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Cancer incidence and cause-specific mortality in 2663 male submariners with service in the Royal Norwegian Navy between 1942 and 2005: a registry-based cohort study

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ABSTRACT

Objectives A previous cohort study of male Norwegian Navy submariners showed higher overall cancer incidence and lower all-cause mortality than the general Norwegian population. We have extended the follow-up and show more precise estimates through seven decades.

Design Historical cohort study using outcome data from Norwegian cancer incidence and cause-of-death registries.

Setting Linkage with the outcome registries was performed by means of unique national identification numbers given to all Norwegian citizens.

Participants 2663 military men who ever served aboard a Navy submarine between 1942 and 2005.

Outcome measures Standardised incidence ratios for cancer and mortality ratios were calculated from national period-specific, gender-specific and age-specific rates. Poisson regression was used to compare cancer incidence in groups with different length of submarine service (>2 years vs ≤2 years).

Results The overall cancer incidence was 15% higher than expected from the national rates, with colon, lung, skin (melanoma and non-melanoma) and urinary tract contributing 90% of the excess number of cases. Most of the excess was confined to those with shorter-time service, who also showed elevated risk of alcohol-related cancers. Excess non-melanoma skin cancer was most clearly seen among submariners with >2 years of service. Mortality from all causes combined was lower among submariners than in the general population, due to a markedly low mortality from non-neoplastic diseases and external causes.

Conclusions Increased risk of non-melanoma skin cancer was found among submariners with long-term service, and skin exposure to carcinogens in petroleum products was hypothesised as an explanation. Less support for occupational risks was found for other cancers, although the lack of specific exposure data and limited statistical power reduced the possibility of identifying such associations. A ‘healthy soldier effect’ appeared in the mortality data, mainly restricted to low mortality from non-neoplastic diseases and external causes.

STRENGTHS AND LIMITATIONS OF THIS STUDY

- ⇒ The strengths of this study include the use of a virtually complete cohort and linkage to high-quality outcome registries, which are regarded as complete for the Norwegian population back to the early 1950s.
- ⇒ We had no loss to follow-up except from emigration at specified dates.
- ⇒ The limited size of the cohort was compensated for with a long observation time.
- ⇒ Study limitations include lack of specific information on exposure to harmful agents in the submarine work environment, and no information on lifestyle factors such as tobacco smoking, alcohol drinking or tanning for our cohort members, which hampers the interpretation of our results.

INTRODUCTION

Cancer incidence and cause-specific mortality among submarine crews are little studied. Most studies on submariners have focused on crews serving aboard nuclear submarines, investigating the effects of continuous isolation at sea for months, as well as radiation hazard from the nuclear reactor and from missiles with nuclear warheads on board. Two studies from the 1990s investigated cause-specific mortality (including cancer mortality) among British[1] and American (US)[2] submarine crews, and an updated study of the American submariners was published in 2022.[3] All studies found that the crews had lower overall mortality than the population average and concluded specifically that submarine service was not associated with increased cancer mortality. Submariners who served the Royal Norwegian Navy in diesel-electric submarines post World War II (WWII) were followed for incident cancers 1953–2008 and for cause-specific mortality 1951–2007 by Strand *et al*.[4] Compared with the general Norwegian population, these submariners showed a statistically significant elevation of overall cancer incidence, of bladder cancer and of non-melanoma skin cancer by 15%, 53% and 85%, respectively. By contrast, a 'healthy soldier effect' in terms of 15% lower total mortality was seen, inclusive of 41% lower mortality from external causes. However, relatively few incident cancers (332) and deaths (303) gave limited statistical strength in the 2011 study. A later update of the Navy vessel crews (Strand *et al*)[5] did not address submariners separately, although their training and work environment obviously may differ from that of surface vessels.

The aim of the present study of submariners with extended follow-up was to see if the deviations from expected values in the previous study are still present, and to gain statistical strength to investigate specific cancers and causes of death. We also wanted to investigate cancer incidence by length of submarine service, assuming that the risk of cancer would increase by length of service if harmful exposures were present onboard. Thus, we extended our follow-up for cancer incidence and mortality through 2021, obtaining an increase of more than 130% in the number of observed incident cancers and deaths. As the cohort's median year of birth is 1953, most additional observation years are expected to cover people at an age above 55.

Our cohort members have served aboard one or more of 30 submarines operated by the Royal Norwegian Navy since 1942. The three oldest vessels were British, transferred to the exiled Royal Norwegian Navy during German occupation in WWII. The newest submarines, launched 1988–1991, remain in service to this date. All Norwegian submarines have been using diesel-electric power, and were, except for WWII raids along the Norwegian coast and escorting of Arctic convoys, intended for invasion defence in coastal waters with missions of relatively short duration.[6 7] Hazardous exposure to the crews might still be caused by vapours from batteries, diesel, diesel exhaust, mineral oil and hydraulic fluids. According to the International Agency for Research on Cancer (IARC),[8] diesel engine exhaust is associated with lung cancer and probably with urinary bladder cancer, and skin contact with mineral oils is associated with non-melanoma skin cancers. Hydraulic fluids are often complex mixtures of mineral oil, water, antioxidative and antiwear additives.[9] However, little is known about possible carcinogenic effects of the additives.

METHODS

Study cohort

The submariners are part of an all-male cohort comprising a virtually complete roster of commissioned and non-commissioned officers and enlisted personnel who served at any time in the Royal Norwegian Navy between 1950 and 2004. The cohort was established from paper-based service history files and the Armed Forces personnel database by the Navy in cooperation with the Cancer Registry of Norway[10] and was later included in the Norwegian Armed Forces Health Registry. The 2663 submariners were identified by vessel name or type of vessel, with service history files dating back to WWII. We extended the cohort slightly compared with our previous study by including 10 seamen who terminated their submarine service before 1950, and 13 who enlisted for their first submarine service in 2005. The median age at start of submarine service was 22, and the average service time onboard a submarine was 2.9 years (table 1). Two of the cohort members mustered off the submarine 'Uredd' just before it was sunk by a German mine in February 1943—the only Norwegian submarine lost to this date.

Table 1 Demographic characteristics of the cohort members

Submariners (N=2663)	
Year of birth, range	1905–1984
Median (IQR)	1953 (1941–65)
Years of service, average (SD)	
Military (all branches)	11.8 (11.4)
Navy	10.6 (10.2)
Aboard all vessels	4.4 (4.0)
Aboard submarines	2.9 (2.7)
Years of service by duration category	
<2 years: median (IQR)	1.0 (0.5–1.3)
>2 years: median (IQR)	4.1 (2.9–6.3)
Age at start of submarine service, range	17.5–58.2
Median (IQR)	22.1 (20.7–24.0)

Outcome registries

Information on cancer and dates of diagnosis was retrieved from the Cancer Registry of Norway, which is regarded as complete back to 1953. Cancer diagnoses were classified according to International Classification of Diseases, Revision 10 (ICD-10) and grouped to be compatible with the different ICD versions back in time. One person may have more than one cancer diagnosis. Information on causes and dates of death was retrieved from the Norwegian Armed Forces Health Registry, which receives such information from the Norwegian Cause-of-Death Registry on a yearly basis. The Cause-of-Death Registry is virtually complete for the Norwegian population back to 1951, and deaths in our cohort were grouped according to the European Shortlist for causes of death,[11] expressed in ICD-10 codes. Information on emigration (and dates) was retrieved from the National Population Register. The unique 11-digit personal identification (ID) number was used to link with the registries, while those who died before ID numbers were introduced in 1960 were identified by name and date of birth.

Definition of alcohol-related cancers

The group of alcohol-related cancers was defined as cancer of the tongue (ICD-10 codes C01–02); mouth (C03–06); pharynx (C09–14); oesophagus (C15); liver (C22) and larynx (C32) combined. This definition was based on evaluations by the IARC (published in 1988)[12] and was applied in the previous studies of Royal Norwegian Navy personnel, inclusive of the submariner cohort.[4 5] It can serve as an indication of alcohol consumption at the group level, for example, when cancer incidence is compared with that of the general population. Today, colorectal cancer could be added to the list,[13] but we kept the older definition to facilitate comparison with earlier studies.

Definition of low-survival cancers

For an earlier study, we defined cancers with less than 25% 5-year relative survival (Norway 2008–2012)[14] as low-survival cancers, of which most sites were associated with lifestyle factors. In a recent study of Norwegian Navy personnel, vessel crews—of which our submariner cohort constituted 17%—showed elevated risk of low-survival cancers.[5] We applied the same definition of low survival to the submariner cohort, including cancer of the oesophagus (ICD-10 code C15); stomach (C16); liver (C22); gall bladder and bile ducts (C23–24); pancreas (C25); other digestive organs (C26); lung and trachea (C33–34); non-mesothelioma cancer in heart, mediastinum and pleura (C38); other or unspecified cancer (C39, C76, C80) and mesothelioma (C45).[14] All other cancers combined were termed 'non-low-survival cancers'. Cancers of prostate, skin, colon, rectum, urinary tract and cancer in lymphoid/haematopoietic tissue contribute most of the cases in the latter group.

Statistical analyses and follow-up

The submarine crews were followed from the first registered day of submarine service, but not earlier than 1 January 1953 for cancer, and from 1 January 1951 for mortality, until whichever came first of death, emigration or the end of the study period, which was 31 December 2021.

Standardised incidence ratios (SIRs) for cancer and standardised mortality ratios (SMRs) were calculated as the ratio between observed numbers in the cohort and expected numbers, the latter calculated from 1-year period-specific and 5-year age-specific rates among all Norwegian men. 95% CIs were calculated assuming a Poisson distribution of the observed cases. SIRs and SMRs were calculated for the overall follow-up. We also calculated SIRs by duration of submarine service. The median overall submarine service duration was 2 years (2.02 years). Those who served aboard for ≤2 years were followed as 'short-term workers', while those with longer service (>2 years) were followed as 'long-term workers'. Poisson regression was used to compare rate ratios (RRs) for the long-term service group, using the short-time workers group as reference with categorical variables to adjust for age and observation period. We chose $p<0.05$ to indicate statistical significance, and 95% CIs were derived for all SIRs, SMRs and RRs. Stata V.17 (StataCorp) and SPSS V.26 software packages were used for statistical analyses.

Patient and public involvement

None.

RESULTS

Cancer incidence, overall cohort

We observed 782 cancer cases during follow-up. Average follow-up was 41.3 years, with a maximum of 69 years. The most frequent cancer sites were prostate (176 cases), lung (84), colon (68), urinary tract (62), and skin melanoma (61) and non-melanoma skin cancers (61). One-third (33%) of all cancers belonged to the low-survival cancer group.

The overall cancer incidence was 15% higher than expected from the national rates, with colon, lung, skin (melanoma and non-melanoma) and urinary tract contributing 90% of the excess number of cases. Alcohol-related cancer by the old definition was 20% elevated, the estimate remaining approximately the same (SIR 1.19, 95% CI 1.01 to 1.41) when we included colorectal cancers. Only a slight excess (<10%) of low-survival cancers was observed, and none of the lower-than-expected SIRs in our study was statistically significant (table 2).

Cancer incidence by length of service

The overall cancer risk in the short-term service group was elevated by 19%. The elevated risk of colon cancer, bladder cancer and cancer of soft tissues, which was found in the overall cohort, was most clearly seen in this group. An elevated risk of alcohol-related cancers was confined to the short-term service group only (table 3).

In the long-term service group, overall cancer incidence was 10% higher than expected. A suggested tripled risk was seen for Hodgkin lymphoma, although based on only five observed cases. Melanoma skin cancer SIRs were elevated in both groups of service length at approximately the same magnitude, while the increase in non-melanomas was most clearly seen among long-term submariners.

The comparison of cancer incidence between the two groups of service length was more favourable for long-term submariners, with a suggested overall RR of 90% (table 4). More favourable RRs were seen for alcohol-related cancers (RR 0.43, 95% CI 0.21 to 0.89), and for bladder cancer and colon cancer, although slightly less marked (RRs around 0.7). Skin cancer appeared more common in the long-term service group, with a risk of non-melanoma suggested to be 30% above the short-term group.

Mortality

The cohort members were followed for an average of 41.4 years. Two submariners, born in 1928 and 1930,

Table 2 Observed (Obs) and expected (Exp) number of cancers, standardised incidence ratios (SIRs) for selected cancers adjusted for age and period, and 95% CI among 2663 Navy submariners for the follow-up period 1953–2021 (110 064 person-years)

Cancer site	ICD-10	Obs	Exp	SIR	95% CI
All sites	C00–96	782	681.30	1.15	1.07 to 1.23
Stomach	C16	17	15.44	1.10	0.64 to 1.76
Small intestine	C17	3	3.64	0.82	0.17 to 2.41
Colon	C18	68	52.39	1.30	1.01 to 1.65
Rectum, rectosigmoid	C19–20	33	32.61	1.01	0.70 to 1.42
Pancreas	C25	12	16.63	0.72	0.37 to 1.26
Lung, trachea	C33–34	84	72.54	1.16	0.92 to 1.43
Melanoma	C43	61	39.02	1.56	1.20 to 2.01
Skin, non-melanoma	C44	61	35.02	1.74	1.33 to 2.24
Mesothelioma	C45	5	3.05	1.64	0.53 to 3.82
Soft tissues	C48–49	8	3.00	2.66	1.15 to 5.25
Prostate	C61	176	179.42	0.98	0.84 to 1.14
Testis	C62	10	12.34	0.81	0.39 to 1.49
Kidney excluding renal pelvis	C64	21	21.21	0.99	0.61 to 1.51
Bladder, renal pelvis and other urinary organs	C65–68	62	46.16	1.34	1.03 to 1.72
Brain, nervous system	C70–72	21	20.69	1.02	0.63 to 1.55
Hodgkin lymphoma	C81	8	3.72	2.15	0.93 to 4.24
Non-Hodgkin's lymphoma	C82–86, C96	27	21.83	1.24	0.82 to 1.80
Immunoproliferative diseases	C88	3	1.73	1.73	0.36 to 5.06
Multiple myeloma	C90	7	9.93	0.70	0.28 to 1.45
Leukaemia	C91–95	22	23.42	0.94	0.59 to 1.42
Lymphoid/haematopoietic tissue	C81–96	67	60.64	1.10	0.86 to 1.41
Alcohol-related cancers	*	38	31.77	1.20	0.85 to 1.64
Low-survival cancers	†	147	135.55	1.08	0.92 to 1.27
Non-low-survival cancers	‡	635	546.75	1.16	1.07 to 1.26

*Tongue (C01–02); mouth (C03–06); pharynx (C09–14); oesophagus (C15); liver (C22) and larynx (C32).
†Oesophagus (C15); stomach (C16); liver (C22); gall bladder and bile ducts (C23–24); pancreas (C25); other digestive organs (C26); lung and trachea (C33–34); heart, mediastinum and pleura (C38); other or unspecified cancer (C39, C76, C80) and mesothelioma (C45).
‡Cancers other than those listed in the footnote (†).
ICD-10, International Classification of Diseases, 10th revision.

were followed through the entire period (71 years). We observed 700 deaths which gave a mortality lower than expected for all causes combined (SMR 0.91, 95% CI 0.84 to 0.98) (table 5). Mortality from external causes inclusive of suicide was particularly low (SMR=0.59), due to low incidence of deaths ascribed to accidents. Mortality from all diseases combined and most groups of diseases were on the low side of unity, markedly so for all non-neoplastic diseases combined and for the subgroup of non-neoplastic respiratory diseases.

Neoplastic mortality overall was 10% above the national rates, including that of cancer of the lung. The risk of death from bladder cancer was as much as twice the national rates (SMR 2.05, 95% CI 1.17 to 3.33, 16 deaths). The number of deaths of unknown cause was more than twice that expected.

For mortality data, we chose not to perform analyses by length of service, as cancer is already covered by incidence data, and mortality from non-neoplastic diseases and from external causes were all lower than expected.

DISCUSSION

Norwegian submariners now followed from the early 1950s through 2021 had a 15% increased SIR for cancer of all types, urinary tract cancers (34%) and non-melanoma skin cancer (74%), largely in line with the 2011 study. New sites with elevated risk were skin melanoma (56%), colon cancer (30%) and alcohol-related cancer (20%). Additionally, increased risk was suggested for lung cancer. The overall mortality (SMR) was nearly 10% lower than

Table 3 Observed (Obs) and expected (Exp) number of cancers, standardised incidence ratios (SIRs) for selected cancers adjusted for age and period, and 95% CI among Navy submariners by duration of submarine service

Cancer site	ICD-10	Duration of submarine service (years)	Obs	Exp	SIR	95% CI
All sites	C00–96	≤2	440	371.24	1.19	1.08 to 1.30
		>2	342	310.07	1.10	0.99 to 1.23
Stomach	C16	≤2	11	8.71	1.26	0.63 to 2.26
		>2	6	6.73	0.89	0.33 to 1.94
Colon	C18	≤2	43	29.08	1.48	1.07 to 1.99
		>2	25	23.31	1.07	0.69 to 1.58
Rectum, rectosigmoid	C19–20	≤2	19	17.91	1.06	0.64 to 1.66
		>2	14	14.70	0.95	0.52 to 1.60
Pancreas	C25	≤2	4	9.13	0.44	0.12 to 1.12
		>2	8	7.50	1.07	0.46 to 2.10
Lung, trachea	C33–34	≤2	46	40.44	1.14	0.83 to 1.52
		>2	38	32.10	1.18	0.84 to 1.63
Melanoma	C43	≤2	31	20.49	1.51	1.03 to 2.15
		>2	30	18.53	1.62	1.09 to 2.31
Skin, non-melanoma	C44	≤2	29	19.88	1.46	0.98 to 2.10
		>2	32	15.14	2.11	1.45 to 2.98
Mesothelioma	C45	≤2	4	1.73	2.31	0.63 to 5.91
		>2	1	1.32	0.76	0.02 to 4.22
Soft tissues	C48–49	≤2	5	1.59	3.14	1.02 to 7.32
		>2	3	1.41	2.13	0.44 to 6.22
Prostate	C61	≤2	95	97.77	0.97	0.79 to 1.19
		>2	81	81.65	0.99	0.79 to 1.23
Testis	C62	≤2	3	5.85	0.51	0.11 to 1.50
		>2	7	6.49	1.08	0.43 to 2.22
Kidney excl. renal pelvis	C64	≤2	10	11.23	0.89	0.43 to 1.64
		>2	11	9.98	1.10	0.55 to 1.97
Bladder, renal pelvis and other urinary organs	C65–68	≤2	39	25.68	1.52	1.08 to 2.08
		>2	23	20.48	1.12	0.71 to 1.69
Brain, nervous system	C70–72	≤2	15	10.78	1.39	0.78 to 2.30
		>2	6	9.91	0.61	0.22 to 1.32
Hodgkin lymphoma	C81	≤2	3	1.90	1.58	0.33 to 4.62
		>2	5	1.82	2.74	0.89 to 6.41
Non-Hodgkin's lymphoma	C82–86, C96	≤2	18	11.63	1.55	0.92 to 2.45
		>2	9	10.20	0.88	0.40 to 1.67
Multiple myeloma	C90	≤2	4	5.44	0.73	0.20 to 1.88
		>2	3	4.49	0.67	0.14 to 1.95
Leukaemia	C91–95	≤2	9	12.68	0.71	0.32 to 1.35
		>2	13	10.74	1.21	0.64 to 2.07
Lymphoid/haematopoietic tissue	C81–96	≤2	37	32.60	1.13	0.80 to 1.56
		>2	30	28.04	1.07	0.72 to 1.53
Alcohol-related cancers	*	≤2	28	17.04	1.64	1.09 to 2.38
		>2	10	14.73	0.68	0.33 to 1.25

Continued

Table 3 Continued

Cancer site	ICD-10	Duration of submarine service (years)	Obs	Exp	SIR	95% CI
Low-survival cancers	*	≤2	84	75.37	1.11	0.89 to 1.38
		>2	63	60.19	1.05	0.80 to 1.34
Non-low-survival cancers	*	≤2	356	295.87	1.20	1.08 to 1.34
		>2	279	249.88	1.12	0.99 to 1.26

Follow-up 1953–2021. Short-term service (≤2 years); n=1320, 56 402 person-years; long term service (>2 years): n=1343, 53 662 person-years.
*See footnotes in table 2.
ICD-10, International Classification of Diseases, 10th revision.

expected, although a 10% increased mortality was suggested for neoplastic disease (cancer of any type), most pronounced for bladder cancer. Mortality from non-neoplastic diseases and from accidents was 20% and 41% lower than expected. Comparisons of risk by length of service, by type of cancer and comparisons with other occupational groups or Navy personnel may be helpful to shed some light on possible explanations.

A previous study found that Norwegian Navy vessel crews had a 13% elevated incidence rate of all cancers combined compared with the general population.[5] Our submariner cohort, which constitutes one-sixth of the vessel crews, showed 17% increased overall SIR during the same follow-up period (through 2017) (Strand, unpublished data). For the group of submariners with long-term service, the cancer excess was mainly confined to melanoma and non-melanoma skin cancer. For the short-term service group, the cancer excess was more pronounced, mainly caused by colon, urinary tract and alcohol-related cancers.

Skin cancer

The excess of melanoma and non-melanoma skin cancer was slightly more pronounced in the long-term service group, rendering some support to the idea that exposures during service could play a role. As known from the general population, an important contribution to skin cancer risk comes from solar ultraviolet radiation, both for melanoma and for other skin cancers.[15] Onboard submarine service constitutes approximately one-fourth of the crews' total military service (table 1). While much of the onshore military service is spent outdoors, uniforms are expected to protect against most of the solar radiation.

A large census and cancer registry-based study on work-related cancers in the Nordic countries also pointed to a slightly elevated risk (SIR 1.2–1.3) of melanoma and non-melanoma skin cancer in male military personnel. At the same time, the highest relative risks among Norwegian men (SIR 1.5–1.8) were observed among indoor professions comprising dentists, medical doctors and administrators,[15] which is indicative of intentional tanning as the

Table 4 Relative risks expressed as rate ratios (RRs) for the incidence of selected cancers among men in the long-term service group using the short-term service group as the reference

Cancer site	ICD-10	RR	95% CI
All sites	C00–96	0.88	0.77 to 1.02
Colon	C18	0.66	0.40 to 1.08
Lung	C33–34	0.99	0.65 to 1.53
Melanoma	C43	1.14	0.69 to 1.88
Non-melanoma skin cancer	C44	1.30	0.79 to 2.15
All skin cancers	C43–44	1.18	0.83 to 1.69
Bladder, renal pelvis and other urinary organs	C65–68	0.71	0.42 to 1.19
Alcohol-related cancers	*	0.43	0.21 to 0.89
Low-survival cancers	*	0.89	0.64 to 1.24
Non-low survival cancers	*	0.88	0.75 to 1.03

Poisson regression analysis was used, with adjustment for observation period and age, providing 95% CI.
*See footnotes in table 2.
ICD-10, International Classification of Diseases, 10th revision.

Table 5 Cause-specific mortality among 2663 Norwegian male submariners followed up during 1951–2021 (110 264) person-years

Cause of death	ICD-10	Obs	Exp	SMR	95% CI
All causes	A00–Y99	700	773.15	0.91	0.84 to 0.98
All diseases	A00–R99	615	678.01	0.91	0.84 to 0.98
Symptoms, signs, abnormal findings, ill-defined causes	R00–R99	18	22.82	0.79	0.47 to 1.25
Unknown due to lack of information	–	38	15.10	2.52	1.78 to 3.45
Neoplastic diseases	C00–D48	269	243.76	1.10	0.98 to 1.24
Lung, trachea	C33–C34	64	55.69	1.15	0.89 to 1.47
Melanoma of skin	C43	7	8.50	0.82	0.33 to 1.70
Urinary bladder	C67	16	7.80	2.05	1.17 to 3.33
Non-neoplastic diseases	A00–B99, D50–Q99	328	411.43	0.80	0.72 to 0.89
Infectious and parasitic diseases	A00–B99	6	11.67	0.51	0.19 to 1.12
Endocrine, nutritional and metabolic diseases	E00–E89	9	17.18	0.52	0.24 to 0.99
Diabetes mellitus	E10–E14	9	12.79	0.70	0.32 to 1.34
Mental and behavioural disorders	F00–F99	22	27.17	0.81	0.51 to 1.23
Alcoholic psychosis/chronic alcohol abuse	F10	7	9.06	0.77	0.31 to 1.59
Diseases of the nervous system and the sense organs	G00–H95	20	28.19	0.71	0.43 to 1.09
Diseases of the circulatory system	I00–I99	204	227.87	0.90	0.78 to 1.03
Ischaemic heart diseases	I20–I25	107	123.81	0.86	0.71 to 1.04
Cerebrovascular diseases	I60–I69	29	41.05	0.71	0.47 to 1.01
Diseases of the respiratory system	J00–J99	42	57.11	0.74	0.53 to 0.99
Pneumonia	J12–J18	6	14.67	0.41	0.15 to 0.89
Chronic lower respiratory diseases	J40–J47	29	34.35	0.84	0.57 to 1.21
Diseases of the digestive system	K00–K92	16	24.05	0.67	0.38 to 1.08
Chronic liver disease	K70, K73–K74	4	8.67	0.46	0.13 to 1.18
External causes of injury and poisoning	V01–Y89	47	80.04	0.59	0.43 to 0.78
Suicide	X60–X84, Y87.0	15	23.96	0.63	0.35 to 1.03
Accidents	V01–X59	31	53.96	0.57	0.39 to 0.82
Transport accidents	V01–V99, Y85	18	19.77	0.91	0.54 to 1.44
Accidental falls	W00–W19	3	10.51	0.29	0.06 to 0.83
Accidental poisoning	X40–X49	2	7.68	0.26	0.03 to 0.94
Accidental drowning and submersion	W65–W74	3	4.15	0.72	0.15 to 2.11

Obs and exp number of deaths, SMR adjusted for age and period with 95% CI.
Exp, expected; ICD-10, International Classification of Diseases, 10th revision; Obs, observed; SMR, standardised mortality ratio.

most important factor. To decide whether skin cancer in submariners may be caused by tanning during waiting, off-duty hours or peace-keeping service in countries closer to the equator is beyond the scope of the present study.

Skin cancer may still be work-related, as mineral oils used for lubrication of engines and in hydraulic power transmission systems contain compounds acting as skin carcinogens.[8] Hydraulic systems have been commonly used in submarines since WWII and operate devices such as the ballast tank vents, steering, dive planes, torpedo tube shutter doors, periscopes and communication mast.[16] The fluids are mostly mineral-oil based and blended with additives such as phenols, amines, organophosphate esters[9] and polychlorinated biphenyls (PCBs).[17 18] According to IARC, skin contact with mineral oils and PCBs are associated with non-melanoma and melanoma skin cancers, respectively.[8] The SIR of non-melanoma skin cancer was elevated among long-term service submariners, suggestive of a dose-related risk.

Urinary tract cancers

Several studies have shown an elevated risk of bladder cancer in seamen,[19 20] and it has been argued that seamen may increase their risk of bladder cancer by inhaling diesel exhaust fumes and other particles which contain polycyclic aromatic hydrocarbons.[21] In general, the number of recognised bladder carcinogens is high,[8] including a wide spectrum of exposures: infections, specific chemicals in occupational settings (dyes, arsenic) and unspecific chemical exposures (painting, rubber production and aluminium smelters), radiation and smoking. Additionally, there is a long list of factors with limited evidence. An association between exposure to straight (mineral oil-based) metalworking fluids and bladder cancer has been shown.[22 23] In industrialised countries, it is estimated that occupational exposures may account for 20% of bladder cancer. Tobacco smoking is a major cause of bladder cancer,[24] taken to account for approximately 50% of such cancers in men.[25] Interestingly, a study including Nordic seamen registered as such in national censuses 1960, 1970 and 1980, showed increased risks (SIRs) of lung and bladder cancer (1.6 and 1.2, respectively), largely believed to be caused by a high prevalence of cigarette smoking.[15] However, if smoking should explain the excess urinary tract cancer in our study, the incidence of lung cancer should also be elevated, which it is not to any substantial degree (SIR 1.1–1.2, table 3). It is also worth noting that the excess is more pronounced among the short-term servicemen, lending less support to an occupational risk.

Alcohol-related cancers

Whether the observed elevated risk of alcohol-related cancers, which was restricted to those with short-term service, can be a sign of drinking combined with premature termination of work, or a consequence of mental stress during submarine service, or linked to other factors, remains uncertain. Elevated risk of alcohol-related cancers is not uncommon in seafarers and was seen in all Norwegian Royal Navy vessel crews[5] and in seamen in the Nordic countries.[15] British Royal Navy submariners showed elevated mortality (SMR=2.21) from liver cirrhosis, and alcohol was a contributory factor in eight out of 12 deaths from this cause.[1] However, the low mortality of chronic liver disease among our submariners, also noted in the 2011 paper through 2007,[4] does not support a high alcohol consumption at the group level, although these diseases are rare, and may also have been present among those registered with an unknown cause of death.

Low-survival cancers

The 8% elevated incidence of such cancers in our cohort is in contrast to the 20% elevated incidence seen in all Norwegian Navy vessel crews[5] and indicates that submariners have less risk of lifestyle-related cancers than other Navy vessel crews.

Colon cancer

Known environmental colon cancer carcinogens are consumption of alcoholic beverages and processed meat, tobacco smoking, and exposure to X- and gamma radiation.[8] Some other lifestyle-related risk factors are also considered important at the public health level, such as overweight and obesity, and lack of physical activity. Increased risk has been shown among occupational groups of military personnel, seamen[15] and firefighters.[26] Occupational exposures that are suspected of leading to increased risk of colon cancer include asbestos, work as a firefighter and night shift work. The absence of increased risk in long-term submariners does not support a strong occupational impact in our group.

Soft tissue cancer

An excess of soft tissue cancers (eight observed against three expected) may be due to random variation, as there is not much evidence of environmental causes. According to IARC, polychlorophenol and their sodium salts, radioiodines and 2,3,7,8-Tetrachlorodibenzo-para-dioxin are agents with limited evidence.[8] An overview by Brown *et al* reported non-statistically significant excess risk of mortality from soft tissue sarcomas in workers in pulp manufacturing (SMR=1.13) and manufacture of pesticides (SMR=1.13),[27] exposures that may not be relevant for our cohort members.

Mortality

Mortality from all causes combined was lower than that in the general population (SMR=0.91), due to lower mortality from non-neoplastic diseases and from external causes. This phenomenon can be perceived as a 'healthy soldier effect', possibly caused by selection of healthy individuals into military service, and potentially strengthened by selection of even more healthy personnel to extended service, combined with a demand to stay physically fit.[28] Some would argue that military personnel can have (in some countries) better access to medical services, but in Norway, there is fairly equal access for the population to health services across geography and socioeconomic strata. Submariners must pass a highly specialised training programme and tolerate living and working in a very limited space, which may be associated with strong self-discipline and a healthy lifestyle. Such training might have contributed to the low observed risk of mortality from external causes, inclusive of accidents and suicide. The low risk of mortality from accidental falls might be due to physical fitness, which is strongly associated with reduced risk of fall-related injuries.[29] The lower than expected SMR for respiratory diseases in our study is in line with the findings among other submariners,[1 3] although the finding is difficult to explain in light of the suggested slight elevation of the SIR and SMR for lung cancer.

For death from neoplastic diseases, we saw no sign of the 'healthy soldier effect'. Factors that predict death from cancer are less likely to be present at the draft-board selection before military service than factors that may predict deaths from other causes. Cancer is known to appear late in life, which may reduce in absolute or relative terms the impact of employment-related factors. Our result is in contrast to the lower than expected cancer mortality seen in British[1] and US submariners,[2 3] perhaps due to the relatively short average follow-up of these cohorts (8–23 years) as the healthy soldier effect seems to decline over time.[5] A reduction over time in the mortality deficit among Norwegian submariners seems to occur also for total mortality, from SMR 0.85 to 2007 in the previous study,[4] to present SMR 0.91 to 2021, in line with results recently reported for the entire Navy cohort.[30]

Study strengths and limitations

The strengths of this study are the use of a virtually complete cohort and linkage to high-quality outcome registries, which are regarded as complete for the Norwegian population back to the early 1950s. However, lack of data on tobacco smoking, alcohol drinking, tanning and detailed exposure to harmful agents in the submarine work environment hampers the interpretation of our results. We compared incident cancers linked to lifestyle factors, compensating for the limited size of the cohort with a long observation time. Still, the number of cases did not allow us to exclude lifestyle as potential causal factors.

Evidence related to the duration of exposure may be vulnerable to healthy worker recruitment and survivor bias, meaning that more healthy individuals are selected into the armed forces and the least vulnerable tend to remain in service, and therefore, accrue more exposure (employment years) than those who change work or retire due to health issues. Crews may also be exposed elsewhere in the military or in other occupations at sea or onshore.

CONCLUSIONS

Except for skin cancers, which may be caused by exposure to mineral oils and additives in hydraulic fluids, there was not much support for an occupational explanation of the cancer excess observed at other sites in submariners. A 'healthy soldier effect' was observed in the mortality from non-neoplastic diseases and from external causes. Mortality ascribed to accidents was particularly low.

Contributors The study was designed by LAS and TKG. JIM and IR performed the statistical analyses, and quality control of data and algorithms was performed by IR, JIM and LAS. All authors interpreted the data. LAS wrote the first draft of the manuscript and is the guarantor of the manuscript. The manuscript was circulated repeatedly between the authors for critical revisions. All authors approved the final version of the manuscript and LAS had the responsibility to submit the manuscript.

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REFERENCES

1 Inskip H, Snee M, Styles L. The mortality of Royal Naval submariners 1960-89. *Occup Environ Med* 1997;54:209–15.
2 Charpentier P, Ostfeld AM, Hadjimichael OC, *et al*. The mortality of US nuclear submariners, 1969-1982. *J Occup Med* 1993;35:501–9.
3 Friedman-Jimenez G, Kato I, Factor-Litvak P, *et al*. Mortality of Enlisted Men Who Served on Nuclear-Powered Submarines in the United States Navy. *J Occup Environ Med* 2022;64:131–9.
4 Strand LA, Martinsen JI, Koefoed VF, *et al*. Cause-specific mortality and cancer incidence among 28,300 Royal Norwegian Navy servicemen followed for more than 50 years. *Scand J Work Environ Health* 2011;37:307–15.
5 Strand LA, Rudvin I, Martinsen JI, *et al*. Lifelong differences in cancer incidence and mortality between subgroups of similar socioeconomic status in the Royal Norwegian Navy. *Occup Environ Med* 2023;80:514–21.
6 Pettersen T. *The fleet plan of 1960 [in Norwegian]*. Bergen (Norway): Sjøforsvarets Forsyningskommando (Navy Supply Command), 1990:1–93.
7 Knudsen SA. *Present and invisible for 100 years. The submarine weapon 1909-2009 [In Norwegian: Tilstede og usynlig i 100 år. Ubåtvåpenet 1909-2009]*. Bergen (Norway): Bodoni, 2009.
8 International Agency for Research on Cancer. *List of classifications by cancer sites with sufficient or limited evidence in humans, IARC Monographs Volumes 1–135. IARC Monographaphs on the Evaluation of Carcinogenic Risks to Humans*. Lyon (France): International Agency for Research on Cancer, 2023:14.
9 Health Effects. *Toxicological profile for hydraulic fluids*. Atlanta (GA): Agency for Toxic Substances and Disease Registry (US), 1997:45–232.
10 Strand LA, Koefoed VF, Oraug TMT, *et al*. Establishment of the Royal Norwegian Navy personnel cohorts for cancer incidence and mortality studies. *Mil Med* 2008;173:785–91.
11 European shortlist for causes of death. 1998. Available: http://ec.europa.eu/eurostat/ramon/nomenclatures/index.cfm?TargetUrl=LST_NOM_DTL_LINEAR&IntCurrentPage=2&StrNom=COD_1998&StrLanguageCode=EN2018
12 IARC. *Monographs on the evaluation of carcinogenic risks to humans. Alcohol drinking. Summary of data reported and evaluation. IARC Monographs on the Evaluation of Carcinogenic Risks to Humans*. Lyon (France): International Agency for Research on Cancer, 1988.
13 Rehm J, Shield KD, Weiderpass E. Alcohol consumption. A leading risk factor for cancer. *Chem Biol Interact* 2020;331:109280.
14 Cancer Registry of Norway. *Cancer incidence, mortality, survival and prevalence in Norway*. Oslo: Cancer Registry of Norway, 2012.
15 Pukkala E, Martinsen JI, Lynge E, *et al*. Occupation and cancer - follow-up of 15 million people in five Nordic countries. *Acta Oncol* 2009;48:646–790.
16 San Francisco Maritime National Park Association. Submarine hydraulic systems - principles of hydraulics. Available: https://www.maritime.org/doc/fleetsub/hydr/index.php [Accessed 15 Apr 2024].
17 Esser A, Schettgen T, Kraus T. Assessment of a potential PCB exposure among (former) underground miners by hydraulic fluids. *J Toxicol Environ Health A* 2020;83:219–32.
18 Polychlorinated biphenyl (PCBs). 2024. Available: https://www.geoforward.com/polychlorinated-biphenyl-pcbs-pcb/ [Accessed 18 Apr 2024].
19 Hadkhale K, Martinsen JI, Weiderpass E, *et al*. Occupation and Risk of Bladder Cancer in Nordic Countries. *J Occup Environ Med* 2016;58:e301–7.

20 Rafnsson V, Sulem P. Cancer incidence among marine engineers, a population-based study (Iceland). *Cancer Causes Control* 2003;14:29–35.
21 Cumberbatch MGK, Jubber I, Black PC, *et al*. Epidemiology of Bladder Cancer: A Systematic Review and Contemporary Update of Risk Factors in 2018. *Eur Urol* 2018;74:784–95.
22 Colin R, Grzebyk M, Wild P, *et al*. Bladder cancer and occupational exposure to metalworking fluid mist: a counter-matched case-control study in French steel-producing factories. *Occup Environ Med* 2018;75:328–36.
23 Park D, Stewart PA, Coble JB. A comprehensive review of the literature on exposure to metalworking fluids. *J Occup Environ Hyg* 2009;6:530–41.
24 IARC. *Monographs on the evaluation of carcinogenic risks to humans. Tobacco smoke and involuntary smoking. IARC Monographs on the Evaluation of Carcinogenic Risks to Humans*. Lyon (France): International Agency for Research on Cancer, 2004.
25 Kogevinas M. Bladder cancer. In: *Occupational cancers*. 2nd edn. Switzerland: Springer Nature, 2020: 487–506.
26 Jalilian H, Ziaei M, Weiderpass E, *et al*. Cancer incidence and mortality among firefighters. *Int J Cancer* 2019;145:2639–46.
27 Brown T, Young C, Rushton L, *et al*. Occupational cancer in Britain. Remaining cancer sites: brain, bone, soft tissue sarcoma and thyroid. *Br J Cancer* 2012;107 Suppl 1:S85–91.
28 Kang HK, Bullman TA. Mortality among U.S. veterans of the Persian Gulf War. *N Engl J Med* 1996;335:1498–504.
29 Dipietro L, Campbell WW, Buchner DM, *et al*. Physical Activity, Injurious Falls, and Physical Function in Aging: An Umbrella Review. *Med Sci Sports Exerc* 2019;51:1303–13.
30 Strand LA, Martinsen JI, Fadum EA, *et al*. Temporal trends in the healthy soldier effect in a cohort of Royal Norwegian Navy servicemen followed for 67 years. *Occup Environ Med* 2020;77:775–81.