

Radiation Doses and Lifetime Attributable Risk of Cancer in Sweden after the Chernobyl Nuclear Power Plant Accident

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Abstract—Methods for estimating radiological consequences in terms of radiation doses and cancer risks are needed for informed decisions on mitigation efforts after a radionuclide event. The 1986 Chernobyl Nuclear Power Plant accident fallout in Sweden was used as a case study. Open-source data on annual sex-specific population data in 1-y classes by municipality (n=290), counties (n=21), and future projection were retrieved from Statistics Sweden from 1986 to 2035. Published organ dose coefficients, cancer risk coefficients, and established methods for dose calculations and cancer risk projections were applied to estimate organ absorbed doses (mGy), effective dose (mSv), collective dose (person-Sv), and lifetime attributable risk (LAR). Due to the geographically variable Chernobyl fallout in Sweden, the variability in absorbed organ doses was greater between municipalities and counties than between organs or sexes. LAR was translated into 377 male and 448 female extra cancer cases over 50 y post-Chernobyl. Overall, 38% of these cancer cases could be attributed to the internal dose in males and 32% in females. The highest number of cancer cases was estimated for Västernorrland county, with only 3% of the Swedish population in 1986, but 18% of the excess cancer cases 1986 to 2035. The collective dose was calculated to 6,028 person-Sv, whereas 2,148 person-Sv (36%) was internal dose. Like for LAR, the population of Västernorrland county got 18% of the total collective dose. The excess number of cancer

cases derived from LAR and collective dose gave similar results. Our methods can be adopted to other countries and different fallout scenarios.

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Keywords: cancer; Chernobyl; dose, absorbed; health effects

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 during a 10-d period with an estimated release of 1,760 PBq ¹³¹I, 85 PBq ¹³⁷Cs and 54 PBq ¹³⁴Cs, but also many short-lived radionuclides (UNSCEAR 2000). A gamma monitoring station at the southern tip of the island of Öland southeast of Sweden recorded an increased dose rate at 7 pm on 27 April 1986 (Kjelle 1986). At first, the nearby island of Gotland was mainly affected by a dry deposition of ¹³¹I resulting in the highest recorded concentration in the Swedish dairy milk. Therefore, grazing was interrupted or stopped when the Chernobyl plume reached the Swedish mainland with a subsequent mitigation of the transfer of ¹³¹I into dairy milk in most counties, but cows were still exposed through inhalation of ¹³¹I in the air when staying indoors in the stables (Devell et al. 1986; Rääf et al. 2019). Due to heavy rainfall, a relatively high fallout of ¹³¹I and radiocesium occurred on the coastal area north of Stockholm from 28 to 29 April 1986. Therefore, the deposition of ¹³⁷Cs was unequally distributed over Sweden from 1 to more than 100 kBq m⁻², in addition to remaining ¹³⁷Cs from the atmospheric nuclear weapons tests of 2–3 kBq m⁻² (Andersson 2007; SRSA 2024).

In one of their very first reports from May 1986, the World Health Organization (WHO) assessed that the radiation levels outside the Union of Soviet Socialist Republics (USSR) was too small to cause any acute radiation effects, but they identified that late effects such as

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cancer could occur. However, the WHO also concluded it was not possible to assess the overall health impact of the contamination unless the distribution of the ^{137}Cs deposition was better known (WHO 1986). In Sweden, it has been estimated that 23 PBq of ^{131}I , 4.25 PBq of ^{137}Cs , and 2.5 PBq of ^{134}Cs was deposited, representing 1.3%, 5.0% and 4.6%, respectively, of these released radionuclides from the Chernobyl NPP accident (UNSCEAR 2000; Mattsson and Moberg 1991).

The very first attempt to estimate the 50-y collective dose to the Swedish population was done in June 1986 giving a more precise, but still uncertain, estimation of a collective dose between 4,000 to 6,000 person-Sv published in December 1986 (Finck et al. 1986). These estimates could at this stage only include dose contribution from inhalation and external irradiation due to the scarcity of data on contaminated foodstuffs. Swedish cancer researchers, using these early assessments of the collective dose, estimated that 340 incident cancer cases and 170 fatal cases might be a result in Sweden from the Chernobyl fallout over a 50-y period (Holm et al. 1986). To predict the latent health effects, a first estimate of collective dose in Europe outside the USSR was presented by Anspaugh et al. (1988) with a collective 50-y dose estimate of 580,000 person-Gy and corresponding to an estimated 10,400 fatal cancers cases. The 50-y collective dose to the Swedish population was estimated at 9,200 person-Gy with a fraction of external dose of 52% (Anspaugh et al. 1988). The most recent revised estimate of the collective population dose in Sweden after the Chernobyl NPP accident has been calculated to 6,000 person-Sv during 50 y; 1,000 person-Sv by internal route and 5,000 person-Sv from external radiation (Edvarson 1991; Falk et al. 1991). The estimated collective dose of 6,000 person-Sv was translated to about 300 extra cancer deaths in the time period 1986 to 2036 (Moberg et al. 1993). However, more thorough data on aerial measurements of ^{137}Cs deposition and additional data from whole body counter measurements, together with more and better modeling of data, have made it possible for a more precise estimate of collective dose (person-Sv) as well as calculation of lifetime attributed risks (LAR) in Sweden after the Chernobyl NPP accident.

In this study, 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 nine most northern counties of Sweden (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.

MATERIALS AND METHODS

Population

In this study, we used the total annual Swedish population in the time period 31 December 1985 to 31 December 2035. For the years 1986 to 2023, we have exact data from Statistics Sweden as of 2024, and for the years 2024 to 2036 we rely on a population forecast done by Statistics Sweden (2024a and b). For each year, there is a number of citizens in each municipality (290 municipalities) categorized by sex (male, female) and by age (0, 1, 2, . . . , 99, 100+ years). We assume that the population on December 31 applies for the period from July 1 of the same year to June 30 of the following year. The data on the population statistics were downloaded on 12 August 2024 from the webpage of Statistics Sweden using the Application Programming Interface (API) with the R package pxweb (Magnusson et al. 2019). The population stratified by sex is presented in Fig. 1.

Proportion of hunter households

In the model estimating the organ absorbed dose, hunters and members of hunter households are assumed 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, they will regularly be exposed to a diet containing higher concentrations of ^{137}Cs (Ågren 1998). Therefore, the transfer factor ($T_{ag,max,Cs}$) differs between hunters (29.3) and non-hunters (11.0) and was also applied to households, respectively. 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 nine counties was obtained from a register of license holders of hunting weapons, and the proportion of hunters in these municipalities was calculated (Tondel

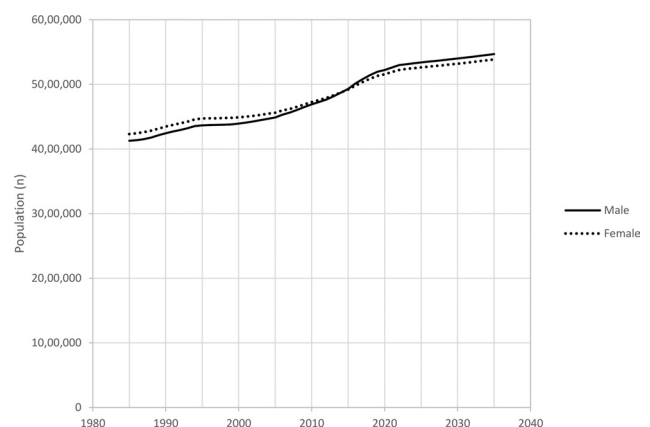


Fig. 1. Total number of inhabitants in Sweden stratified by sex 1986 to 2023 and a forecast for the years 2024 to 2036.

et al. 2022). For the remaining 12 counties in Sweden, the proportion of male hunters was calculated in the same way, as the number of male hunters living in these counties divided by the total number of males older than 18 y of age in 1986. There were 55,678 hunters and 2,336,883 male adults, which gives an average of 2.38% hunters in the municipalities in these 12 counties. The same hunter proportion is applied for males, females, and children, for all age categories, and for every year in the calculations (Tondel et al. 2025).

Organ absorbed doses (mGy)

The method for calculation of absorbed organ doses in this study is an extended and updated version of a previous manual (Tondel et al. 2023a). The organs included in the absorbed dose calculations follow the ones proposed by the National Cancer Institute (NCI) to be prone to develop cancer after radiation exposure and have therefore been used in a previous methodological paper (Isaksson et al. 2021). The organ dose coefficients for the external effective dose have been published previously by Rääf et al. (2020) and have recently been updated by ICRP (2020). Hence, we could calculate organ absorbed doses from both external and internal exposure. The internal exposure of body organs to the Chernobyl fallout was predominantly by radiocesium (^{134}Cs and ^{137}Cs). However, the exposure of the thyroid to the Chernobyl fallout is different from other organs in the body because it also includes contribution from ^{131}I exposure through inhalation and dairy milk (e.g., Rääf et al. 2019). The organ absorbed dose is calculated for the time period 28 April 1986 until 27 April 2036. In order to use the annual population size in the models, we divided this 50-y period in the shorter time intervals: from 28 April 1986 to 30 June 1986, annual intervals from July 1 to June 30 of the following year, and from 1 July 2035 to 27 April 2036. We denote these shorter intervals as (t_{i-1}, t_i) , where $t_0 = 0$ (28 April 1986) and $t_{51} = 50$ (27 April 2036).

External dose

The absorbed dose from external gamma radiation exposure to a specific organ during any time interval t_{i-1} to t_i can be estimated by eqn (1):

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

where:

$A_{\text{esd,municip}}$ = the average deposition of ^{137}Cs in each municipality (kBq m^{-2});

d_{Cs} = a constant with a value of 1.017 (mSv y^{-1}) / (kBq m^{-2}). The rationale for this coefficient is given by Jönsson et al. (2017);

$\phi_{\text{Kerma}/H}$ = the ratio between air kerma and ambient dose equivalent for 600 keV photons $0.83 \text{ mGy mSv}^{-1}$ (Portal et al. 1992);

$f_{\text{shield, snow, county}}$ = the average snow shielding factor by county;

$k_{\text{SEQ,organ,sex,ext}}$ = the sex-specific external organ dose coefficient;

f_{out} = the annual average proportion of outdoor stay;

$f_{\text{shield, municip}}$ = the building shielding factor by municipality;

$k_{\text{organ,sex}}(\text{age}(t))$ = the age dependent organ dose coefficient correcting for ages <20 years; and

$r(t)$ = a normalized function describing the decrease in ambient dose equivalent rate with time. All parameter values can be found in the dose calculation manual (Tondel et al. 2025).

Internal dose

The internal absorbed dose to a specific body organ during any time interval from t_{i-1} to t_i from ingestion is estimated by eqn (2):

$$D_{\text{ing,organ}}(t_{i-1}, t_i) = A_{\text{esd, county}} \cdot T_{\text{ag,max,Cs}} \cdot S_{\text{alim,ent}} \cdot \int_{t_{i-1}}^{t_i} \left(1 - e^{-\frac{\ln(2)}{\tau_1} \cdot t}\right) \cdot \left(c_1 \cdot e^{-\frac{\ln(2)}{\tau_2} \cdot t} + c_2 \cdot e^{-\frac{\ln(2)}{\tau_3} \cdot t}\right) \cdot f_{\text{sex}}(\text{age}(t)) \cdot \left(C_{\text{S-137,organ,sex}} \cdot w_{\text{sex}}(\text{age}(t)) \cdot \left(\frac{w_{\text{sex}}(\text{age}(t))}{w_{\text{adult,sex}}}\right)^{-0.889} + FR \cdot C_{\text{S-134,organ,sex}} \cdot w_{\text{sex}}(\text{age}(t)) \cdot \left(\frac{w_{\text{sex}}(\text{age}(t))}{w_{\text{adult,sex}}}\right)^{-0.812} \cdot e^{-\left(\frac{\ln(2)}{\tau_1/2, \text{Cs-134}} - \frac{\ln(2)}{\tau_1/2, \text{Cs-137}}\right) \cdot t}\right) dt, \quad (2)$$

where:

$A_{\text{esd, county}}$ = the average deposition of ^{137}Cs in each county (kBq m^{-2});

$T_{\text{ag,max,Cs}}$ is the transfer factor from ground to body concentration of ^{137}Cs (Bq kg^{-1}) / (kBq m^{-2}), that differ between hunter households (29.3) and non-hunter households (11.0);

$S_{\text{alim,ent}}$ = a factor describing the effects of countermeasures to reduce the transfer to humans of radionuclides through foodstuff;

$\tau_1 - \tau_3$ and $c_1 - c_2$ = the time dependency of the transfer factors that differ between hunter households and non-hunter households;

$f_{\text{sex}}(\text{age}(t))$ = the average sex difference in food consumption;

$\epsilon_{\text{Cs-137,organ,sex}}$ = the sex-specific internal organ dose coefficient for ^{137}Cs [$\text{mGy}/(\text{Bq y})$];

$\epsilon_{\text{Cs-134,organ,sex}}$ = the sex-specific internal organ dose coefficient for ^{134}Cs [$\text{mGy}/(\text{Bq y})$];

FR = the isotopic ratio $^{134}\text{Cs}/^{137}\text{Cs}$ in the Chernobyl fallout over Sweden;

$w_{\text{adult,sex}}$ = the average body weight for adults by sex (kg);

$w_{sex}(age(t))$ = the age dependent weight of persons <20 y (kg);

$T_{\frac{1}{2}Cs-134}$ = the physical half-life of ^{134}Cs (y); and

$T_{\frac{1}{2}Cs-137}$ = the physical half-life of ^{137}Cs (y). All parameter values and their rationales can be found in the dose calculation manual (Tondel et al. 2025).

Total dose

The total absorbed dose in any time interval t_{i-1} to t_i , after 28 April 1986, is the sum of the external and internal dose as described in eqn (3):

$$D_{tot,organ}(t_{i-1}, t_i) = D_{ext,organ}(t_{i-1}, t_i) + D_{ing,organ}(t_{i-1}, t_i), \quad (3)$$

where $D_{tot,organ}(t_{i-1}, t_i)$ is the total organ absorbed dose from external radiation $D_{ext,organ}(t_{i-1}, t_i)$ and internal radiation $D_{ing,organ}(t_{i-1}, t_i)$.

Equation (3) can be used for all organs except for the thyroid, where there is a significant contribution from ^{131}I from milk and inhalation. Due to the short half-life of ^{131}I ($T_{\frac{1}{2}} = 8$ d), this contribution only applies to the first 50 d (0.14 y) after 28 April 1986. Therefore, to calculate the total absorbed thyroid dose in the time interval 28 April 1986 ($t_0 = 0$) to 30 June 1986 ($t_1 = 0.17$ year), eqn (4) is needed. After 30 June 1986, eqn (3) can be applied:

$$D_{tot,Thyroid}(t_{i-1}, t_i) = D_{ext,Thyroid}(t_{i-1}, t_i) + D_{ing,Thyroid}(t_{i-1}, t_i) + D_{milk,Thyroid}(t_{i-1}, t_i) + D_{inh,Thyroid}(t_{i-1}, t_i), \quad (4)$$

where $D_{ext,Thyroid}$ = the external dose contribution from ^{134}Cs , ^{137}Cs and short-lived nuclides deposited on the ground;

$D_{ing,Thyroid}$ = the dose contribution from ingestion of ^{134}Cs and ^{137}Cs ;

$D_{milk,Thyroid}$ = ^{131}I contribution from milk; and

$D_{inh,Thyroid}$ = inhalation of airborne ^{131}I .

Details how the thyroid absorbed dose is calculated is given in the dose manual (Tondel et al. 2025).

Lifetime attributable risk (LAR)

Lifetime attributable risk (LAR) of radiation-induced cancer in various organs is calculated with a method proposed by the US Environmental Protection Agency (US EPA 2011). LAR at a certain 1-y age group, during a certain time interval t_{i-1} , t_i , was obtained by multiplying the absorbed dose to a specific organ with the corresponding age- and sex-specific LAR-coefficient, here denoted as $LAR_{age,sex}$ for cancer incidence in that organ (US EPA 2011).

The estimated number of attributable cancer cases (AC) from the Chernobyl fallout, in each time interval, for each municipality was calculated using the (1) organ absorbed doses in each 1-y age category, (2) the number of individuals in that municipality by age, and (3) the age- and cancer site-specific LAR-coefficients. 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 as provided by eqn (5):

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

and

$$AC_{Sweden,F}(t_{i-1}, t_i) = \sum_{municip=1}^{290} \sum_{age=0}^{100} D_{pop,municip,age,F}(t_{i-1}, t_i) \cdot LAR_{age,F} \cdot 10^{-7}, \quad (5)$$

where $D_{pop,municip,age,sex}(t_{i-1}, t_i)$ is the sex-specific total absorbed dose to a specific organ at a certain age during the time t_{i-1} and t_i years, multiplied with the total number of persons in that age group and municipality taking percentage of hunter households in each municipality into account; $LAR_{org,age,sex}$ is the age- and sex-specific LAR-coefficient for a specific cancer site retrieved from a linear interpolation between age groups defined by US EPA (Tondel et al. 2025); and 10^{-7} is a factor converting number of cases per 10,000 individuals per Gy organ-specific absorbed dose into number of cancer cases per person-mGy, since the LAR coefficients taken from US EPA (2011) are expressed in cases per 10,000 person-Gy.

Finally, the number of attributable cancer cases of all sites combined was obtained by summing all organ-specific attributable cases from 28 April 1986 to 27 April 2036.

Effective dose (mSv)

The effective dose and collective effective dose are calculated using a method suggested by the International Commission of Radiological Protection (ICRP, 2007). 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 in eqn (6):

$$E_{tot}(t_{i-1}, t_i) = \sum_{all\ tissues} w_T \cdot D_{ext,tissue}(t_{i-1}, t_i) + \sum_{all\ tissues} w_T \cdot D_{ing,tissue}(t_{i-1}, t_i) + 0.04 \cdot D_{milk,Thyroid}(t_{i-1}, t_i) + 0.04 \cdot D_{inh,Thyroid}(t_{i-1}, t_i), \quad (6)$$

where the tissue weighting factor (w_T) is retrieved from ICRP (2007). The internal dose via dairy milk and inhalation contributes almost uniquely to the thyroid, which has been assigned a tissue weighting factor of 0.04 (ICRP 2007).

The collective effective dose in Sweden, S , in a certain time interval (t_{i-1} , t_i), was calculated as $E_{tot}(t_{i-1}, t_i)$ times the number of individuals in the age category in the municipality, summed over all age categories and all municipalities for a total collective dose in Sweden:

$$S(t_{i-1}, t_i) = \sum_{municip=1}^{290} \sum_{age=0}^{100} n_{municip,age}(t_{i-1}, t_i) \cdot E_{municip,age}(t_{i-1}, t_i), \quad (7)$$

where $n_{municip,age}(t_{i-1}, t_i)$ is the total population in a specific municipality and time interval (t_{i-1}, t_i) , as retrieved from Statistics Sweden, and $E_{municip,age}(t_{i-1}, t_i)$ is the age-specific mean effective dose to that age group residing in the municipality during time t_{i-1} and t_i .

To comply with the ICRP recommendations for adults, the collective doses have been cumulated over 50 y (in analogy with the same time-period used for summing the total number of all attributable cancer cases). The ICRP suggests cumulating the collective dose over 70 y for children, but the population forecast up to 2056 is deemed too uncertain to allow such calculation.

Statistical methods

The calculations of organ absorbed doses, LAR, and effective doses were done with R statistics software, version 4.2.2 (R Core Team 2022).⁶

As all data were publicly available, a formal approval from the Swedish Ethical Review Authority was therefore not needed.

RESULTS

The organ absorbed doses rapidly decline from 1986 to 2036 with slightly higher doses for males compared to females. These trends are similar for most organs, but with a high variability depending on municipality. Fig. 2 shows the average absorbed doses to the thyroid gland by county and sex for the year 1986. The order of counties in terms of highest exposure were the same between the sexes with the exception of Dalarna for females, who had a slightly higher absorbed thyroid dose than in Jämtland compared to the reverse order for males. The high deposition of $^{134,137}\text{Cs}$ and short-lived radionuclides (external) on the ground in the counties of Västernorrland, Uppsala, and

Gävleborg give a considerable contribution to the total thyroid dose. In contrast, total thyroid exposures were dominated by ^{131}I in Gotland via inhalation and ingestion during the first year. The relative contribution from these sources is shown in bar plots in the Supplemental Digital Content, <http://links.lww.com/HP/A318>. The variability is even greater when it comes to municipalities because of differences in deposition from the lowest deposition of ^{137}Cs of 0.99 kBq m^{-2} in Lidköping municipality in Västra Götaland county to the highest deposition in Gävle municipality in Gävleborg county of 49.72 kBq m^{-2} (Tondel et al. 2025).

The lifetime attributable risk (LAR) translated into number of attributable extra cancer cases (AC) can be estimated to 377 cancer cases in males and 448 cancer cases in females in the 50 y period in Sweden post-Chernobyl (Table 1 and tables by county in the Supplemental Digital Content, <http://links.lww.com/HP/A318>). These figures can be translated into an average individual life-time absolute increased risk for incident cancer in Sweden of 0.09 per thousand for males and 0.10 per thousand for females for 50 y (Table 2). The municipality with the highest LAR was Härnösand municipality in Västernorrland county with 0.70 per thousand for males and 0.82 per thousand for females. In Sweden, 38% of the cancer cases could be attributed to the internal dose in males and 32% in females (Table 1). The highest number of cancer cases is estimated for Västernorrland with 68 cancer cases in males and 79 cases in females (Table 2). Out of all cancer cases in Sweden that could be attributed to the Chernobyl NPP accident, 18% are expected to occur in Västernorrland compared with only 3% of the population in 1986.

The estimated collective effective dose in Sweden is in total 6,028 person-Sv, of which 2,148 person-Sv (36%) is from internal exposure. Like for the attributable cancer cases, Västernorrland county obtained 18% of the total collective effective dose. The relative contribution from internal and external effective collective dose over time is shown in Fig. 3 and by county in Table 3.

⁶The organ absorbed dose to an individual was calculated with R package absorbedDose version 1.1.0, which can be download from <https://github.com/absorbedDose/absorbedDose>. Accessed.

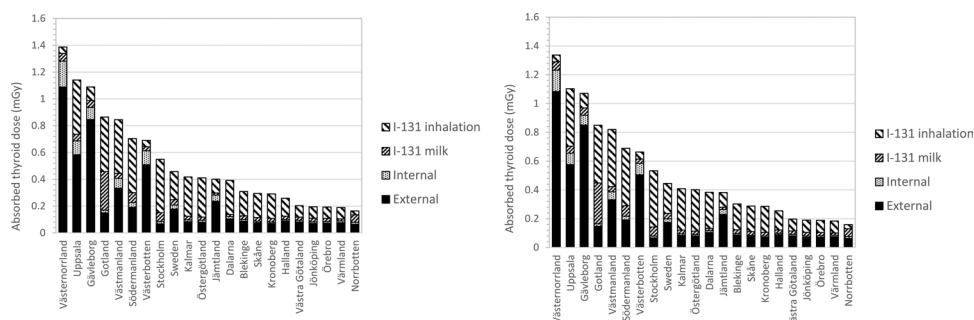


Fig. 2. (a) Average male thyroid absorbed dose (mGy) in 1986 from ^{131}I , external dose from ^{137}Cs and internal dose from ^{134}Cs and ^{137}Cs . (b) Average female thyroid absorbed dose (mGy) in 1986 from ^{131}I , external dose from ^{137}Cs and internal dose from ^{134}Cs and ^{137}Cs .

Table 1. Number of attributable cancer cases in Sweden post-Chernobyl 1986 to 2036.

Cancer	Sweden					
	Male			Female		
	External	Internal	Total	External	Internal	Total
Bone	0.54	0.44	0.98	0.53	0.35	0.87
Breast	0.00	0.00	0.00	61.85	14.30	76.15
Colon	28.69	17.61	46.29	18.58	9.12	27.70
Kidneys	4.81	3.37	8.18	4.54	2.54	7.08
Leukemia	17.14	16.46	33.60	13.58	8.88	22.46
Liver	7.34	4.97	12.31	4.07	2.08	6.15
Lung	24.44	19.24	43.69	62.44	34.94	97.38
Ovary	0.00	0.00	0.00	6.32	2.90	9.22
Prostate	18.03	10.12	28.15	0.00	0.00	0.00
Residual	51.80	41.74	93.54	55.18	34.60	89.78
Skin	44.06	9.21	53.26	23.63	4.48	28.11
Stomach	11.39	6.86	18.25	14.97	6.63	21.60
Thyroid	4.39	5.13	9.52	13.32	15.81	29.13
Urinary bladder	18.99	9.80	28.79	19.19	6.92	26.11
Uterus	0.00	0.00	0.00	4.41	1.90	6.31
Sum of cases	231.62	144.94	376.56	302.59	145.45	448.03

DISCUSSION

The geographically varying fallout of radionuclides over Sweden resulted in a corresponding geographical variability in absorbed radiation doses to exposed organs.

Table 2. The average life-time attributable cancer risk (LAR) and number of attributable cancer cases (AC) by county and in Sweden post-Chernobyl 1986 to 2036.

County		Male		Female	
Name	Code	LAR	AC	LAR	AC
Stockholm	1	4.21×10^{-5}	35.46	4.95×10^{-5}	43.39
Uppsala	3	3.02×10^{-4}	41.68	3.55×10^{-4}	49.81
Södermanland	4	9.73×10^{-5}	12.43	1.16×10^{-4}	14.87
Östergötland	5	4.15×10^{-5}	8.39	4.96×10^{-5}	10.12
Jönköping	6	3.51×10^{-5}	5.67	4.17×10^{-5}	6.81
Kronoberg	7	3.40×10^{-5}	3.04	4.16×10^{-5}	3.66
Kalmar	8	4.08×10^{-5}	4.85	4.93×10^{-5}	5.89
Gotland	9	7.10×10^{-5}	2.01	8.91×10^{-5}	2.55
Blekinge	10	4.07×10^{-5}	3.07	4.88×10^{-5}	3.68
Skåne	12	3.68×10^{-5}	19.70	4.38×10^{-5}	24.22
Halland	13	4.21×10^{-5}	5.44	5.13×10^{-5}	6.63
Västra Götaland	14	3.94×10^{-5}	28.47	4.66×10^{-5}	34.17
Värmland	17	3.68×10^{-5}	5.11	4.27×10^{-5}	6.02
Örebro	18	3.57×10^{-5}	4.82	4.17×10^{-5}	5.78
Västmanland	19	1.81×10^{-4}	23.34	2.11×10^{-4}	27.07
Dalarna	20	5.08×10^{-5}	7.20	6.07×10^{-5}	8.65
Gävleborg	21	3.52×10^{-4}	50.16	4.23×10^{-4}	60.85
Västernorrland	22	5.29×10^{-4}	67.71	6.09×10^{-4}	78.50
Jämtland	23	1.19×10^{-4}	7.96	1.36×10^{-4}	9.01
Västerbotten	24	2.79×10^{-4}	35.19	3.24×10^{-4}	40.83
Norrbottn	25	3.69×10^{-5}	4.86	4.29×10^{-5}	5.50
Sweden		8.75×10^{-5}	376.56	1.02×10^{-4}	448.03

The excess number of cancer cases in Sweden attributed to the radioactive fallout from the Chernobyl NPP accident is estimated at 825 cases incurred under 50 y post-accident. The lifetime risk of getting cancer is estimated to about 30% in Sweden, compared to LAR in our study of 1 per 10,000 from Table 2 and the highest LAR in Härnösand municipality of 8 per 10,000 (Socialstyrelsen 2023). According to cancer statistics in Sweden, in total 1.9 million cancer cases were registered from 1986 to 2023 (Socialstyrelsen 2025). Assuming the same number of cancer cases per year as in 2023, because no population growth is expected according to Statistics Sweden, an additional number of 850,000 cancer cases can be estimated up to 2036 making a total of 2.8 million for the full

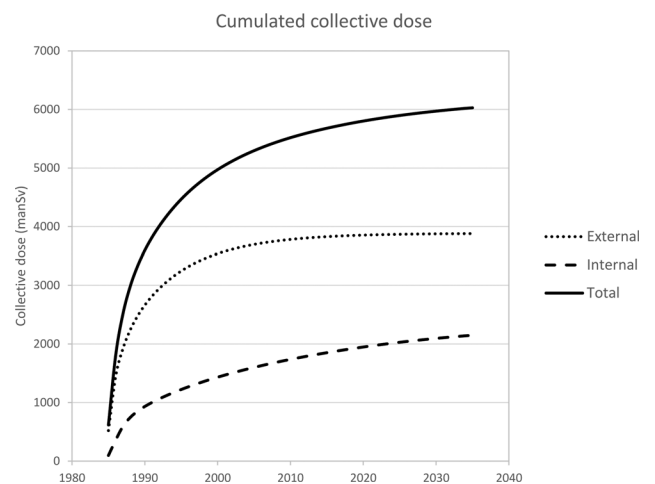
**Fig. 3.** The relative contribution from internal and external collective dose in Sweden 1986-2036 (person-Sv).

Table 3. Collective dose by county and in Sweden (person-Sv) post-Chernobyl 1986 to 2036.

County	population 1986	External	Internal	Total
Västernorrland	261,089	721	386	1107
Gävleborg	287,691	631	202	833
Uppsala	254,938	404	239	643
Stockholm	1,593,333	289	266	555
Västerbotten	245,204	329	215	544
Västra Götaland	1,403,503	306	149	454
Västmanland	254,423	220	148	368
Skåne	1,033,684	210	110	320
Södermanland	249,479	127	72	199
Östergötland	394,753	83	51	134
Jämtland	133,543	79	49	129
Dalarna	283,191	76	41	117
Jönköping	317,212	59	31	90
Halland	242,250	59	26	86
Värmland	278,861	54	30	84
Kalmar	237,417	52	28	80
Örebro	269,620	50	28	79
Norrbottn	261,039	43	33	76
Blekinge	150,258	34	16	50
Kronoberg	173,853	32	16	48
Gotland	56,174	22	11	33
Sweden	8,381,515	3,880	2,148	6,028

time period 1986 to 2036. Therefore, our additional 825 LAR estimated attributable cases due to Chernobyl fallout amounts to 0.029% of the gross background cancer cases in Sweden. Like the attributable cancer cases, the collective dose was also unequally distributed across counties, with a total of 6,028 person-Sv in Sweden, of which 2,148 person-Sv (36%) emanate from internal exposure.

Gamma measurements within 1 mo after the accident, performed in Västerbotten in northern Sweden, showed absorbed doses to the thyroid from 0 to 3.7 mGy, with a mean of 0.37 mGy in 66 persons (Olofsson and Svensson 1988). These values are comparable to the average thyroid dose in Västerbotten in our study: 0.69 mGy in males and 0.66 mGy in females. The highest thyroid doses in 1986 in Sweden ranged from 2.7 to 4.4 mGy, measured on 38 persons in Gotland (Andersson and Nyholm 1986). These values are higher than we estimated: 0.86 mGy in males and 0.85 mGy in females.

Our estimate of collective dose of 6,028 person-Sv is almost identical with a previous estimate of 6,000 person-Sv under 50y, but our estimate of the internal contribution of 2,148 person-Sv is more than double that previous estimate of 1,000 person-Sv (Edvarson 1991; Falk et al. 1991). Applying the nominal risk coefficient for cancer incidence of 17.15% per Sv from ICRP, the number of cancer cases in our study could be estimated to 665 extra cases from external radiation, 368 from internal radiation and in total 1,034 extra cancer cases in Sweden

(ICRP 2007). Given the very low detriment expressed for skin cancer by US EPA, a perhaps more appropriate comparison with the collective dose detriment can be obtained by ignoring the ICRP stated detriment for skin cancer of 10.00% per Sv. The 1,034 extra cancer cases are then reduced to 431 extra cancer cases, which is about 47% lower than the estimated AC of 825 cases. However, the ICRP risk coefficients include a Dose and Dose Rate Effectiveness Factor (DDREF) of 2.0 (ICRP 2007), whereas US EPA uses a factor of 1.5 (US EPA 2011). The ICRP is currently evaluating this factor, but if DDREF will be lowered to unity, the relative difference between the LAR derived number of extra cases (825 extra cases) and the detriment derived number of 431 cases (excluding skin cancers) will decrease. Applying the DDREF of 1.5 for US EPA cases results in AC of 1,238 cancer cases and 825 cases when excluding skin cancer, respectively. Furthermore, the LAR-derived number of extra cancer cases would have been greater if US EPA had included risk coefficients for cancer in the oral cavity and pharynx, esophagus, gall bladder, pancreas, and central nervous system, as the National Cancer Institute has suggested those cancer sites at increased risk after radiation exposure (Tondel et al. 2025). The numbers of excess cancer cases are still higher than initially anticipated of 340 incident cancer cases (Holm et al. 1986).

For comparison, the US National Academy of Sciences suggest a DDREF of 1.5. The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) does not apply a DDREF (i.e., DDREF 1.0) as WHO did after the Fukushima NPP accident. Also, the German Commission on Radiological Protection suggests that the DDREF should be abolished, i.e., apply unity (NRC 2006; UNSCEAR 2010; WHO 2013; SSK 2014). If a DDREF of 1.0 would be applied in our study, the estimated number of extra cases would be doubled to 2,064 extra cases based on our collective dose assessment of 6,028 person-Sv.

There are three major strengths in our study. First, we have used accurate and annual sex-specific population data in 1-y classes and applied published organ dose coefficients. Second, we demonstrated application of established methods for dose calculations and cancer risk projections based on published organ dose coefficients and cancer risk coefficients (Räaf et al. 2020; Isaksson et al. 2021; ICRP 2020; US EPA 2011). Such detailed exposure and risk assessment have not previously been performed in Sweden. Third, for the first time, we have been able to compare the attributable number of cancer cases from LAR with estimations from collective effective dose calculations. We arrive here with similar results for the two different methods. Our methods are transparent and can be applied in other contexts with necessary modification

of the published code⁷ using our manual (Tondel et al. 2025).

The limitation of our study is that we used municipality average deposition of ¹³⁷Cs instead of coordinates on each person's dwelling as we did in a previous study, making the present study more of an ecological design (Tondel et al. 2023b). Moreover, our building shielding factor is also on municipality level instead of each dwelling's characteristics, and the snow shielding factor is on county level at one point in time and therefore does not take into account effects of less snow coverage due to climate change during our 50-y time period (Finck 1992). For the internal dose, we could only use county values of ¹³¹I in milk and county average air concentration of ¹³¹I available for inhalation; however, since radioiodine only contributes a smaller fraction of the total radiation dose during our study period, we can consider this as a minor limitation. Instead, using hunter household as a proxy for internal contamination from game is a more important limitation as it does not take into account the amount of intake of radiation-contaminated foodstuff by each hunter household. The register of hunters with licensed weapons was only available in 1986 and therefore does not include new hunters, probably resulting in an underestimated number of later hunter households with misclassification of internal exposure. Based on previous uncertainty assessments, we can estimate the total uncertainty (1 σ) of the calculated exposures (absorbed doses) to be as high as 50%, mainly due to uncertainties associated with the transfer factor between regional ground deposition and body burden of radiocesium ($T_{ag,max,Cs}$ in eqn 2) and the ecological half-time of the external dose to residents, represented by $r(t)$ in eqn (1) (Isaksson et al. 2019; Rääf et al. 2020).

CONCLUSION

Due to the variable fallout of radionuclides in Sweden, the organ absorbed doses in the Swedish population also exhibit a high variability between municipalities and counties rather than between organs in the body or when comparing the absorbed doses between sexes. Our total collective effective dose assessment is almost identical with previous estimates but with a relatively higher contribution from internal contamination. For the first time in Sweden, we have estimated attributable cancer cases based on the LAR-coefficients resulting in similar estimates of number of extra cancer cases compared to applying collective effective dose under 50 y after the

Chernobyl NPP accident. Our program code and dose manual are freely available and can be adopted to other countries and different fallout scenarios.

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Availability of data and materials: The absorbed doses, LAR values, and effective dose in each municipality and year can be made available upon request.

Authors contribution: M.T. took the lead in conceptualisation, investigation, methodology, administration, visualization, writing, and editing. K.G. is responsible for data extraction, data curation, programming, analysis, validation, and reviewing the manuscript. M.I. and C.R. were equally active in the conceptualisation, investigation, methodology, supervision, validation, reviewing, and editing of the manuscript. All co-authors have been active in the interpretation of the data and have also approved the final version of the submitted manuscript.

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