Lee et al. BMC Public Health (2025) 25:1690
https://doi.org/10.1186/s12889-025-22961-4

BMC Public Health

RESEARCH

Open Access

Incidence of solid cancers among residents near nuclear facilities: a systematic review and meta-analysis

Ga Bin Lee[1], Yerin Hwang[2], Soojin Park[1], Eun-Shil Cha[1], Dalnim Lee[1], Kyungsik Kim[3,4], Sue K. Park[3,4,5], Minsu Cho[1] and Songwon Seo[1*]

Abstract

Background Concerns about the potential health effects of radiation exposure in communities living near nuclear facilities persist, prompting ongoing studies across various countries. However, research on solid cancers in these communities remains limited. This systematic review and meta-analysis aimed to comprehensively investigate the incidence of various solid cancers among residents near nuclear facilities, providing up-to-date scientific evidence on potential health effects in the context of energy security and net-zero emission targets.

Methods A comprehensive search of the databases PubMed, Excerpta Medica Database, and Web of Science was conducted. Data were extracted from 13 studies on breast, bladder, thyroid, CNS, and respiratory cancers, with the meta-analysis focusing on cancer types supported by at least five quantitative estimates to account for study heterogeneity. Study quality was assessed using the Office of Health Assessment and Translation tool. Pooled standardized incidence ratios (SIRs) were calculated using random-effects models, and publication bias was evaluated using funnel plots and Egger's test.

Results The meta-analyses included the following number of cases for each selected cancer type: breast, $n = 20{,}701$; bladder, $n = 5{,}398$; thyroid, $n = 9{,}907$; CNS, $n = 3{,}634$; and respiratory system, $n = 18{,}033$. Pooled SIRs for all cancer subtypes were statistically insignificant and ranged from 0.99 to 1.04, with substantial heterogeneity among studies (I^2 range: 64%–96%). Little evidence of publication bias was revealed upon visual inspection of the funnel plots and performing Egger's test.

Conclusions Current scientific evidence regarding the incidence of solid cancers in populations living near nuclear facilities is insufficient to draw definitive conclusions. Nonetheless, the wide range of heterogeneity among studies highlights the need for further research with refined study designs, particularly with regard to radiation exposure and individual-level confounding factors, to provide more robust evidence on the public health implications for residents near nuclear facilities.

Keywords Environmental Exposure, Radiation Exposure, Radiation-Induced Neoplasms, Systematic Review, Meta-Analysis, Epidemiologic Studies

*Correspondence:
Songwon Seo
seo@kirams.re.kr
Full list of author information is available at the end of the article

Introduction

Significant attention has been focused on residents near nuclear facilities because of concerns about potential health impacts, especially after reports highlighted the elevated childhood leukemia incidence after accidents in Sellafield, England [1]. Numerous studies have consequently explored cancer risk among people living near nuclear facilities across Europe. The Kinderkrebs in der Umgebung von Kernkraftwerken (Childhood Cancer in the Vicinity of Nuclear Power Plants) study in Germany [2] and Geocap study in France [3] are notable examples. Both studies indicated an increased childhood leukemia incidence within 5 km of nuclear power plants (NPPs), although insignificant associations have been reported in other countries. Moreover, at the request of the United States (US) Nuclear Regulatory Commission, the US National Academy of Sciences initiated a pilot study on cancer risk in populations living near nuclear facilities [4]. However, the project was terminated because of challenges in obtaining usable results within a reasonable timeframe. Despite this factor, concerns persist regarding the potential health effects of minimal radiation release in communities living around nuclear facilities, thereby prompting ongoing studies in various countries.

In the meantime, nuclear energy has drawn growing attention for its role in sustainable energy security and carbon neutrality goals [5]. In particular, several East Asian and European countries have shifted from a nuclear phase-out policy to the expansion of nuclear power to respond to energy demands and climate policies [6, 7]. However, safety issues regarding potential health effects and the varied public opinions on NPPs remain, raising concerns about its implementation.

Although a lot of attention has been paid to the childhood leukemia in populations living near nuclear facilities, resulting in the publication of comprehensive meta-analyses [8, 9], relatively limited research exists on solid tumor risks among residents living near nuclear facilities. This limitation underscores the persistent gap in the literature concerning the comprehensive review of solid tumor types associated with nuclear facilities. To address this gap, we conducted a systematic review and meta-analysis of the incidence of solid tumor types among residents living near nuclear facilities.

Methods

Eligibility criteria

A systematic review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [10], and the protocol was registered in the International Prospective Register of Systematic Reviews (CRD42023442229) on July 15, 2023. The review was structured using a PICO framework: the Population consisted of residents near nuclear facilities; the Exposure (Intervention) referred to the routine operations of these facilities (excluding studies on nuclear weapon testing or accidents, such as those in the Marshall Islands-Bikini and Chernobyl-Ukraine); the Comparison groups were primarily the general population or residents living farther from these facilities; and the Outcome was initially intended to assess overall cancer incidence and mortality. However, given the broad scope of these outcomes, we initially focused various types of cancer incidence and mortality, but later narrowed the scope to exclusively examine the incidence of solid tumors for a more focused analysis. Detailed changes from the original study protocol are provided in Supplementary Material 1.

For the systematic review, studies employing comprehensive exposure metrics such as distance from facilities, regional hosting facilities, or regional radiation levels were considered. Since most studies used distance or geographic regions as practical surrogates for radiation exposure, the meta-analysis excluded studies that used radiation levels as exposure metrics due to the limited number of studies. In addition to the meta-analysis, we conducted two narrative reviews: one on solid cancer subtypes excluded from the meta-analysis due to a lack of quantitative estimates, and another on the impact of radiation exposure on cancer incidence. This review allowed for a broader understanding of cancer incidences and complemented the meta-analysis findings by addressing cancers that were outside the scope of the quantitative analysis. We included English-language articles, excluding reviews, letters, and commentaries, provided they contained relevant estimates.

Search strategy and database

We systematically searched PubMed (National Center for Biotechnology Information, Bethesda, MD, USA), Excerpta Medica Database (EMBASE; Elsevier, Amsterdam, the Netherlands), and Web of Science (Clarivate, Philadelphia, PA, USA) for studies published from 1960 to January 9th, 2023. The search strategies combined Medical Subject Headings terms and keywords related to cancer risk and residence near nuclear facilities, using Boolean operators (OR) for comprehensive inclusion of relevant literature, with a filter applied for human studies only. Further details on the search strategies are provided in Supplementary Material 2.

Screening

The review process consisted of two stages: an initial screening of titles and abstracts for relevance, conducted by G.B.L and S.J.P, followed by a full-text review of the retrieved articles, also conducted by G.B.L and S.J.P. The process was overseen by a team of reviewers (G.B.L, S.J.P, and S.W.S), all of whom are experts in epidemiology, to ensure a rigorous evaluation of the retrieved articles. Any discrepancies or conflicts were addressed during the review to reach a consensus.

Quality assessment

To ensure the quality and reliability of the included studies, a detailed quality assessment was independently conducted by two reviewers (G.B.L and Y.R.H) using the Office of Health Assessment and Translation (OHAT) criteria, widely recognized for evaluating study quality in environmental health research [11]. This assessment included elements such as selection bias, confounding bias, attrition/exclusion bias, exposure characterization, outcome assessment, selective reporting bias, and other potential sources of bias. Based on the assessment results, each study was classified into one of three tiers reflecting the overall risk of bias. Studies in Tier 1 were rated as having"definitely low"or"probably low"risk of bias for key elements and most other criteria. Tier 2 consisted of studies that did not meet the criteria for either Tier 1 or Tier 3, indicating a moderate risk of bias. Tier 3 included studies rated as having"definitely high"or"probably high"risk of bias for key elements and most other criteria. Any discrepancies in the quality assessment were resolved through discussion or consultation with the senior author (S.W.S). Detailed information regarding the individual risk of bias scores and their corresponding tier ratings can be found in Supplementary Matarial 3.

Data extraction

The included articles underwent data abstraction to capture essential publication details such as authors, year of publication, country of origin, study design, and specific nuclear facilities involved. Additionally, the following items were recorded: geographic regions or distances considered, population demographics (i.e., age and sex), assessed outcomes, reference groups, case counts, statistical estimates, and corresponding 95% confidence intervals (CIs).

The SIR was used as the primary measure across the studies, with IRR and RR considered as alternative estimates. Where only observed and expected counts were available, we calculated SIRs as the ratio of observed to expected cases. The corresponding 95% confidence intervals were estimated using a normal approximation for observed counts greater than 30, and an exact method based on the Poisson distribution for smaller counts. Separate estimations of individual nuclear facilities in the study region were combined. In cases where multiple estimates were available for different distances, wider distances from the facilities were prioritized to align with the regions under investigation. These regions typically encompassed the entire area hosting the nuclear facilities or extended to at least 25 km from the facilities, which was the most common distance range used in the included studies. The original values reported in the articles, along with the calculated and combined values, are presented in Supplementary Material 4. The calculations were performed using the LaMorte Epidemiology/Biostatistics tool [12].

Statistical analysis

To account for study heterogeneity, the meta-analysis was conducted only for cancer types with a minimum of five studies providing relevant quantitative estimates (e.g., SIR, IRR, RR) [13]. A random-effects model using the inverse variance method was employed to combine effect sizes, given the anticiapted interstudy heterogeneity, with Knapp–Hartung adjustments applied to compute the 95% CIs around the pooled effect [14]. Forest plots were generated to visually present the SIRs and corresponding 95% CIs across studies. Heterogeneity variance (τ^2) was estimated using the method of DerSimonian and Laird [15], with residual heterogeneity assessed using Cochran's Q statistic. The I^2 statistic of Higgins and Thompson [16] was used to assess the proportion of variability in effect sizes that were not attributable to sampling errors. Higher I^2 values indicated greater heterogeneity. We also computed prediction intervals (PIs) around the overall pooled effect based on the estimated interstudy heterogeneity variance and standard error of the pooled effect [17]. Possible publication bias was evaluated by using Egger's test and visual inspection of a funnel plot [18]. For sensitivity analyses, to assess the potential impact of publication bias in our meta-analysis, the trim-and-fill procedure was used [19]. Additionally, in the case of brain and central nervous system (CNS) tumors, for which the included studies covered a wide age range, the SIRs were pooled after excluding studies focusing on children aged 0 to 14 years. Lastly, we conducted analyses by including only studies of higher quality (i.e., Tier 2 or above) based on the assessment of study quality. All statistical models were fitted using R, version 4.3.2 (R Foundation, Vienna, Austria). *P*-values were two-sided, with a significance level of 0.05.

Results

Figure 1 presents the study selection process, including reasons for exclusion at each stage. A total of 2481 records were identified through database searches (PubMed, Embase, and Web of Science). After removing duplicates, 1,686 records were screened based on titles and abstracts. Of these, 137 full-text articles were sought for retrieval, and 121 were successfully obtained

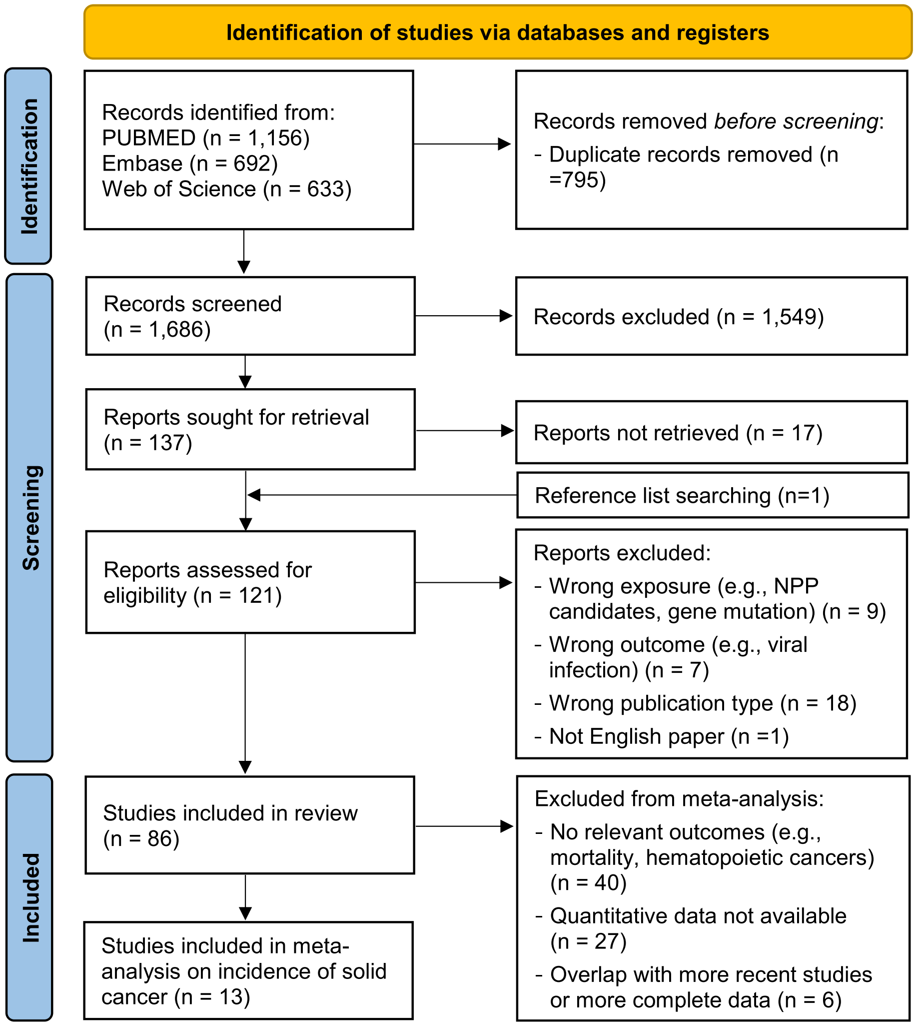

Fig. 1 Flowchart of the systematic review search process for assessing solid cancer incidence among individuals residing near nuclear facilities

and assessed for eligibility. Ultimately, 86 studies were included in the systematic review. Of these, 13 studies provided sufficient quantitative data and were included in the meta-analysis on solid cancer incidence. Studies were excluded from the meta-analysis for the following reasons: reporting non-relevant outcomes (e.g., mortality, hematopoietic cancers) ($n = 40$); lacking the quantitative data required for effect size estimation ($n = 27$); or overlapping with more recent or comprehensive studies ($n = 6$). The meta-analysis focused on five cancer types: breast, bladder, central nervous system (CNS), thyroid, and respiratory system cancers (e.g., lung, bronchus, trachea).

The characteristics of the 13 selected studies are summarized in Table 1. Two studies were retrospective cohort studies, and the remaining studies had an ecological design. These studies spanned 11 countries and covered 45 nuclear facilities, which included NPPs, radioactive waste storage facilities, and nuclear fuel processing plants involved in the processing of radium, uranium, and plutonium. The numbers of cases (n) for each cancer type included in the meta-analyses were as follows: breast, $n = 20{,}701$; bladder, $n = 5{,}398$; thyroid, $n = 9{,}907$; CNS, $n = 3{,}634$; and respiratory system, $n = 18{,}033$. Based on the OHAT risk of bias assessment, 5 out of 13 studies were classified as Tier 2, indicating moderate risk of bias. The remaining studies were classified as Tier 3, indicating high risk of bias.

All five cancer types had moderate-to-high heterogeneity, with I^2 values ranging from 64 to 96%. The PI included the value of 1, indicating that uncertainty remains regarding the direction and magnitude of the association between cancer incidence and proximity to nuclear facilities. Figure 2 presents forest plots of the summary estimates derived from the random-effects model for each tumor type. The pooled SIRs for cancers of the breast (1.01, 95% CI: 0.96,1.06), CNS

Table 1 The main characteristics of 13 studies included in the meta-analysis of solid cancer incidences and living near nuclear facilities

Author (year)	Country	Study design	Study period	Facility	Regions, distances	Reference	Index	Outcome	Age	Sex	Case	Estimates (95% CI)	Confounding factors
Prindull et al. (1993) [20]	Germany	Ecological	1980–1988	NPP (Wurgassen)	< 25 km	West German pediatric incidence rates	SIR	CNS tumor	0–14	total	14	1.70 (0.90–2.80)	Age
Sharp et al. (1999) [21]	Scotland	Ecological	1975–1994	Seven nuclear facilities	< 25 km	Scottish national incidence rates	SIR	CNS tumor	0–14	total	202	1.06 (0.92–1.21)	Age, sex, deprivation, urban–rural status
Zadnik et al. (2008) [22]	Slovenia	Ecological	1984–2003	NPP and waste repository	Spodnje-posavska, regions hosting facilities	Slovenian national incidence rates	SIR	Breast cancer	all	women	NA	0.98 (0.90–1.07)	Age, sex, region
								Thyroid cancer		women	NA	0.94 (0.67–1.28)	
Boice. Jr. et al. (2009) [23]	US	Ecological	1984–2004	Two former nuclear processor	Apollo and Parks, regions hosting facilities	Pennsylvanian incidence rates	SIR	Breast cancer	all	women	361	0.96 (0.86–1.06)	Age, sex, race
								Brain and nervous system	all	total	21	0.64 (0.40–0.99)	
								Trachea, bronchus, lung, pleura	all	total	382	1.00 (0.90–1.10)	
								Bladder tumor	all	total	155	1.17 (0.99–1.37)	
								Thyroid cancer	all	total	15	0.53 (0.30–0.87)	
F. Ma et al. (2011) [24]	US	Ecological	1986–2005	Seven NPPs	≤ 32 km	Illinois state incidence rates	SIR	CNS and miscellaneous intracranial and intraspinal neoplasm	0–14	total	536	1.12 (0.97–1.29)	Age, sex, race
Bazyka et al. (2012) [25]	Ukraine	Ecological	2003–2008	Nuclear processor, radioactive waste storage	Regions hosting facilities	Ukrainian national incidence rates	SIR	Breast cancer	all	total	1,000	1.14 (1.07–1.21)	Age, sex
								Trachea, bronchus, lung	all	total	1,141	1.23 (1.16–1.30)	
								Thyroid cancer	all	total	156	1.06 (0.90–1.23)	

Table 1 (continued)

Author (year)	Country	Study design	Study period	Facility	Regions, distances	Reference	Index	Outcome	Age	Sex	Case	Estimates (95% CI)	Confounding factors
Chen et al. (2013) [26]	Canada	Ecological	1992–2007	Nuclear processing facilities	Port Hope, regions hosting facilities	Ontario incidence rates	SIR	Breast cancer	all	women	165	0.95 (0.81–1.11)	Age, sex, and socio-economic status using various reference populations
								Brain tumor	all	total	18	0.92 (0.55–1.46)	
								Lung, bronchus	all	total	230	1.26 (1.10–1.43)	
								Bladder tumor	all	total	48	1.04 (0.77–1.38)	
								Thyroid cancer	all	women	11	0.55 (0.27–0.98)	
Lane et al. (2013) [27]	Canada	Ecological	1990–2008	Three NPPs (Pickering, Bruce, Darlington)	< 25 km	Ontario incidence rates	SIR	Breast cancer	all	women	16,067	0.98 (0.96–0.99)	Age, sex
								Brain and NS tumor	all	total	2,286	0.94 (0.90–0.98)	
								Lung, bronchus	all	total	16,067	0.89 (0.88–0.91)	
								Bladder tumor	all	total	4,106	0.95 (0.92–0.98)	
								Thyroid cancer	all	total	4,591	1.34 (1.30–1.38)	
Salerno et al. (2016) [28]	Italy	Ecological	2002–2010	Two former nuclear facilities (NPP and radioactive waste disposal)	Regions hosting facilities	Turin city incidence rates	SIR	Breast cancer	all	women	182	1.03 (0.88–1.17)	Age, sex
								Lung	all	total	137	0.90 (0.75–1.06)	
								Bladder tumor	all	total	110	0.91 (0.75–1.10)	
								Thyroid cancer	all	total	20	1.36 (0.83–2.10)	
Desbiolles et al. (2018) [29]	France	Ecological	1995–2011	Seven NPPs and two nuclear facilities (La-Hague)	< 20 km	France metro-politan incidence rates	IRR	Breast cancer	+ 15	women	4,103	0.99 (0.95–1.03)	Regional tobacco and alcohol consumption, deprivation, urbanization, pesticides, and other environmental factors
								Brain and CNS tumor	+ 15	total	435	1.06 (0.96–1.16)	
								Bladder tumor	+ 15	total	979	1.10 (1.03–1.17)	
								Thyroid cancer	+ 15	total	671	0.92 (0.85–0.99)	

Table 1 (continued)

Author (year)	Country	Study design	Study period	Facility	Regions, distances	Reference	Index	Outcome	Age	Sex	Case	Estimates (95% CI)	Confounding factors
Bunch et al. (2014) [30]	UK	Retrospective birth cohort	1971–2006	Nuclear fuel reprocessing (Sellafield)	Copeland and Allerdale, regions hosting facilities	England national incidence rates	SIR	Breast cancer	all	total	389	0.93 (0.84–1.03)	Age, sex
								Brain and CNS tumor	all	total	122	0.86 (0.71–1.02)	
								Lung, trachea, and lower respiratory tract tumors	all	total	76	1.02 (0.80–1.28)	
								Thyroid cancer	all	total	30	0.85 (0.58–1.22)	
Levin et al. (2013) [31]	US	Retrospective cohort	1990–2009	NPP (TMI)	Dauphin, York, Lancaster, regions expected to be exposed to iodine	Pennsylvanian incidence rates	SIR	Thyroid cancer	all	total	2,652	1.12 (1.08–1.17)	Age, year of diagnosis, county
Demoury et al. (2017) [32]	Belgium	Ecological	2000–2014	Two NPPs and two nuclear sites	< 20 km	Flemish, Wallon incidence rates	IRR	Thyroid cancer	all	total	1,761	0.91 (0.87–0.95)	Age, sex, year, region

SIR age-standardized incidence ratio, *IRR* incidence rate ratio

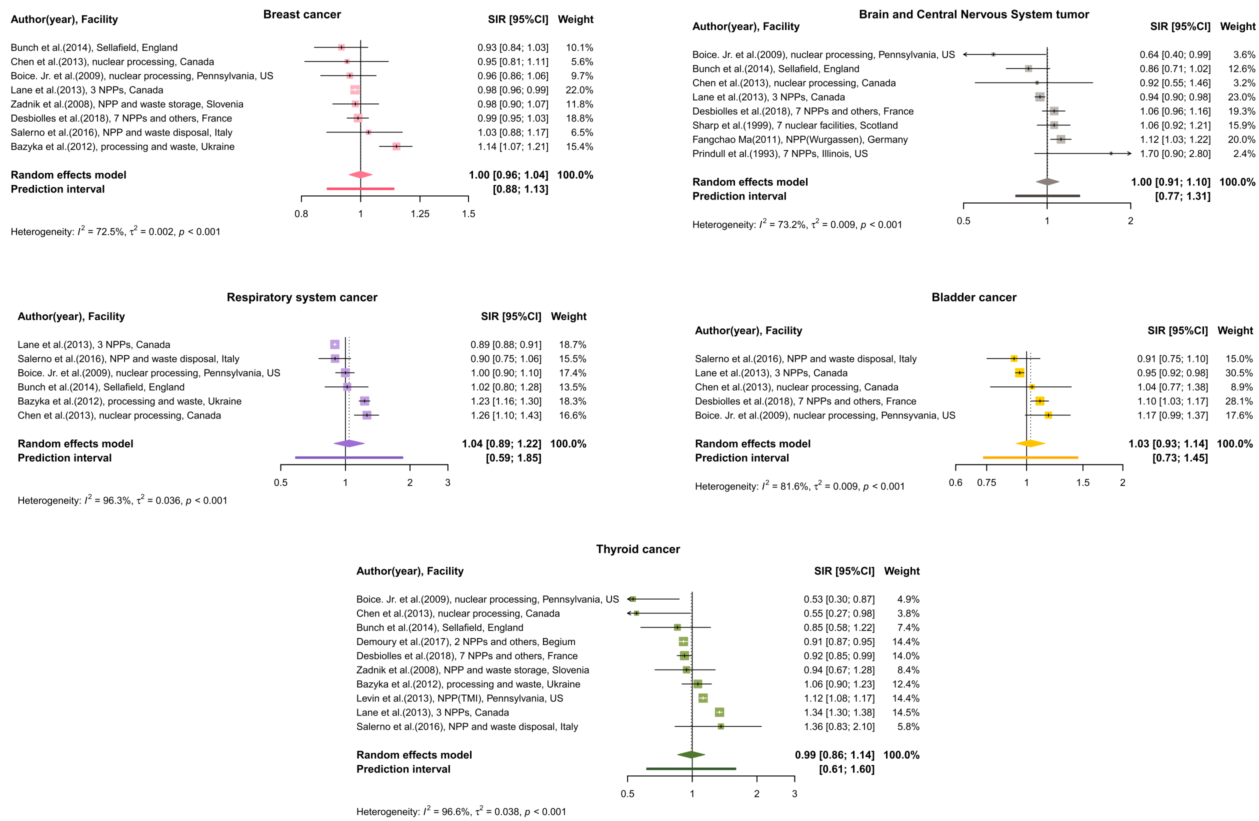

Fig. 2 Forest plots illustrating pooled standardized incidence ratios (SIRs) for solid cancer subtypes among individuals residing near nuclear facilities

(1.00, 95% CI: 0.92,1.10), respiratory system (1.04, 95% CI: 0.89,1.23), bladder (1.03, 95% CI: 0.93,1.14), and thyroid (0.99, 95% CI: 0.86,1.14) showed no statistically significant increases or decreases associated with residing near nuclear facilities. Visual inspection of the funnel plots and Egger's test results indicated minimal evidence of publication bias, with statistically nonsignificant findings for each cancer type (Supplementary Material 5).

In the sensitivity analysis, using the trim-and-fill method, the size and statistical significance of the pooled SIRs remained consistent across all cancer types except for thyroid cancer (Supplementary Material 6). For thyroid cancer, the inclusion of imputed studies increased the pooled estimate to 1.21 (95% CI: 1.05, 1.40), with the PIs ranging from 0.69 to 2.12, reflecting ongoing uncertainty in the results. The results from the Tier 2 studies showed similar findings, with no statistically significant differences observed for any of the cancer types (Supplementary Material 7).

Discussion

This study investigated the incidence of various solid tumors among residents living near nuclear facilities. The meta-analysis found no statistically significant differences in solid tumor incidence between the residents and the general population, with pooled results for breast, bladder, CNS, respiratory system, and thyroid cancer incidence ratios approaching 1, indicating comparable results with the general population. These results may have been influenced by the inconsistencies reported in previous studies. In particular, substantial heterogeneity existed among the studies, which may be attributable to variations in nuclear facility types, the range of interested areas, and sample sizes. This is reflected in the wide PIs, which indicate uncertainty regarding the direction and magnitude of the association. Given this variability in study findings, we emphasize the importance of cautiously interpreting the pooled results.

Breast cancer

Our statistically non-significant findings are consistent with those of most previous studies. Studies conducted in US regions (e.g., Apollo and Parks in the state of Pennsylvania) near decommissioned nuclear processors did not detect increases in breast cancer incidence [23, 33]. A Korean prospective cohort study spanning from 1992 to 2010 similarly reported no increase in female breast cancer incidence among residents living within 5 km of nuclear facilities [34], even after adjusting for socioeconomic status (SES), body mass index, medical utilization, and other factors. In addition, studies on Canadian NPPs and nuclear processors have reported null findings [26, 27]. These results remained consistent, even when examining non-movers (i.e., individuals who had lived at the same address for the previous 6 years) near the Pickering NPP (Pickering, Ontario, Canada) [35]. However, two studies reported a significantly increased incidence of breast cancer near nuclear facilities: one study in the Ukraine investigated uranium mining and processing enterprises with extensive tailing waste areas [25], and one study in the US focused on regions within 1.6 km from a decommissioned nuclear processor (e.g., Apollo) [36]. However, a factor that should be noted is that, unlike studies reporting statistically non-significant findings, these studies did not adjust for confounding factors. For example, factors such as screening effects among nuclear facility employees [25] and demographic factors, such as SES and health behaviors [36] presumably influence the observed associations.

Bladder cancer

A French study involving seven NPPs reported a significantly increased incidence of bladder cancer in men (RR: 1.08, 95% CI: 1.00, 1.17) and in women (RR: 1.19, 95% CI: 1.02, 1.39), even after adjusting for municipality-level confounders. This increase was primarily associated with the Flamanville NPP and the nearby La Hague nuclear waste treatment center, known for chemical contaminants (e.g., arsenic) that are recognized as bladder cancer risk factors [29]. However, a series of studies conducted in the US involving former nuclear processing plants, which were updated to confirm the validity of residential addresses, yielded no significant associations [23, 33]. Residents near Canadian NPPs and uranium processing plants similarly showed no increase in bladder cancer incidence [26, 27]. However, the results varied among Canadian NPPs. Incidences were significantly higher near the Darlington NPP but significantly lower near the Pickering and Bruce NPPs [27], with smoking presumed to be a confounding factor influencing the results [37]

Brain and CNS tumors

All three studies included in our meta-analyses that examined childhood CNS tumor incidences reported increasing rates, but this trend did not reach statistical significance [20, 21, 24]. In contrast, studies encompassing all age groups demonstrated either decreasing rates or results comparable to the general population [23, 26, 27, 29, 30]. The sensitivity analysis, which excluded studies focusing on children, did not alter the overall results; the pooled SIRs remained at 0.95 (95% CI: 0.81, 1.10). A retrospective birth cohort study conducted in regions surrounding Sellafield identified no increase in CNS tumor incidence [30]. Canadian studies on uranium processing plants [26] and NPPs [27], as well as French NPPs studies [29], which adjusted for municipality-level confounding factors, also reported nonsignificant increases. In contrast, US studies investigating former nuclear processing plants in Pennsylvania reported a significantly lower incidence of CNS tumors [23, 33]. However, it is crucial to note the limitations of their descriptive and population registry-based study design, which did not adjust for individual-level confounders. An Italian study [28], by comparison, reported nearly double the incidence of nervous system tumors near radioactive waste storage sites and NPPs. This study, however, included a broader range of nervous system tumors, rather than focusing solely on brain and CNS tumors.

Thyroid cancer

Our findings, along with substantial interstudy heterogeneity in thyroid cancer incidence, align with the findings in previous meta-analyses [38] and in individual studies conducted in the Ukraine [25], Slovenia [22], Italy [28], and Taiwan [39]. Additionally, cross-sectional studies conducted in the US around Three Mile Island (TMI) predominantly reported non-significant findings [31, 40, 41]. However, a French study [29] on NPPs reported a reduced incidence of female thyroid cancer, possibly owing to differences in medical practices. In contrast, two notable studies have reported significantly higher incidence rates. Canadian studies on three NPPs indicated that the release of radioactive iodine, the primary cause of radiation-related thyroid cancer, was below detection limits during the study period, which was significantly lower than the natural background radiation and the public dose limits (i.e., 1 mSv/year) [27]. This suggests that thyroid cancer incidence is unlikely to increase around certain NPPs (e.g., Pickering and Darlington). A Korean prospective cohort study, focusing on the period of 1992 to 2010, reported a 1.9-fold increased incidence (95% CI: 1.13, 3.21) of thyroid cancer among women living within 5 km of NPPs compared to the risk among women living more than 30 km away, after adjusting for confounding factors [34]. However, these findings warrant cautious interpretation, particularly as radiation levels in residential areas remain far below the established dose limit. In addition, subsequent ecological studies in Belgium presented inconsistent findings [32, 42, 43], although some significant results based on distances from facilities or hypothetical radiation exposure became nonsignificant in follow-up studies, significant results persisted in other studies. Although the latter studies were conducted at the smallest geographical level, the ecological study design may lack the sensitivity required to follow up on these findings [43].

Respiratory system cancer

We were unable to exclusively evaluate lung cancer owing to data limitations. Previous studies covered a wide range of outcomes, resulting in substantial heterogeneity among studies. US studies in regions near former nuclear processing plants (e.g., Apollo and Parks) revealed no differences in lung cancer incidences among residents compared with that among the Pennsylvanian population [23, 33]. However, recent results for one of these regions (i.e., Apollo) revealed a significant increase in lung and bronchial cancer (SIR: 1.48, 95% CI: 1.32, 1.65), possibly attributed to unintended release of insoluble uranium-235 or unmeasured confounders, such as smoking and the SES. A Ukrainian study [25] reported a significantly higher incidence (1.23-fold) of tracheal, bronchial, and lung cancers near nuclear facilities, which suggested a screening effect due to the more rigorous medical surveillance undertaken by employees. Similarly, a Canadian study found a significantly increased incidence of lung cancer among female residents near uranium processing plants, likely due to unadjusted tobacco use, as the low radiation levels (< 0.69 mSv/year) from these facilities are unlikely to cause increased cancer incidences [26]. Findings from Canadian NPP studies on lung and bronchial cancer have been inconsistent, with certain NPPs showing significant increases and others showing decreases. Conversely, studies from Taiwan [39], Italy [28], France [29], and the US (TMI) [44, 45] reported statistically non-significant findings.

Solid cancer subtypes not included in the meta-analyses

Excluded from the meta-analyses were various solid tumor subtypes, such as stomach, liver, kidney, colon, esophagus, and oral cavity cancers, which are susceptible to radiation-induced effects. Notably, a Korean prospective cohort study found a significantly increased incidence of stomach cancer in men living within 5 km of NPPs (hazard ratio [HR]: 1.60, 95% CI: 1.10, 2.43), compared to men residing farther away. However, no significant association was found in the aggregated radio-inducible cancer group (HR: 1.20, 95% CI: 0.92, 1.54) [34]. To conclusively attribute these findings to radiation releases from the facility is challenging, given the low estimated radiation releases, specific results limited to certain sexes or comparison groups, and small sample sizes [34]. Furthermore, an Italian ecological study [28] conducted in areas with a history of radioactive waste disposal and a nearby NPP reported significantly elevated incidences of various cancers, ranging from 1.8 to 14 times higher SIRs, including tumors of the oral cavity, kidney, nervous system, and bone. Potential factors such as viral origin and occupational exposure may contribute to the elevated risk of tumors, which highlights the need for further research to assess the impact of unmeasured factors on cancer incidences [28]. In contrast, several US ecological studies conducted at former nuclear material processing sites (i.e., Apollo and Parks) did not reveal significant findings. However, a recent study focusing on areas within 1.6 km of the Apollo site reported notable increases in the incidences of colon, stomach, kidney (in women), and oral cavity (in men) tumors [36]. These findings may be influenced by occupational exposure, particularly in regions historically associated with steel production, which suggests potential non-radiation-related factors; additionally, uncontrolled variables such as smoking habits, SES, and other lifestyle factors may have contributed to these results. Other studies conducted in Canada [26, 27] and Taiwan [39] did not report significant results, which adds to the complexity of comprehending the impact of residing near nuclear facilities on cancer incidence.

Literature on solid tumors related to radiation exposure

Several studies have assessed the incidence of solid tumors with respect to radiation exposure. In a Canadian retrospective cohort study involving the Pickering NPP, an increased breast cancer incidence was observed among female residents, compared with the incidence among the general population (HR: 2.34, 95% CI: 1.32–4.46); however, this finding was not associated with tritium levels [35]. Another retrospective cohort study conducted among residents within a 5-mile radius of the TMI NPP in the US, spanning the years 1982 to 1995, utilized the maximum and likely whole-body gamma doses from the TMI accident, calculated based on residential location and duration of stay during the 10 days after the accident [46]; no evidence of increased incidence of malignant neoplasms was found in relation to radiation exposure, even after adjusting for multiple confounding factors, including background radiation. Ecological studies in Belgium employed distance and hypothetical radioactive discharges of iodine-131 as surrogate markers of radiation exposure; these studies revealed a significantly increasing trend in thyroid cancer incidence around Fleurus, a major production site of radio-iodine [43] and around Mol-Dessel, a facility for managing radioactive materials [32]. This trend corresponds to decreased distance and increased hypothetical radioactive discharge, calculated using a mathematical dispersion model. Additionally, a retrospective cohort study [47] conducted in the US at the Hanford site, a nuclear production complex in Washington state, investigated self-reported thyroid radiation exposure from facility releases during infancy and childhood. However, no association existed between such exposures and thyroid diseases.

Strengths and limitations

This systematic review and meta-analysis is the first comprehensive effort to investigate the incidence of solid tumors among people living near nuclear facilities. However, several critical considerations must be made when interpreting these results.

First, most included studies were ecological or descriptive in nature, with no consideration for individual-level confounding factors such as health behaviors and SES. These factors, including current smoking status, alcohol consumption, and physical inactivity, are well-established contributors to cancer risk [48]. The absence of such data could introduce bias into the estimates of cancer incidence from nuclear facilities, particularly if these factors vary between populations living near nuclear facilities and the comparison populations [49]. For example, in Korea, individuals living near NPPs undergo more thyroid screening tests than the general population [50], which may influence the diagnosis of thyroid cancer. Additionally, a significant limitation of many previous studies is their inability to capture residence duration. This makes interpreting the results challenging, particularly since the minimum latency period for solid tumors is typically assumed to be 10 years [4]. Without this information, whether individuals in the communities of interest have resided for extended periods or been exposed to measurable radiation associated with industrial activities is unclear. Furthermore, the ecological design of most studies introduces limitations due to the use of aggregated data. This can compromise the independence of observations, as observations from regions with shared factors may be correlated, which could affect the precision and generalizability of the findings.

Second, the decision to assess radiation exposure near nuclear facilities presents several challenges. One major challenge stemmed from the limited availability of studies directly assessing radiation exposure, which precluded their inclusion in the meta-analyses. We consequently relied on the distance from nuclear facilities as a surrogate marker for exposure despite its potential limitations in accurately reflecting radiation exposure levels. This reliance on distance alone overlooks the impact of individual behaviors such as food consumption and water use [51] and overlooks natural background or cosmic radiation [4] which is known to influence individual radiation exposure. A factor worth noting is that the estimation of individual radiation exposure is more difficult among residents than among radiation workers because workers typically undergo monitoring by using individual dosimeters, which provides more accurate data [52]. Moreover, radiation levels are not uniformly distributed relative to the distance from nuclear facilities [53], and this factor can confound the association between distance and cancer incidence.

Third, the exceptionally low estimated radiation released from routine operations, which falls below the public dose limit and average natural radiation background [27, 34, 54], poses an additional challenge in detecting any noticeable effect on cancer incidence. This challenge is primarily attributed to the limited statistical power of capturing the statistical significance of the relationship between cancer incidence and minimal radiation exposure [4]. Distinguishing these low levels from the natural background or medical radiation exposure adds another layer of complexity.

Furthermore, the wide range of interested regions and types of nuclear facilities could contribute to the heterogeneity observed among the studies. Varying definitions of study regions, ranging from close proximity to nuclear facilities to the entire host region, have led to diverse sample sizes, often resulting in inconsistent findings. Additionally, different types of nuclear facilities, including NPPs, radioactive waste storage sites, and nuclear material processing plants, release varying levels of radiation [55, 56], which may have different impacts on health. Operational differences, safety measures, and the types of radioactive isotopes produced or stored in these facilities can also affect the extent of radiological release. Although these factors are critical, our ability to quantitatively analyze their specific impacts was limited because of insufficient data. Most research has examined nuclear facilities as a whole rather than distinguishing between specific types of facilities or radiological releases. Other potentially attributable risks beyond radiation, including chemical materials such as arsenic and steel, are also important to consider [29, 36]. These complexities underscore the challenges inherent in investigating the relationship between residence near nuclear facilities and the incidence of solid tumors. Lastly, we restricted the inclusion of studies to English-language articles due to practical challenges in translating and interpreting non-English studies. While this restriction was necessary to maintain a uniform standard of data quality, it may affect the comprehensiveness of the findings.

Conclusion

Understanding the relationship between residing near nuclear facilities and cancer incidence is essential for risk assessment, regulatory decisions, and public health interventions, particularly in the current context of energy security and net-zero emission targets. In this regard, our systematic review and meta-analysis significantly contribute to the understanding of the incidence of solid tumors among people living near nuclear facilities. Although definitive scientific evidence regarding the incidence of solid tumors among residents living near nuclear facilities remains unclear, our study highlighted critical limitations, including reliance on ecological or descriptive studies, absence of considering individual-level confounding factors, challenges in measuring radiation exposure, and significant heterogeneity among studies. Future research should employ a well-structured design that considers radiation exposure and individual-level confounding factors in order to provide more robust evidence.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12889-025-22961-4.

Supplementary Material 1.

Supplementary Material 2.

Supplementary Material 3.

Supplementary Material 4.

Supplementary Material 5.

Supplementary Material 6.

Supplementary Material 7.

Acknowledgements
None.

Authors' contributions
Conceptualization: S.W.S, G.B.L, Data curation: G.B.L, S.J.P, Formal analysis: G.B.L. Funding acquisition: M.S.C, Methodology: S.W.S, S.K.P, E.S.C, G.B.L. Software: G.B.L. Supervision: S.W.S, Validation: G.B.L, Y.R.H. Visualization: G.B.L. Writing—original draft: G.B.L. Writing—review & editing: S.W.S, G.B.L, S.K.P, K.S.K, S.J.P, E.S.C, D.L, M.S.C, Y.R.H.

Funding
This work was supported by the Korea Institute of Radiological and Medical Sciences, supported by the Nuclear Safety and Security Commission, Republic of Korea [grant No. 50091].

Data availability
The datasets generated and/or analyzed during the current study were extracted from published articles. These data are publicly available from the original publications cited in the manuscript.

Declarations

Ethics approval and consent to participate
This study was literature-based. Therefore, approval by an institutional review board and informed consent were not required.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

Author details
[1]National Radiation Emergency Medical Center, Korea Institute of Radiological and Medical Sciences, 75 Nowon-Ro, Nowon-Gu, Seoul 01812, Republic of Korea. [2]Seoul Mental Health and Welfare Commission, Seoul Mental Health Welfare Center, Seoul, Korea. [3]Department of Preventive Medicine, Seoul National University College of Medicine, Seoul, Korea. [4]Cancer Research Institute, Seoul National University College of Medicine, Seoul, Korea. [5]Integrated Major in Innovative Medical Science, Seoul National University Graduate School, Seoul, Korea.

Received: 11 December 2024 Accepted: 28 April 2025
Published online: 07 May 2025

References

1. Black D. Investigation of the possible increased incidence of cancer in West Cumbria. Report of the Independent Advisory Group. 1984. Available from: https://pdf.library.soton.ac.uk/BOPCRIS/22690/pdf/22690_1.pdf.
2. Spix C, Schmiedel S, Kaatsch P, Schulze-Rath R, Blettner M. Case–control study on childhood cancer in the vicinity of nuclear power plants in Germany 1980–2003. Eur J Cancer. 2008;44(2):275–84.
3. Sermage-Faure C, Laurier D, Goujon-Bellec S, Chartier M, Guyot-Goubin A, Rudant J, Hémon D, Clavel J. Childhood leukemia around French nuclear power plants—the Geocap study, 2002–2007. Int J Cancer. 2012;131(5):E769–80.
4. Committee on the Analysis of Cancer Risks in Populations near Nuclear Facilities—Phase I, Nuclear and Radiation Studies Board, Division on Earth and Life Studies, National Research Council. Analysis of cancer risks in populations near nuclear facilities: Phase 1. Washington (DC): National Academies Press; 2012. https://doi.org/10.17226/13388.
5. Liu L, Guo H, Dai L, Liu M, Xiao Y, Cong T, Gu H. The role of nuclear energy in the carbon neutrality goal. Prog Nucl Energy. 2023;162:104772.
6. Jun E, Cho Y, Lee K. Nuclear power to mitigate climate change: pathways to a sustainable future. Korean J Chem Eng. 2024;41(10):2843–9.
7. Krayem A, Thorin E. Sustainability assessment of Sweden's nuclear power: implications of the new expansion plans. Environ Dev Sustain. 2024;34(5):12345–65.
8. Baker PJ, Hoel DG. Meta-analysis of standardized incidence and mortality rates of childhood leukaemia in proximity to nuclear facilities. Eur J Cancer Care (Engl). 2007;16(4):355–63.
9. Mueller W, Gilham C. Childhood leukemia and proximity to nuclear power plants: a systematic review and meta-analysis. J Cancer Policy. 2015;6:44–56.
10. Moher D, Liberati A, Tetzlaff J, Altman DG, PRISMA Group. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. Int J Surg. 2010;8(5):336–41.
11. Office of Health Assessment and Translation (OHAT). Handbook for conducting a literature-based health assessment using the OHAT approach for systematic review and evidence integration. Research Triangle Park (NC): National Toxicology Program, National Institute of Environmental Health Sciences; 2019. Available from: https://ntp.niehs.nih.gov/sites/default/files/ntp/ohat/pubs/handbookmarch2019_508.pdf.
12. LaMorte W. Epidemiology/biostatistics tool. Boston University Medical Campus; 2006. Available from: https://www.bumc.bu.edu/medlib/files/2018/06/LaMorte.xls.
13. Jackson D, Turner R. Power analysis for random-effects meta-analysis. Res Synth Methods. 2017;8(3):290–302.
14. Knapp G, Hartung J. Improved tests for a random effects meta-regression with a single covariate. Stat Med. 2003;22(17):2693–710.
15. DerSimonian R, Laird N. Meta-analysis in clinical trials. Control Clin Trials. 1986;7(3):177–88.
16. Higgins JP, Thompson SG. Quantifying heterogeneity in a meta-analysis. Stat Med. 2002;21(11):1539–58.

17. IntHout J, Ioannidis JP, Rovers MM, Goeman JJ. Plea for routinely presenting prediction intervals in meta-analysis. BMJ Open. 2016;6(7):e010247.
18. Egger M, Davey Smith G, Schneider M, Minder C. Bias in meta-analysis detected by a simple, graphical test. BMJ. 1997;315(7109):629–34.
19. Duval S, Tweedie R. Trim and fill: a simple funnel-plot–based method of testing and adjusting for publication bias in meta-analysis. Biometrics. 2000;56(2):455–63.
20. Prindull G, Demuth M, Wehinger H. Cancer morbidity rates of children from the vicinity of the nuclear power plant of Würgassen (FRG). Acta Haematol. 1993;90(2):90–3.
21. Sharp L, McKinney PA, Black RJ. Incidence of childhood brain and other non-haematopoietic neoplasms near nuclear sites in Scotland, 1975–94. Occup Environ Med. 1999;56(5):308–14.
22. Zadnik V, Žagar T, Drobne S, Primic ŽM. Estimation of cancer burden in Brežice municipality, a community neighboring Krško nuclear power plant in Slovenia. Croat Med J. 2008;49(2):257–66.
23. Boice JD Jr, Bigbee WL, Mumma MT, Heath CW Jr, Blot WJ. Cancer incidence in municipalities near two former nuclear materials processing facilities in Pennsylvania—an update. Health Phys. 2009;96(2):118–27.
24. Ma F, Lehnherr M, Fornoff J, Shen T. Childhood cancer incidence in proximity to nuclear power plants in Illinois. Arch Environ Occup Health. 2011;66(2):87–94.
25. Bazyka DA, Prysyazhnyuk AY, Romanenko AY, Fedorenko ZP, Gudzenko NA, Fuzik MM, Khukhrianska OM, Trotsyuk NK, Gulak LO, Goroch YE, Sumkina YE. Cancer incidence and nuclear facilities in Ukraine: a community-based study. Exp Oncol. 2012;34(2):116–20.
26. Chen J, Moir D, Lane R, Thompson P. An ecological study of cancer incidence in Port Hope, Ontario from 1992 to 2007. J Radiol Prot. 2013;33(1):227–42.
27. Lane R, Dagher E, Burtt J, Thompson PA. Radiation exposure and cancer incidence (1990 to 2008) around nuclear power plants in Ontario, Canada. J Environ Prot (Irvine, Calif). 2013;4(9):888–913.
28. Salerno C, Marciani P, Vanhaecht K, Palin LA, Panella M. Incidence of oncological pathologies 2002–2010 in the southwestern Piedmont area, province of Vercelli, neighbouring municipalities of former nuclear sites. Ann Ig. 2016;28(3):208–17.
29. Desbiolles A, Roudier C, Goria S, Stempfelet M, Kairo C, Quintin C, Bidondo ML, Monnereau A, Vacquier B. Cancer incidence in adults living in the vicinity of nuclear power plants in France, based on data from the French Network of Cancer Registries. Int J Cancer. 2018;142(5):899–909.
30. Bunch KJ, Vincent TJ, Black RJ, Pearce MS, McNally RJ, McKinney PA, Parker L, Craft AW, Murphy MF. Updated investigations of cancer excesses in individuals born or resident in the vicinity of Sellafield and Dounreay. Br J Cancer. 2014;111(9):1814–23.
31. Levin RJ, De Simone NF, Slotkin JF, Henson BL. Incidence of thyroid cancer surrounding Three Mile Island nuclear facility: the 30-year follow-up. Laryngoscope. 2013;123(8):2064–71.
32. Demoury C, De Smedt T, De Schutter H, Sonck M, Van Damme N, Bollaerts K, Molenberghs G, Van Bladel L, Van Nieuwenhuyse A. Thyroid cancer incidence around the Belgian nuclear sites, 2000–2014. Int J Environ Res Public Health. 2017;14(9):988.
33. Boice JD Jr, Bigbee WL, Mumma MT, Blot WJ. Cancer incidence in municipalities near two former nuclear materials processing facilities in Pennsylvania. Health Phys. 2003;85(6):678–90.
34. Ahn Y-O, Li ZM. Cancer risk in adult residents near nuclear power plants in Korea—a cohort study of 1992–2010. J Korean Med Sci. 2012;27(9):999–1008.
35. Wanigaratne S, Holowaty E, Jiang H, Norwood TA, Pietrusiak MA, Brown P. Estimating cancer risk in relation to tritium exposure from routine operation of a nuclear-generating station in Pickering, Ontario. Health Promot Chronic Dis Prev Can. 2013;33(4):247–56.
36. Kelly-Reif K, Richardson DB, Wing S. Cancer incidence surrounding the former Apollo nuclear facility 1990–2010. J Expo Sci Environ Epidemiol. 2019;29(6):852–9.
37. IARC Working Group on the Evaluation of Carcinogenic Risks to Humans, World Health Organization, International Agency for Research on Cancer. Tobacco smoke and involuntary smoking. IARC Monogr Eval Carcinog Risks Hum. 2004;83:1–1438.
38. Kim J, Bang Y, Lee WJ. Living near nuclear power plants and thyroid cancer risk: a systematic review and meta-analysis. Environ Int. 2016;87:42–8.
39. Wang S-I, Yaung C-L, Lee L-T, Chiou S-J. Cancer incidence in the vicinity of nuclear power plants in Taiwan: a population-based study. Environ Sci Pollut Res Int. 2016;23(1):571–80.
40. Levin RJ. Incidence of thyroid cancer in residents surrounding the Three Mile Island nuclear facility. Laryngoscope. 2008;118(4):618–28.
41. Goyal N, Camacho F, Mangano J, Goldenberg D. Thyroid cancer characteristics in the population surrounding Three Mile Island. Laryngoscope. 2012;122(6):1415–21.
42. Bollaerts K, Fierens S, Van Bladel L, Simons K, Sonck M, Poffijn A, Geraets D, Gosselin P, Van Oyen H, Francart J, Van Nieuwenhuyse A. Thyroid cancer incidence in the vicinity of nuclear sites in Belgium, 2000–2008. Thyroid. 2014;24(5):906–17.
43. Demoury C, De Schutter H, Faes C, Carbonnelle S, Fierens S, Molenberghs G, Van Damme N, Van Bladel L, Van Nieuwenhuyse A, Vleminckx C. Thyroid cancer incidence near nuclear sites in Belgium: an ecological study at small geographical level. Int J Cancer. 2020;146(11):3034–43.
44. Hatch MC, Wallenstein S, Beyea J, Nieves JW, Susser M. Cancer rates after the Three Mile Island nuclear accident and proximity of residence to the plant. Am J Public Health. 1991;81(6):719–24.
45. Hatch MC, Beyea J, Nieves JW, Susser M. Cancer near the Three Mile Island nuclear plant: radiation emissions. Am J Epidemiol. 1990;132(3):397–412.
46. Han Y-Y, Youk AO, Sasser H, Talbott EO. Cancer incidence among residents of the Three Mile Island accident area: 1982–1995. Environ Res. 2011;111(8):1230–5.
47. Davis S, Kopecky KJ, Hamilton TE, Onstad L. Hanford Thyroid Disease Study Team Thyroid neoplasia, autoimmune thyroiditis, and hypothyroidism in persons exposed to iodine 131 from the Hanford nuclear site. JAMA. 2004;292(21):2600–13.
48. Clegg LX, Reichman ME, Miller BA, Hankey BF, Singh GK, Lin YD, Goodman MT, Lynch CF, Schwartz SM, Chen VW, Bernstein L, Gomez SL, Graff JJ, Lin CC, Johnson NJ, Edwards BK. Impact of socioeconomic status on cancer incidence and stage at diagnosis: selected findings from the Surveillance, Epidemiology, and End Results: National Longitudinal Mortality Study. Cancer Causes Control. 2009;20(4):417–35.
49. Wing S, Richardson DB, Hoffmann W. Cancer risks near nuclear facilities: the importance of research design and explicit study hypotheses. Environ Health Perspect. 2011;119(4):417–21.
50. Lee GB, Park S, Jang WI, Park S, Jun JK, Seo S. Increased screening rates for thyroid cancer among residents living near nuclear power plants. J Korean Med Sci. 2023;38(44):e369.
51. Moon EK, Ha WH, Seo S, Jin YW, Jeong KH, Yoon HJ, Kim HS, Hwang MS, Choi H, Lee WJ. Estimates of radiation doses and cancer risk from food intake in Korea. J Korean Med Sci. 2016;31(1):9–12.
52. National Research Council. Health risks from exposure to low levels of ionizing radiation: BEIR VII phase 2. Washington (DC): The National Academies Press; 2006. Available from: https://doi.org/10.17226/11340.
53. López-Abente G, Vidal-Ocabo E, Tello-Anchuela O, Aragonés N, García-Pérez J, Pastor-Barriuso R, Pérez-Gómez B, Jiménez MA, Martín-Valdepeñas JM, García-Talavera M, Ramos L, Pollán M. Exposure to ionising radiations arising from the operation of nuclear installations and cancer mortality. Int J Environ Sci Technol. 2014;11(1):97–110.
54. Liu CC, Chao JH, Lin CC. Tritium release from nuclear power plants in Taiwan. Health Phys. 2003;84(3):361–7.
55. Birkholzer JT, Houseworth J, Tsang CF. Geologic disposal of high-level radioactive waste: status, key issues, and trends. Annu Rev Environ Resour. 2012;37:79–106.
56. Harris JT, Miller DW. Radiological effluents released by U.S. commercial nuclear power plants from 1995–2005. Health Phys. 2008;95(6):734–43.

Publisher's Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.