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Epidemiological study of mortality among veterans of French nuclear tests in the Pacific (1966–1996)

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Abstract – France conducted 193 nuclear tests (both atmospheric and underground) from 1966 to 1996 in the Pacific. The mortality in a sub-cohort of male veterans (n=26,514) who were monitored for external radiation exposure during their participation in the tests has been studied for the period from 1966 to 2015. The mortality was compared to those of the French population using standardized mortality ratios (SMRs), then estimated according to dosimetry status using categorical regression models adjusted for attained age, calendar period, and military unit. "Non-null dosimetry" (at least one positive dosimetric result, *i.e.*, higher than the threshold value of 0.2 mSv) was reported for 8% of the veterans. In total, 8,094 deaths were recorded. The all-cause and major causes SMRs were < 1. The SMR estimated for tumors was close to 1, *i.e.*, the sub-mortality was lower than that of other major causes of death. There were non-significant excesses in the "non-null dosimetry" group relative to the "null dosimetry" group for deaths related to mesothelioma and thyroid, central nervous system, bone, and hematological malignancies. A sensitivity analysis performed on veterans (after the exclusion of health services) who wore their first dosimeter during atmospheric tests highlighted significant excess mortality for bone tumors, hematological malignancies and non-Hodgkin lymphomas. Further analyses should consider extended follow-up and include ionizing radiation doses and the dates of exposure.

Keywords: nuclear tests / mortality / cohort / French Polynesia

1 Introduction

In an atmospheric nuclear test, explosion results in the release and dispersal of radioactive material into the environment. Local populations and military personnel may be thus faced with two types of radiation exposure: external exposure related to immersion in the radioactive plume and deposits on the ground and internal exposure related to inhaling air containing radioactive particles and ingesting contaminated water and food products (Inserm, 2020). Previous studies of nuclear weapons test participants conducted in the United States, the United Kingdom, New Zealand, and Australia were reviewed in a recent report (Inserm, 2020). Ionizing radiation is a recognized risk factor for several diseases, specifically for so-called "radio-induced" cancers and, at a lower level, for non-cancerous diseases, such as cardiovascular diseases (Inserm, 2020). The effects of ionizing radiation on the body vary depending on the dose received and numerous other factors. Radio-induced cancers, among others, have the distinction of occurring several years after exposure and being no different from cancers induced by other risk factors (UNSCEAR, 2006; Inserm, 2008). Ionizing radiation is classified as a well-recognized carcinogen for humans according to the International Agency for Research on Cancer (IARC).

But if atmospheric nuclear tests carry a potential danger linked to the effects of ionizing radiation, the risk incurred by a given person depends on his or her personal exposure (Pasquier *et al.*, 2024). Epidemiologic studies are necessary to objectify the risk.

France conducted 193 nuclear tests on the Mururoa and Fangataufa Polynesian atolls of the Pacific Experimental Centre (Centre d'études du Pacifique CEP): 46 atmospheric tests from 1966 to 1974 and 147 underground tests from 1975 to 1996 (Ministère de la Défense, 2006). The Ministry of Defense reported the particular operations that gave rise to exposure of its staff: piloted penetration and cloud-tracking missions, radiological buoy array listening missions, investigations and sampling in the nearby fallout area, locating of and trawling for rocket heads fired into the cloud, airborne missions, and decontamination of equipment (Ministère de la Défense, 2006). Following the wish of the President of the French Republic Jacques Chirac, a Liaison committee for the coordination of health monitoring of French nuclear tests (CSSEN) was established on 15 January 2004 by joint decision

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of the Ministers of Defense and Health and headed by the Chairman of the Nuclear Safety Authority (ASN) and the Nuclear Safety and Radiation Protection Delegate for Activities and Installations of Interest to Defense (DSND) with the mandate: – to define and characterize pathologies likely to be radiation-induced, – to characterize the categories of persons concerned, – to take stock of the available data on exposure to ionizing radiation during nuclear tests, – and to formulate recommendations (CSSEN, 2007).

Afterwards a retrospective epidemiologic study was initiated following the concerns of former veterans of the CEP. It analyzed, notably, the mortality of veterans with at least one recorded photographic dosimeter result up to 2008 (on the basis of a monthly report) (Pédrono *et al.,* 2011; Martin and Ségala, 2013). The Kodak photographic dosimeter, type CB DMA – CEA "PS1", used during the period of atmospheric tests and until the 1980s, was developed in close collaboration between the Central Establishment of ElectroRadiology of the Armed Forces (ECERA), the Commissariat à l'Energie Atomique (CEA), and the company Kodak-Pathé. Reading of the dosimetric films was carried out in the photo dosimetry laboratory of the Mixed Service of Radiological Monitoring, located in the center of Mahina in Tahiti until 1975 and then in Mururoa. The dosimetric information available per individual was either all dosimeter results being negative or at least one dosimeter being positive, *i.e.*, doses were either below or above the detection threshold of 0.2 mSv (IRSN, 2008). A healthy worker effect was highlighted relative to national data for all-cause and major-cause mortality, including malignant tumors. All-cause and cancer mortality of veterans with dosimetry above the detection threshold was similar to that of other veterans (Pédrono *et al.,* 2011). However, a significant excess of hematological malignancies in the "non-null dosimetry" group (veterans with at least one positive dosimetric record) relative to the "null dosimetry" group (veterans with all dosimetric records below the reporting limit) was highlighted after adjusting for individual factors (RR – 1.82, 95%CI [1.6–2.0]) (Pédrono *et al.,* 2011).

As cancer has a long latency period, it was essential to extend the duration of follow-up in this mortality study, *i.e.*, 7 more years. The objective of this new analysis was to assess the mortality of veterans between 1968 and 2015 (mortality analysis started in 1968 because this is the first year for which the cause of death was available). As in the previous analysis, mortality was compared with that of the French population (external comparison) and between veterans with 'non-zero dosimetry' and those with 'zero dosimetry' (internal comparison).

2 Methods

2.1 Mortality cohort definition

The "mortality cohort" consisted of the 26,514 male veterans (Ministry of Defense personnel only) who were present on the site of the French nuclear experiments center in the Pacific between 1966 and 1996 and for whom external dosimetry monitoring recordings were available. Construction of the cohort has been previously detailed (Pédrono *et al.,* 2011). The following individual information was provided by the "Département de Suivi des Centres d'Expérimentations Nucléaires" (Monitoring Department of Nuclear Experimental Centres; DSCEN) attached to the "Délégation Générale à l'Armement" (General Delegation for Armaments; DGA): military unit (navy, ground forces, air force, health services, civil staff), first and last dosimetry dates (month and year only), total number of dosimetry records, and number of non-null dosimetry records.

The date of entry into the cohort corresponds to the date of the first dosimetry (by default, the 15th of the month). Data on the vital status from January 1, 1966 to December 31, 2015 were extracted from the "Répertoire National d'Identification des Personnes Physiques" (National Directory for the Identification of Natural Persons; RNIPP), the linkage being made through the following items: last name, first name, gender, and place and date of birth. Cause-of-death data were obtained from the "Base des Causes Médicales de Décès" (Causes of Death Registry), which has existed in France since 1968. The causes of death were coded according to the International Classification of Diseases (ICD): the 8th revision (ICD-8) for deaths occurring from 1968 to 1978, the 9th (ICD-9) for those occurring from 1979 to 1999, and the 10th (ICD-10) for those occurring from 2000 to 2015. The causes of death were classified into 14 major groups, plus several specific types of radiation-induced malignant tumors.

2.2 Dosimetric monitoring

Two groups were distinguished: "non-null dosimetry", consisting of veterans who had at least one non-null dosimetric record, *i.e.*, higher than the reporting threshold (0.2 mSv), and "null dosimetry", consisting of those with only null dosimetric records. The dosimetric measures were external and represented air concentration levels. The used dosimeter was the Kodak photographic one (presented in the "Introduction" section). The dosimetric value came from a photographic interpretation. The level of 0.2 mSv corresponded to the reporting threshold value of detection associated with this process (IRSN, 2008). Under this level, any recording was not interpretable and was considered as a null dosimetric record. The "non-nul dosimetry" group consisted of 2,130 veterans and the "null dosimetry" group consisted of 24,384 veterans.

2.3 Statistical analyses

Deaths were described by major causes, as well as the type of malignant tumor for 1968 to 2015. Analyses were conducted over the same period using SMR and Poisson regression models. Observed and expected deaths, based on the French male population death rates specific for age (five-year categories) and calendar period (five-year intervals), were used to estimate SMRs by indirect standardization. Significance was assessed using the test recommended by Breslow and Day (Breslow and Day, 1987). An exact 95% confidence interval (CI) of the SMR was calculated (Liddell, 1984).

Categorical Poisson regression models were used to assess differences between the "null dosimetry" and "non-null dosimetry" groups. The models were stratified for attained age, calendar period, and military unit, with the number of person-years associated with each stratum considered as an "offset" variable. Sensitivity analyses using Poisson regression

models, were performed for veterans present during the period of atmospheric tests, after the exclusion of health services staff (n = 24,422), in the “non-null dosimetry” group relative to the “null dosimetry” group. All analyses were conducted using SAS 9.1 software. The significance threshold for statistical tests was set at 5%.

3 Results

The mortality cohort consists of 26,514 male veterans followed for an average of 42.5 yr, corresponding to 1,125,987 person-years. The various characteristics of the cohort are presented in Table 1. Most of the veterans in the cohort were included between 1966 and 1967, the period corresponding to the beginning of nuclear experiments in the Pacific. In contrast, only 7.8% of veterans were included during the underground tests (1975–1996). Most of the veterans (68%) in the cohort belong to the navy, followed by ground forces (15.3%), and air force (12.2%). Civil staff and health personnel account for < 2.5%. A non-null dosimeter was reported for 8% of veterans in the cohort (7.4% during the atmospheric tests and 15.8% during underground tests). The proportion of non-null dosimetry was highest among health services veterans (36.4%), followed by air force veterans (16.3%), and ranged between 5.5% and 10.9% for other military units. Only 79 veterans (0.3% of the total population) were born in French Polynesia.

In total, 8,094 deaths were recorded between 1966 and 2015 (30.5%). Among them, 7,869 causes of death were available, leaving 2.8% with a missing cause. Among deceased veterans, 552 (7%) had a non-null dosimetry and 7,317 (93%) null dosimetry. Nearly 45% died from tumors. The second cause of death was diseases of the circulatory system, accounting for close to 20%.

The SMRs for all causes, circulatory system causes, and malignant tumors are presented in Table 2. The SMRs for other major causes of deaths are presented in Table 3. The all-cause and major causes SMRs were < 1. The SMR estimated for tumors was close to 1, *i.e.*, this sub-mortality was lower than that of other major causes of death. Among malignant tumors, mesothelioma was the only pathology with a SMR significantly > 1, revealing excess mortality of 54% for the veterans relative to the French population. Interestingly, 37 of the 49 cases of mesothelioma occurred in navy veterans.

The Poisson regression model results for mortality due to all causes, circulatory system causes, and malignant tumors are presented in Table 4. The RR results for other major causes of death are presented in Table 5. Non-significant sub-mortality was observed in the "non-null dosimetry” group relative to the "null dosimetry" group for all-cause mortality. There was no significant excess mortality due to cancer in the “non-null dosimetry” group relative to the “null dosimetry” group. Non-significant excesses were observed for deaths related to mesothelioma and thyroid, central nervous system, bone, and hematologic malignancies.

The sensitivity analysis of veterans who wore their first dosimeter during atmospheric tests highlighted significant excess mortality due to bone tumors in the "non-null dosimetry" group relative to the "null dosimetry" group (RR = 4.00 [1.43–11.19]), as well as for hematological malignancies (RR = 1.56 [1.03–2.36]) and non-Hodgkin lymphomas (RR = 2.15 [1.07–4.31]).

Table 1. Characteristics of the mortality cohort (1966–2015) of French nuclear test veterans.

	Mortality Cohort (N=26,514)
Vital Status n (%)	
Alive on 31/12/2015	18,408 (69.42)
Dead before 2016	8,094 (30.53)
Lost to follow-up	12 (0.005)
Military Unit n (%)	
Ground forces	4,060 (15.3)
Navy	18,040 (68)
Air force	3,209 (12.2)
Civil staff	530 (2)
Health services	675 (2.5)
Periods of first dosimetry results? (%)	
During atmospheric nuclear tests (1966–1974)	24,437 (92.2)
During underground nuclear test (1975–1996)	2,077 (7.8)
Dosimetry status n (%)	
« Null dosimetry » group	24,384 (92)
« Non-null dosimetry » group	2,130 (8)
Age at the first dosimeter (years)	25.1 (7.3)
Mean (standard deviation)	21
Median	16–64
Minimum-Maximum	
Duration of follow-up (years)	
Mean (standard deviation)	42.5 (9.6)
Median	48
Minimum-Maximum	0–50
Age at end of follow up	
Mean (standard deviation)	67.6 (10.3)
Median	68

4 Discussion

4.1 Dosimetric results

The non-null dosimeter proportion during atmospheric tests was similar to that reported in a UK cohort (8%) (Gillies and Haylock, 2022). Unlike the other military units, almost all health services veterans (97.8%) were included in the cohort during underground nuclear tests. During this period, dosimeters were distributed to veterans based on their professional activity-related exposure risk (Ministère de la Défense, 2006). For health services veterans, dosimeters were issued for activities related to medical radiology (Ministère de la Défense, 2006).

4.2 Comparison to the general population

We observed a “healthy worker effect” in the mortality study comparing veterans to the general population as in the previous analysis (Pédrono *et al.*, 2011). The “healthy worker” effect (HWE) is a particular type of selection bias, typically seen in occupational cohorts with an improper choice of

Table 2. Comparison of veterans mortality to that of the French population for all cause and tumors mortality (Mortality Cohort, 1968–2015).

	Observed deaths	Expected deaths	SMR[(1)]	95%CI*	*p*-value
All-cause mortality	8,090	9,528.1	**0.85**	**0.83–0.87**	**< 0.01**
Malignant tumors	3,418	3,611.3	**0.95**	**0.92–0.98**	**0.01**
Esophageal cancer	156	179.8	0.87	0.74–1.02	0.08
Stomach cancer	80	119.6	**0.67**	**0.53–0.83**	**< 0.01**
Colon cancer	181	213.6	**0.85**	**0.73–0.98**	**0.03**
Rectal/Anal cancer	62	88.1	**0.70**	**0.54–0.90**	**0.01**
Liver cancer and biliary tract cancer	205	221.5	0.93	0.80–1.06	0.28
Pancreatic cancer	149	175.1	**0.85**	**0.72–0.999**	**0.05**
Respiratory tract cancer	1,115	1,097.6	1.02	0.96–1.08	0.61
Bronchus and lung cancer	1,027	996.1	1.03	0.97–1.10	0.34
Larynx cancer	88	101.4	0.87	0.70–1.07	0.20
Mesotheliomas + pleural cancer	49	31.8	**1.54**	**1.14–2.04**	**< 0.01**
Melanoma	41	34.4	1.19	0.86–1.62	0.29
Prostate cancer	176	199.5	0.88	0.76–1.02	0.10
Kidney cancer	75	80.1	0.94	0.74–1.17	0.61
Bladder cancer	121	115.3	1.05	0.87–1.25	0.63
Tumor of the lips, oral cavity and pharynx	218	228.0	0.96	0.83–1.09	0.53
Breast cancer	5	6.2	0.81	0.26–1.89	0.84
Thyroid cancer	10	6.9	1.44	0.69–2.65	0.32
Central nervous system cancer	70	82.1	0.85	0.66–1.08	0.20
Bone cancer	15	16.1	0.93	0.52–1.54	0.88
Lympho-hematopoietic tumors	197	245.0	**0.80**	**0.70–0.92**	**<0.01**
Leukemia (except chronic lymphoid leukemia)	67	85.1	0.79	0.61–1.0001	0.06
Multiple myeloma	35	40.3	0.87	0.60–1.21	0.45
Non-Hodgkin lymphoma	63	83.3	**0.76**	**0.58–0.97**	**0,03**

Note. SMRs significantly different from 1 are presented in bold ; CI : confidence interval

Table 3. Comparison of veterans mortality, for main causes other than cancers, to that of the French population (Mortality Cohort, 1968–2015).

	Observed deaths	Expected deaths	SMR	95%CI	*p*-value
Infectious and parasitic diseases	112	180.7	**0.62**	**0.51–0.75**	**< 0.01**
Diseases of the blood and hematopoietic organs	22	28.5	0.77	0.48–1.17	0.26
Endocrine, nutritional and metabolic diseases	154	217.1	**0.71**	**0.60–0.83**	**< 0.01**
Behavioral and mental disorders	181	229.6	**0.79**	**0.68–0.91**	**< 0.01**
Nervous system and sensory organ diseases	201	271.9	**0.74**	**0.64–0.85**	**< 0.01**
Diseases of the circulatory system	1,523	1,993.6	**0.76**	**0.73–0.80**	**< 0.01**
Respiratory diseases	308	448.6	**0.69**	**0.61–0.77**	**< 0.01**
Digestive diseases	459	595.7	**0.77**	**0.70–0.84**	**< 0.01**
Skin and subcutaneous cell/tissue diseases	5	9.5	0.53	0.17–1.23	0.18
Osteo-articular system diseases	19	32.6	**0.58**	**0.35–0.91**	**0.02**
Diseases of the genitourinary system	54	89.0	**0.61**	**0.46–0.79**	**< 0.01**
Ill-defined symptoms and morbid states	410	554.8	**0.74**	**0.67–0.81**	**< 0.01**
External causes	918	1,149.3	**0.80**	**0.75–0.85**	**< 0.01**

Note. SMRs significantly different from 1 are presented in bold

comparison group (usually the general population). It is characterized by the mortality rate in occupational population really lower than in the general population. This mortality cohort includes both career soldiers and those who were in good health at the time of their incorporation into military service. They would therefore be considered as a cohort of healthy workers by comparison to the general population (Kirkeleit *et al.,* 2013).

This study highlights significant excess death from mesothelioma relative to the general population. Such an excess is generally found in populations that have been professionally exposed to asbestos and has been reported in previous cohorts of U.S. Veterans, with most mesothelioma deaths occurring in sailors (Till *et al.,* 2018; Boice *et al.,* 2022a) and, more specifically, among enlisted naval personnel (Till *et al.*, 2024). There was no link with dosimetry status, with the same proportion of mesothelioma deaths in the two

Table 4. Relative risks (RR) of death between veterans with "non-null dosimetry" and with "null dosimetry" for all cause and tumors mortality (Mortality Cohort, 1968–2015).

	Adjusted RR*	95%CI	*p*-value	Number of deaths "non-null dosimetry"/"null dosimetry"
All-cause mortality	0.95	0.86–1.05	0.32	552/7,869
Diseases of the circulatory system	0.91	0.67–1.24	0.54	106/1,523
Malignant tumors	0.95	0.77–1.18	0.65	242/3,418
Esophageal cancer	0.79(1)	0.40–1.57	0.50	9/156
Stomach cancer	0.65(1)	0.27–1.55	0.33	4/80
Colon cancer	0.91	0.56–1.49	0.71	13/181
Rectal/Anal cancer	0.87(2)	0.36–2.11	0.76	4/62
Liver cancer and biliary tract cancer	0.77	0.44–1.37	0.37	12/205
Pancreatic cancer	0.78(1)	0.34–1.78	0.55	9/149
Respiratory tract cancer	0.98	0.74–1.30	0.90	80/1,115
Bronchus and lung cancer	1.01	0.75–1.36	0.97	76/1,027
Larynx cancer	0.67(1,3)	0.20–2.25	0.52	4/88
Mesotheliomas + pleural cancer	1.09(1)	0.52–2.25	0.82	4/49
Malignant melanoma	0.57	0.03–11.44	0.72	2/41
Prostate cancer	0.55	0.21–1.42	0.21	8/176
Kidney cancer	0.99(2)	0.39–2.53	0.98	6/75
Bladder cancer	0.60(1)	0.30–1.19	0.14	6/121
Tumor of lips, oral cavity and pharynx	0.72	0.30–1.73	0.46	11/218
Breast cancer			>0.99	0/5
Thyroid cancer	1.30(3,4)	0.43–3.96	0.65	1/10
Central nervous system cancer	1.38(1)	0.55–3.43	0.49	7/70
Bone cancer	2.76(5)	0.67–11.42	0.16	3/15
Lympho-hematopoietic malignant tumors	1.45	0.94–2.22	0.09	20/197
Leukemia (except chronic lymphoid leukemia)	1.48	0.77–2.86	0.24	7/67
Multiple myeloma	2.04(1)	0.95–4.38	0.07	5/35
Non-Hodgkin lymphoma	1.88	0.89–3.97	0.10	8/63

*Poisson regression model, adjusted for age (grouped into four classes: 15–54, 55–64, 65–74, and 75 yr or older, except for "all causes", with five-year classes from 15–19 to 85 yr or older), calendar period (grouped into three classes: 1968–1996, 1997–2005, and 2006–2015), and military unit (navy, ground forces, air force, health services, civil staff)

(1) Civil staff and health services combined (no deaths in health services)

(2) Civil staff, health services, and air force combined (no deaths in civil staff and health services)

(3) Creation of a class for 65 yr of age and above (no deaths in 75 yr of age and above)

(4) Deaths in the navy only

(5) Civil staff and health services combined (no deaths in civil staff)

groups. Exposure to asbestos, a material widely used on naval vessels, appears to be the main cause of these mesothelioma cases (Boice *et al.*, 2022a; Till *et al.*, 2024). Thus mesothelioma in our cohort may be linked to asbestos exposure.

The mortality cohort showed non-significant excess mortality due to thyroid cancer and melanomas relative to the general population. Thyroid cancer (Cardis *et al.*, 2005; Kesminiene *et al.*, 2012) and melanoma (Telle-Lamberton *et al.*, 2007) have been described as possibly associated with ionizing radiation. In our cohort, such excess mortality was not significant; moreover, there was no link with dosimetry: 9 of 10 deaths from thyroid cancer and 39 of 41 from melanoma occurred among veterans of the "null dosimetry" group.

Internal comparison of "non-null dosimetry" group vs "null dosimetry" group

There was no difference in "all-cause", "circulatory system disease", or "all tumors" mortality between the two veterans' groups in the internal analysis. The RR for all hematological malignancies was significant in the previous analysis in 2011 (Pédrono *et al.*, 2011). In the current analysis, we found non-significant excess mortality after adjustment for attained age, period, and military unit for certain conditions in the "non-null dosimetry" group relative to the "null dosimetry" group. Such small and non-significant excess mortality was found for potentially radio-induced diseases, *i.e.*, mesotheliomas, thyroid tumors, central nervous system tumors, bone tumors, and hematological malignancies. Moreover, sensitivity analysis restricted to veterans whose first dosimeter was worn during atmospheric tests and excluding health personnel provided significant results for all hematological malignancies, non-Hodgkin lymphoma, and bone tumors.

Our results are similar to those observed in other international cohorts. The New Zealand cohort study showed a significantly increased risk of mortality for hematopoietic tissue tumors (RR = 3.8 [1.4; 10.8]), more specifically

Table 5. Relative risks (RR) of main causes of death other than cancers between veterans with "non-null dosimetry" and with "null dosimetry" (Mortality Cohort, 1968–2015).

	Adjusted RR*	95%CI	*p*-value	Number of deaths "non-null dosimetry"/"null dosimetry"
Infectious and parasitic diseases	1.48	0.75–2.90	0.26	12/112
Diseases of the blood and hematopoietic organs	1.61(1)	0.55–4.68	0.39	3/22
Endocrine, nutritional and metabolic diseases	1.04(2)	0.67–1.62	0.84	12/154
Behavioral and mental disorders	0.76	0.42–1.40	0.38	11/181
Nervous system and sensory organ diseases	0.99(2)	0.61–1.59	0.95	16/201
Diseases of the circulatory system	0.91	0.67–1.24	0.54	106/1,523
Respiratory diseases	0.72	0.45–1.18	0.19	17/308
Digestive diseases	1.003	0.66–1.51	0.99	34/459
Skin and subcutaneous cell/tissue diseases			>0.99	0/5
Osteo-articular system diseases			>0.99	0/19
Diseases of the genitourinary system	0.60	0.19–1.91	0.39	3/54
Ill-defined symptoms and morbid states	0.85	0.49–1.48	0.57	27/410
External causes	0.98	0.72–1.35	0.91	65/918

*Poisson regression model, adjusted for age (grouped into four classes: 15–54, 55–64, 65–74, and 75 yr or older with five-year classes from 15–19 to 85 yr or older), calendar period (grouped into three classes: 1968–1996, 1997–2005, and 2006–2015) and military unit (navy, ground forces, air force, health services, civil staff)

(1) Civil staff and health services combined (no deaths in civil staff)

(2) Civil staff and health services combined (no deaths in health services)

leukemia (RR = 5.6 [1.0; 41.7]), although this study included only a limited number of veterans (528 men) (Pearce *et al.*, 1997). In this study, the RR for other hematological malignancies was also high, but not significant: RR = 5.7 [0.4; 1.65] for non-Hodgkin lymphoma and RR = 1.4 [0.1; 18] for multiple myeloma (Pearce *et al.*, 1997). More than 20,000 British veterans were also tracked and compared to both the British population and a control group (Gillies and Haylock, 2022; Muirhead *et al.*, 2004). There was significant excess mortality in the exposed-veteran group relative to the control group for leukemia (chronic lymphoid leukemia excluded): RR = 1.83 [1.15; 2.93], but there was no excess risk relative to national data; also no significant risk of death was observed relative to the control group for bone cancer (RR = 2.11 [0.19; 44.14]), lymphoma (RR = 0.92 [0.62; 1.35]), or multiple myeloma (RR = 1.32 [0.74; 2.37]) (Muirhead *et al.*, 2004). Regarding the last study (Gillies and Haylock, 2022), non-significant excess mortality in the exposed-veteran group relative to the control group were registered over the 1952–2017 period: RR = 1.19 [0.93; 1.51] for pleural cancer and 1.26 [0.98; 1.62] for leukemia (chronic lymphoid leukemia excluded). But, over the 1952–1998 period, RR were higher and significant : RR = 2.09 [1.10; 3.98] for pleural cancer and 1.82 [1.18; 2.82] for leukemia (chronic lymphoid leukemia excluded) (Gillies and Haylock, 2022). The U.S. Veterans Study of Nuclear Tests conducted between 1945 and 1962 compared mortality between a group of veterans exposed to 50 mSv or more (1,010 veterans) and a group of veterans exposed to 2.5 mSv or less (2,870 veterans) (Dalager *et al.*, 2000). All-cause mortality and hematopoietic cancer mortality were significantly higher (RR = 1.22 [1.04; 1.44] and RR = 3.72 [1.28; 10.82]), but this was not the case for other specific causes. Although excess leukemia deaths were observed relative to the national population in a recent U.S. study of the cohort of veterans present at the Smoky test in Nevada, no link was found between the estimated bone marrow dose and the risk of leukemia. The authors raised the possibility that the observed excess was related to chance due to the small numbers and/or smoking habits (Caldwell *et al.*, 2016). Similarly, the results of the international cohort study Inworks reinforce the evidence of the existence of a relationship between leukemia risk and exposure to ionizing radiation. They showed that such a relationship is observed for chronic exposure to low doses of radiation (Leuraud *et al.*, 2024). The most recent study on US military participants of eight above-ground nuclear test series provided no evidence for an increasing trend of leukemia (excluding CLL) or multiple myeloma with radiation dose (Boice *et al.*, 2022a). Although studies of nuclear test veterans do not report excess bone cancer, two recent studies at weapons manufacturing plants reported an excess risk related to plutonium exposure for bone tumors (Sokolnikov *et al.*, 2008; Boice *et al.*, 2022b).

The French Polynesian veterans represented a tiny fraction of the cohort. So, it was very difficult to determine significant results for such a small number of veterans. Moreover, for the 2005–2010 period, the standardized mortality rate from malignant tumors among male population of French Polynesia (156 deaths per 100,000 inhabitants) was not significantly different from that of metropolitan France (158.2 deaths per 100,000 inhabitants) (Yen Kai Sun *et al.*, 2016).

4.3 Strengths

The main strengths of the mortality cohort are the large number of veterans and an average follow-up for vital status of 42.5 yr. This large number of people had various affiliations and functions (Inserm, 2020). The mortality cohort concerns the 26,514 veterans from National Defense who received external dosimetry monitoring and for whom the results of the

number of non-null dosimeter results were available, as well as the individual data required for linkage with national databases.

4.4 Limitations

Although the statistical power of this study is generally sufficient for external comparisons with national databases, this is not necessarily true for the detection of low-level excess risk for comparisons within the cohort. Especially as a larger number of people were present during the Pacific nuclear tests (Ministère de la Défense, 2006). First and last dosimetry dates (month and year only), total number of dosimetry records, and number of non-null dosimetry records were the available data. Whether it was possible to determine the nuclear tests period during which the 1st dosimeter was worn (atmospheric vs underground), the lack of precision of the dates, and the missing information on intermediate dosimeter data, did not allow for a precise determination of the dosimeter installation in relation to the date of the nuclear tests.

There is overall uncertainty related to the determination of the dose equivalent by a dosimeter, regardless of the type, which is due to both the statistical uncertainty related to the reading of the dosimeter and the systematic uncertainties that affect its response: calibration, energy and angular dependencies, non-linearity of the response, and the effects of temperature, humidity, and light. There are also conditions independent of the dosimeter itself: isotropic or directive radiation, the relative position of the individual in relation to the source, and the place on the body where the dosimeter is worn. The reliability of the results for values above the detection threshold is ± 50%, with systematic underestimation on the order of 50% if the exposure did not occur from the front (IRSN, 2008). Moreover, the threshold of 0.2 mSv was a detection threshold (*i.e.*, the lowest detectable exposure value above background noise) (IRSN, 2008) and not a health threshold.

In the present study, the only available indicator of exposure was the distinction between the "non-null dosimetry" and "null dosimetry" group. A major limitation of this study is the lack of knowledge about the cumulative dose, preventing calculation of a dose-response relationship, and the timing of the exposures. Indeed, the dates of the non-zero dosimeter results were not communicated. Nevertheless, it is unlikely that there would have been significant misclassification between the two subpopulations of veterans. It is likely that veterans with all negative dosimeter results (below the detection threshold of 0.2 mSv) represent the fraction of veterans who were not exposed or exposed to very low doses. Because of unavailability of data, the missed dose issue, that is to assign to veterans without a dosimetry record a dose equal to the average dose of veterans with positive dosimetry records from the military units that performed similar activities during the time period, could not be applied. Photographic dosimeters have a detection threshold value that may have varied from 0.2 to 0.3 mSv, below which any record is considered insignificant and accepted as null. Thus, for an individual who has undergone monthly dosimetric monitoring, and if the annual dose recorded in his file is equal to 0, this individual may actually have received a maximum of $12 \times 0.3 = 3.6$ mSv/yr. This extreme value is unlikely, however, as the probability that an individual will have received a dose at the limit of the registration threshold 12 times a year is very low.

In this study, as in many retrospective studies, no individual confounding factors could be considered. However, mortality is dependent on a large number of individual factors, such as smoking (active and passive), alcohol consumption, professional history (asbestos exposure...), lifestyle (food, sports activity), socio-economic level, marital status, heredity, etc. The results should therefore be interpreted with caution, as they were not adjusted for these individual factors. Furthermore, the latency between exposure and the occurrence of the health event could not be studied, given the lack of information on the dates of the non-zero dosimeter results.

Another limitation was that the study lacked optimal hindsight, given the time frame for the onset of radio-induced diseases. Veterans in the cohort have now had an average follow-up of 42.5 yr for the 1966–2015 study period and 69% (79% at the end of 2008) were alive at the end of the study, with an average age of 70 yr. As a result, this cohort will provide most of the mortality information in the coming years. It should also be noted that mortality data can only partially explain the impact of nuclear tests on health.

Finally, it was difficult to compare the results of this study with previous ones (Pédrono *et al.*, 2011) because the statistical methods used to calculate and analyze the RRs were partially different:.

5 Conclusion

A "healthy worker effect" characterized by sub-mortality in the cohort relative to the French population was observed for all causes and all malignant tumors. Among malignant tumors, mesothelioma was the only pathology with an excess mortality which was significant. ..However, excess risk for bone and hematological malignancies is suggested for veterans present during atmospheric tests who had at least one dosimeter above the detection threshold.

A recent expert report on the impact of nuclear tests in French Polynesia (Inserm, 2020) recommends new studies that include doses measured on film dosimeters, as well as the results of anthropogammametry. Extension of the follow-up and improvement of individual dosimetric data (accurate background of monitoring, measured and missed doses) would be of great interest for further analyses of the cohort.

Finally the consolidated results of this particular French epidemiologic study and other similar studies on atmospheric nuclear tests can be expected to contribute to the next evolution of the radiological protection system by the ICRP (Laurier and Schneider, 2024) in a similar way to the Life Span Study of Hiroshima and Nagasaki survivors.

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Conflicts of interest

The authors of this manuscript declare no relationship with any companies, whose products or services may be related to the subject matter of the article.

Data availability statement

The Department of Monitoring of Nuclear Experimentation Centers (DSCEN) provided the veterans' data and the Inserm Center for Research in Epidemiology and Population Health and the CNAMTS provided national mortality data. OSV had the role of the trusted third-party between data providers and SEPIA-Santé.

Author contribution statement

E. Cassagne, data analysis and redaction.
N. Grandjean, redaction.
Claire Ségala, study design and revision.

Ethics approval

For this study, the protocol received approval of the "Comité Consultatif sur le Traitement de l'Information en matière de Recherche dans le domaine de la Santé" (CCTIRS) (n°07.286, September 3, 2007) and the "Commission Nationale de l'Informatique et des Libertés" (CNIL) (n°: 907312, December 12, 2007).

Informed consent

Informed consent was not required.

References

Boice JD, Cohen SS, Mumma MT, Chen H, Golden AP, Beck HL, *et al.* 2022a. Mortality among US military participants at eight above ground nuclear weapons test series. *Int J Radiat Biol*. https:doi.org/10.1080/09553002.2020.1787543.

Boice JD, Cohen SS, Mumma MT, Golden AP, Howard SC, Girardi DJ, *et al.* 2022b. Mortality among workers at the Los Alamos National Laboratory, 1943-2017. *Int J Rad Biol*. https:doi.org/10.1080/09553002.2021.1917784.

Breslow NE, Day NE. 1987. Statistical methods in cancer research. Volume II – the design and analysis of cohort studies. *IARC Sci Publ* 82: 1–406.

Caldwell GG, Zack MM, Mumma MT, Falk H, Heath CW, Till JE, *et al.* 2016. Mortality among military participants at the 1957 Olumbbob nuclear weapons test series and on leukemia among participants at the Smoky test. *J Radiol Prot* 36: 474–489.

Cardis E, Kesminiene A, Ivanov V, Malakhova I, Shibata Y, Khrouch V, *et al.* 2005. Risk of cancer after exposure to 131I in childhood. *J Natl Cancer Inst* 97: 724–732.

CSSEN. 2007. Rapport du Comité de liaison pour la coordination du suivi sanitaire des essais nucléaires français. https://ificantdance.studio/performingColonialToxicityTestimonyTranslationProject/downloads/RAPPORT-DU-COMIT%C3%89-DE-LIAISON.pdf

Dalager NA, Kang HK, Mahan CM. 2000. Cancer mortality among the highest exposed US atmospheric nuclear test participants. *J Occup Environ Med* 42: 798–805.

Gillies M, Haylock RGE. 2022. Mortality and cancer incidence 1952–2017 in United Kingdom participants in the United Kingdom's atmospheric nuclear weapon tests and experimental programmes. *J Radiol Prot.* 42: 021507.

Inserm. 2008. Cancers-environnement. Editions INSERM, Collection Expertise Collective. https://hal-lara.archives-ouvertes.fr/hal-01570675v1/file/INSERM_2008_cancer_environnement_vers_final.pdf

Inserm. 2020. Essais nucléaires et santé. Conséquences en Polynésie française. Collection Expertise collective. Montrouge: EDP Sciences. https://www.inserm.fr/expertise-collective/essais-nucleaires-et-sante-consequences-en-polynesie-franc%CC%A7aise/

IRSN. 2008. Efficacité des dosimètres individuels et d'ambiance utilisés pour la radioprotection lors des essais nucléaires français au Sahara et en Polynésie. *Rapport DRPH/ 2008–09. Direction de la Radioprotection de l'Homme*.

Kesminiene A, Evrard A, Ivanov V, Malakhova I, Kurtinaitise J, Stengrevics A, *et al.* 2012. Risk of Thyroid cancer among Chernobyl liquidators. *Radiat Res* 178: 425–436.

Kirkeleit J, Riise T, Bjørge T, Christiani DC. 2013. The healthy worker effect in cancer incidence studies. *Am J Epidemiol* 177 (11): 1218–1224.

Laurier D, Schneider T. 2024. Un atelier sur l'avenir de la radioprotection. *Radioprotection* 59 (4): 256–260.

Leuraud K, Laurier D, Gillies M, Haylock R, Kelly-Reif K, Bertke S, *et al.* 2024. Leukaemia, lymphoma, and multiple myeloma mortality after low-level exposure to ionising radiation in nuclear workers (INWORKS): updated findings from an international cohort study. *Lancet Haematol* 11 (10): e761–e769.

Liddell FD. 1984. Simple exact analysis of the standardized mortality ratio. *J Epidemiol Community Health* 38: 85–88.

Martin S, Ségala C. 2013. Affections de longue durée des vétérans avec surveillance dosimétrique lors des essais nucléaires français du Pacifique. *Bull Epidémiol Hebd* 41-42: 535–541.

Ministère de la Défense. 2006. La dimension radiologique des essais nucléaires français en Polynésie. À l'épreuve des faits. Ministère de la Défense. https://www-dam.cea.fr/dam/wp-content/uploads/2024/06/LIVRE-Les-essais-nucleaires-en-Polynesie-francaise.pdf

Muirhead CR, Kendall GM, Darby SC, Doll R, Haylock RGE, O'Hagan JA, *et al.* 2004. Epidemiological studies of UK who participated in the UK test veterans: II. Mortality and cancer incidence. *J Radiol Prot* 24: 219–241.

Pasquier JL, Bourguignon M, Bertho JM. 2024. Une dialectique récurrente : des dangers aux risques des expositions aux rayonnements ionisants. *Radioprotection* 59 (4): 250–255.

Pearce N, Winkelmann R, Kennedy J, Lewis S, Purdie G, Slater T, *et al.* 1997. Further follow-up of New-Zealand participants in United Kingdom atmospheric nuclear weapons tests in the Pacific. *Cancer Cause Control* 8: 139–45.

Pédrono G, Pachol H, Ségala C. 2011. Etude de mortalité des vétérans ayant bénéficié d'une surveillance dosimétrique lors des essais nucléaires français dans le Pacifique. *Rev Epidemiol Sante Publique* 59 (3): 187–196.

Sokolnikov ME, Gilbert ES, Preston DL, Ron E, Shilnikova NS, Khokhryakov VV, *et al.* 2008. Lung, liver and bone cancer mortality in Mayak workers. *Int J Cancer* 123: 905–911.

Telle-Lamberton M, Samson E, Caër S, Bergot D, Bard D, Bermann F, *et al.* 2007. External radiation exposure and mortality in a cohort of French nuclear Workers. *Occup Environ Med* 64: 694–700.

Till JE, Beck HL, Boice JD, Mohler HJ, Mumma MT, Aanenson JW, *et al.* 2018. Asbestos exposure and mesothelioma mortality among atomic veterans. *Int J Radiat Biol* 4: 1–15.

Till JE, Beck HL, Boice JD, Mohler HJ, Mumma MT, Aanenson JW, *et al.* 2024. Asbestos exposure and mesothelioma mortality among atomic veterans. In: *Chapter of "The Million Person Study of Low-Dose Radiation Health Effects" Book*. 1st edn. London: CRC Press.

UNSCEAR. 2006. Report, Volume I. Effects of Ionizing Radiation. Report to the General Assembly, Scientific Annexes A and B.

Yen Kai Sun L, Ghosn W, Rey G. 2016. Les causes de décès en Polynésie Française : analyse de la période 2005– 2010 et tendances évolutives de 1984 à 2010. *Bull Epidémiol Hebd* 10: 183–195.

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