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Cancer incidence among Chernobyl cleanup workers from Estonia: A 34-year follow-up

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Abstract

From 1986 to 1991, 4831 men from Estonia were sent to clean up radioactively contaminated areas near Chernobyl (Chornobyl). Their cancer incidence during 1986 to 2019 was compared to that of the male population of Estonia. The cohort of cleanup workers was linked to national population and cancer registers based on unique personal identification numbers. Nineteen (0.4%) workers could not be traced. A total of 4812 men contributing 120 770 person-years of follow-up were eligible for the analyses. Standardized incidence ratios (SIR) and adjusted relative risks (ARR, expressed as ratios of SIRs) with 95% confidence intervals (CI) were calculated. A total of 687 incident cancer cases were registered in the cohort (SIR 1.11, 95% CI 1.03-1.19). Presumptive radiation-related cancers combined were in excess, but not when smoking- and alcohol-related cancers were excluded (SIR 0.92, 95% CI 0.71-1.18). For smoking-related cancers, the SIR was 1.24 (95% CI 1.13-1.36) and for alcohol-related cancer the SIR was 1.53 (95% CI 1.31-1.75). Less educated workers had a higher risk of all cancers (ARR = 1.21, 95% CI 1.02-1.44) and smoking-related cancers (ARR = 1.42, 95% CI 1.14-1.76). An elevated risk of alcohol-related cancers was evident 15 to 24 years (vs <15 years) after return from the Chernobyl area. This updated register-based follow-up of Chernobyl cleanup workers from Estonia revealed an excess of radiation-related cancer sites combined, but the excess was not apparent after excluding cancers associated with smoking and alcohol.

KEYWORDS

cancer incidence, Chernobyl accident, cleanup workers, cohort study, radiation

What's new?

After the 1986 Chernobyl nuclear reactor explosion, nearly 5000 men from Estonia were sent to clean up the radioactively contaminated areas. Here, the authors present their cancer incidence during 34-year follow-up compared with that of the male population of Estonia. This updated register-based study found no evidence of increased cancer risk due to protracted radiation exposure among the cleanup workers. In contrast, increased risks were apparent for cancer sites related to tobacco smoking and alcohol consumption.

Abbreviations: ARR, adjusted relative risk; CI, confidence interval; ICD, International Classification of Diseases; RR, relative risk; SIR, standardized incidence ratio; SMR, standardized mortality ratio.

1 | INTRODUCTION

The Chernobyl nuclear reactor explosion in April 1986 was at the time the worst industrial accident in history[1] and led to releases of large amounts of radionuclides into the environment, spreading over the entire Northern Hemisphere. After the accident, cleanup work including environmental decontamination and recovery activities in the Chernobyl area involved approximately 530 000 persons.[2] These workers incorporated nearly 5000 male residents of Estonia (mainly military reservists) sent to the Chernobyl area during 1986 to 1991.

Previous collaborative international studies showed that the typical radiation doses among Estonian cleanup workers were low (arithmetic mean of 10 cGy) and cancer incidence, compared to the overall male population, was not increased.[3] We have surveyed cleanup workers for cancer incidence over time starting in 1986, with follow-ups through 1993,[4] 1998,[5] 2007,[6] 2008[3] and 2012.[7] Recently, we reported cause-specific mortality through 2020.[8]

Although low doses of ionizing radiation are frequently encountered in medical, environmental and occupational settings, their possible health effects remain imprecisely characterized. Monitoring the health status of Chernobyl cleanup workers who experienced low-level exposures over several months on average is relevant to understanding the range of possible health effects from protracted exposures.[9-11] The relatively high quality of cancer and population registration in Estonia, coupled with cytogenetic studies and physical examinations, offers a reference point for Chernobyl cohort studies conducted in other former Soviet countries. Such studies become even more informative as the worker populations age and health outcomes manifest later in life.

TABLE 1 Characteristics of the Estonian cohort of 4812 male Chernobyl cleanup workers on December 31, 2019.

Characteristic	No.	%	Person-years at risk
Total	4812	100	120 770
Vital status on December 31, 2019			
Living in Estonia	2672	55.5	87 632
Dead	1448	30.1	26 844
Emigrated	692	14.4	6293
Age at start of follow-up (years)			
≤19	80	1.7	2366
20-29	1846	38.4	50 215
30-39	2311	48.0	55 673
40-49	541	11.2	11 700
≥50	34	0.7	815
Calendar year of arrival in the Chernobyl area			
1986	2924	60.8	76 486
1987	1087	22.6	26 610
1988	564	11.7	12 820
1989-1991	109	2.3	2104
Unknown	128	2.7	2749
Duration of stay in the Chernobyl area (days)			
≤29	270	5.6	7360
30-91	1997	41.5	50 804
92-149	1451	30.2	36 195
150-209	852	17.7	20 914
≥210	75	1.6	1993
Unknown	167	3.5	3502
Ethnicity			
Estonian	2354	48.9	66 400
Non-Estonian	2453	51.0	54 329
Unknown	5	0.1	41
Education			
Higher	396	8.2	11 251
Secondary	3059	63.6	84 006
Basic or less	963	20.0	23 037
Unknown	394	8.2	2476

This article extends the assessment of overall and site-specific cancer incidence in the Chernobyl cleanup worker cohort from Estonia. Our objective was to estimate cancer risk in the cohort during 1986 to 2019, adding 7 years to the last follow-up.

2 | MATERIALS AND METHODS

The male Chernobyl cleanup worker cohort from Estonia was assembled in 1992 to 1994 using records from military and other institutions. The cohort design has been reported in previous publications.[12-14]

Based on the unique personal identification number assigned to all Estonian residents, the cleanup worker roster was linked to the national population register to obtain information on ethnicity and education, and to update vital status (date of death or emigration). Each cohort member was followed from the date of return to Estonia from Chernobyl (start of follow-up) until death, emigration, or December 31, 2019, whichever occurred first. Of the initial cohort of 4831 men, 19 (0.4%) were excluded as not traceable. Thus, a total of 4812 men contributing 120 770 person-years at risk during 1986 to 2019 were eligible for analyses.

To obtain the date and site of all cancer diagnoses according to ICD-10 (C00-C97) the cohort was linked to the nationwide cancer register.[15] Cancer incidence was evaluated for three overlapping groups of sites with sufficient evidence of carcinogenicity.[16,17] Presumed radiation-related sites comprised the salivary glands (ICD-10 C07-C08), esophagus (C15), stomach (C16), colon (C18), liver (C22), trachea, bronchus and lung (C33-C34), bone (C40-C41), nonmelanoma skin (C44), urinary organs (C64-C68), central nervous system (C70-C72), thyroid gland (C73) and leukemia (except chronic lymphocytic leukemia) (C91-C95, except C91.1). Alcohol-related sites comprised the oral cavity (C01-C08), pharynx (C09-C14), esophagus (C15), colon (C18), rectum (C19-C21), liver (C22) and larynx (C32). Smoking-related sites comprised the oral cavity (C01-C08), pharynx (C09-C14), esophagus (C15), colon (C18), rectum (C19-C21), liver (C22), pancreas (C25), respiratory organs (C30-C34), urinary tract (C64-C68) and myeloid leukemia (C92).

To estimate cancer risk in the cohort compared to the male population of Estonia, standardized incidence ratios (SIR, the ratio of the observed to expected number of incident cancer cases) with 95% confidence intervals (CI) (assuming Poisson distribution for the observed cancer cases) were calculated. The expected number of cancer cases in the cohort was calculated by multiplying person-years at risk with the national male cancer incidence rates stratified by 5-year age groups (≤19, 20-24, 25-29, …, 80-84, ≥85) and by 5-year calendar periods except the last interval of 4 years (1986-1990, 1991-1995, …, 2011-2015, 2016-2019).

In a separate analysis to determine the effect of several characteristics on cancer risk, crude relative risks (RR) and adjusted relative risks (ARR) for selected cancer groups (all sites, all presumed radiation-related sites, all smoking-related sites and all alcohol-related sites) were modeled using Poisson regression with the logarithm of the expected number of cases as the offset variable.[18] The following characteristics were used in the models: year of arrival in the Chernobyl area (1986, 1987-1991) and duration of stay in the Chernobyl area (<92, ≥92 days; median duration 92 days) as crude proxies for radiation dose; time since return from the Chernobyl area (<15, 15-24, ≥25 years); ethnicity (Estonian, non-Estonian); educational level (higher [≥15 years of schooling], secondary [11-14 years], basic or less [< 11 years]); and age at start of follow-up (<30, 30-39, ≥40 years). Because of unknown education, ethnicity or duration of stay in the Chernobyl area, 523 workers contributing 5755 person-years were excluded. In addition, SIRs for this subcohort were calculated.

Linkages and data analyses were performed using Visual FoxPro 9.0 (Microsoft Corporation, Redmond, WA) and Stata 14 (StataCorp LP, College Station, TX).

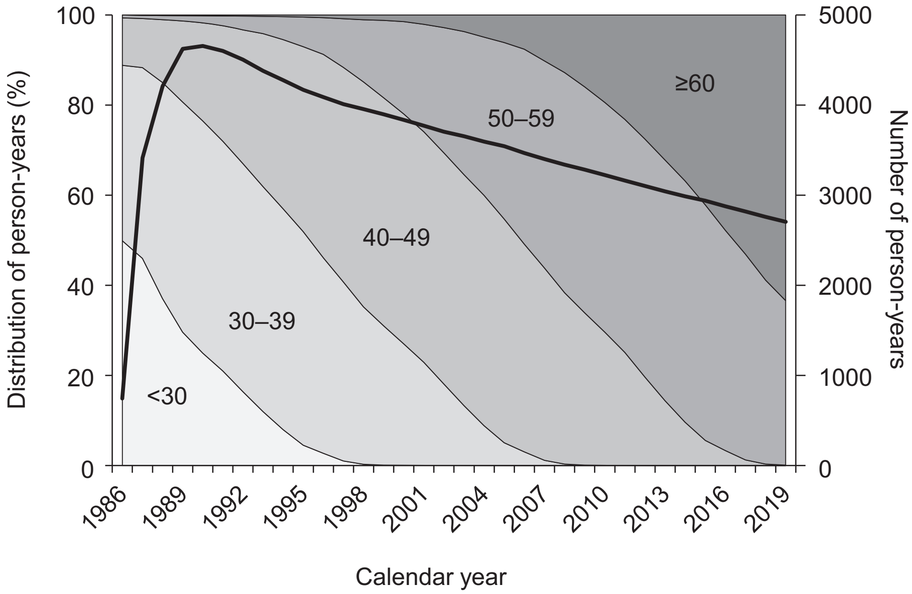

FIGURE 1 Number of person-years accumulated in the cohort of Chernobyl cleanup workers from Estonia, and their distribution by age group, 1986 to 2019. The numbers inside the figure pertain to age at observation, the dark line pertains to the total number of person-years of alive persons in a certain calendar year since the beginning of follow-up. Follow-up starts in 1986 and ends in 2019.

3 | RESULTS

By the end of 2019, 2672 (55.5%) male cleanup workers were still living in Estonia (Table 1). The majority (86.4%) of the workers were 20 to 39 years old at the start of the follow-up. With time, the distribution of person-years by age at observation has significantly changed (Figure 1). Of all the person-years in 1986 to 1990, 82.4% were contributed by the <40-year age group and 0.1% by the ≥60-year age

TABLE 2 Observed number of incident cancer cases and standardized incidence ratio (SIR) with 95% confidence interval (CI) in the Estonian cohort of 4812 male Chernobyl cleanup workers by cancer site, 1986 to 2019.

ICD-10	Cancer site	No. of cancer cases	SIR (95% CI)
C00-C97	All caner sites	687	1.11 (1.03-1.19)
C00-C97, except C44	All sites, except nonmelanoma skin	648	1.14 (1.05-1.23)
C00-C14	Mouth, pharynx	52	1.69 (1.27-2.22)
C07-C08	Salivary glands	1	0.73 (0.02-4.04)
C09-C14	Pharynx	31	2.10 (1.43-2.98)
C01-C15, C32	Upper aerodigestive tract	92	1.61 (1.30-1.97)
C15-C26	Digestive organs	188	1.33 (1.14-1.52)
C15	Esophagus	27	2.12 (1.40-3.09)
C16	Stomach	43	1.07 (0.78-1.45)
C18	Colon	41	1.37 (0.98-1.86)
C19-C21	Rectum	39	1.63 (1.16-2.22)
C22	Liver	12	1.28 (0.66-2.24)
C30-C39	Respiratory organs	143	1.22 (1.02-1.42)
C32	Larynx	15	1.00 (0.56-1.65)
C33-C34	Trachea, bronchus, lung	126	1.27 (1.05-1.49)
C40-C41	Bone	3	2.10 (0.43-6.13)
C43	Melanoma of skin	13	1.02 (0.54-1.74)
C44	Nonmelanoma skin	39	0.75 (0.54-1.03)
C45-C49	Mesothelial and soft tissues	2	0.44 (0.05-1.57)
C50	Breast	1	1.32 (0.03-7.37)
C60-C63	Male genital organs	120	0.84 (0.69-0.99)
C61	Prostate	115	0.84 (0.69-0.99)
C64-C68	Urinary tract	48	0.89 (0.66-1.18)
C69	Eye	2	1.80 (0.22-6.51)
C70-C72	Central nervous system	15	1.38 (0.77-2.27)
C71	Brain	13	1.27 (0.67-2.17)
C73	Thyroid gland	6	2.08 (0.76-4.52)
C76-C80	Site unknown or uncertain	12	1.10 (0.57-1.92)
C81	Hodgkin lymphoma	3	1.00 (0.21-2.92)
C82-C85, C96	Non-Hodgkin lymphoma	16	1.26 (0.72-2.05)
C88, C90	Immunoproliferative diseases, multiple myeloma	8	1.34 (0.58-2.65)
C91-C95	Leukemia	16	1.09 (0.62-1.77)
C91-C95, except C91.1	Leukemia, except chronic lymphocytic	6	0.88 (0.32-1.91)
C07-C08, C15, C16, C18, C22, C33-C34, C40-C41, C44, C64-C68, C70-C73, C91-C95 (except C91.1)	Radiation-related sites	367	1.14 (1.03-1.26)
C01-C16, C18-C22, C25, C30-C34, C64-C68, C92	Smoking-related sites	425	1.24 (1.13-1.36)
C01-C15, C18-C22, C32	Alcohol-related sites	184	1.53 (1.31-1.75)
C40-C41, C44, C70-C73, C91 (except C91.1), C93-C95	Radiation-related sites, except smoking- and alcohol-related sites	63	0.92 (0.71-1.18)

group; in the period 2015 to 2019, the corresponding numbers were 0.0% and 52.8%.

Nearly 61% of the workers arrived in the Chernobyl area in 1986, and 77.3% worked there for less than 5 months with a median duration of 92 days. The ethnicity of nearly half of the cleanup workers was Estonian, and the other half was mainly Russian. One fifth of the workers had a basic or lower educational level.

A total of 687 incident cancer cases were diagnosed in the cohort vs 619.91 expected, showing an increased overall SIR 1.11 (95% CI 1.03-1.19) (Table 2). An elevated incidence was observed for the cancers of the pharynx, upper aerodigestive tract, esophagus, rectum, and trachea, bronchus and lung. Leukemia risk was not increased (SIR 0.88, 95% CI 0.32-1.91). Additionally, an excess risk was found for combined cancer sites related to radiation (SIR 1.14, 95% CI 1.03-1.26), smoking (SIR 1.24, 95% CI 1.13-1.36) and alcohol (SIR 1.53, 95% CI 1.31-1.75). After excluding smoking- and alcohol-related cancers from the presumed radiation-related cancers, the SIR was 0.92 (95% CI 0.71-1.18). The distribution of the three overlapping cancer groups is presented on the Venn diagram (Figure 2).

There were 24 cancer cases diagnosed in the subcohort of 523 cleanup workers with unknown characteristics. In this subcohort, corresponding SIRs were 0.94 (95% CI 0.61-1.41) for all cancers, 0.89 (95% CI 0.46-1.56) for radiation-related cancers, 1.23 (95% CI 0.45-2.68) for alcohol-related cancers, and 1.06 (95% CI 0.59-1.75) for smoking-related cancers.

A higher overall cancer risk in cleanup workers with basic or lower educational level was observed (Table 3). Less educated workers also had a high risk of smoking-related cancers. An elevated risk of alcohol-related cancers was evident 15 to 24 years (vs <15 years) after return from the Chernobyl area.

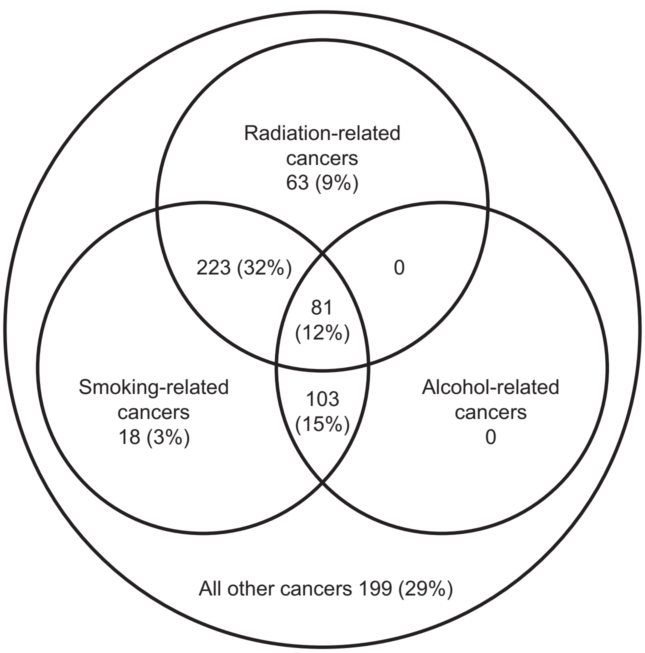

FIGURE 2 Number of overlapping incident cancer cases related to radiation, smoking and alcohol.

4 | DISCUSSION

Cancer incidence was evaluated among male Chernobyl cleanup workers during 34 years after the accident in 1986. The current results confirm our previous findings[3-7] with elevated cancer risks mainly attributable to behavioral factors such as smoking and alcohol consumption, but no clear evidence for increased risk attributable to the low protracted radiation exposure experienced during the cleanups.

Elevated cancer risks were seen in each of three overlapping exposure groups, that is, radiation, smoking and alcohol. Following removal of smoking- and alcohol-related sites from the group of presumed radiation-related sites, the SIR for this latter group was below unity. Even if some of cancers of these sites may be coattributable to both smoking and radiation, or alcohol and radiation combined, it appears unlikely that a radiation-induced excess would occur only in the cancer sites known to be associated with not only radiation, but also smoking and alcohol consumption. As discussed below, the current small number of cancer cases temper the strength of study conclusions, although SIR greater than 1.18 can be excluded with 95% confidence.

The SIR for leukemia other than chronic lymphocytic leukemia, was 0.88 (95% CI 0.32-1.91) based on only six incident cases. Given the relatively low mean radiation dose (approximately 10 cGy), demonstrated by glycophorin A locus mutation assay analyses[19] and chromosomal translocation analyses,[20] no detectable excess of leukemia would be expected.

For all cancers combined, the SIR (1.11) was similar in magnitude to the standardized mortality ratio (SMR 1.16, 95% CI 1.03-1.28) for all cancer deaths observed during the follow-up 1986 to 2020.[8] Also, the SIRs for radiation-, smoking- and alcohol-related cancers were nearly the same as the corresponding SMRs.

Our results are in accord with recent observations by Smailyte et al[21] showing increased risk of cancer sites related to smoking and alcohol use in the cohort of Lithuanian Chernobyl cleanup workers followed in 1986 to 2012. Unfortunately, cohort studies of cleanup workers from different countries cannot be accurately compared because of differences in reporting, registration, follow-up and analyses; mortality vs incidence outcomes; special health screenings or not; available information on cofactors (eg, education, ethnicity, smoking); methods of radiation dose determination; and effect measures such as SIR, SMR, excess relative risk per dose unit.[22-24] For example, the Russian cohort of 67 568 Chernobyl cleanup workers reported a statistically significant dose response for all incident solid cancers based on official recorded doses (arithmetic mean of 13 cGy) and over the follow-up period 1992 to 2009.[25] However, no attempt was possible, as the authors recognized, to estimate the impact of behavioral factors on cancer risk: "As a weakness of the present study, the analyses did not take into account recognized risk factors such as smoking, alcohol consumption, genetic predisposition, marital status, education, occupational status."[25] Somewhat surprisingly, and also unexplained, the SMR for all solid cancers was significantly below one, whereas the SIR for all solid cancers was significantly above one. An existing dilemma for Chernobyl worker studies is that while a small study such as ours can obtain personal characteristics and bloods on

TABLE 3 Number of incident cancer cases, crude (RR) and adjusted (ARR) relative cancer risk with 95% confidence interval (CI) in the Estonian cohort of 4289 male Chernobyl cleanup workers by cancer site and selected characteristics, 1986 to 2019.[a]

	No. of cancer cases in the subcohorts			
Cancer site/characteristic	Index	Reference	RR (95% CI)	ARR[b] (95% CI)
All sites				
Year of arrival in the Chernobyl area				
1986 vs 1987-1991	384	279	0.90 (0.77-1.05)	0.93 (0.79-1.09)
Duration of stay in the Chernobyl area (days)				
≥92 vs <92	312	351	0.96 (0.82-1.12)	0.97 (0.83-1.14)
Time since return from the Chernobyl area (years)				
15-24 vs <15	223	113	0.93 (0.74-1.16)	0.93 (0.74-1.16)
≥25 vs <15	327	113	0.87 (0.70-1.08)	0.89 (0.71-1.10)
Ethnicity				
Non-Estonian vs Estonian	290	373	1.02 (0.88-1.19)	1.05 (0.90-1.23)
Education				
Basic or less vs higher or secondary	198	465	1.22 (1.04-1.45)	1.21 (1.02-1.44)
Radiation-related sites				
Year of arrival in the Chernobyl area				
1986 vs 1987-1991	208	147	0.92 (0.74-1.14)	0.93 (0.75-1.56)
Duration of stay in the Chernobyl area (days)				
≥92 vs <92	169	186	0.99 (0.80-1.21)	0.99 (0.80-1.22)
Time since return from the Chernobyl area (years)				
15-24 vs <15	109	71	0.82 (0.61-1.11)	0.83 (0.62-1.12)
≥25 vs <15	175	71	0.96 (0.72-1.26)	0.98 (0.74-1.29)
Ethnicity				
Non-Estonian vs Estonian	167	188	1.17 (0.95-1.44)	1.18 (0.95-1.46)
Education				
Basic or less vs higher or secondary	98	257	1.08 (0.86-1.36)	1.10 (0.86-1.40)
Smoking-related sites				
Year of arrival in the Chernobyl area				
1986 vs 1987-1991	236	174	0.89 (0.73-1.09)	0.89 (0.73-1.10)
Duration of stay in the Chernobyl area (days)				
≥92 vs <92	197	213	1.00 (0.83-1.22)	1.01 (0.83-1.23)
Time since return from the Chernobyl area (years)				
15-24 vs <15	149	68	1.20 (0.90-1.60)	1.21 (0.91-1.61)
≥25 vs <15	193	68	1.16 (0.88-1.53)	1.19 (0.90-1.59)
Ethnicity				
Non-Estonian vs Estonian	192	218	1.15 (0.95-1.39)	1.21 (0.99-1.48)
Education				
Basic or less vs higher or secondary	133	277	1.34 (1.09-1.65)	1.42 (1.14-1.76)
Alcohol-related sites				
Year of arrival in the Chernobyl area				
1986 vs 1987-1991	99	79	0.82 (0.61-1.11)	0.85 (0.63-1.16)
Duration of stay in the Chernobyl area (days)				
≥92 vs <92	89	89	1.08 (0.80-1.44)	1.11 (0.83-1.50)
Time since return from the Chernobyl area (years)				
15-24 vs <15	74	24	1.68 (1.06-2.66)	1.73 (1.09-2.74)
≥25 vs <15	80	24	1.22 (0.77-1.93)	1.32 (0.83-2.11)

TABLE 3 (Continued)

Cancer site/characteristic	No. of cancer cases in the subcohorts: Index	Reference	RR (95% CI)	ARR[b] (95% CI)
Ethnicity				
Non-Estonian vs Estonian	79	99	1.04 (0.78-1.40)	1.07 (0.79-1.45)
Education				
Basic or less vs higher or secondary	55	123	1.29 (0.94-1.77)	1.26 (0.90-1.75)

[a]Five hundred and twenty-three subjects with unknown characteristics were excluded from the analysis.
[b]Age at start of follow-up, year of arrival, duration of stay, time since return from the Chernobyl area, ethnicity, and education in the model.

individual workers and can use unique personal identification numbers to link to population registries for cancer identification and near complete follow-up, the numbers are not sufficient to be definitive and can only rule out a somewhat high level of risk. Large studies, such as the Russian cohort study, have reported statistically significant results, but the dosimetry is uncertain, the likelihood of confounding influences is high, cancer diagnosis, ascertainment and registration are provided by devoted special institutions of uncertain comprehensiveness, quality and standardization.

There are conflicting assessments of the health impacts caused by the Chernobyl accident. At the extreme, some of accounts read like a "horror story,"[26-29] attributing practically all diagnosed diseases to radioactive contamination in both adjacent and remote regions around Chernobyl. As noted by Smith[30,p. 340] such scaremongers "very clearly did not know that nonradiation-related cancer was very common across the world." Fortunately, other assessments rely on the consistency of sound scientific studies that do not indicate widespread public or occupational health detriments from Chernobyl fallout with the noted exception of high thyroid cancer risk following ingestion of I-131 contaminated milk in childhood or adolescence.[31-34] Skeptics of scientific findings, among whom were many Estonian workers, do not appreciate or accept the consequences of aging, that is, that the sheer numbers of disease cases and deaths will always increase over time.[35] They seem eager to misinterpret the increasing death rates, for example, since about one third of the cleanup workers have died to date, then, without doubt, the radioactive exposures from Chernobyl were to blame. Certainly, public perceptions about low-dose radiation have long been known as being complex and influenced by opinions and negative stereotypes.[36]

In previous articles,[3,7] the small size of the Estonian cohort was regarded as a study limitation. When considering the total number of all Chernobyl cleanup workers is about 530 000, the Estonian cohort of nearly 5000 workers is notably small. In addition, our dose reconstruction methods indicated a relatively low mean dose that was below the official recorded dose.[19,20] Given the differences from our biological measures of dose and the recorded doses, coupled with the understanding that the recorded doses of Chernobyl workers are known to be biased and uncertain,[37-39] we chose to use proxies for radiation dose, that is, calendar years and time spent at Chernobyl. We recognize the limitations of such proxy measures, and that a good estimate of whole-body dose for individuals would be preferred but unfortunately it is not available. We note, however, that our extensive cytogenetic and glycophorin A assays[19,20] indicate that the mean dose for the cohort is 10 cGy which can be taken into account when interpreting study results.

Several strengths of the study point to its information value. First is the rigorous design and conduct. The Estonian national population and disease (cancer, death) registers and unique personal identification numbers facilitate near complete follow-up over 34 years after the accident with minimal loss to follow-up. Second, the comprehensive approach to dose assessment with recorded dose records and blood sample evaluations allowed reasonably accurate characterization of the population dose. Third, continuing the follow-up, will contribute to increased opportunities to observe any adverse consequences as over 50% of the cohort is alive at the end of 2019. Fourth, the cohort has reported significant increases of suicide that remain high at last follow-up indicating that consequences not directly related to radiation may be important and not always anticipated.[8] The possible psychosocial influences on smoking- and alcohol-related behaviors and subsequent health effects may be another factor of more importance than presumed radiation harm. Finally, the 95% confidence limits about grouped and specific health effects can provide indications of what level of risk can be excluded with some assurance. Or conversely, indicating what level of effects is consistent with the findings.

It was unfortunate that our dose reconstruction methods failed to confirm the accuracy of the recorded individual radiation doses among cohort members. This limitation prevents us from conducting valid dose-response analyses and calculating risk estimates per gray as done in other cohorts,[24,25] but subject to uncertainties of unknown magnitude.[38,39] Nonetheless, the results of the Estonian study are relevant to other exposed populations with similar exposure levels, that is, mean doses of the order of 10 cGy.

Decades ago, at the beginning of the study, it was envisioned that collaborating with epidemiologists from the Baltic countries and Belarus could result in a large combined cohort of 20 000 to 40 000 cleanup workers with reasonable statistical power to detect any radiation effect on leukemia incidence.[13,p. 33] However, over time, it became evident that actual exposures were too low to result in a detectable risk of leukemia. Further, the research infrastructure varied considerably by country and thwarted the creation of a combined cohort. One collaborative achievement, however, was a study of cancer risk among 17 040 cleanup workers from the three Baltic countries using a proportional incidence ratio approach.[6] In this collaboration, no increase was found in risks of radiation-related cancers. Current military turmoil in Europe seriously limits cooperation between the countries where Chernobyl cleanup workers originate.

5 | CONCLUSION

The updated register-based follow-up of Chernobyl cleanup workers from Estonia found an increased cancer incidence that was more closely related to alcohol consumption and tobacco smoking than to ionizing radiation.

AUTHOR CONTRIBUTIONS

Study concept and design: John D. Boice, Anssi Auvinen, Mati Rahu, Kaja Rahu. *Acquisition of data and statistical analyses*: Kaja Rahu. *Interpretation of results*: Kaja Rahu, John D. Boice, Hajo Zeeb, Anssi Auvinen, Mati Rahu. *Drafting of manuscript*: Kaja Rahu, Mati Rahu, John D. Boice, Anssi Auvinen. *Revision of manuscript*: John D. Boice, Anssi Auvinen, Hajo Zeeb, Kaja Rahu, Mati Rahu. The work reported in the paper has been performed by the authors, unless clearly specified in the text.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of our study are available from the corresponding author (Kaja Rahu), upon reasonable request.

ETHICS STATEMENT

Ethics approval for conducting our study phase was obtained from the Research Ethics Committee of the National Institute for Health Development (no. 703, 16 June 2021).

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REFERENCES

1. Mihailidou EK, Antoniadis KD, Assael MJ. The 319 major industrial accidents since 1917. *Int Rev Chem Eng*. 2012;4(4):529-540.
2. United Nations Scientific Committee on the Effects of Atomic Radiation. Sources and effects of ionizing radiation. *UNSCEAR 2008 Report to the General Assembly. Scientific Annex D: Health Effects Due to Radiation from the Chernobyl Accident*. Vol 2. New York: United Nations; 2011.
3. Rahu K, Auvinen A, Hakulinen T, et al. Chernobyl cleanup workers from Estonia: follow-up for cancer incidence and mortality. *J Radiol Prot*. 2013;33(2):395-411. doi:10.1088/0952-4746/33/2/395
4. Rahu M, Tekkel M, Veidebaum T, et al. The Estonian study of Chernobyl cleanup workers: II. Incidence of cancer and mortality. *Radiat Res*. 1997;47(5):653-657. doi:10.2307/3579632
5. Rahu M, Rahu K, Auvinen A, et al. Cancer risk among Chernobyl cleanup workers in Estonia and Latvia, 1986-1998. *Int J Cancer*. 2006;119(1):162-168. doi:10.1002/ijc.21733
6. Rahu K, Hakulinen T, Smailyte G, et al. Site-specific cancer risk in the Baltic cohort of Chernobyl cleanup workers, 1986-2007. *Eur J Cancer*. 2013;49(13):2926-2933. doi:10.1016/j.ejca.2013.04.014
7. Rahu K, Rahu M. Tšernobõli veteranide Eesti kohortuuring: vähihaigestumus 1986-2012 ja suremus 1986-2014 (The Estonian Study of Chernobyl Cleanup Workers: cancer incidence (1986-2012) and mortality (1986-2014)). *Eesti Arst*. 2016;95(9):575-580. (In Estonian). doi:10.15157/ea.v0i0.13136
8. Rahu K, Rahu M, Zeeb H, Auvinen A, Bromet E, Boice JD Jr. Suicide and other causes of death among Chernobyl cleanup workers from Estonia, 1986-2020: an update. *Eur J Epidemiol*. 2023;38(2):225-232. doi:10.1007/s10654-022-00957-3
9. Cardis E, Hatch M. The Chernobyl accident—an epidemiological perspective. *Clin Oncol*. 2011;23(4):251-260. doi:10.1016/j.clon.2011.01.510
10. Kamiya K, Ozasa K, Akiba S, et al. Long-term effects of radiation exposure on health. *Lancet*. 2015;386(9992):469-478. 10.1016/S0140-6736(15)61167-9
11. Preston RJ. Integrating basic radiobiological science and epidemiological studies: why and how. *Health Phys*. 2015;108(2):125-130. doi:10.1097/HP.0000000000000224
12. Tekkel M, Rahu M, Veidebaum T, et al. The Estonian study of Chernobyl cleanup workers: I. Design and questionnaire data. *Radiat Res*. 1997;147(5):641-652. doi:10.2307/3579631
13. Auvinen A, Rahu M, Veidebaum T, et al., eds. *Cancer Incidence and Thyroid Disease Among Estonian Chernobyl Clean-up Workers*. Publication No. STUK-A158. Helsinki: STUK—Radiation and Nuclear Safety Authority; 1998.
14. Rahu K, Rahu M, Tekkel M, et al. Chernobyl cleanup workers from Estonia: cohort description and related epidemiological research. *J Radiol Prot*. 2015;35(4):R35-R45. doi:10.1088/0952-4746/35/4/R35
15. Rahu M, Rahu K. The Estonian Cancer Registry: foundation and further history. *Acta Oncol*. 2018;57(10):1407-1410. doi:10.1080/0284186X.2018.1457798
16. Cogliano VJ, Baan R, Straif K, et al. Preventable exposures associated with human cancers. *J Natl Cancer Inst*. 2011;103(24):1827-1839. doi:10.1093/jnci/djr483
17. Sadakane A, French B, Brenner AV, et al. Radiation and risk of liver, biliary tract, and pancreatic cancers among atomic bomb survivors in Hiroshima and Nagasaki: 1958-2009. *Radiat Res*. 2019;192(3):299-310. doi:10.1667/RR15341.1
18. Clayton D, Hills M. *Statistical Models in Epidemiology*. New York: Oxford University Press; 1993:141-152.
19. Bigbee WL, Jensen RH, Veidebaum T, et al. Biodosimetry of Chernobyl cleanup workers from Estonia and Latvia using the glycophorin A in vivo somatic cell mutation assay. *Radiat Res*. 1997;147(2):215-224. doi:10.2307/3579423

20. Littlefield LG, McFee AF, Salomaa SI, et al. Do recorded doses overestimate true doses received by Chernobyl cleanup workers? Results of cytogenetic analyses of Estonian workers by fluorescence in situ hybridization. *Radiat Res*. 1998;150(2):237-249. doi:10.2307/3579859
21. Smailyte G, Kaceniene A, Steponaviciene R, Kesminiene A. Lithuanian cohort of Chernobyl cleanup workers: cancer incidence follow-up 1986-2012. *Cancer Epidemiol*. 2021;74:102015. doi:10.1016/j.canep.2021.102015
22. Liubarets TF, Shibata Y, Saenko VA, et al. Childhood leukemia in Ukraine after the Chornobyl accident. *Radiat Environ Biophys*. 2019;58(4):553-562. doi:10.1007/s00411-019-00810-4
23. Bazyka D, Gudzenko N, Dyagil I, et al. Cancers after Chornobyl: from epidemiology to molecular quantification. *Cancer*. 2019;11(9):1291. doi:10.3390/cancers11091291
24. Ivanov VK, Karpenko SV, Kashcheev VV, et al. Relationship between follow-up periods and the low-dose ranges with statistically significant radiation-induced risk of all solid cancers in the Russian cohort of Chernobyl emergency workers. *Radiat Environ Biophys*. 2020;59(3):415-421. doi:10.1007/s00411-020-00850-1
25. Kashcheev VV, Chekin SY, Maksiutov MA, et al. Incidence and mortality of solid cancer among emergency workers of the Chernobyl accident: assessment of radiation risks for the follow-up of 1992-2009. *Radiat Environ Biophys*. 2015;54(1):13-23. doi:10.1007/s00411-014-0572-3
26. Wakeford R. What to believe and what not to believe. *J Radiol Prot*. 2008;28(1):5-7. doi:10.1088/0952-4746/28/1/E03
27. Rahu M. Health effects of the Chernobyl accident: fears, rumours and the truth. *Eur J Cancer*. 2003;39(3):295-299. doi:10.1016/s0959-8049(02)00764-5
28. Vaiserman A, Koliada A, Zabuga O, Socol Y. Health impacts of low-dose ionizing radiation: current scientific debates and regulatory issues. *Dose-Response*. 2018;16(3):1559325818796331. doi:10.1177/1559325818796331
29. Jargin SV. Debate on the Chernobyl disaster: response to Alison Rosamund Katz. *Int J Health Serv*. 2017;47(1):150-159. doi:10.1177/0020731416679343
30. Smith S. Review of *Manual for survival* by Kate Brown. *J Radiol Prot*. 2020;40(1):337-348. doi:10.1088/1361-6498/ab17f2
31. Reville WJ. Perceptions of the health impact of Chernobyl. *J Radiol Prot*. 2006;26(1):111-117. doi:10.1088/0952-4746/26/1/M01
32. 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(7):933-939. doi:10.1289/ehp.1002674
33. Gluzman SF. The Chernobyl accident—a personal perspective. *Clin Oncol*. 2011;23(4):306-307. doi:10.1016/j.clon.2011.01.504
34. Balonov MI. On protecting the inexperienced reader from Chernobyl myths. *J Radiol Prot*. 2012;32(2):181-189. doi:10.1088/0952-4746/32/2/181
35. Rahu M, Rahu K, Sisask M. Tšernobõli veteranide mured ja kõhklused: vastus internetikommentaaridele (Worries and confusions among Chernobyl veterans: a response to internet comments). *Akadeemia*. 2016;28(4):635-669. (In Estonian).
36. Hurlbert M, Shasko L, Neetz M. Addressing risk perceptions of low-dose radiation exposure. *Dose-Response*. 2022;20(1):15593258221088428. doi:10.1177/15593258221088428
37. Bouville A, Kryuchkov V. Increased occupational radiation doses: nuclear fuel cycle. *Health Phys*. 2014;106(2):259-271. doi:10.1097/HP.0000000000000066
38. Drozdovitch V, Chumak V, Kesminiene A, Ostroumova E, Bouville A. Doses for post-Chernobyl epidemiological studies: are they reliable? *J Radiol Prot*. 2016;36(3):R36-R73. doi:10.1088/0952-4746/36/3/R36
39. Drozdovitch V, Masiuk S, Kryuchkov V, et al. Assessment of uncertainties and errors in post-Chernobyl dosimetry. *Radiat Res*. 2023;199(5):517-531. doi:10.1667/RADE-22-00138.1

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