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First epidemiological study on occupational radar exposure in the French Navy: a 26-year cohort study

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This retrospective cohort study deals with the causes of death among 57,000 military personnel who served in the French Navy surface vessels and were observed over the period 1975–2000. We successively compared the mortality rate and the specific causes of death between two groups differing in their potential exposure levels to radar. Occupational exposure was defined according to the on-board workplace (radar and control groups). The age-adjusted death ratios of the navy personnel were compared. For all causes of death, the results showed that 885 deaths in the radar group and 299 in the control group occurred (RR = 1.00 (95 % CI: 0.88–1.14)). RRs were 0.92 (95 % CI: 0.69–1.24) for neoplasms. For the duration of follow-up, the results did not show an increased health risk for military personnel exposed to higher levels of radio frequencies in the radar group, but the number of deaths was very small for some cancer sites.

Keywords: occupational hazards; radiofrequency; exposure; mortality; epidemiology

Introduction

After the first use of radars during the Second World War, radio-radar applications and devices increased extensively in the armed forces, e.g. for steering aircraft, boats and vehicles, and also for guiding or jamming anti-aircraft missiles. Since the 80s, some concerns have emerged about occupational health hazards incurred by military personnel exposed to electromagnetic fields (EMF; Breckenkamp et al. 2003). The possible effects of such exposure on cancer incidence have been examined in several studies. Among occupational exposures, Garland et al. (1990) found a correlation between leukaemia incidence and EMF for electrician's mates in the Navy concerning (Garland et al. 1990). Szmigielski et al. reported a correlation between exposure to high frequencies (radiofrequency and microwave) and cancer morbidity among Polish military personnel for the period 1971–1985. In this study, an increased incidence of leukaemia and lymphoma was found in the most exposed groups (Szmigielski 1996). A case-control study realized in the Brazilian Navy showed more primary brain tumours among health personnel than in other radar occupational categories (Santana et al. 1999). Furthermore, in the 1990s, congenital abnormalities were reported among children whose fathers had served on board Norwegian missile torpedo boats but no causal relationship with radar

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exposure was established (Mageroy et al. 2006, 2007). Conversely, in another cohort study, no significant increase in cancer morbidity was observed in the US-enlisted Naval personnel after occupational radar exposure during the Korean War period (Robinette et al. 1980; Groves et al. 2002). No increase in all-cause mortality was shown in Belgian battalions equipped with radars for anti-aircraft defence between 1963 and 1994 (Degrave et al. 2005). In the same period, the authors analysed the causes of death and found an increase in the incidence of hemolymphatic cancers. They suggested that no causal relation could be established and this effect might be due to ionizing radiation (Degrave & Autier 2009). More recently, Mollerlokken et al. (Mollerlokken & Moen 2008) discussed the possibility of a link between exposure to radio-radar equipment and reduced fertility among Royal Norwegian Navy personnel.

Recently, the International Agency for Research on Cancer investigated brain tumours, leukaemia, lymphoma and other types of malignancy, including uveal melanoma, and cancers of the testis, breast, lung and skin related to long-term exposure of radio frequency. The evidence was judged inadequate for occupational exposure. The Working Group noted that the studies had methodological limitations and the results were inconsistent (Baan et al. 2011). Currently, the delayed occupational effects of long-time exposure to microwaves remain questionable.

In this context, there are still some concerns in the armed forces regarding the safety of radar exposure and the adequacy of the current safety standards deriving from the ICNIRP guidelines. We took advantage of the large population exposed to radars in the French Naval forces and the knowledge of electromagnetic field distribution on the ships for high-frequency fields (HF, 2–30 MHz) and radar L (1300–1375 MHz), S (2900–3200 MHz) and X (9380–9450 MHz) frequency ranges. This, together with the traceability of employments and accessibility to personal data, allowed us to assess different exposure conditions on board. The present epidemiological study was conducted on military personnel who had served on board over a 20-year period (1975–1995). It was designed as a retrospective cohort study and the health data were analysed over the period 1975–2000. The aim of the study was to compare the overall mortality rate as well as the causes of death between two professional military groups differing in their exposure level to radars.

Methods

Cohort characterization

The initial population supplied by the Navy Central database was composed of military personnel who served on Navy ships for the period 1975–1995. Only partial information could be obtained for many people from the French overseas departments and territories (DOM/TOM). In this context, the analysis was restricted to metropolitan subjects born in France and referenced in the national register “Repertoire national d’identification des personnes physiques” (RNIPP i.e. National directory for the identification of natural persons) maintained by the National Institute for Statistics and Economic Studies since 1946. Validation by the RNIPP was an obligatory step before assessing the vital status of the individuals. In order to control that the whole information requirement was fulfilled, a double-check procedure was performed. The Navy list was matched with the list of the RNIPP. The matching process was probabilistic and used five keys: name and first name, date of birth, date and place of death. Several categories of personnel were excluded from the population, i.e. female military personnel, personnel of the flotilla (aero navy aviation) and those who had spent fewer than 200 days on board. The level of exposure could not be assessed for the aero navy aviation personnel because it was impossible for us to obtain data concerning the time spent aboard for this category of personnel. For women, their number was very few and they had spent less than 200 days on board. The on-board periods were then chronologically recorded and the specialties (jobs on board) individually collected for exposure assessment.

The dosimetry limited to exposure assessment (see below) showed that there were two main exposure levels aboard. The studied population was divided into two groups: one on the deck, called the "radar group" constituted by military employees whose various occupations took place above the main desk, while the second group was constituted by the Navy personnel whose various occupations were situated under the main deck. As the electric field is low under the deck, this sample was considered to be the non-exposed group compared to the radar group; this was called the "control group."

Occupational exposure to EMF

For exposure assessment, power density was measured in different areas occupied by the military population. Electric field measurements were taken in locations where radar exposure level was supposed to be maximum according to numerical simulations. The data were derived from 50 measurements of the electric field taken at different points on the deck and 10 locations under the deck. A single value was performed at each location corresponding to the maximum value found in a volume of 1 m^3. The "mean" and "peak" values represented temporal measurements. The peak value (dPpeak) is the maximum power level emitted during the pulse. The mean value (dPmean) is the level corresponding to the power averaged over 1 s.

Due to multiple exposure sources present on Naval ships, it was necessary to distinguish between HF (2–30 MHz) and radar L (1300–1375 MHz), S (2900–3200 MHz) and X (9380–9450 MHz) bands.

The measurements were performed with the following apparatus:

(1) Fieldmeter (NARDA, NY, USA type 8616, 8712 and 8718) equipped with electric or magnetic field probes (8621, 8623, 8733D, 8741D, 8721D, 8723D, 8760D).
(2) Spectrum analyser HP 8564E (Hewlett Packard, CA, USA) equipped with EMCO 3115 horn antenna.
(3) Spectrum analyser FSH 6 (Rohde & Schwarz; München, Germany) with different antennas HL050, HE200 and the field probe RSEMF30.
(4) The uncertainty due to calibration of the apparatus and to their precision level was considered to be less than 1.5 dB.

For radar emitting devices, numerical calculation (simulation) before the experimental measurements was performed. The values were estimated by using an "in-house" software based on an analytical calculation method (Malabiau 1975) used in the armed forces (Commission Interarmées de Normalization, "GAM DRAM 2," 1992). An estimation of the illumination of the source by successive comparisons of the radiation patterns was obtained in far field with those of the studied antenna. The near-field electromagnetic distribution could be obtained from the illumination of the source law using an asymptotic development in the second order. These calculations were compared to direct measurements: the difference between the results obtained by numerical simulation and measurement was less than 3 dB.

The exposure assessment (measurements and numerical calculation) was done by the service that is responsible for checking the levels of EMF on surface vessels and regulatory compliance (DRAM/CTSN). This was done routinely and was not specially realized for our study.

Classification of personal exposure

The total duration of service on board was expressed in person-year, which is the overall duration effectively spent on board during the period of the study (1975–1995). It began on 1 January 1975 for military personnel already in service at this date, and at the time of first boarding for all others. Follow-up ended either on the date of death, or on 31 December 2000 for military personnel still alive, or on the date of departure from the Navy for military personnel who had left the Navy.

Occupational activities on board are usually categorized into 95 specific jobs (specialties). Two types of tasks were considered relative to the radar exposure leading to distinguishing the location of jobs with respect to their position above or under the main deck corresponding to the two identified exposed levels (control group n = 18,310 and radar group n = 21,540).

Vital status and causes of death

The vital status (dead or alive) was completed for each subject from January 1975 until 31 December 2000 by matching the Navy files with those obtained from the French National Register (RNIPP).

Registration of cause of death is confidential in France. A special licence delivered by the National Commission for Computers and Freedom (Commission Nationale de l'Informatique et des Libertés, i.e. CNIL, agreement number 902369, February 2003) was required for this study. The causes of death for deceased subjects were obtained from the Centre for Epidemiology of Medical Causes of Death service of the French Health Ministry. The causes of death were coded using the international classification of diseases ninth revision ICD-9 (Centers for Medicare and Medicaid Services 2009). The Navy database was then matched with the French Epidemiology Centre on the medical causes of death (Centre d'épidémiologie sur les causes médicales de décès, i.e. CepiDC, INSERM). The CepiDC criteria (12 personal parameters), namely date of birth and date of death, were used as variables to validate the match between death certificate and RNIPP. If the matching was equivocal, the cause of death could not be used. The Ethical Committee of the French Army Health Service also approved the study.

Statistical analysis

The analysis was performed with Stata software V9 (data analysis and statistical software, StataCorp LP Texas USA). The Mann–Whitney and Kruskal–Wallis statistical analyses were used to test differences in age medians. All p-values were two-sided.

The number of deaths was classified by age and the annual age-specific death rates were calculated for each age category. To compare death rates between radar and control subjects, the age-standardized mortality incidence rate ratio (IRR) method was used. The number of deaths was calculated in the exposed group and in the control group for each age category. The 95 % confidence interval (95 % CI) was estimated using normal approximation. A Chi-square Mantel–Haenszel test of homogeneity was used, after death age stratification.

Results

Cohort characterization

The initial register from the Navy was composed of 57,545 subjects (Table 1), of whom 54,431 were born in metropolitan France and only 48,290 could be validated by the RNIPP (population B in Table 1).

Several exclusion criteria were considered, such as female gender, military personnel of the flotilla and those whose cumulative mission duration was short (< 200 days). This led to a studied cohort of 39,850 military personnel (population C), i.e. a reduction to 69.3 % of the initial population. Population C was used to establish the age-adjusted ratio for death.

Dosimetry and exposure assessment

Exposure levels were obtained from the data collected on a French Navy ship considered as representative of the ships, where the studied military population was embarked. The measurements were taken according to the method described in Material and Methods. The values obtained on the deck and under the deck were expressed as current density (E field, V/m) for the lower frequency range (HF band), and power density (dPmean and dPpeak, W/m²) for the radar frequencies in the L, S and X bands (Table 2). The uncertainty in measurement was ± 3 dB.

For occupational exposure, the ICNIRP (International Commission on Nonionizing Radiation Protection) reference levels mentioned in the guidelines are 610/f in the HF band (frequency in MHz, thus 305 V/m for 2 MHz) and 61 V/m in the 1–10 and 10–400 MHz ranges (ICNIRP 2009). For the L band (1300–1375 MHz), the current power density limit is f/40 (32.5–34.4 W/m^2). For the S and X frequency bands, the reference level is defined as 50 W/m^2.

All exposure levels measured on the vessel were below the limit values, recommended by the ICNIRP, for occupational exposure. No location was found, with

Table 1. Numbers and percentages of military personnel included in the French Navy survey after elimination of unusable and exclusion factors.

	Population	Number	%
A	Total number of military personnel in the marine database (1975–1995)	57,545	100
	Number of military personnel born in metropolitan France	54,460	94.6
	Lost to follow-up (RNIPP)	6291	10.9
B	Total number of studied military personnel (validated by the RNIPP)	48,169	83.7
	Excluded subgroups:		
	Military women	193	0.3
	Military personnel of the flotilla	5150	8.9
	Military personnel with accumulated mission < 200 days	2976	5.2
	Total number of excluded subjects	8319	14.5
C	Total number of military personnel included for statistical analysis	39,850	69.3

Table 2. Classes of age amongst French militaries in the radar and the control groups.

Age at death time (Years)	Radar group Number of deaths (%)	Control group Number of deaths (%)
≤ 20	12 (1)	4 (1)
21–30	53 (6)	24 (8)
31–40	209 (24)	77 (26)
41–50	341 (39)	114 (38)
≥ 51	270 (31)	80 (27)
Total	885	299

exposure levels exceeding the recommended limits. The specific absorption rate (SAR) could not be calculated precisely because individual data were not available.

Two levels of exposure were clearly identified. The power density was found to be 100 times higher on the deck compared to that under the deck for higher frequencies and three times higher for HF.

Time durations of service (on board) expressed in person-year varied from six months to eight years. These values were considered to be representative of the exposure duration parameter.

Analysis of the data

Exposure level and death rates: death IRR calculations

In a first step, the vital status was analysed in the cohort on 31 December 2000 according to the RNIPP data (Table 1, population C). Of the 39,850 subjects, 1185 deaths were recorded and the overall mortality level was 3.04 %.

For further analysis, the number of subjects was classified as a function of their age at this date, or at the time of their death if before. Five classes were defined: under 20 years, 21–30 years, 31–40 years, 41–50 years and above 51 years (see Table 2). The mean age of Navy men who are alive are 38.8 years old (SD = 8.6) (not shown) and the mean age of death was 41.7 years old (SD = 12.9) at the time of the study. No significant difference between the groups (control and radar) was shown after Chi-square analysis of the data. The distributions of person-years of subjects in the radar and the control group were the same in the different age classes.

Table 3. Exposure levels on the deck and under the deck for the different frequency ranges (*E* fields, V/m; power density, W/m²).

Frequency range	Exposure level on the deck	Exposure level under the deck
HF Band – 2–30 MHz	$E < 30$ V/m	$E < 10$ V/m
L Band – 1300–1375 MHz	dPmean < 2 W/m²	dPmean < 0.02 W/m²
	dPpeak < 350 W/m²	dPpeak < 3.50 W/m²
S Band – 2900–3200 MHz	dPmean < 3 W/m²	dPmean < 0.03 W/m²
	dPpeak < 250 W/m²	dPpeak < 2.50 W/m²
X Band – 9380–9450 MHz	dPmean < 1 W/m²	dPmean < 0.01 W/m²
	dPpeak < 1200 W/m²	dPpeak < 12 W/m²

The analysis of IRR was carried out on population C. The numbers of deaths identified within the radar and control groups were 885 and 299, respectively. This is reported in Table 3 along with the total duration of exposure for each group corresponding to the total time duration of service (person-year). The IRR for the radar vs. the control population was computed for the five age classes previously described (age-adjusted IRR,) and for the whole population (crude IRR) (not shown). Compared to unexposed personnel, the crude and age group death incidence rate among exposed sailors was not significantly different.

Causes of death analysis

In population C, 1184 deaths were recorded on 31 December 2000 (radar and control groups). The causes of death were obtained from death certificates from the epidemiological centre on the medical causes of death (CepiDC). The ICD-9 chapter "Neoplasm" contains the codes for most benign and all malignant neoplasms; unknown pathologies are not coded (Table 4).

The causes of death were unknown for 391 (44.2 %) and 120 (40.1 %) military employees from the radar and control groups, respectively. They were identified for 673 deceased subjects corresponding to 56.8 % of the sample.

There was a statistically significant difference between the two groups for death from disease of the respiratory system, the number of which was lower in the radar group (RR = 0.17 95 % CI: 0.03–0.92). The mortality rate ratio between the radar and control populations was not significantly different for all other causes of death. The death level due to injuries and external causes was 24.3 % of the causes of death among younger military personnel (mean age 30.5 years old) without any link with the exposure level.

The deaths related to the ICD-9 chapters containing neoplasms were analysed in more detail. The number of deaths from different types of cancer identified in the radar and the control group are reported in Table 5. Respiratory and intrathoracic organ cancers represented the main causes of death, 46.7 and 46.0 % of all cancer deaths in each group, respectively.

Electromagnetic field exposure duration and cancer death rates

The number of person-years spent in the cohort by each individual in each age category was computed using the number of on-board periods and the duration of each on-board period (Table 6).

As shown above, compared to unexposed sailors the cancer death incidence rate among radar sailors was not significantly different from controls, irrespective of the time

Table 4. Comparison of the crude IRR with 95 % confidence interval, amongst radar and control military personnel in population C.

	Radar group	Control group	Total
Number of deaths	885	299	1184
Number of person-years	79,114	23,480	102,594
IRR	0.86 [0.76; 0.98]: p =0.68		

Table 5. Main causes of death amongst radar and control groups (ICD-9 codes), death rate ratio and age at death (mean value and SD) amongst French Navy personnel.

Causes of death (ICD-9 codes)	Number of deaths and % of the group: Radar	Control	Rate ratio	95 % CI	Mean age (SD)
Neoplasms (140–239)	137 (15.5)	50 (16.7)	0.92	0.69–1.24	48.3 (9.4)
Endocrine, metabolic and immunity disorders (240–279)	2 (0.2)	1 (0.3)	0.67	0.06–7.42	38.3 (1.7)
Mental disorders (290–319)	17 (1.9)	6 (2.0)	0.96	0.38–2.40	46.3 (10.3)
Nervous system and sense organs (320–389)	8 (0.9)	1 (0.3)	2.70	0.34–21.52	42.4 (8.9)
Circulatory system (390–459)	67 (7.6)	29 (9.7)	0.78	0.51–1.18	43.8 (11.3)
Respiratory system (460–519)	2 (0.2)	4 (1.3)	0.17*	0.03–0.92	48.3 (15.0)
Digestive system (520–579)	14 (1.6)	4 (1.3)	1.18	0.39–3.56	48.8 (9.7)
Congenital anomalies (740–759)	1 (0.1)	0	–	–	20.90
Symptoms, signs, ill-defined conditions (780–799)	31 (3.5)	12 (4.0)	0.87	0.45–1.68	38.8 (9.9)
Injuries and external causes (800–999-E)	215 (24.3)	72 (24.1)	1.00	0.80–1.27	30.5 (8.6)
No data on cause of death	391 (44.2)	120 (40.1)	1.10	0.94–1.29	44.9 (12.9)
All causes of death	885	299	1.00	0.88–1.14	41.7 (12.9)

Note: Statistical analysis was performed with the Kruskal–Wallis test (*$p < 0.02$).

spent on board. The age-adjusted group's rate ratios did not show any effect of age on the risk of dying from cancer in the two groups over the time covered by this study (data not shown).

Discussion

Our study was the first epidemiological study on the possible health effects of radars carried out in the French Army. All the professional military personnel who served between 1975 and 1995 in radar-equipped surface Warship units were included in the database. The results did not suggest an increased health risk for military personnel exposed to higher levels of EMF in particular microwaves emitted by radars and HF communication emitters.

The initial population included more than 57,000 subjects. Before performing the statistical analysis, a first selection was carried out in order to obtain a homogeneous cohort, composed of well-identified subjects excluding those with incomplete or no representative characteristics. Several exclusion criteria were used. This led to a further reduction to 39,850 military personnel (population C), i.e. 69.3 % of the initial population, corresponding to the studied cohort.

The French military personnel who served in the Navy were not altogether serving on the same vessel at the same time but their lifestyles did not differ much on the different vessels. This population cannot be compared to the general French population because military personnel are recruited on the basis of their physical capacities and have to maintain good physical condition through regular training. This healthy worker effect has been recently confirmed by Haus-Cheymol et al. in the French armed forces

Table 6. Number of deaths from various cancers (ICD-9; 140-239) amongst French Navy personnel.

Tumour site (ICD-9 codes)	Number of deaths and % in the group		Rate ratio	95 % CI
	Radar	Control		
Lip, mouth and pharynx (140–149)	8 (5.8)	4 (8.0)	0.73	0.23–2.32
Digestive organs and peritoneum (150–159)	32 (23.4)	14 (28.0)	0.83	0.49–1.43
Respiratory and intrathoracic organs (160–169)	64 (46.7)	23 (46.0)	1.01	0.71–1.44
Bone, connective tissue, skin and breast (170–178)	3 (2.2)	0	–	–
Genito-urinary organs (179–189)	4 (2.9)	0	–	–
Lymphatic and hematopoietic tissue (200–208)	9 (6.6)	2 (4.0)	1.64	0.37–7.34
Eye, brain and nervous system (190–192)	4 (2.9)	2 (4.0)	0.73	0.14–3.86
Other and unspecified sites (193–199)	13 (9.5)	5 (10.0)	0.95	0.36–2.53
All cancers (140–199)	137	50	0.92	0.69–1.24

Statistical analysis was performed with the Kruskal–Wallis test ($p < 0.02$).

Table 7. Comparison of age-adjusted cancer death IRR with 95 % confidence interval, amongst radar and control military personnel in population C.

	Radar	Control	Total
Cancer deaths	137	50	187
Person-years	2372	629	3001

(Haus-Cheymol et al. 2012). Thus, the choice of the control group was important for this study.

Two exposure levels from electromagnetic field measurements realized on a representative vessel were considered. It was not possible to focus only on radar exposure as the vessels were also equipped with other radio-frequency sources: exposure assessment took into account the exposure level due to radars in the L, S and X ranges and HF frequency emissions at lower frequencies. The mean exposure levels in the L, S and X microwave frequencies were well below the recommended reference levels of 50 W/m^2, typically 1–3 W/m^2 on the deck and 100 times lower under the deck. The population was divided into two groups, depending on their job and location on (higher exposure) or under (lower exposure) the deck. To simplify this, the group with higher exposure located on the deck was called the radar group, and those with lower exposure, the control group.

The SAR cannot be determined precisely due to a lack of individual exposure data. In the two groups, compliance with the basic restriction of 0.4 W/kg (whole body) for occupational exposure was ensured by compliance with the electric field values according to the applicable regulation. The second important parameter for exposure assessment was the duration of the exposure. Exposed time duration was estimated from the accumulated time spent on board by each subject (person-years), which could be calculated on the basis of the retrospective employment data. In a first step, we tried to determine more precisely the distribution of exposures as a function of job classifications (not shown). This led to a multitude of categories with a great uncertainty on the personal exposure as previously explained. This is why we decided to limit the study to the comparison of two populations with higher and lowest average exposure levels assessed aboard. There was no possibility to obtain a retrospective assessment of the personal exposure depending on job classification, which represents a limitation of our study.

The control and radar groups had the same conditions regarding food and sleeping but differed for EM exposure. The climatic conditions might be a confounding factor. However, no data were available on some confounding factors such as smoking, alcohol drinking and dietary habits, or contact with different chemical substances (e.g. diesel exhausts). We have assumed that those usual confounding factors were comparable in both groups. Smoking and alcohol consumption were not considered as risk factors for hemolymphatic or brain cancer by Degrave et al. (2005, 2009). We note, however, that Groves et al. found a large difference in respiratory cancers for different service jobs, suggesting differential smoking rates.

In the whole cohort, 1184 deaths were recorded over 26 years (period 1975–2000). All-cause mortality and disease-specific mortality rates were compared between the two groups as a function of exposure level and exposure time.

The IRR for the radar vs. the control population was computed for five age classes (age-adjusted IRR) and for the whole population (crude IRR). The statistical analysis showed that the death incidence rate among exposed sailors was not significantly different from that of the control group with a crude IRR of 0.86 (95 % CI: 0.76–0.98). No statistically significant increase of the risk was found related to the level and duration of exposure (Table 7).

The results are in accordance with those of Robinette where the evaluation of the exposure was also based on the type of job, radiofrequency power level and exposure duration (Robinette et al. 1980). Similarly to our study, two occupational exposure groups were defined as high-level exposure (more than 10 mW/cm^2) and low-level exposure (not exceeding 1 mW/cm^2). No details on the methodology employed for electric field measurements were provided (Robinette et al. 1980). Later, Groves and colleagues reported a mortality follow-up over 40 years of more than 40,000 Navy veterans of the Korean war (Groves et al. 2002). They concluded that radar had little effect on mortality in this cohort. This was not confirmed by other studies. Finally, Degrave et al. found no increase in all-cause mortality rate in the military personnel of radar units (Degrave et al. 2005). The crude death rate cannot be compared between this study and ours because the considered periods were not comparable (Degrave et al. 2005). It took 37 years from the beginning of exposure and the end of mortality follow-up in this study (1968–2004), which leads to a higher number of deaths.

The causes of death obtained for the radar and control populations were not significantly different except for the respiratory system where the number of deaths was lower in the radar group. Nevertheless, this result corresponded to two vs. four cases, which is insufficient to suggest a causal effect. The overall death level due to injuries and external causes (mainly accidents, poisoning, adverse effect of drugs, suicide) was 24.3 % of the causes of death (vs. 56 % in Haus-Cheymol et al.'s study (2012)) for a mean population age of 30.5 years; no correlation with the EMF level was found.

The percentage of death due to cancer was 16 % (all types). This level is higher in the study of Degrave et al., but here again, the time period does not allow a strict comparison because the military population was older at the end of the Belgian study. Nevertheless, there was a higher number of unknown causes of death in our study (43 % vs. 14 %), possibly due to a less rigorous recording of the causes of death 10 years ago. In the study carried out in the French Armed Forces comprising Army, Navy, Air Force and Military Police (*Gendarmerie*), 16.7 % of death by cancer was registered (Haus-Cheymol et al. 2012), but surprisingly, only 6.2 % was found for the Navy for a total number of 130 all known causes of deaths (period 2006–2010).

Considering the types of cancer, respiratory and intrathoracic organs were the main tumour sites with similar levels for the two groups (46.7 and 46 %), confirming that is the most lethal cancer in French male population. The cancer death incidence rate was not significantly different among exposed and non-exposed radar sailors. Although it is 6.6 % in the radar group and 4 % in the control group, the risk of leukaemia was not found to be significantly higher in the radar group (RR = 1.64 (95 % CI, 0.37–7.34)); this result has to be discussed.

Previously, Santana and colleagues reported excess brain tumour mortality in the Brazilian Navy by carrying out a case-control study (Santana et al. 1999). Lack of information on exposure levels, confounders and potential bias represent limitations to this study. In the US and the Belgian cohorts, similar rates of respiratory cancer were found in the two groups with no significant difference related to the exposure, respectively, 33.8 % and 33.7 % in the highly exposed group vs. 36.7 % and 38.9 % in the control group (Groves et al. 2002; Degrave et al. 2009). The two papers reported a slight increase in leukaemia (5.8 % and 8.2 % in the highly exposed group; and 3.2 % and 1.3 % in the control group). In our study, the higher rate ratio was observed for lymphatic and hematopoietic tissues compared to other tumour sites, but this result is not statistically significant (1.64 (95 % CI: 0.37–7.34). Degrave et al. found a statistically significant rate ratio of 7.22 (95 % CI: 1.09–47.91), and Groves et al. found 1.48 (95 % CI: 1.01–2.17). Nevertheless, the number of cases was 69 and 44 in the high and the low radar exposure groups, respectively, in the latter, while the numbers of cases in our study was similar to the Belgium study representing a relatively small number (respectively 9 and 2, and 11 and 1). Our results do not reinforce the previous findings, but the confidence interval is wide (0.37–7.34). That might suggest a bias. Furthermore, the absolute risk of mortality from tumors of lymphatic and hematopoietic tissue is so small in this population that there are too few cases to be able to determine an accurate rate ratio. Inferences cannot be drawn with such a small sample size. It is also possible that accounting for the 43 % missing causes of death would increase the confidence intervals in a noticeable way, although cancer sample size effects may dominate. To go further, a trend analysis of lymphatic and hematopoietic cancers as a function of exposure lengths (person years) and job classification aboard could have been done. Nevertheless, the small number of cases for this cancer, added to the widely dispersed durations of service on board and lack of personal exposure, were not in favour of the possibility of giving a clear conclusion, whatever the results.

Furthermore the knowledge of exposure and of technical parameters of the radars is not precise enough to make an easy comparison possible between the studies. It is known that electronic devices producing high-power microwaves give rise to a parasite emission of ionizing radiation (low doses of X-rays). In France, a recent study was carried out to determine the radiation exposure level of the personnel assigned to the maintenance of radar; and radiological zoning confirmed a slight exposure to the direct vicinity of transmitters (Michel et al. 2013). A report in Germany also described the occurrence of ionizing radiation related to three radar devices in the Army (GermanRadarCommission 2003). Degrave et al. (2009) raised the question of a possible effect of ionizing radiation emitted by anti-aircraft radars that existed in Western Europe from the 1960s until the 1990s that could be responsible for an increase in the incidence of hemolymphatic cancers. Nevertheless, the authors further mentioned that a higher hemolymphatic cancer rate was not found confined to the fraction of personnel in closer contact with the tubes (Degrave & Autier 2009). Based on calculations carried out on “Hawk” radars, the doses, Beyea et al. concluded that it is very unlikely that X-ray exposures could explain this seven-fold increased risk of hemolymphatic cancers. The authors suggested that future epidemiologic studies should investigate possible interactions between EMF and X-rays with individual assessment of exposures (Beyea et al. 2014).

The relevance of the observation period used in our study can be discussed. The progression from normal cell growth to invasive tumour is known as a multistage process involving damage to DNA and subsequent fixation of damage through non repair or misrepair. The initiation is the primary and essential step in the process (chemical carcinogens, viruses, unknown factors, radiation, UV, replication errors …). An initiation–promotion–progression model was also proposed (Cohen 1998), where the changes related to promotion are reversible and give rise to a benign tumour. Progression has come to imply the evolution from benign to malignant tumour. Five years may be sufficient to observe the consequences of an effect at the promotion level while up to 30 years may be necessary to confirm a tumour initiating effect. Because the follow-up period in our study is less than 30 years, a tumour initiating effect cannot be excluded and the analysis of the cohort should be repeated later on. In the case of non-ionizing radiation, unlike ionizing radiations, microwaves are not able to cause link breaks inside the molecules and no plausible mechanism has been identified supporting that hypothesis. A promoting effect, if any, seems more likely. It should be considered that our results are relative to chronic exposure and long-term effects of EMF, nevertheless the data were collected in 2000, period which doesn’t represent a very long time after exposure for the last to be enrolled. Another statistical analysis of the cohort, using the same methodology, might be repeated.

Conclusions

Both, the strengths and limitations of our study have to be considered for any further interpretation of the results. The main strength of the study was the design of a cohort that included a large number of military personnel experiencing similar situations during service on board. It was possible to identify two groups, homogeneous in age and sex (no women), and different in their exposure to radars. The limitations of the study include, 43 % missing causes of death, limited follow up, crude exposure surrogates, lack of individualized exposure estimates, and lack of smoking data. This study brings additional information to the current knowledge and will contribute to occupational EMF risk assessment, for example, as part of future meta-analyses and/or pooling studies. The results do not suggest that military occupational exposure to radio frequency-emitting sources is related to an increased health risk regarding all-cause mortality as well as specific causes of mortality, especially cancers. A more precise knowledge of individual exposure would have been desirable and could be achieved in the future by using personal dosimeters.

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