	EPA cancer site[a]	ICRP risk organ[b]	$k_{\mathrm{SEQ,organ,ext}}$	a_0	a_1	a_2	a_3
St-stem	Stomach	Stomach	0.722	1.35	-0.0187	6.56×10^{-5}	0
Testes	Residual	Testes	0.917	1.37	-0.0472	1.43×10^{-3}	0
Thymus	Residual	Remainder	0.754	1.40	-0.0522	1.61×10^{-3}	0
Thyroid	Thyroid	Thyroid	0.819	1.20	-0.0203	5.03×10^{-4}	0
Tongue	Residual	Not defined	—	—	—	—	—
Tonsils	Residual	Not defined	—	—	—	—	—
Total body	All sites	Not defined	0.767	1.38	-0.0218	1.40×10^{-4}	0
UB-wall	Urinary bladder	Urinary bladder	0.754	1.52	-0.0416	7.72×10^{-4}	0
Ureters	Residual	Not defined	—	—	—	—	—
Uterus	Not defined	Not defined	—	—	—	—	—
—	Residual[1]	—	0.767	1.38	-0.0218	1.40×10^{-4}	0
—	—	Remainder[2]	0.765	1.41	-0.0352	7.31×10^{-4}	0

[a]Organ/tissues included by EPA (2011) that are used for computation of lifetime attributable risk (LAR).
[b]Organ/tissues included by ICRP that are used for computation of organ absorbed dose and effective dose.
[1]Represented by coefficients for Colon.
[2]Calculated from the remaining organs as described in Subsection A.3.

Table 10. Coefficients in the model for computation of external dose to tissue/organs for females included in the calculation of i) Lifetime attributable risk (EPA, 2011) and ii) effective dose (ICRP, 2007). The coefficients are derived from listed organ coefficients in ICRP (2020). The coefficients for Remainder are calculated from the coefficients for the remaining organs, as described in Subsection A.3.

Organ included and defined in ICRP 144	EPA cancer site[a]	ICRP risk organ[b]	$k_{\mathrm{SEQ,organ,ext}}$	a_0	a_1	a_2	a_3
Adipose	Residual	Not defined	—	—	—	—	—
Adrenals	Residual	Remainder	0.722	1.47	-0.0467	1.16×10^{-3}	0
Brain	Residual	Brain	0.832	1.26	-0.0415	1.42×10^{-3}	0
Breast	Breast	Breast	0.858	1.25	-0.0312	9.30×10^{-4}	0
Bronch-bas Bronch-sec Bchiol-sec AI	Lung	Lung	0.819	1.31	-0.0433	1.38×10^{-3}	0
Endost-BS (Skeletal endosteum)	Bone	Bone surface	0.930	1.10	-0.0121	3.46×10^{-4}	0
ET1-bas ET2-bas	Residual Residual	Remainder	0.852	1.22	-0.0221	5.44×10^{-4}	0
Eye-lens	Residual	Not defined	—	—	—	—	—
GB-wall	Residual	Remainder	0.741	1.39	-0.0310	5.70×10^{-4}	0
Ht-wall	Residual	Remainder	0.774	1.35	-0.0491	1.58×10^{-3}	0
Kidneys	Kidneys	Remainder	0.761	1.44	-0.0445	1.13×10^{-3}	0
Liver	Liver	Liver	0.774	1.31	-0.0347	9.51×10^{-4}	0
LN-ET LN-Sys LN-Th	Residual	Remainder	0.819	1.40	-0.0417	1.09×10^{-3}	0
Muscle	Residual	Remainder	0.891	1.30	-0.0195	2.30×10^{-4}	0
O-mucosa	Residual	Remainder	0.852	1.36	-0.0415	1.18×10^{-3}	0
Oesophagus	Residual	Oesophagus	0.748	1.41	-0.0523	1.58×10^{-3}	0
Ovaries	Ovary	Ovaries	0.748	1.41	-0.0359	7.67×10^{-4}	0
P-gland	Residual	Not defined	—	—	—	—	—
Pancreas	Residual	Remainder	0.754	1.42	-0.0396	9.43×10^{-4}	0
Prostate	Not defined	Not defined	—	—	—	—	—
R-marrow	Leukemia	Red marrow	0.780	1.28	-0.0211	3.55×10^{-4}	0
RC-stem LC-stem RS-stem	Colon	Colon	0.780	1.44	-0.0389	8.49×10^{-4}	0
S-glands	Residual	Salivary glands	0.878	1.23	-0.0131	8.92×10^{-5}	0
SI-stem	Residual	Remainder	0.767	1.45	-0.0462	1.20×10^{-3}	0
Skin	Skin	Skin	0.975	1.19	-0.0214	5.96×10^{-4}	0
Spleen	Residual	Remainder	0.793	1.28	-0.0237	4.87×10^{-4}	0

[a]Organ/tissues included by EPA (2011) that are used for computation of lifetime attributable risk (LAR).

[b]Organ/tissues included by ICRP that are used for computation of organ absorbed dose and effective dose.

[1]Represented by coefficients for Colon.

[2]Calculated from the remaining organs as described in Subsection A.3.

Table 10. *(continued)*

Organ included and defined in ICRP 144	EPA cancer site[a]	ICRP risk organ[b]	$k_{\mathrm{SEQ,organ,ext}}$	a_0	a_1	a_2	a_3
St-stem	Stomach	Stomach	0.806	1.24	-0.0266	7.21×10^{-4}	0
Testes	Not defined	Not defined	—	—	—	—	—
Thymus	Residual	Remainder	0.780	1.32	-0.0411	1.27×10^{-3}	0
Thyroid	Thyroid	Thyroid	0.813	1.24	-0.0234	5.61×10^{-4}	0
Tongue	Residual	Not defined	—	—	—	—	—
Tonsils	Residual	Not defined	—	—	—	—	—
Total body	All sites	Not defined	0.780	1.44	-0.0389	8.49×10^{-4}	0
UB-wall	Urinary bladder	Urinary bladder	0.813	1.50	-0.0583	1.66×10^{-3}	0
Ureters	Residual	Not defined	—	—	—	—	—
Uterus	Uterus	Remainder	0.735	1.42	-0.0304	4.68×10^{-4}	0
—	Residual[1]	—	0.780	1.44	-0.0389	8.49×10^{-4}	0
—	—	Remainder[2]	0.788	1.37	-0.0364	9.04×10^{-4}	0

[a]Organ/tissues included by EPA (2011) that are used for computation of lifetime attributable risk (LAR).
[b]Organ/tissues included by ICRP that are used for computation of organ absorbed dose and effective dose.
[1]Represented by coefficients for Colon.
[2]Calculated from the remaining organs as described in Subsection A.3.

Table 11. Absorbed dose rate coefficients $\epsilon_{Cs\text{-}137,organ,sex}$ and $\epsilon_{Cs\text{-}134,organ,sex}$ (Gy/(Bq s)) computation of internal dose to tissue/organs for both sexes included in the calculation of i) Lifetime attributable risk (EPA, 2011) and ii) effective dose (ICRP, 2007). The coefficients are retrieved from Isaksson et al. (2021).

Tissues listed in Isaksson et al. (2021)	EPA cancer site[a]	ICRP risk organ[b]	Male ^{134}Cs	Male ^{137}Cs	Female ^{134}Cs	Female ^{137}Cs
Adipose	Residual	Not defined	—	—	—	—
Adrenals	Residual	Remainder	—	—	—	—
Brain	Residual	Brain	7.733×10^{-16}	5.114×10^{-16}	8.657×10^{-16}	5.741×10^{-16}
Breast	Breast	Breast	7.442×10^{-16}	3.906×10^{-16}	9.128×10^{-16}	4.799×10^{-16}
Bronch-bas Bronch-sec Bchiol-sec AI	Lung[2]	Lung[2]	1.506×10^{-15}	9.951×10^{-16}	1.852×10^{-15}	1.209×10^{-15}
Endost-BS (Skeletal endosteum)	Bone	Bone surface	2.057×10^{-15}	1.257×10^{-15}	2.499×10^{-15}	1.461×10^{-15}
ET1-bas ET2-bas	Residual Residual	Remainder[4]	—	—	—	—
Eye-lens	Residual	Not defined	—	—	—	—
GB-wall	Residual	Remainder	—	—	—	—
Ht-wall	Residual	Remainder	—	—	—	—
Kidneys	Kidneys	Remainder	1.552×10^{-15}	9.139×10^{-16}	1.999×10^{-15}	1.150×10^{-15}
Liver	Liver	Liver	1.409×10^{-15}	8.294×10^{-16}	1.721×10^{-15}	1.042×10^{-15}
LN-ET	Residual	Remainder[5]	—	—	—	—
LN-Sys	Residual	Remainder[5]	—	—	—	—
LN-Th	Residual	Remainder[5]	—	—	—	—
Muscle	Residual	Remainder	—	—	—	—
O-mucosa	Residual	Remainder	—	—	—	—
Oesophagus	Residual	Oesophagus	1.203×10^{-15}	5.583×10^{-16}	1.576×10^{-15}	7.460×10^{-16}
Ovaries	Ovary	Ovaries	—	—	1.935×10^{-15}	8.799×10^{-16}
P-gland	Residual	Not defined	—	—	—	—
Pancreas	Residual	Remainder	—	—	—	—
Prostate	Prostate	Remainder	1.588×10^{-15}	7.140×10^{-16}	—	—
R-marrow	Leukemia	Red marrow	1.836×10^{-15}	1.183×10^{-15}	2.273×10^{-15}	1.396×10^{-15}
RC-stem LC-stem RS-stem	Colon[1]	Colon[1]	1.367×10^{-15}	7.970×10^{-16}	1.856×10^{-15}	1.028×10^{-15}
S-glands	Residual	Salivary glands	9.189×10^{-16}	4.798×10^{-16}	1.079×10^{-15}	5.638×10^{-16}
SI-stem	Residual	Remainder	—	—	—	—

[a]Organ/tissues included by EPA (2011) that are used for computation of lifetime attributable risk (LAR).
[b]Organ/tissues included by ICRP that are used for computation of organ absorbed dose and effective dose.
[1]Weighted dose rate with weighting factors 0.4 (RC-stem), 0.4 (LC-stem), 0.2 (RS-stem) (ICRP, 2016).
[2]Weighted dose rate with weighting factors 1/6 (Bronch-bas), 1/6 (Bronch-sec), 1/3 (Bchiol-sec), 1/3 (Al) (ICRP, 2016).
[3]Sum of imparted energy rate divided by total mass of included tissues.
[4]Weighted dose rate with weighting factors 0.001 (ET1-bas), 0.999 (ET2-bas), included in Remainder (ICRP, 2016).
[5]Weighted dose rate with weighting factors 0.08 (LN-ET), 0.08 (LN-Th), 0.84 (LN-Sys), included in Remainder (ICRP, 2016).
[6]Arithmetic mean of dose rate to tissues included in Remainder (ICRP, 2007).

Table 11. *(continued)*

Tissues listed in Isaksson et al. (2021)	EPA cancer site[a]	ICRP risk organ[b]	Male		Female	
			^{134}Cs	^{137}Cs	^{134}Cs	^{137}Cs
Skin	Skin	Skin	7.484×10^{-16}	3.698×10^{-16}	8.423×10^{-16}	4.338×10^{-16}
Spleen	Residual	Remainder	—	—	—	—
St-stem	Stomach	Stomach	1.247×10^{-15}	7.481×10^{-16}	1.568×10^{-15}	9.214×10^{-16}
Testes	Residual	Testes	1.191×10^{-15}	5.613×10^{-16}	—	—
Thymus	Residual	Remainder	—	—	—	—
Thyroid	Thyroid	Thyroid	1.149×10^{-15}	5.498×10^{-16}	1.522×10^{-15}	7.633×10^{-16}
Tongue	Residual	Not defined	—	—	—	—
Tonsils	Residual	Not defined	—	—	—	—
Total body	All sites	Not defined	1.554×10^{-15}	1.083×10^{-15}	1.851×10^{-15}	1.292×10^{-15}
UB-wall	Urinary bladder	Urinary bladder	1.397×10^{-15}	6.362×10^{-16}	1.608×10^{-15}	7.609×10^{-16}
Ureters	Residual	Not defined	—	—	—	—
Uterus	Uterus	Remainder	—	—	1.792×10^{-15}	8.220×10^{-16}
—	Residual[3]	—	1.603×10^{-15}	1.144×10^{-15}	1.908×10^{-15}	1.362×10^{-15}
—	—	Remainder[6]	1.359×10^{-15}	7.726×10^{-16}	1.745×10^{-15}	1.015×10^{-15}

[a]Organ/tissues included by EPA (2011) that are used for computation of lifetime attributable risk (LAR).
[b]Organ/tissues included by ICRP that are used for computation of organ absorbed dose and effective dose.
[1]Weighted dose rate with weighting factors 0.4 (RC-stem), 0.4 (LC-stem), 0.2 (RS-stem) (ICRP, 2016).
[2]Weighted dose rate with weighting factors 1/6 (Bronch-bas), 1/6 (Bronch-sec), 1/3 (Bchiol-sec), 1/3 (Al) (ICRP, 2016).
[3]Sum of imparted energy rate divided by total mass of included tissues.
[4]Weighted dose rate with weighting factors 0.001 (ET1-bas), 0.999 (ET2-bas), included in Remainder (ICRP, 2016).
[5]Weighted dose rate with weighting factors 0.08 (LN-ET), 0.08 (LN-Th), 0.84 (LN-Sys), included in Remainder (ICRP, 2016).
[6]Arithmetic mean of dose rate to tissues included in Remainder (ICRP, 2007).

A.2 Plots of age-dependent polynomials

A.2.1 $k_{\text{organ,sex}}$ per organ as a function of age (age < 20)

Values of $k_{\text{organ,sex}}$ for external dose for children (age < 20) are modelled separately for different organs and for female and male as a function of age by a polynomial. Coefficients of the polynomials can be found in Table 9 and 10.

Figure 3. Values of $k_{\text{organ,sex}}$ for children (age < 20) for Adrenals.

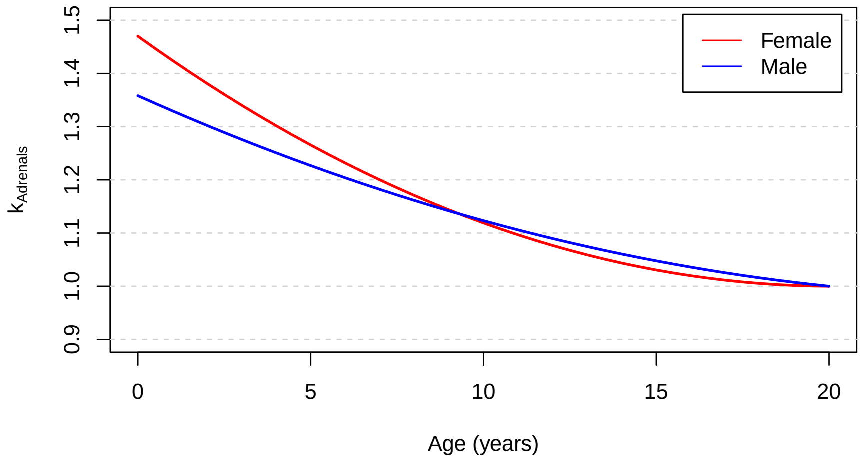


Figure 4. Values of $k_{\text{organ,sex}}$ for children (age < 20) for Brain.

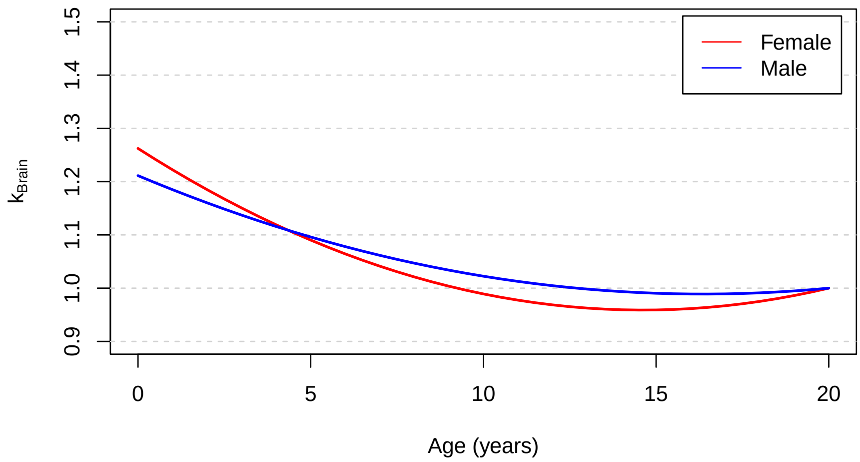


Figure 5. Values of $k_{\text{organ,sex}}$ for children (age < 20) for Breast.

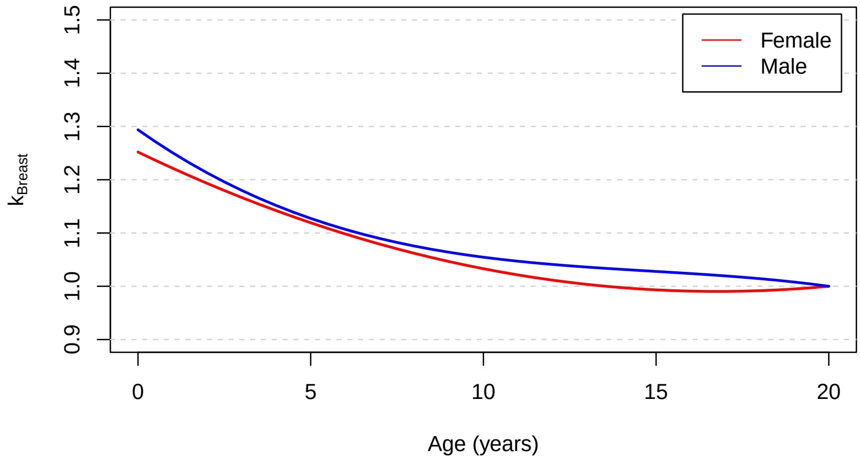


Figure 6. Values of $k_{\text{organ,sex}}$ for children (age < 20) for Colon (RC-stem, LC-stem, RS-stem), All sites and Residual.

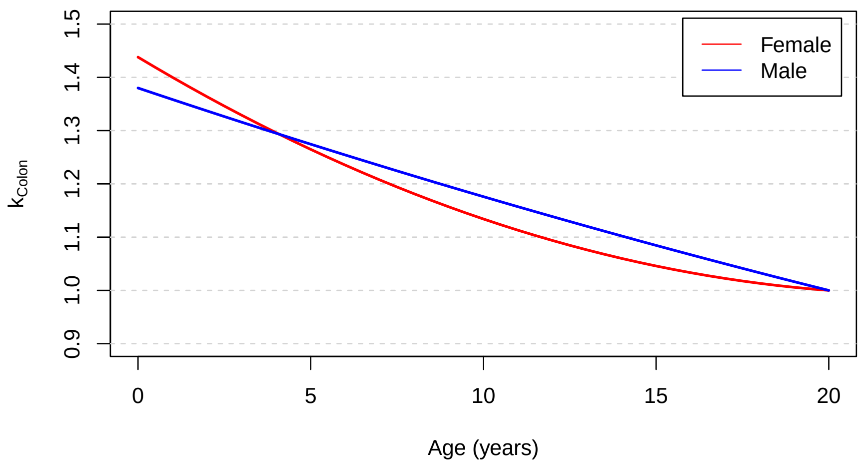


Figure 7. Values of $k_{\text{organ,sex}}$ for children (age < 20) for Endost-BS.

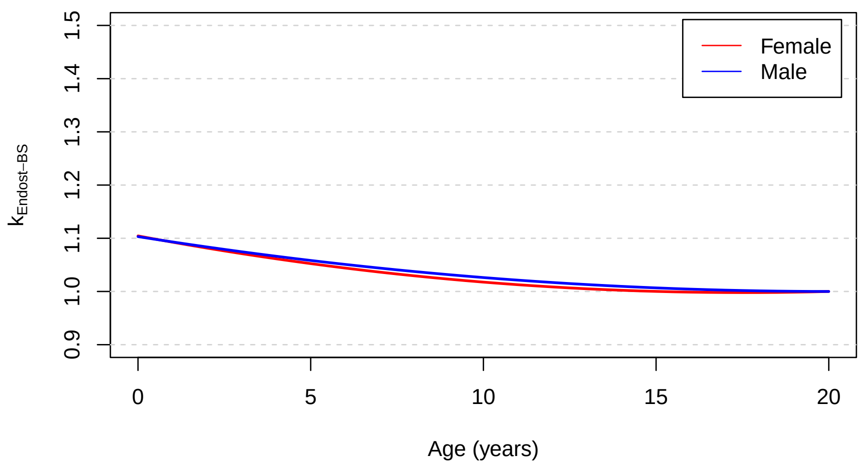


Figure 8. Values of $k_{\mathrm{organ,sex}}$ for children (age < 20) for ET (ET1-bas, ET2-bas).

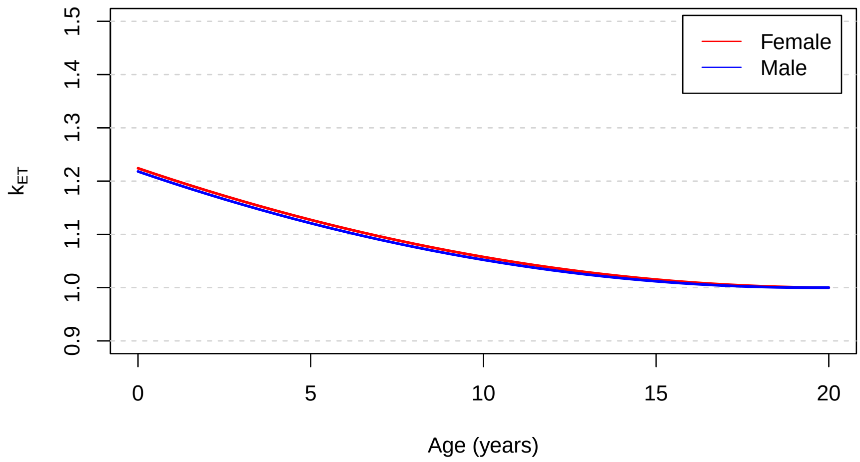


Figure 9. Values of $k_{\mathrm{organ,sex}}$ for children (age < 20) for GB-wall.

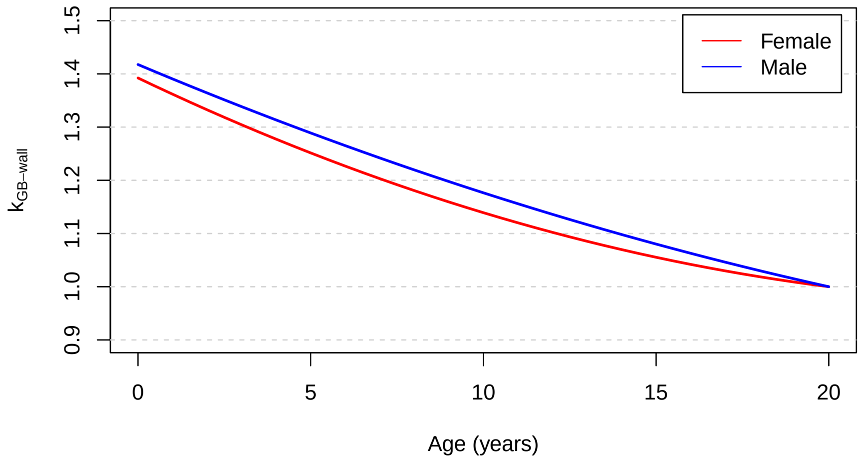


Figure 10. Values of $k_{\mathrm{organ,sex}}$ for children (age < 20) for Ht-wall.

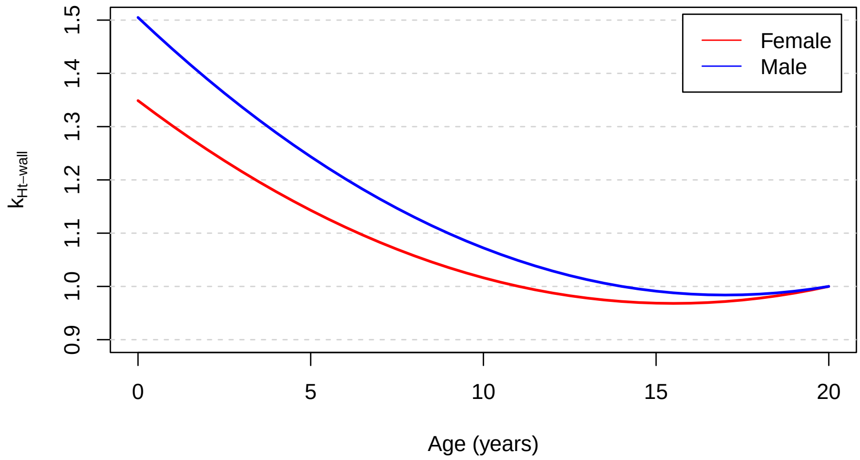


Figure 11. Values of $k_{\text{organ,sex}}$ for children (age < 20) for Kidneys.

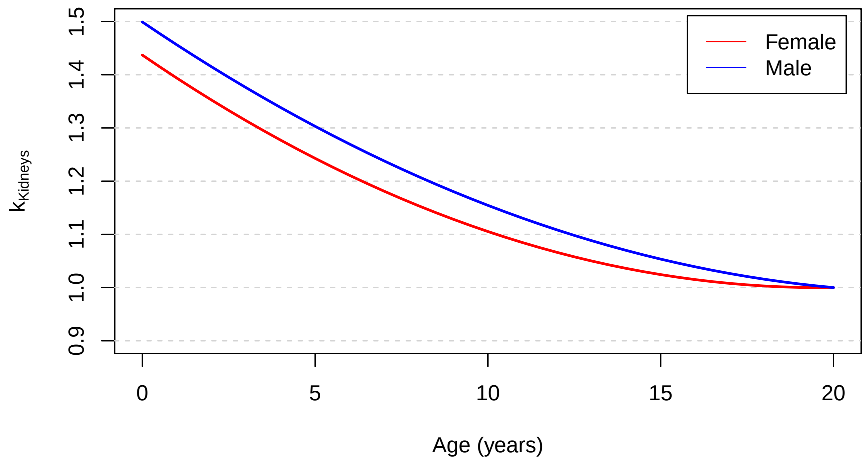


Figure 12. Values of $k_{\text{organ,sex}}$ for children (age < 20) for Liver.

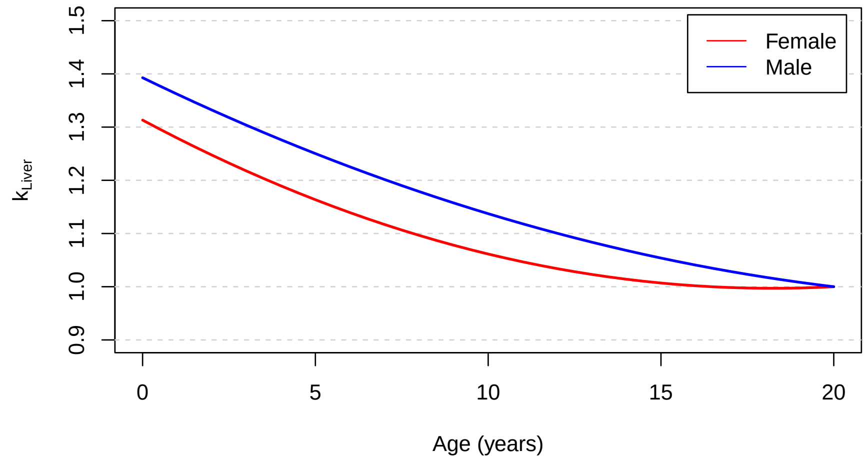


Figure 13. Values of $k_{\text{organ,sex}}$ for children (age < 20) for Lungs (Bronch-bas, Bronch-sec, Bchiol-sec, AI).

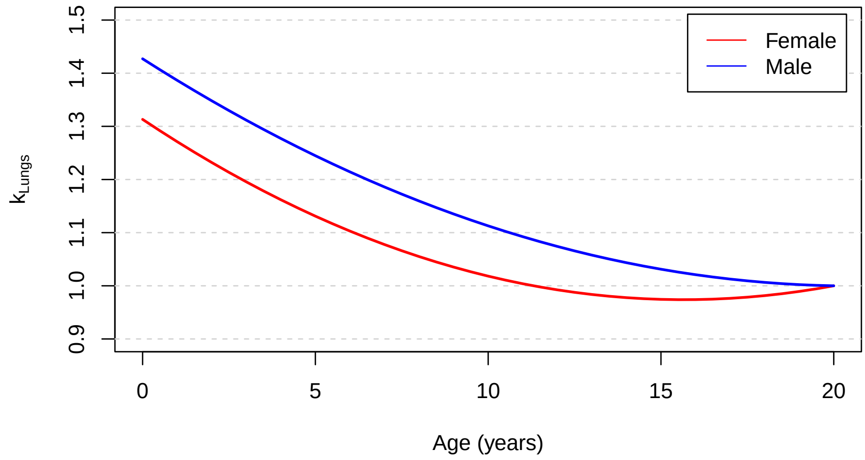


Figure 14. Values of $k_{\text{organ,sex}}$ for children (age < 20) for Lymph (LN-ET, LN-Sys, LN-Th).

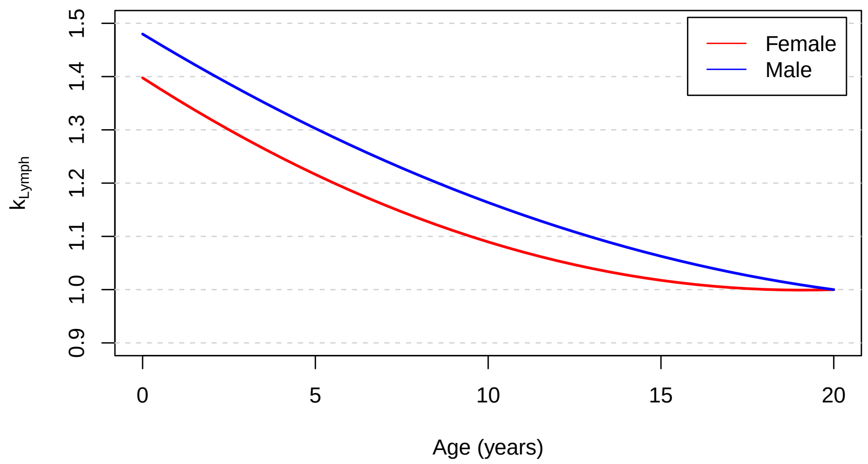


Figure 15. Values of $k_{\text{organ,sex}}$ for children (age < 20) for Muscle.

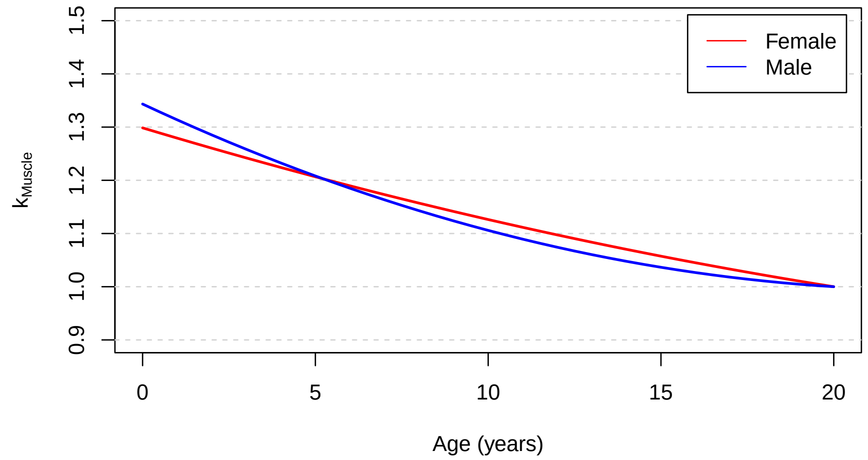


Figure 16. Values of $k_{\text{organ,sex}}$ for children (age < 20) for O-mucosa.

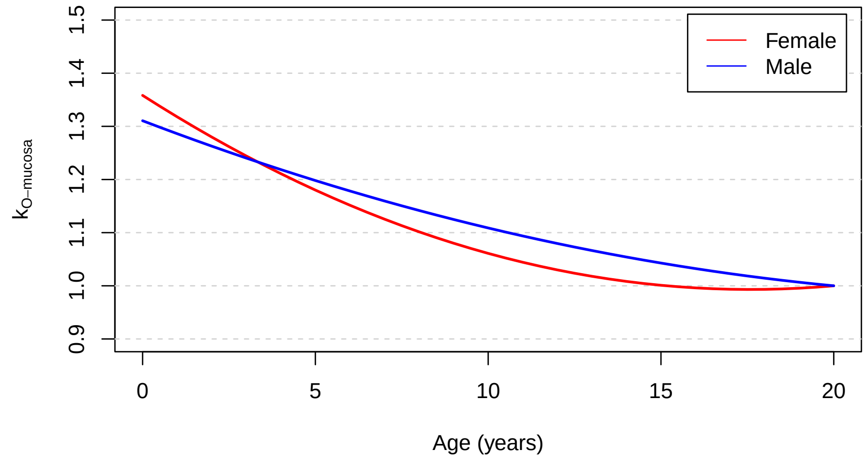


Figure 17. Values of $k_{\text{organ,sex}}$ for children (age < 20) for Oesophagus.

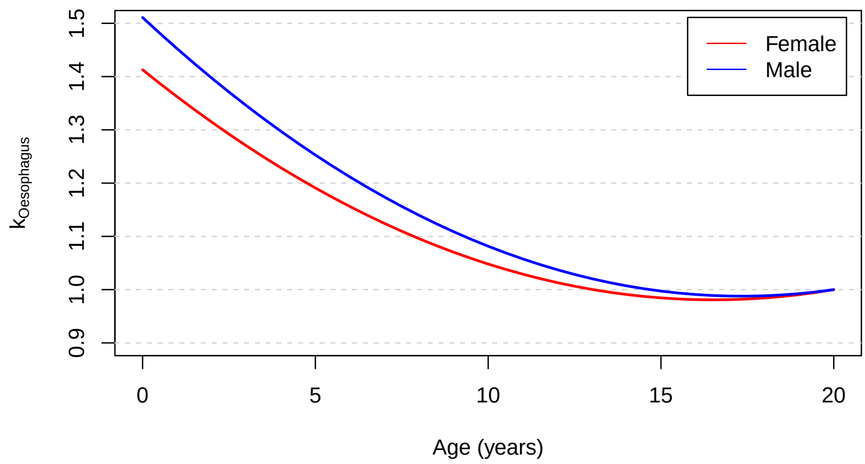


Figure 18. Values of $k_{\text{organ,sex}}$ for children (age < 20) for Ovaries.

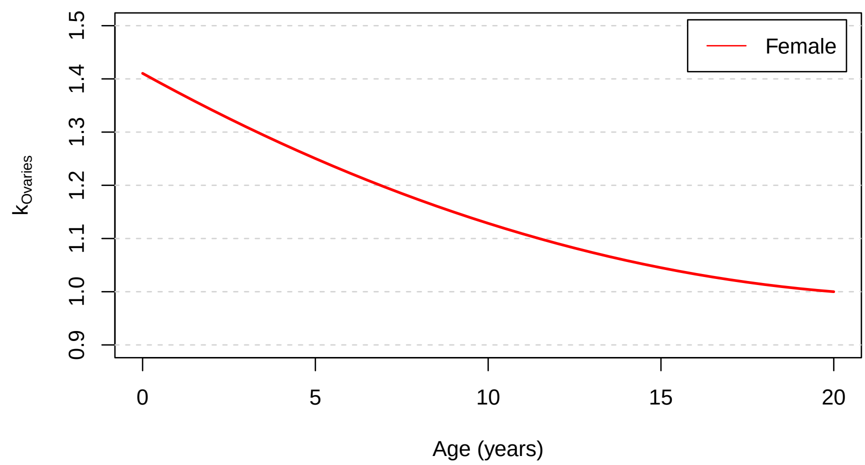


Figure 19. Values of $k_{\text{organ,sex}}$ for children (age < 20) for Pancreas.

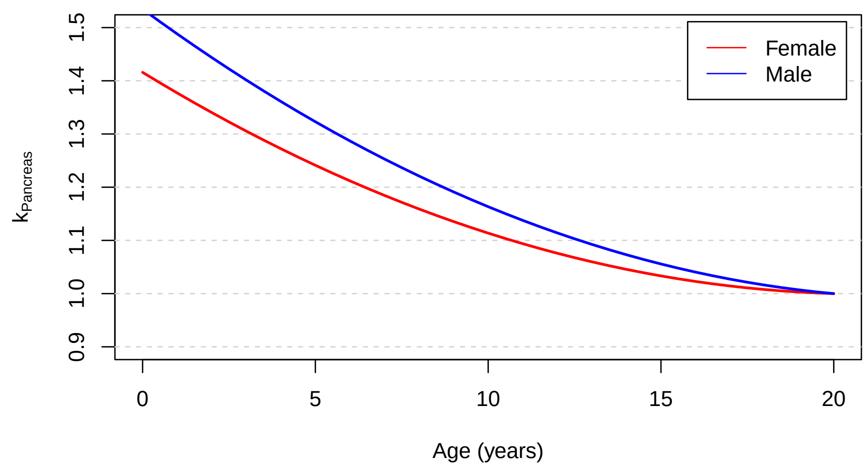


Figure 20. Values of $k_{\text{organ,sex}}$ for children (age $<$ 20) for Prostate.

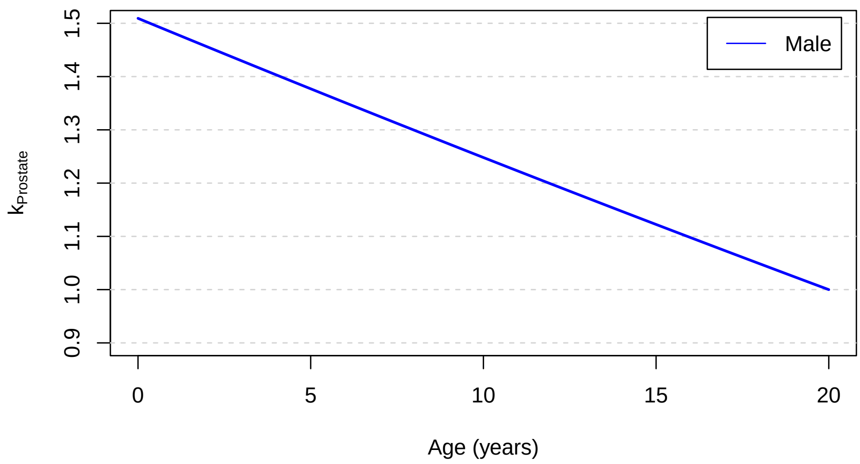


Figure 21. Values of $k_{\text{organ,sex}}$ for children (age $<$ 20) for R-marrow.

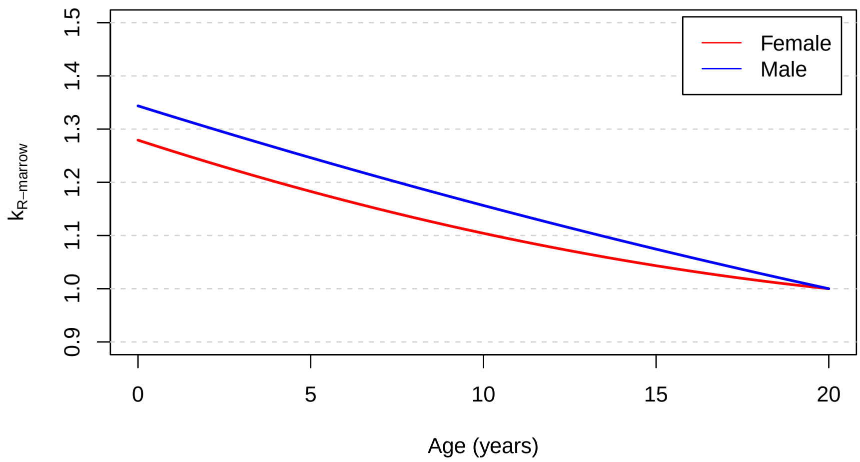


Figure 22. Values of $k_{\text{organ,sex}}$ for children (age $<$ 20) for Remainder.

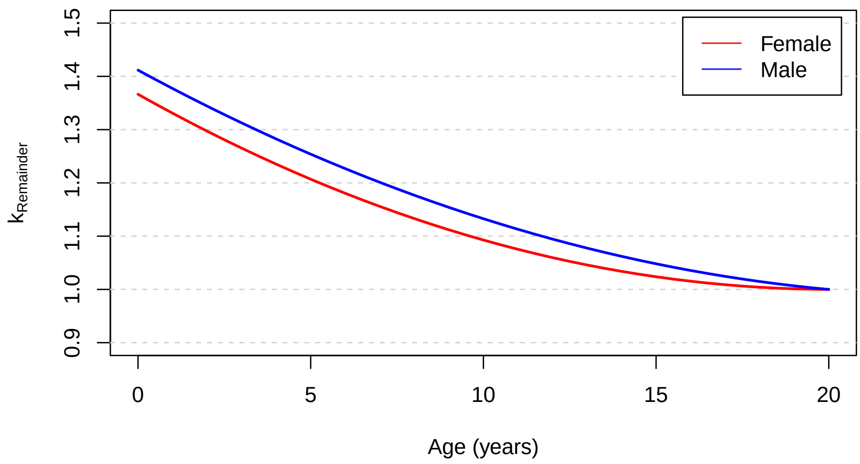


Figure 23. Values of $k_{\text{organ,sex}}$ for children (age < 20) for S-glands.

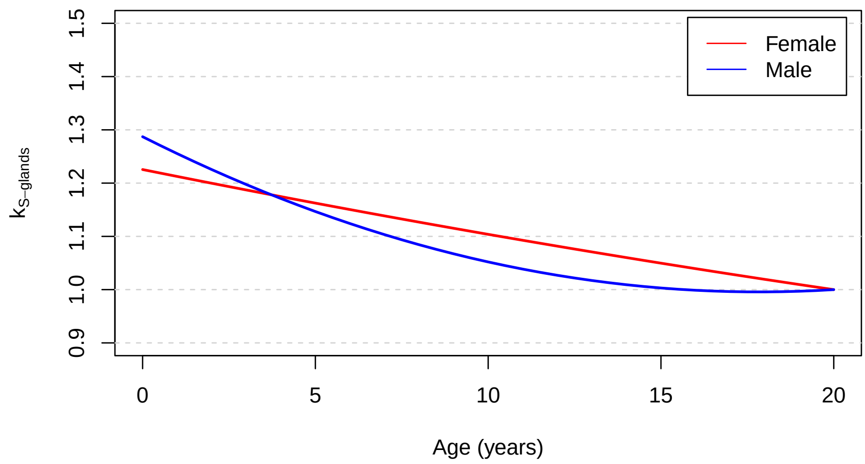


Figure 24. Values of $k_{\text{organ,sex}}$ for children (age < 20) for SI-stem.

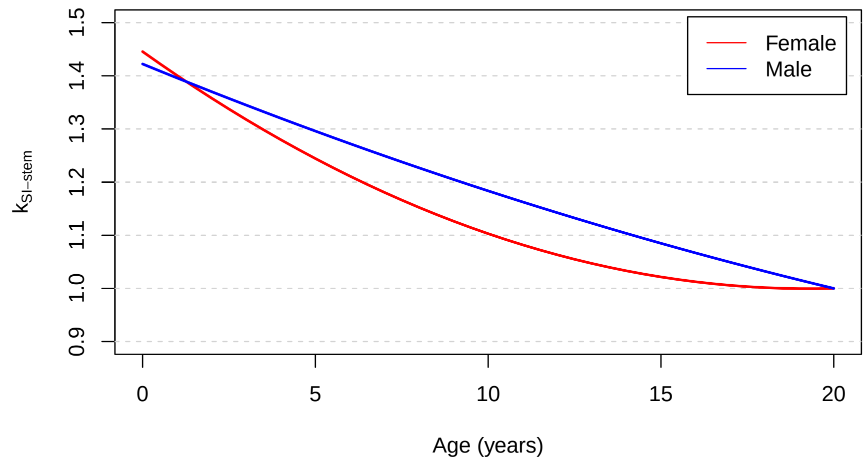


Figure 25. Values of $k_{\text{organ,sex}}$ for children (age < 20) for Skin.

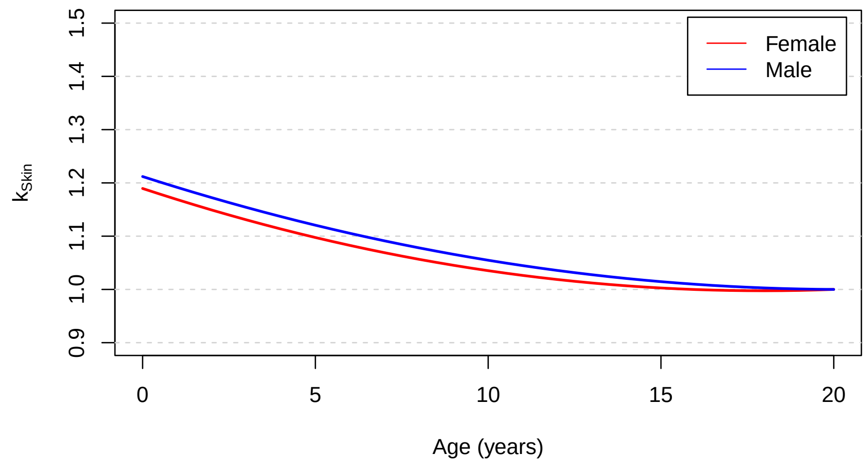


Figure 26. Values of $k_{\text{organ,sex}}$ for children (age < 20) for Spleen.

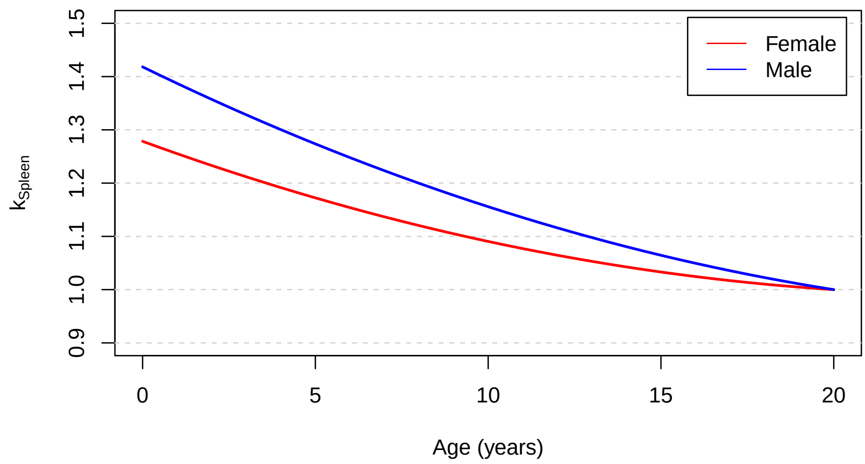


Figure 27. Values of $k_{\text{organ,sex}}$ for children (age < 20) for St-stem.

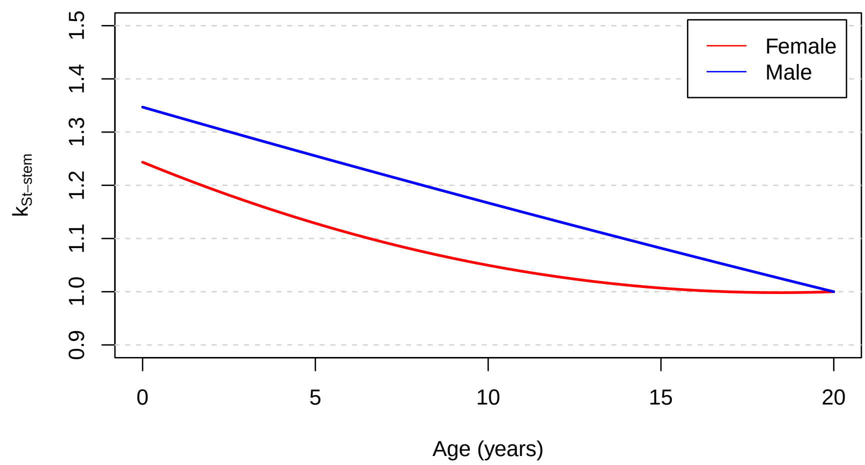


Figure 28. Values of $k_{\text{organ,sex}}$ for children (age < 20) for Testes.

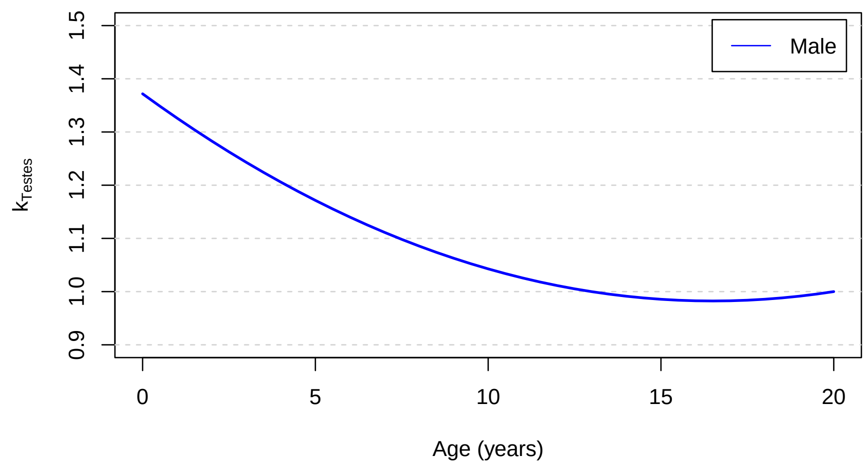


Figure 29. Values of $k_{\text{organ,sex}}$ for children (age < 20) for Thymus.

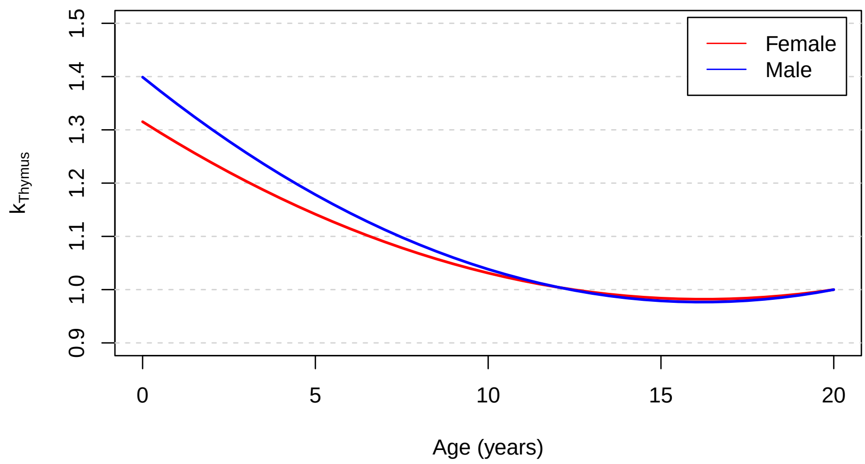


Figure 30. Values of $k_{\text{organ,sex}}$ for children (age < 20) for Thyroid.

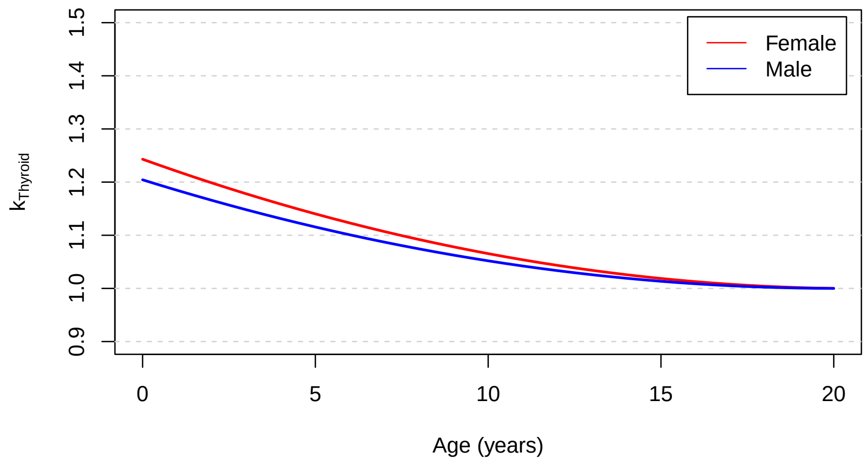


Figure 31. Values of $k_{\text{organ,sex}}$ for children (age < 20) for UB-wall.

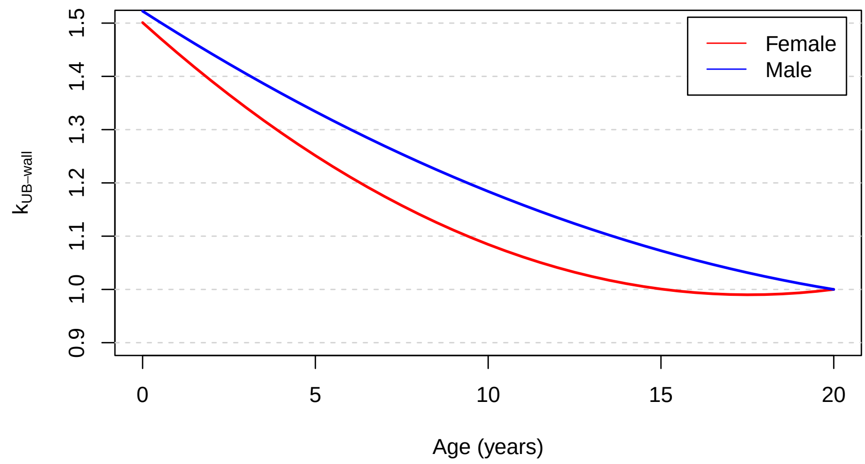
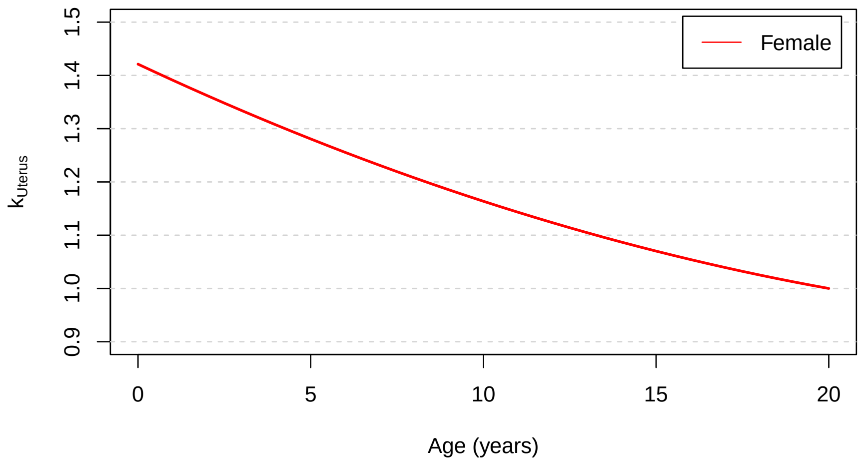


Figure 32. Values of $k_{\text{organ,sex}}$ for children (age < 20) for Uterus.



A.2.2 Weight as a function of age (age < 20)

Weight of children (age < 20) is modelled separately for female and male as a function of age by a polynomial. Coefficients of the polynomials can be found in Table 3.

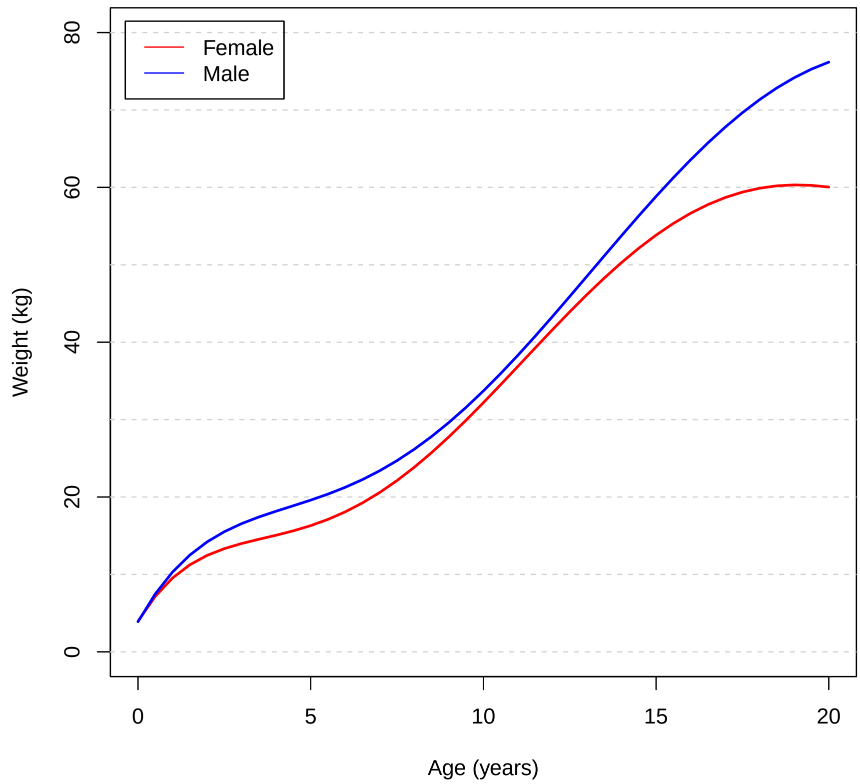


Figure 33. Weight of children (age < 20)

A.3 Calculation of coefficients for remainder

The external absorbed dose for remainder is calculated as an average external absorbed dose to the remaining organs. In our model, this is equivalent to calculating the external dose for the remainder directly using the coefficients derived from the coefficients of the remaining organs listed in Table 9 and Table 10. The calculation of the coefficients is presented below:

$$
\begin{aligned}
D_{\text{ext, remainder}}(t_i, t_{i+1}) =& \frac{1}{13} \sum_{\text{organ}=1}^{13} A_{\text{esd,municip}} \cdot d_{\text{Cs}} \cdot \phi_{\text{Kerma/H}} \cdot F_{\text{snow,county}} \cdot k_{\text{SEQ, organ,sex,ext}} \\
& \cdot (f_{\text{out}} + (1 - f_{\text{out}}) \cdot f_{\text{shield,municip}}) \cdot \int_{t_i}^{t_{i+1}} k_{\text{organ,sex}}(\text{age}(t)) \cdot r(t) \, \mathrm{d}t \\
=& \frac{1}{13} \sum_{\text{organ}=1}^{13} C_{\text{municip, county}} \cdot k_{\text{SEQ, organ,sex,ext}} \cdot \int_{t_i}^{t_{i+1}} k_{\text{organ,sex}}(\text{age}(t)) \cdot r(t) \, \mathrm{d}t \\
=& C_{\text{municip, county}} \cdot \frac{1}{13} \sum_{\text{organ}=1}^{13} k_{\text{SEQ, organ,sex,ext}} \cdot \\
& \int_{t_i}^{t_{i+1}} (a_{0,org} + a_{1,org} \cdot \text{age}(t) + a_{2,\text{org}} \cdot \text{age}(t)^2 + a_{3,\text{org}} \cdot \text{age}(t)^3) \cdot r(t) \, \mathrm{d}t \\
=& C_{\text{municip, county}} \cdot \frac{1}{13} \sum_{\text{organ}=1}^{13} k_{\text{SEQ, organ,sex,ext}} \cdot \\
& \left(\int_{t_i}^{t_{i+1}} a_{0,\text{org}} \cdot r(t) \, \mathrm{d}t + \int_{t_i}^{t_{i+1}} a_{1,\text{org}} \cdot \text{age}(t) \cdot r(t) \, \mathrm{d}t \right. \\
& \left. + \int_{t_i}^{t_{i+1}} a_{2,\text{org}} \cdot \text{age}(t)^2 \cdot r(t) \, \mathrm{d}t + \int_{t_i}^{t_{i+1}} a_{3,\text{org}} \cdot \text{age}(t)^3 \cdot r(t) \, \mathrm{d}t \right) \\
=& C_{\text{municip, county}} \cdot \\
& \left(\frac{1}{13} \sum_{\text{organ}=1}^{13} k_{\text{SEQ, organ,sex,ext}} \cdot a_{0,\text{org}} \cdot \int_{t_i}^{t_{i+1}} r(t) \, \mathrm{d}t \right. \\
& + \frac{1}{13} \sum_{\text{organ}=1}^{13} k_{\text{SEQ, organ,sex,ext}} \cdot a_{1,\text{org}} \cdot \int_{t_i}^{t_{i+1}} \text{age}(t) \cdot r(t) \, \mathrm{d}t \\
& + \frac{1}{13} \sum_{\text{organ}=1}^{13} k_{\text{SEQ, organ,sex,ext}} \cdot a_{2,\text{org}} \cdot \int_{t_i}^{t_{i+1}} \text{age}(t)^2 \cdot r(t) \, \mathrm{d}t \\
& \left. + \frac{1}{13} \sum_{\text{organ}=1}^{13} k_{\text{SEQ, organ,sex,ext}} \cdot a_{3,\text{org}} \cdot \int_{t_i}^{t_{i+1}} \text{age}(t)^3 \cdot r(t) \, \mathrm{d}t \right) \\
=& C_{\text{municip, county}} \cdot k_{\text{SEQ,remainder,sex,ext}} \cdot \\
& \left(\frac{1}{13} \cdot \frac{1}{k_{\text{SEQ,remainder,sex,ext}}} \sum_{\text{organ}=1}^{13} k_{\text{SEQ, organ,sex,ext}} \cdot a_{0,\text{org}} \cdot \int_{t_i}^{t_{i+1}} r(t) \, \mathrm{d}t \right. \\
& + \frac{1}{13} \cdot \frac{1}{k_{\text{SEQ,remainder,sex,ext}}} \sum_{\text{organ}=1}^{13} k_{\text{SEQ, organ,sex,ext}} \cdot a_{1,\text{org}} \cdot \int_{t_i}^{t_{i+1}} \text{age}(t) \cdot r(t) \, \mathrm{d}t \\
& + \frac{1}{13} \cdot \frac{1}{k_{\text{SEQ,remainder,sex,ext}}} \sum_{\text{organ}=1}^{13} k_{\text{SEQ, organ,sex,ext}} \cdot a_{2,\text{org}} \cdot \int_{t_i}^{t_{i+1}} \text{age}(t)^2 \cdot r(t) \, \mathrm{d}t \\
& \left. + \frac{1}{13} \cdot \frac{1}{k_{\text{SEQ,remainder,sex,ext}}} \sum_{\text{organ}=1}^{13} k_{\text{SEQ, organ,sex,ext}} \cdot a_{3,\text{org}} \cdot \int_{t_i}^{t_{i+1}} \text{age}(t)^3 \cdot r(t) \, \mathrm{d}t \right) \\
=& C_{\text{municip, county}} \cdot k_{\text{SEQ,remainder,sex,ext}} \cdot \\
& \left(a_{0,\text{rem}} \cdot \int_{t_i}^{t_{i+1}} r(t) \, \mathrm{d}t + a_{1,\text{rem}} \cdot \int_{t_i}^{t_{i+1}} \text{age}(t) \cdot r(t) \, \mathrm{d}t \right.
\end{aligned}
$$

$$+\ a_{2,\text{rem}} \cdot \int_{t_i}^{t_{i+1}} \text{age}(t)^2 \cdot r(t)\ \text{d}t + a_{3,\text{rem}} \cdot \int_{t_i}^{t_{i+1}} \text{age}(t)^3 \cdot r(t)\ \text{d}t \Big)$$

$$= C_{\text{municip, county}} \cdot k_{\text{SEQ,remainder,sex,ext}} \cdot \int_{t_i}^{t_{i+1}} \left(a_{0,\text{rem}} \cdot + a_{1,\text{rem}} \cdot \text{age}(t) + a_{2,\text{rem}} \cdot \text{age}(t)^2 \cdot + a_{3,\text{rem}} \cdot \text{age}(t)^3\right) \cdot r(t)\ \text{d}t,$$

where

$$C_{\text{municip, county}} = A_{\text{esd,municip}} \cdot d_{\text{Cs}} \cdot \phi_{\text{Kerma/H}} \cdot F_{\text{snow,county}} \cdot (f_{\text{out}} + (1 - f_{\text{out}}) \cdot f_{\text{shield,municip}})$$

$$k_{\text{SEQ,remainder,sex,ext}} = \frac{1}{13} \sum_{\text{organ}=1}^{13} k_{\text{SEQ, organ,sex,ext}},$$

$$a_{0,\text{rem}} = \frac{1}{13} \cdot \frac{1}{k_{\text{SEQ,remainder,sex,ext}}} \sum_{\text{organ}=1}^{13} k_{\text{SEQ, organ,sex,ext}} \cdot a_{0,\text{org}},$$

$$a_{1,\text{rem}} = \frac{1}{13} \cdot \frac{1}{k_{\text{SEQ,remainder,sex,ext}}} \sum_{\text{organ}=1}^{13} k_{\text{SEQ, organ,sex,ext}} \cdot a_{1,\text{org}},$$

$$a_{2,\text{rem}} = \frac{1}{13} \cdot \frac{1}{k_{\text{SEQ,remainder,sex,ext}}} \sum_{\text{organ}=1}^{13} k_{\text{SEQ,organ,sex,ext}} \cdot a_{2,\text{org}},$$

$$a_{3,\text{rem}} = \frac{1}{13} \cdot \frac{1}{k_{\text{SEQ,remainder,sex,ext}}} \sum_{\text{organ}=1}^{13} k_{\text{SEQ,organ,sex,ext}} \cdot a_{3,\text{org}}.$$

A.4 LAR coefficients

A.4.1 Organ cancer risk coefficients

Table 12. LAR for cancer incidence[1] by age at exposure for males. The coefficients are from Table 3-12a in EPA (2011). In addition, we set coefficient to 0 at age 100. N.B. A Dose and Dose Rate Effectiveness Factor (DDREF) of 1.5 is applied by EPA for all cancer sites other than leukemia, bone, and skin. Nonfatal skin cancers are excluded.

Cancer site	Age at exposure											
	0	5	10	15	20	30	40	50	60	70	80	100
Stomach	168.0	139	114.0	94.0	77.0	51	48.0	43.0	35.0	24.0	12	0
Colon	342.0	292	248.0	210.0	179.0	129	126.0	117.0	97.0	65.0	29	0
Liver	103.0	86	71.0	59.0	49.0	34	33.0	29.0	24.0	17.0	9	0
Lung	320.0	268	222.0	185.0	154.0	108	107.0	104.0	90.0	65.0	35	0
Prostate	198.0	172	148.0	127.0	110.0	82	83.0	80.0	61.0	30.0	9	0
Urinary bladder	219.0	188	159.0	135.0	116.0	84	84.0	81.0	71.0	50.0	24	0
Thyroid	123.0	107	58.0	32.0	23.0	11	5.0	2.0	1.0	0.0	0	0
Residual	1180.0	653	498.0	394.0	313.0	199	174.0	142.0	101.0	58.0	24	0
Kidneys	102.0	55	44.0	37.0	31.0	22	20.0	16.0	11.0	6.0	2	0
Bone	10.4	8	6.1	4.6	3.5	2	1.1	0.6	0.3	0.1	0	0
Skin	1720.0	917	484.0	256.0	136.0	38	10.0	3.0	1.0	0.0	0	0
Solid	2760.0	1970	1570.0	1280.0	1050.0	722	682.0	616.0	492.0	314.0	144	0
Leukemia	193.0	142	112.0	97.0	89.0	78	79.0	83.0	88.0	87.0	64	0
All sites	2950.0	2110	1680.0	1370.0	1140.0	801	761.0	699.0	580.0	402.0	208	0

[1]Cases per 10 000 person-Gy.

Table 13. LAR for cancer incidence[1] by age at exposure for females. The coefficients are from Table 3-12b in EPA (2011). In addition, we set coefficient to 0 at age 100. N.B. A Dose and Dose Rate Effectiveness Factor (DDREF) of 1.5 is applied by EPA for all cancer sites other than leukemia, bone, and skin. Nonfatal skin cancers are excluded.

Cancer site	Age at exposure											
	0	5	10	15	20	30	40	50	60	70	80	100
Stomach	212.0	175	144.0	118.0	97.0	64.0	61.0	55.0	46.0	33.0	18	0
Colon	225.0	193	164.0	139.0	118.0	84.0	82.0	76.0	65.0	46.0	23	0
Liver	57.0	47	39.0	32.0	26.0	18.0	18.0	16.0	14.0	10.0	6	0
Lung	785.0	660	552.0	462.0	387.0	272.0	269.0	255.0	217.0	150.0	79	0
Breast	1260.0	982	761.0	588.0	454.0	265.0	146.0	72.0	32.0	12.0	4	0
Uterus	66.0	55	46.0	38.0	31.0	21.0	19.0	16.0	12.0	8.0	4	0
Ovary	91.0	77	64.0	53.0	45.0	31.0	28.0	24.0	17.0	11.0	5	0
Urinary bladder	221.0	189	161.0	137.0	116.0	84.0	83.0	78.0	67.0	48.0	24	0
Thyroid	386.0	352	196.0	106.0	73.0	30.0	12.0	4.0	1.0	0.0	0	0
Residual	1410.0	707	534.0	422.0	336.0	213.0	184.0	151.0	112.0	69.0	31	0
Kidneys	133.0	53	41.0	34.0	28.0	20.0	17.0	14.0	10.0	5.0	2	0
Bone	10.4	8	6.1	4.7	3.6	2.1	1.2	0.6	0.3	0.1	0	0
Skin	972.0	517	273.0	144.0	76.0	21.0	6.0	2.0	0.0	0.0	0	0
Solid	4850.0	3500	2710.0	2130.0	1720.0	1100.0	920.0	764.0	594.0	393.0	195	0
Leukemia	173.0	117	88.0	75.0	69.0	60.0	61.0	63.0	65.0	63.0	47	0
All sites	5020.0	3620	2800.0	2210.0	1780.0	1160.0	981.0	827.0	659.0	456.0	242	0

[1]Cases per 10 000 person-Gy.

A.4.2 Plots of LAR coefficients by age

Figure 34. LAR for cancer incidence to All sites (per 10 000 person-Gy) by sex and age at exposure.

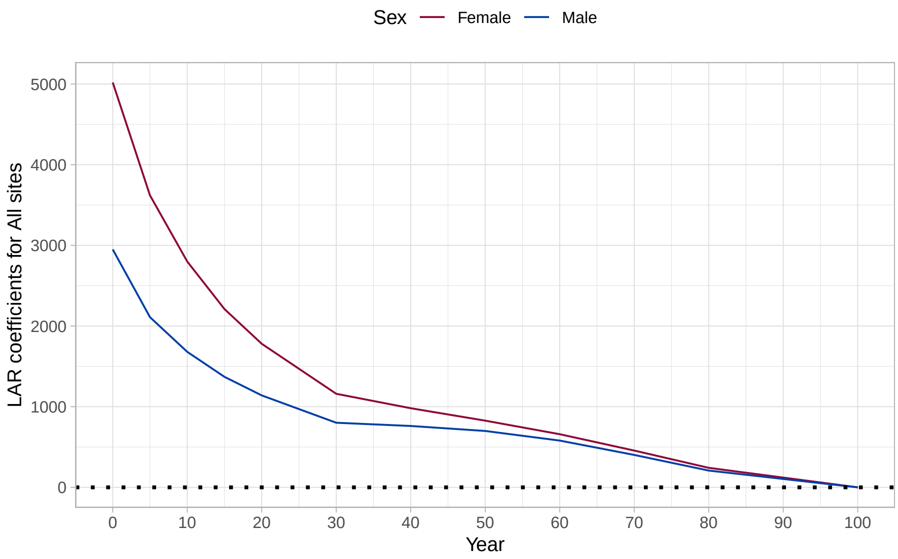


Figure 35. LAR for cancer incidence to Bone (per 10 000 person-Gy) by sex and age at exposure.

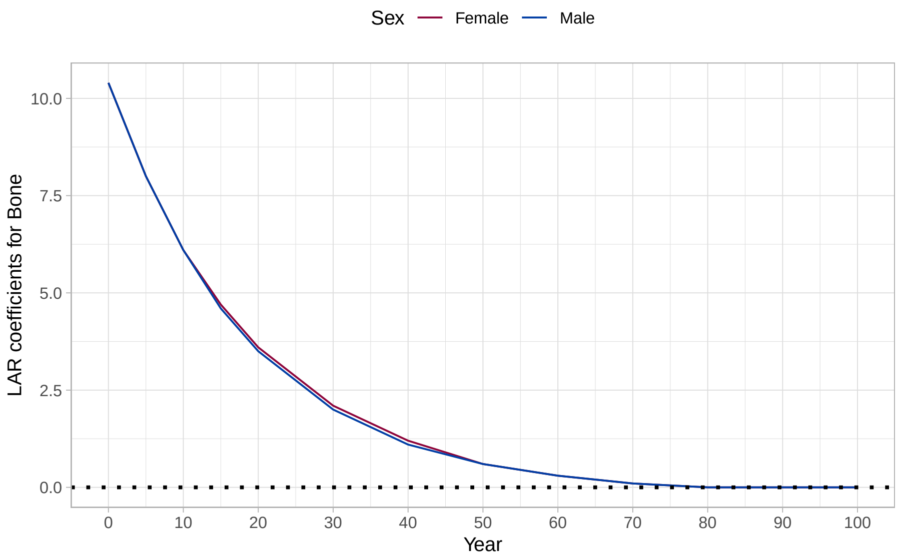


Figure 36. LAR for cancer incidence to Breast (per 10 000 person-Gy) by age at exposure.

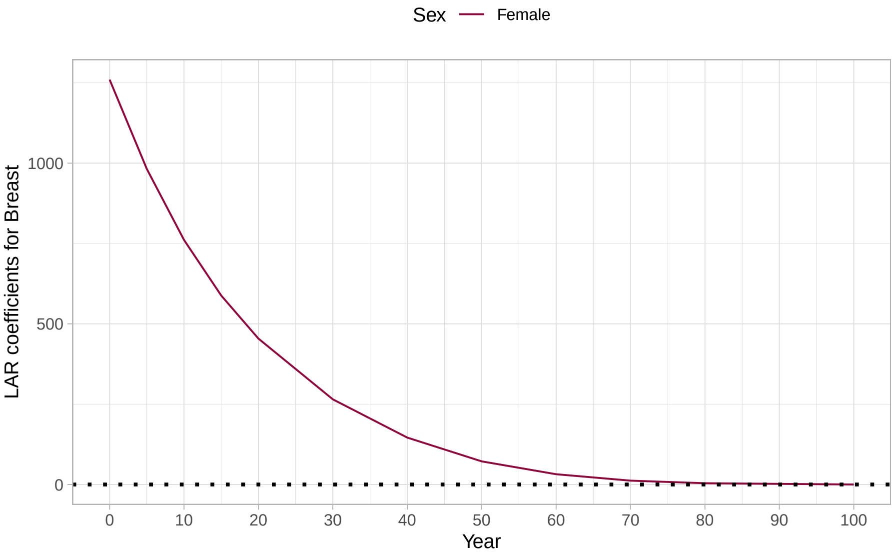


Figure 37. LAR for cancer incidence to Colon (per 10 000 person-Gy) by sex and age at exposure.

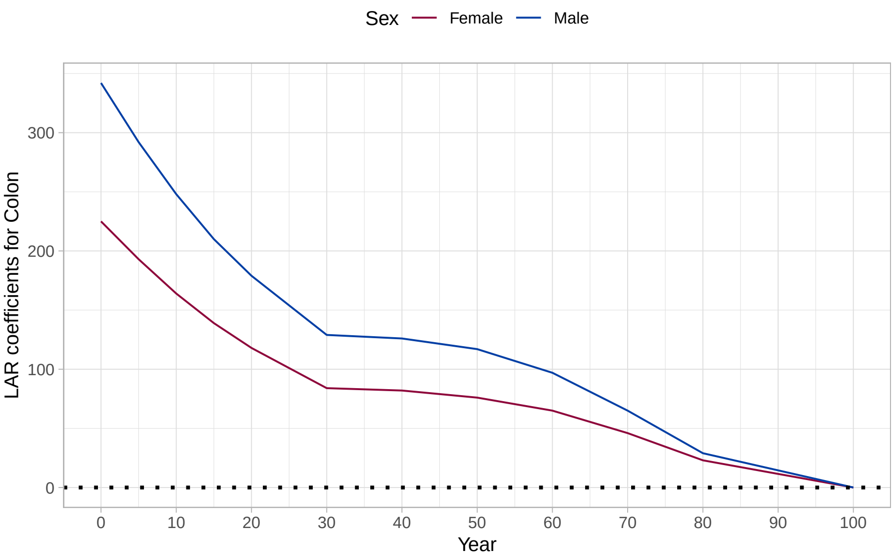


Figure 38. LAR for cancer incidence to Kidneys (per 10 000 person-Gy) by sex and age at exposure.

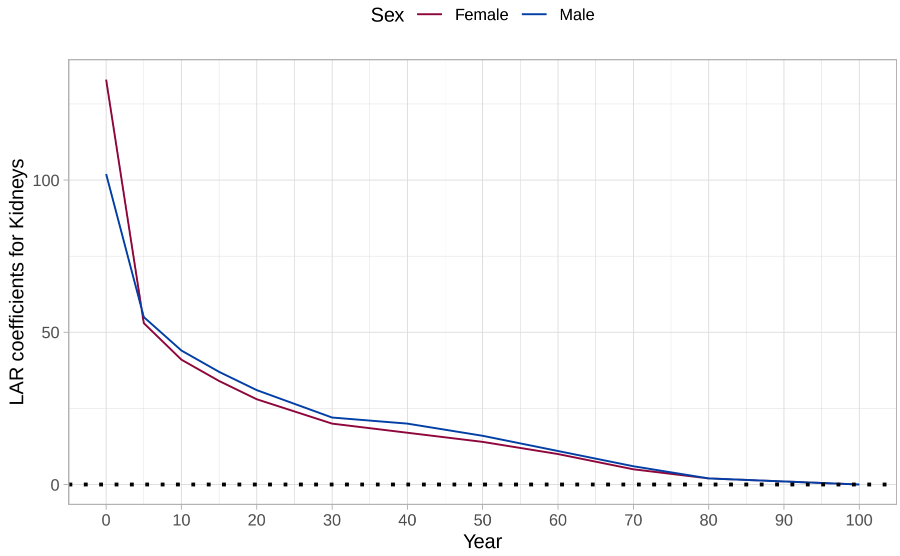


Figure 39. LAR for cancer incidence to Leukemia (per 10 000 person-Gy) by sex and age at exposure.

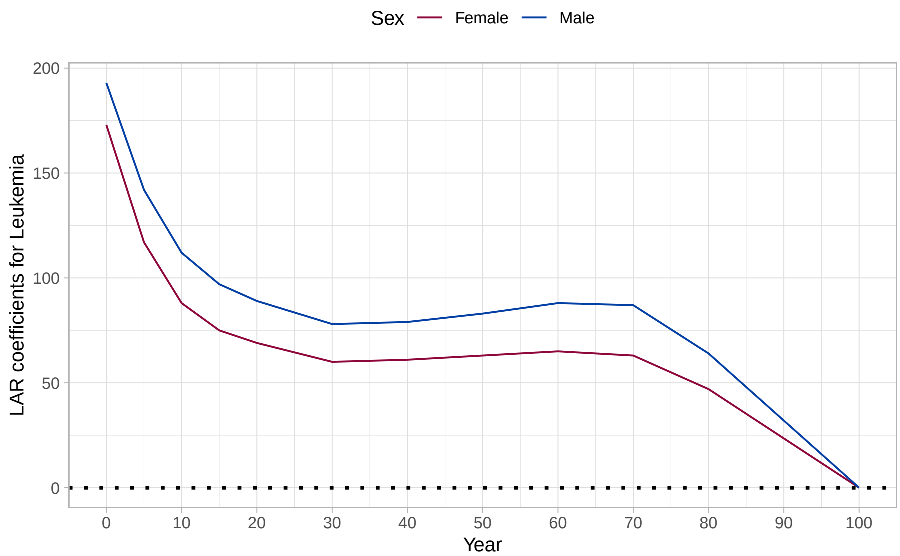


Figure 40. LAR for cancer incidence to Liver (per 10 000 person-Gy) by sex and age at exposure.

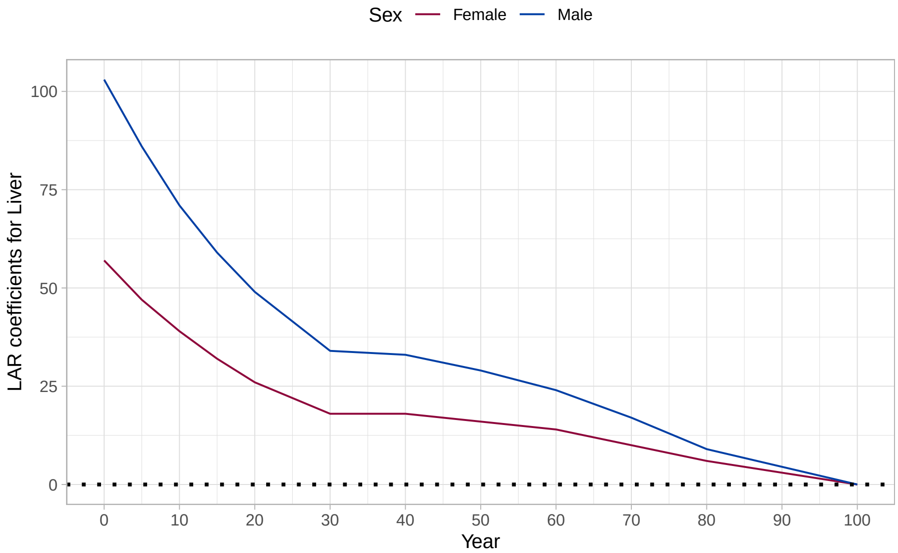


Figure 41. LAR for cancer incidence to Lung (per 10 000 person-Gy) by sex and age at exposure.

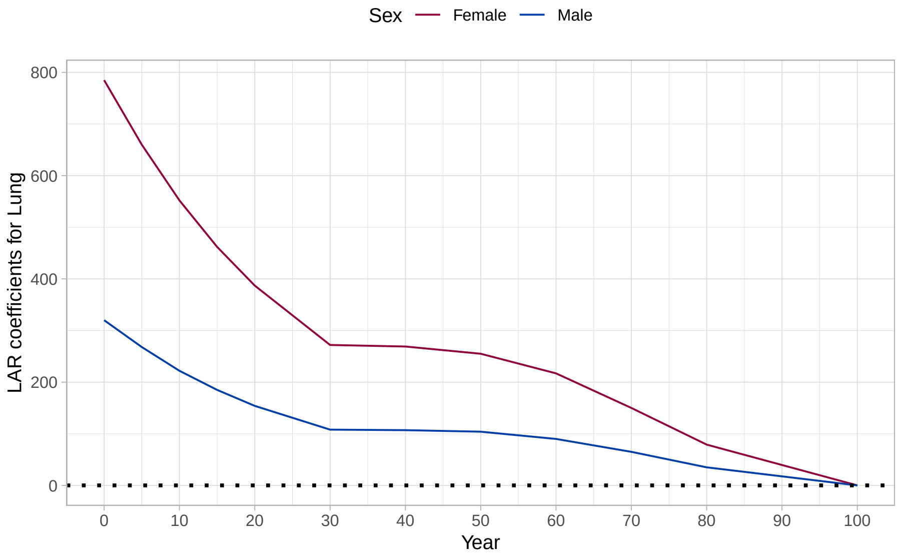


Figure 42. LAR for cancer incidence to Ovary (per 10 000 person-Gy) by age at exposure.

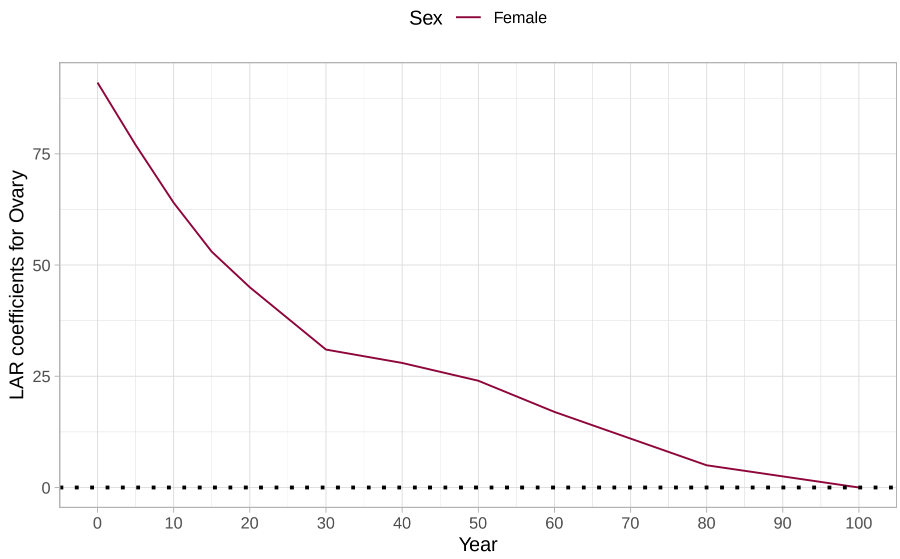


Figure 43. LAR for cancer incidence to Prostate (per 10 000 person-Gy) by age at exposure.

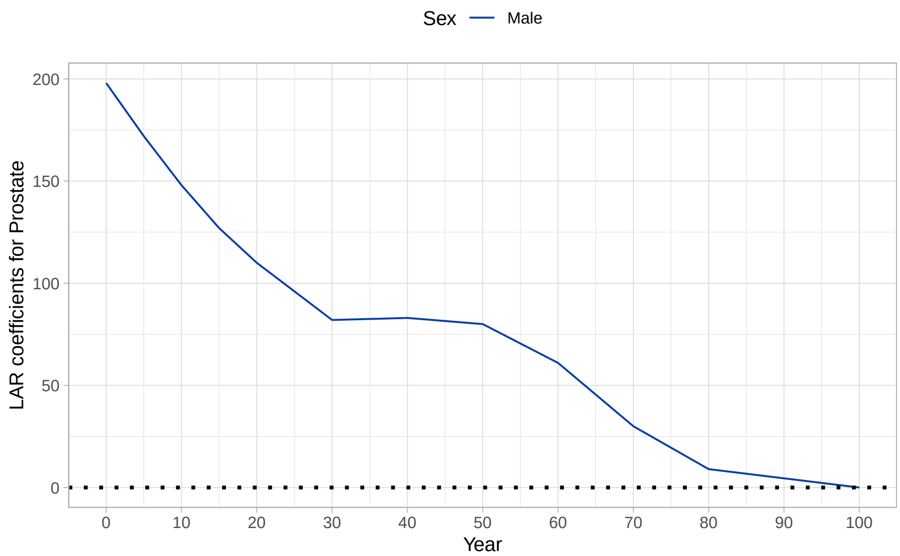


Figure 44. LAR for cancer incidence to Residual (per 10 000 person-Gy) by sex and age at exposure.

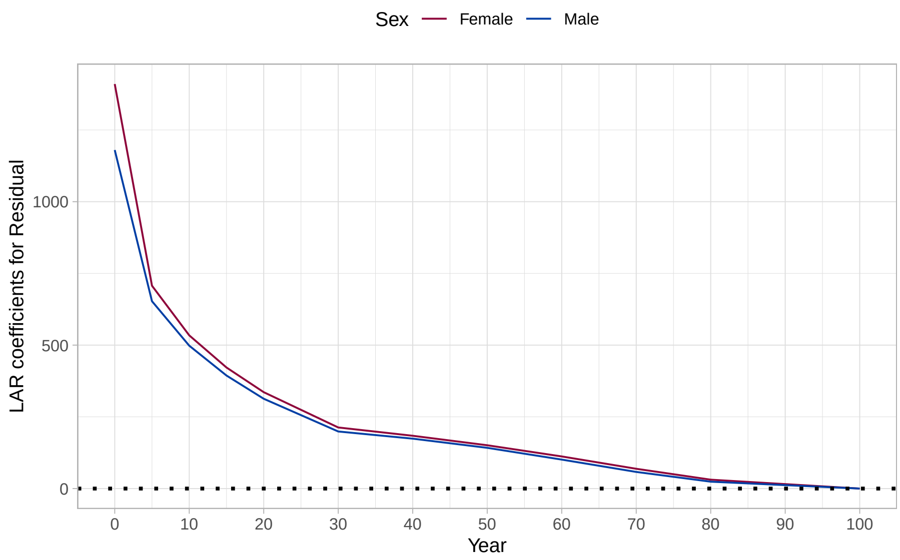


Figure 45. LAR for cancer incidence to Skin (per 10 000 person-Gy) by sex and age at exposure.

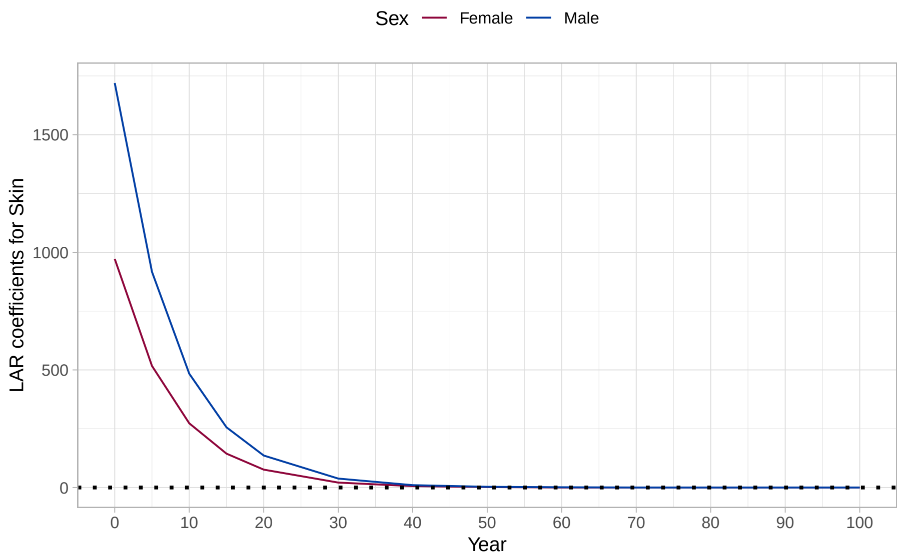


Figure 46. LAR for cancer incidence to Solid (per 10 000 person-Gy) by sex and age at exposure.

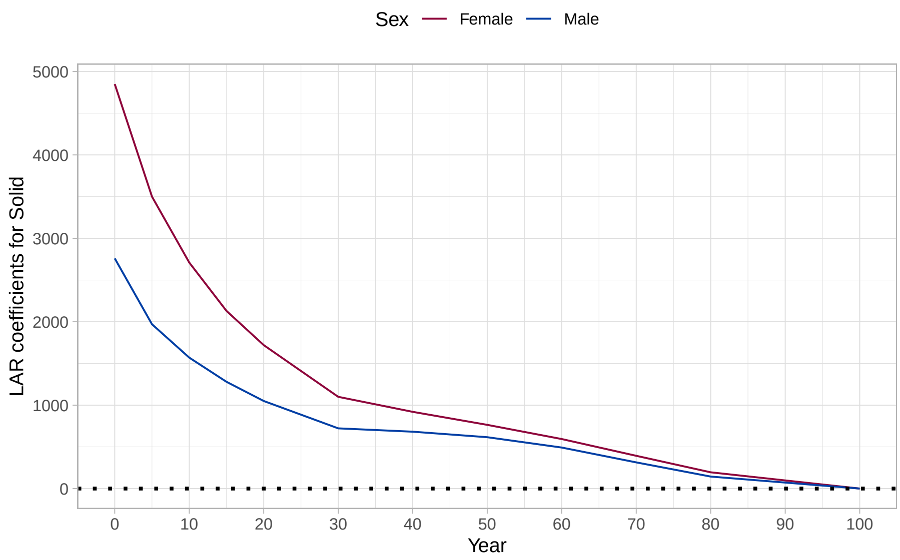


Figure 47. LAR for cancer incidence to Stomach (per 10 000 person-Gy) by sex and age at exposure.

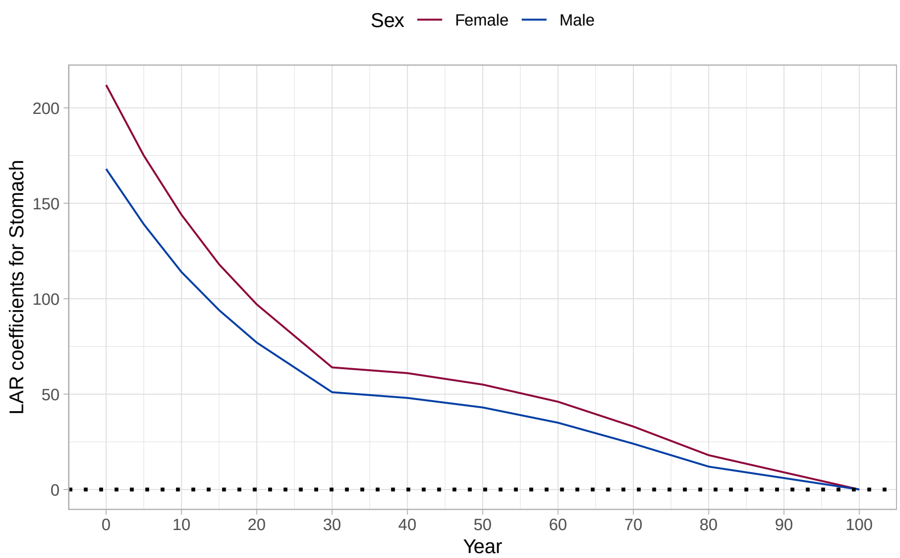


Figure 48. LAR for cancer incidence to Thyroid (per 10 000 person-Gy) by sex and age at exposure.

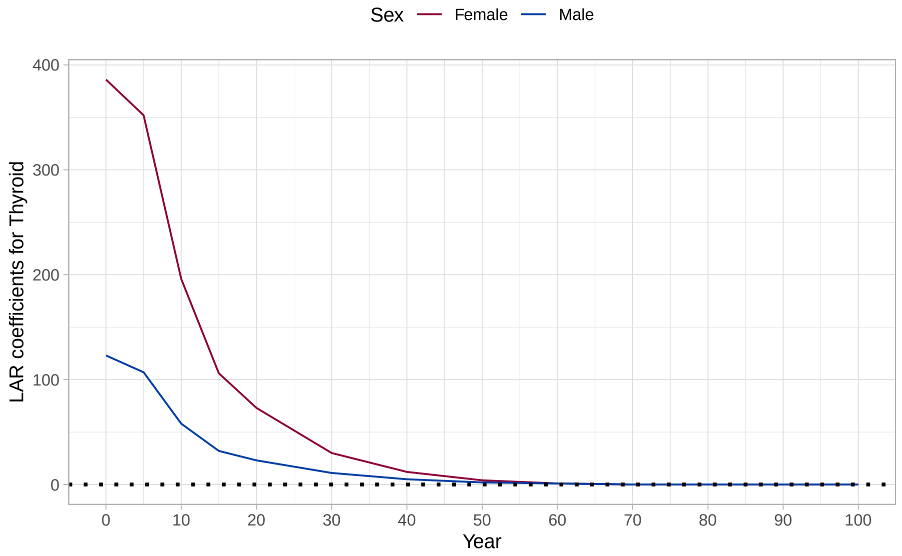


Figure 49. LAR for cancer incidence to Urinary bladder (per 10 000 person-Gy) by sex and age at exposure.

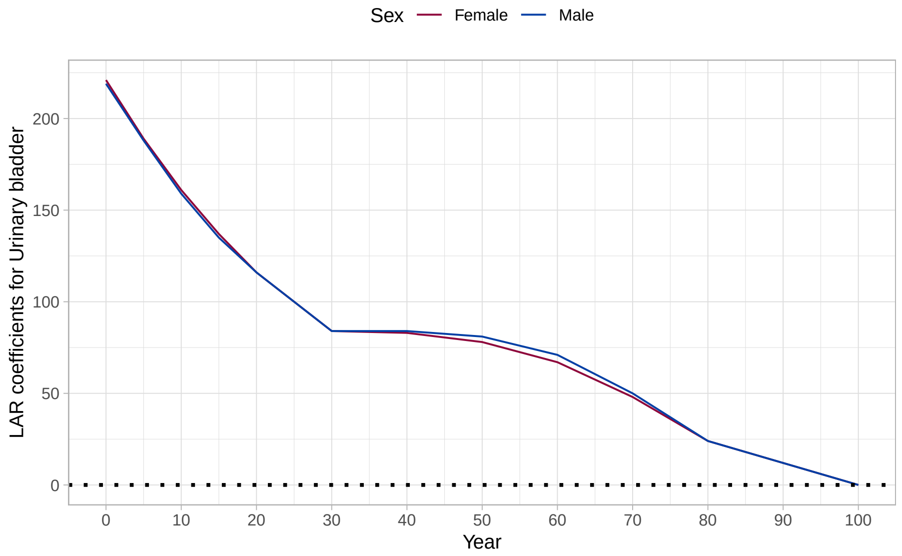


Figure 50. LAR for cancer incidence to Uterus (per 10 000 person-Gy) by age at exposure.