BMJ Open

Total cancer incidence in relation to ^{137}Cs fallout in the most contaminated counties in Sweden after the Chernobyl nuclear power plant accident: a register-based study

Hassan Alinaghizadeh, Robert Wålinder, Eva Vingård, Martin Tondel

CrossMark

Department of Medical Sciences, Occupational and Environmental Medicine, Uppsala University, Uppsala, Sweden

Correspondence to
Dr Robert Wålinder;
robert.walinder@medsci.uu.se

ABSTRACT

Objectives: To determine the total cancer incidence in relation to a 5-year exposure to caesium-137 (^{137}Cs) from the 1986 Chernobyl nuclear power plant accident.

Methods: A closed cohort was defined as all individuals living in the three most contaminated counties in mid-Sweden in 1986. Fallout of ^{137}Cs was retrieved as a digital map from the Geological Survey of Sweden, demographic data from Statistics Sweden, and cancer diagnosis from the National Board of Health and Welfare. Individuals were assigned an annual ^{137}Cs exposure based on their place of residence (1986–1990), from which 5-year cumulative ^{137}Cs exposures were calculated, accounting for the physical decay of ^{137}Cs and changing residencies. HRs were adjusted for age, sex, rural/non-rural residence and pre-Chernobyl total cancer incidence.

Results: The 734 537 people identified were categorised by exposure: the first quartile was low exposure (0.0–45.4 kBq/m^2), the second and third quartiles were intermediate exposure (45.41–118.8 kBq/m^2), and the fourth quartile was the highest exposure (118.81–564.71 kBq/m^2). Between 1991 and 2010, 82 495 cancer cases were registered in the 3 counties. Adjusted HRs (95% CI) were 1.03 (1.01 to 1.05) for intermediate exposure and 1.05 (1.03 to 1.07) for the highest exposure compared to the reference exposure.

Conclusions: We found a small overall exposure–response pattern of the total cancer incidence related to ^{137}Cs after adjustment for age, sex, rural residence and pre-Chernobyl cancer incidence.

Strengths and limitations of this study

- A methodological strength of the study is that the study population did not have any cancer diagnosis prior to the follow-up period.
- Another strength is that the risk estimate was based on the cancer incidence rather than cancer mortality.
- By restricting the study to three counties, we reduced confounding from socioeconomic factors with regional differences potentially associated with ^{137}Cs ground deposition.
- Using a 5-year cumulative exposure estimate, we increased the precision compared to previous studies.
- The main limitation of the study is that the exposure assessment is only based on aerial measurements and that the individual effective external dose could not be calculated.

INTRODUCTION

Of the caesium-137 (^{137}Cs) released from the 1986 Chernobyl nuclear power plant accident, about 5% was deposited in Sweden, with the highest fallout in the coastal counties on the Bothnian Sea.[1] Estimated effective doses to some parts of the population in the years after the accident were 1–2 mSv per year.[2 3] Based on the estimates of collective dose, the Swedish Radiation Authority calculated that 300 extra cancer deaths could occur in Sweden in the 50 years after the accident.[2] A food regulation programme introduced in 1986 limited the ^{137}Cs activity in food sold to the public to 300 Bq/kg to assure that the dose from food intake was below 1 mSv per year. In 1987, a new limit of 1500 Bq/kg was introduced for game and reindeer meat, wild berries, mushrooms, fresh water fish and nuts sold to the public.[4 5] Still, 30 years after the accident, radiation from some game and reindeer meat exceeds the limit of 1500 Bq/kg.[6 7]

Despite a relatively large public concern in Western Europe about the health effects of radiation, such as cancer, surprisingly few studies have investigated the incidence of cancer after the Chernobyl accident. Follow-up studies in the Nordic countries

BMJ

7–24 years after the accident have reported conflicting results whether the increased incidence of cancer in the exposed areas can be attributed to the accident.[8–15] These studies have been using different methods in classifying the exposure from the 200×200 m grid to the average ^{137}Cs deposition on the county level, from 2 to 6 exposure categories, different age groups, different follow-up periods and therefore very different statistical power to detect a small increased risk of cancer related to the deposition of ^{137}Cs. The initial reports studied mainly childhood leukaemia assumed to have the shortest latency period, with a relatively small number of cases showing no association to the ^{137}Cs fallout, but all had a relatively short follow-up period to 1992.[11–13] On the contrary, two Swedish studies, with a large number of cases, reported a slight increase in the overall cancer rates related to ^{137}Cs deposition after the Chernobyl accident.[8 14] Two studies from Finland with an even larger number of cancer cases, but also with about half of the number of cases in the reference category, could not detect any increase in cancer rates using an exposure matrix of 8×8 km based on dose rate measurements in 1050 locations.[9 15] In a previous Swedish study, by our group, we could not verify any exposure–response pattern and instead suggested that the association found in the previous Swedish studies was spurious and could perhaps be the result of confounding from unadjusted regional differences in the incidence of cancer before the accident.[10] However, that study had an ecological design, so in the current study, we decided to restrict the population to the most affected counties in 1986 and to increase the precision in the exposure assessment by using ^{137}Cs deposition on their dwelling coordinates.

The aim of this epidemiological study was to study the exposure–response relationship between the total cancer incidence and a 5-year exposure assessment derived from the ^{137}Cs fallout at the place of residence.

MATERIALS AND METHODS
Exposure assessment
On assignment from the Swedish Radiation Safety Authority (SSM), each year the Geological Survey of Sweden (SGU) measures gamma radiation (including the gamma-spectrum of ^{137}Cs) with a specially equipped aeroplane that flies in a back-and-forth pattern 30–60 m above the ground with 200–5000 m between each pass. The measurements are collected in a database consisting of 9.9 million measurements and are expressed in kilo Becquerel per square metre (kBq/m^2) of ^{137}Cs in a 200×200 m digital grid map calibrated to 1 May 1986.[16 17] The reference coordinates system SWEREF 99 (Swedish reference frame 1999) was used to create this digital map. The annual geographic coordinates of each individual's residence throughout the country during the first 5 years after the accident (1986 through 1990) were retrieved from the Land Survey of Sweden

(Lantmäteriet) and matched to the ^{137}Cs map by Statistic Sweden (SCB).

A proxy for the external dose rate at the individual level was calculated in kBq/m^2 with an algorithm presented by Chase[18] for 5 years of exposure, taking into account changes in residence. Calculating this individual exposure included the physical decay of ^{137}Cs (T$_{1/2}$ 30.2 years) using the following algorithm:

$$N_p = \sum_{i=1}^{p} N_0 \times e^{\left(-\frac{\ln(2)}{T_{1/2}}(t_i - t_0) \right)} = \sum_{i=1}^{p} N_0 \times e^{(-\lambda(t_i - t_0))}, i = 1, \ldots, p$$

where N_p is the cumulative exposure since reference date (^{137}Cs kBq/m^2); N_0 is the initial caesium activity (kBq/m^2) at reference date; $T_{1/2}$ is the half-life time for ^{137}Cs, which is 30.18712 years; t_i is the year for dwelling coordinate (1986, 1987, 1988, 1989, and 1990, respectively); and t_0 is the reference date (1986).

With this formula, all individuals received a single value for cumulative ^{137}Cs exposure between 1986 and 1990 in kBq/m^2.

Study population
We defined a closed cohort consisting of all persons living in the three counties in Sweden having the highest ground deposition of ^{137}Cs (Uppsala, Gävleborg and Västernorrland) as of 31 December 1986. The population in these 3 counties was 803 703 in 1986 and included 199 711 individuals in the highest quartile of radiation exposure throughout the country (higher than 25.42 kBq/m^2). In all of Sweden, 226 063 individuals were exposed above 25.42 kBq/m^2, and 88% of the individuals in the highest quartile of exposure lived in the Uppsala, Gävleborg and Västernorrland counties in 1986. From Statistics Sweden (SCB), we retrieved information on each individual including sex, social security number (date of birth) and rural/non-rural residence.

Of the original study population, we excluded 9936 individuals because of missing data, 26 965 who died between 1986 and 1991, and 31 674 who had cancer before 1990 (figure 1). The national cancer register was searched up to 31 December 2010 to identify which of the 734 537 remaining individuals ever received a diagnosis of cancer. Data from the 163 797 individuals who died between 1991 and 2010 were included as censored observations if they had not had any cancer. Data from individuals emigrating from the region after 1991 are included as lost to follow-up if they had never had cancer. Tables 1 and 2 show descriptive data from the cohort, divided by gender and exposure categories, respectively.

End point
Individuals in the closed cohort with a diagnosis of cancer between 1958 and 2010 were identified by their
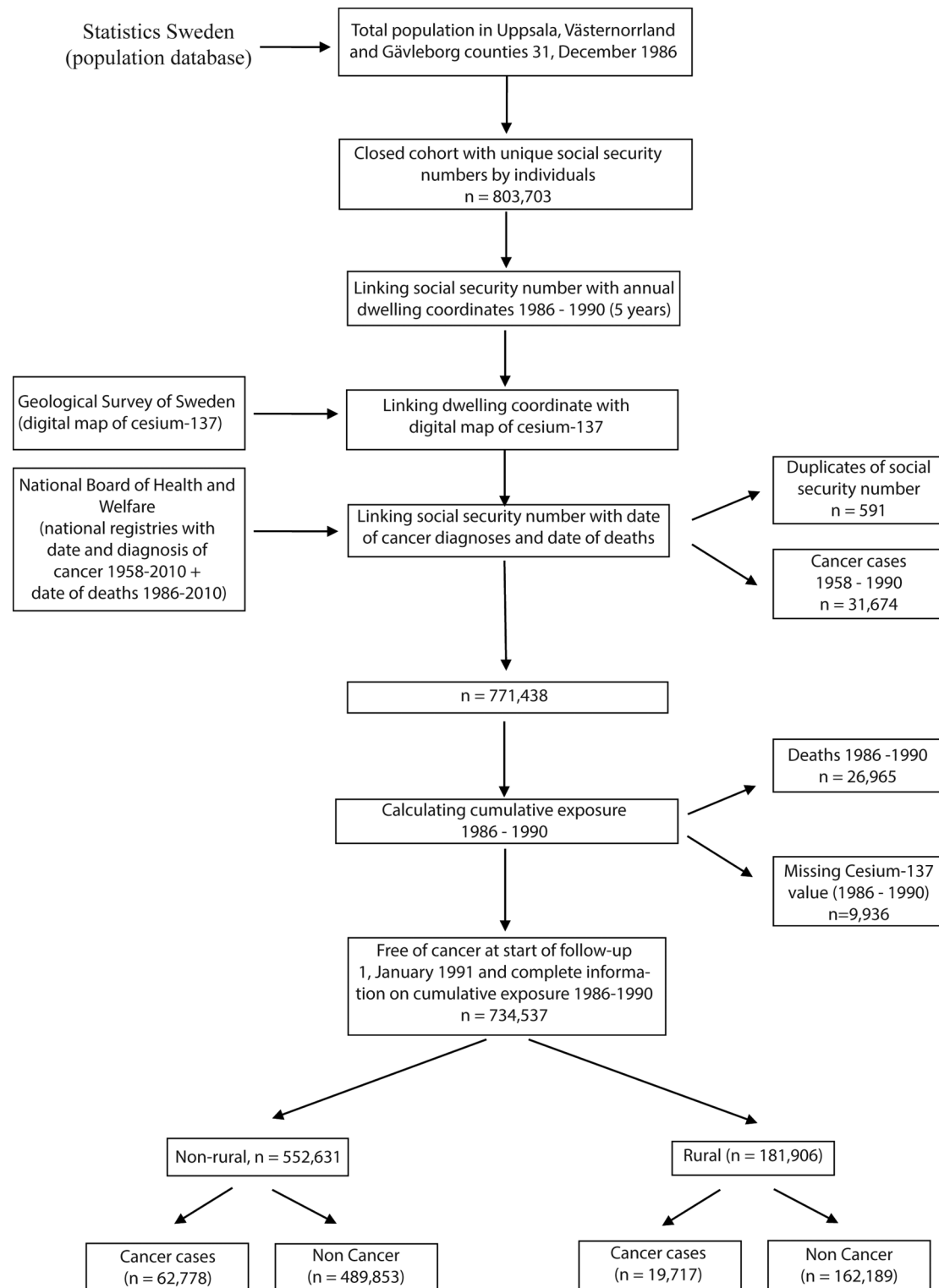
Figure 1 Sample selection in a study of the effect of cumulative caesium-137 exposure from the 1986 Chernobyl nuclear accident on cancer rates in three counties in Sweden, 1991–2010.

social security number from Statistics Sweden in the national cancer registry at the National Board of Health and Welfare along with date of death between 1986 and 2010. Individuals with any type of cancer between 1958, when the registry was started, and 1990 were excluded (figure 1). A diagnosis of cancer between 1 January 1991 and 31 December 2010 was considered to be the initial event. In case of multiple cancer diagnoses, only the date of the first diagnosis was used in the analysis. The remaining individuals were considered to be alive at the end of follow-up on 31 December 2010, and their data were censored.

Table 1 Estimated Cancer Incidence in Three Swedish Counties, 1991–2010, by Residence and Sex

Sex	Individuals enrolled as of 1 January 1991 (n)	Cancer cases 1991–2010 (n)	1991–2010, person-years of follow-up	Incidence rate/10^5	Incidence rate ratio	95% CI
Non-rural residence (a population centre with more than 3000 inhabitants)						
Males	270 311	28 471	4 706 786	605	Reference	–
Females	282 320	34 307	4 826 952	711	1.18	1.16 to 1.19
Rural residence (a population centre with 3000 inhabitants or less)						
Males	94 763	9765	1 634 368	597	Reference	–
Females	87 143	9952	1 504 594	661	1.11	1.08 to 1.14

Non-rural and rural residence

Since the total cancer incidence tends to be higher in urban areas,[19] we adjusted the risk estimates with a variable for population density created by Statistics Sweden. Rural residence was defined as living in a population centre with <3000 inhabitants in 1986. Statistics Sweden defines a population centre as a congregation of buildings with the largest distance between buildings being 200 m and having more than 200 inhabitants. The definition is purely geographical and does not consider administrative boundaries, such as municipalities.[20 21]

Pre-Chernobyl cancer incidence density

To account for the pre-Chernobyl municipality differences in the incidence of total cancer, an average of direct age-standardised and sex-standardised cancer incidence per 100 000 person-years was calculated from 1980 to 1985 (using the Swedish general population from year 2000 as a standard population). This factor was therefore matched to each individual of the cohort and included in the model as a covariate to control for pre-Chernobyl cancer incidence at the municipality level.

Age and sex

Age was defined as the age at exposure in 1986. The decision to adjust for sex and age was based on the differences in the incidence of cancer between sexes at different ages, according to official statistics.[20]

Statistical methods

Cox regression was applied to analyse time to the first diagnosis of cancer between 1991 and 2010. The first quartile of cases was used as the reference exposure category (0.0–45.4 kBq/m²), the second and third quartiles were considered as the intermediate exposure category (45.41–118.8 kBq/m²) and the fourth quartile was used as the highest exposure category (118.81–564.71 kBq/m²). No collinearity or interaction was observed among the variables. HRs were calculated with 95% CIs. α was set at 0.05, and all tests were two tailed. All data were analysed with SAS V.9.4 (SAS Institute, Cary, North Carolina, USA) and Stata V.14.1 (StataCorp LP, College Station, Texas, USA).

RESULTS

The individual cumulative 5-year exposure ranged from 0 to 565 kBq/m², and the distributions were almost identical between the sexes (figure 2). The incidence rate ratios of total cancer were higher for women than for men in non-rural and rural residencies (table 1) and tended to increase in both sexes at higher exposures (table 2).

In the fully adjusted model, using all covariates, an exposure–response pattern was seen, although the HRs

Table 2 Estimated Cancer Incidence in Three Swedish Counties, 1991–2010, by Sex and Exposure Category

Cumulative exposure, 1986–1990, ^{137}Cs (kBq/m²)*	Individuals enrolled as of 1 January 1991 (n)	Cancer cases 1991–2010 (n)	1991–2010, Person-years of follow-up	Incidence rate/10^5	Incidence rate ratio	95% CI
Males						
1st quartile	91 304	9000	1 579 919	570	Reference	–
2nd—3rd quartiles	181 078	19 045	3 153 482	604	1.06	(1.03 to 1.09)
4th quartile	92 692	10 191	1 607 752	634	1.11	(1.08 to 1.14)
Females						
1st quartile	92 347	10 772	1 572 854	685	Reference	–
2nd—3rd quartiles	186 149	22 212	3 192 657	696	1.02	(0.99 to 1.04)
4th quartile	90 967	11 275	1 566 035	720	1.05	(1.02 to 1.08)

*Cumulative exposure (kBq/m²) from 1986 through 1990 in three categories; lowest, in the first quartile (0.00–45.40; reference category); intermediate, in the second and third quartiles (45.41–118.80); and highest, in the fourth quartile (118.81–564.71).

Figure 2 Cumulative
caesium-137 exposures from
1986 through 1991 in three
counties in Sweden, by sex.
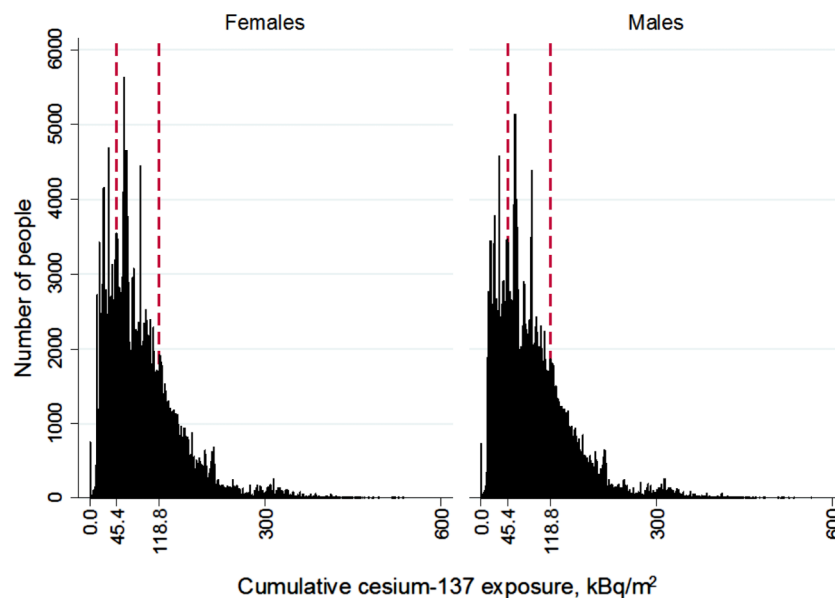
were lower than that in the crude analysis, indicating a slight positive confounding for the covariates when taken together. The HR (95% CI) was 1.03 (1.01 to 1.05) at intermediate exposures and 1.05 (1.03 to 1.07) at the highest exposures when compared to the reference category (table 3).

DISCUSSION

The fully adjusted Cox regression model revealed an exposure–response pattern between the 5-year cumulative ^{137}Cs exposure from the Chernobyl nuclear power plant accident and the HR of cancer in 3 Swedish counties. Considering the small increased HR, and owing to overlapping CIs between exposure categories, caution should be exercised when interpreting a causal inference.

Somewhat remarkably, the HRs did not change much in the stepwise analysis, indicating only weak confounding from the covariates in the models. We cannot exclude confounding by unknown risk factors for total cancer, but such factors have to be associated with the ^{137}Cs fallout to the extent that they affect the risk estimates. However, even weak confounding could influence the small HRs we found and hence affect the interpretation.

Individual effective doses can be determined in nuclear workers from exposure data collected from personal dosimeters, but exact radiation dose estimation is not possible using only fallout maps and register-based data, especially retrospectively, as we did here, 30 years after the Chernobyl accident. Instead, this epidemiological study has to rely on a proxy for dose that is based on the activity determined from fallout maps.

In an earlier ecological study, we found no exposure–response pattern at the county, municipality or parish level.[10] We have now refined the analysis by estimating

the individual exposure at the annual registration of the place of residence (as a proxy for external dose) during 5 years after the accident, to improve the validity of our risk estimates. Instead of a one-time exposure value from 1986, we preferred a 5-year cumulative estimate, taking into account changes in residence, to increase the precision in the exposure assessment. The fallout, mainly nuclides of iodine and caesium, was unevenly deposited in Sweden because it rained during the first week after the accident. Therefore, ecological studies using mean values at the county, municipality or parish level have less precision in detecting an association between ionising radiation from deposited nuclides and cancer. Also, imprecise estimates of outcomes, such as the total cancer incidence, could obscure a true relationship because different cancer sites have different associations with ionising radiation.

However, a Finnish study with a larger population (2 million) but with a similar follow-up time (1988 through 2007), and with a radiation map with a resolution (250 m×250 m) and considering only the first year of exposure, did not find an increased risk of cancer. The outcome in this study was 'any cancer', except breast, prostate and lung cancers.[9] However, a reanalysis of the same data identified a significant increase in colon cancer among women.[15] A Swedish study of 1 million inhabitants between 1988 and 1999 found an excess risk of cancer that could have been related to the Chernobyl fallout.[8] The resolution of the exposure map (200 m×200 m) was similar to that used in the present study and the Finnish study.[9]

In Belarus, Ukraine and western Russia, the incidence of thyroid cancer in children increased sharply after the accident. Epidemiological studies in these countries have found strong exposure–response relationships between individual thyroid radiation dose and the risk of thyroid cancer.[22–25] Case–control studies in the

Table 3 Estimated Relationships between Cumulative Radiation Exposure and Cancer Incidence Adjusted by Age, Sex, Residence and Pre-Chernobyl Cancer Incidence

Cumulative exposure, 1986–1990, ^{137}Cs (kBq/m²)*	Cancer cases 1991–2010 (n)	HR (95% CI)				
		Crude	Adjusted by age	Adjusted by age and sex	Adjusted by age, sex and residence	Adjusted by age, sex, residence and pre-Chernobyl incidence
1st quartile	19 772	Reference	Reference	Reference	Reference	Reference
2nd—3rd quartiles	41 257	1.04 (1.02 to 1.05)	1.04 (1.02 to 1.06)	1.04 (1.02 to 1.06)	1.04 (1.02 to 1.05)	1.03 (1.01 to 1.05)
4th quartile	21 466	1.08 (1.06 to 1.10)	1.06 (1.04 to 1.08)	1.06 (1.04 to 1.08)	1.06 (1.04 to 1.08)	1.05 (1.03 to 1.07)

*Cumulative exposure (kBq/m²) from 1986 through 1990 in three categories; lowest, in the first quartile (0.00–45.40; reference category); intermediate, in the second and third quartiles (45.41–118.80); and highest, in the fourth quartile (118.81–564.71).

general population on childhood leukaemia have also found an increased risk related to the individual bone marrow dose in Ukraine,[26] [27] but not in Belarus or western Russia.[28]

In the Nordic countries, epidemiological studies have also focused on childhood cancer, especially leukaemia, because it has the shortest latency period in children after radiation exposure. However, these studies have found no clear relationship to fallout from Chernobyl.[11–13]

All previous studies used a single exposure value from 1986, whereas we tried to reduce the exposure misclassification of people moving within Sweden by assigning each individual a yearly exposure value of ^{137}Cs, depending on their place of residence each year from 1986 to 1990.

The individuals in our cohort did not have cancer before the start of the follow-up period, and we based our calculations on only the first cancer diagnosis during the follow-up period. This approach is a methodological strength of our study because it reduces the possibility that multiple cancers in an individual would be dependent on events and perhaps secondary to treatment by cytostatic drugs or radiation therapy. Furthermore, our risk estimates were based on the cancer incidence rather than cancer mortality, which increases the statistical power of the study and therefore also accounted for successfully treated cancer cases.

Our study was also restricted to the three counties with the highest fallout to reduce bias from regional differences from other risk factors for cancer, such as socioeconomic, lifestyle and occupational risk factors.[20] This restriction can also be justified because the population of the three counties comprised 88% of the highest exposure quartile in all of Sweden. However, this restriction could to some extent reduce the contrast of exposure because the lowest exposed (reference) category would also likely be high. We assume such effect is relatively weak, however, because ^{137}Cs was deposited unevenly in the three counties. The contrast between the reference and other exposure categories was sufficient to show differences in HR. An additional advantage of using only three counties is that the pre-Chernobyl cancer incidence rate probably had less confounding than that in our previous study.[10]

Personal dosimetry of internal doses of radiation in the population cannot be obtained 30 years after the nuclear accident. However, the Swedish Defence Research Agency assessed the internal doses of persons living in different parts of Sweden using whole-body measurements of ^{134}Cs and ^{137}Cs.[29] According to these measurements, yearly doses up to 10 mSv could have been received in the first years after the accident. The activity of ^{137}caesium isotopes in farmers in mid-Sweden was almost 10 times higher than that in persons from southern Sweden.

The maximum recorded ^{137}Cs activity in the study region (in a 200 m grid cell), 180 kBq/m² in the municipality of Gävle, would (according to the radiometric

algorithms) correspond to a received external absorbed dose of 3.6 mGy from ^{137}Cs during the first year, assuming minimal shielding from building materials and seasonal snow cover.[30]

We assumed that our proxy for exposure, from a fallout map, could be related to the external dose rate. It is also possible that a higher deposition of ^{137}Cs on the ground might be associated with higher internal contamination according to the radio-ecological transfer factors given by Rääf et al[29] for different subgroups in the Swedish population. Caesium is water soluble and is a chemical and metabolic analogue to potassium in living tissue; accordingly, it is absorbed by plants and mushrooms and concentrated in muscle tissue consumed as meat. Still, 30 years after the accident, the recommended exposure limit of ^{137}Cs is exceeded in berries, fish and game in areas with high fallout.[7] Therefore, the proxy for external effective dose we used might also be associated with the internal dose, although we are aware of the inherent risk of misclassification of the total radiation dose. Moreover, dose assessments based only on external radiation may also underestimate the total effective dose. With these uncertainties in dose assessment, we chose to present our data in cumulative kBq/m^2 instead of converting them into mSv with a risk of introducing an even larger bias.

CONCLUSIONS

We found a small overall exposure–response pattern of the total cancer incidence related to a 5-year cumulative exposure based on the place of residence annually to a digital ^{137}Cs fallout map. Stepwise adjustment for the possible confounding from age, sex, rural habitat and pre-Chernobyl cancer incidence was performed. However, given the limitations in our exposure assessment, small risk estimates and overlapping CIs, we cannot claim causal inference. Further studies attempting to assess cumulative exposure after the Chernobyl nuclear power plant accident are therefore warranted to clarify these relationships further because even small increased risks can represent a considerable number of preventable cases, given that a large part of the European population was exposed to this radioactive fallout.

Ethics approval The study was approved by the regional Ethical Committee of Uppsala (No. 2010/434 and 2013/060).

Provenance and peer review Not commissioned; externally peer reviewed.

Data sharing statement No additional data are available.

REFERENCES

1. Mattsson S, Moberg L. Fallout from Chernobyl and atmospheric nuclear weapons tests. Chernobyl in perspective. In: Moberg L, ed. *The Chernobyl fallout in Sweden-results from a research programme on environmental radiology*. Stockholm: Swedish Radiation Protection Institute, 1991:591–627.
2. Moberg L, Reizenstein P. Health effects in Sweden of the Chernobyl accident [in Swedish]. *Nord Med* 1993;108:117–20.
3. National Institute of Radiation Protection. *Chernobyl—its impact on Sweden*. Stockholm, Sweden: National Institute of Radiation Protection, 1986:24.
4. Persson K, Prethun J. Food production after radioactive fallout. Umeå: Swedish Defence Research Agency, 2002:93.
5. Snihs JO. *Contamination and radiation exposure, evaluation and measures in the Nordic countries after the Chernobyl accident*. Swedish Radiation Protection Institute, 1996:41.
6. National Food Agency. *The Chernobyl accident-the situation after 25 years [in Swedish]. National Food Agency*. Uppsala, Sweden, 2011.
7. Swedish Radiation Safety Authority. Cesium database-searchable environmental data. 25 September 2014. http://www.stralsakerhetsmyndigheten.se/Yrkesverksam/Miljoovervakning/Sokbara-miljodata/Cesium/Cesium-Search-Page-New/
8. Tondel M, Lindgren P, Hjalmarsson P, et al. Increased incidence of malignancies in Sweden after the Chernobyl accident – a promoting effect? *Am J Ind Med* 2006;49:159–68.
9. Kurttio P, Seppä K, Pasanen K, et al. Fallout from the Chernobyl accident and overall cancer incidence in Finland. *Cancer Epidemiol* 2013;37:585–92.
10. Alinaghizadeh H, Tondel M, Walinder R. Cancer incidence in northern Sweden before and after the Chernobyl nuclear power plant accident. *Radiat Environ Biophys* 2014;53:495–504.
11. Hjalmars U, Kulldorff M, Gustafsson G. Risk of acute childhood leukaemia in Sweden after the Chernobyl reactor accident. Swedish Child Leukaemia Group. *BMJ* 1994;309:154–7.
12. Auvinen A, Hakama M, Arvela H, et al. Fallout from Chernobyl and incidence of childhood leukaemia in Finland, 1976–92. *BMJ* 1994;309:151–4.
13. Tondel M, Carlsson G, Hardell L, et al. Incidence of neoplasms in ages 0–19 y in parts of Sweden with high 137Cs fallout after the Chernobyl accident. *Health Phys* 1996;71:947–50.
14. Tondel M, Hjalmarsson P, Hardell L, et al. Increase of regional total cancer incidence in north Sweden due to the Chernobyl accident? *J Epidemiol Community Health* 2004;58:1011–6.
15. Auvinen A, Seppa K, Pasanen K, et al. Chernobyl fallout and cancer incidence in Finland. *Int J Cancer* 2014;134:2253–63.
16. Linden A, Mellander H. Airbone measurements in Sweden of the radioactive fallout after the nuclear reactor accident in Chernobyl, USSR. In: Swedish Geological Company AD, ed. Sweden: Swedish Geological Company, Airborne Division. 1986.
17. Mellander H. *A description of the SGAB airborne radiometry system. Swedish Geological Co, Airborne Division*. 1986, Report TFRAP 8605. Sweden, 1986.
18. Chase DC, Rabinowitz JL. *Principles of radioisotope methodology*. Minneapolis (MN): Burgess Publishing Company, 1967.
19. Schouten LJ, Meijer H, Huveneers JA, et al. Urban-rural differences in cancer incidence in The Netherlands 1989–1991. *Int J Epidemiol* 1996;25:729–36.
20. National Board of Health and Welfare. *Cancer incidence in Sweden—2011*. Stockholm, Sweden, 2012.
21. Statistics Sweden. *Regional divisions in Sweden on 1 January 2011 [in Swedish]*. Örebro, Sweden: Regional Sevices and Planning Unit, 2011.
22. Brenner AV, Tronko MD, Hatch M, et al. I-131 dose response for incident thyroid cancers in Ukraine related to the Chornobyl accident. *Environ Health Perspect* 2011;119:933–9.
23. Cardis E, Kesminiene A, Ivanov V, et al. Risk of thyroid cancer after exposure to 131I in childhood. *J Natl Cancer Inst* 2005;97:724–32.

24. Ivanov VK, Kashcheev VV, Chekin SY, *et al*. Radiation-epidemiological studies of thyroid cancer incidence in Russia after the Chernobyl accident (estimation of radiation risks, 1991–2008 follow-up period). *Radiat Prot Dosimetry* 2012;151:489–99.
25. Zablotska LB, Ron E, Rozhko AV, *et al*. Thyroid cancer risk in Belarus among children and adolescents exposed to radioiodine after the Chornobyl accident. *Br J Cancer* 2011;104:181–7.
26. Noshchenko AG, Zamostyan PV, Bondar OY, *et al*. Radiation-induced leukemia risk among those aged 0–20 at the time of the Chernobyl accident: a case-control study in the Ukraine. *Int J Cancer* 2002;99:609–18.
27. Noshchenko AG, Bondar OY, Drozdova VD. Radiation-induced leukemia among children aged 0–5 years at the time of the Chernobyl accident. *Int J Cancer* 2010;127:412–26.
28. Davis S, Day RW, Kopecky KJ, *et al*. Childhood leukaemia in Belarus, Russia, and Ukraine following the Chernobyl power station accident: results from an international collaborative population-based case-control study. *Int J Epidemiol* 2006;35:386–96.
29. Rääf CL, Hubbard L, Falk R, *et al*. Transfer of 137Cs from Chernobyl debris and nuclear weapons fallout to different Swedish population groups. *Sci Total Environ* 2006;367:324–40.
30. Finck RR. *High resolution field gamma spectrometry and its application to problems in environmental radiology*. Dissertation. Departments of Radiation Physics. Malmö and Lund: Lund University, 1992.