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Cancer in Korean War Navy Technicians: Mortality Survey after 40 Years

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This study reports on over 40 years of mortality follow-up of 40,581 Navy veterans of the Korean War with potential exposure to high-intensity radar. The cohort death rates were compared with mortality rates for White US men using standardized mortality ratios, and the death rates for men in occupations considered a priori to have high radar exposure were compared with the rates for men in low-exposure occupations using Poisson regression. Deaths from all diseases and all cancers were significantly below expectation overall and for the 20,021 sailors with high radar exposure potential. There was no evidence of increased brain cancer in the entire cohort (standardized mortality ratio (SMR) = 0.9, 95% confidence interval (CI): 0.7, 1.1) or in high-exposure occupations (SMR = 0.7, 95% CI: 0.5, 1.0). Testicular cancer deaths also occurred less frequently than expected in the entire cohort and high-exposure occupations. Death rates for several smoking-related diseases were significantly lower in the high-exposure occupations. Nonlymphocytic leukemia was significantly elevated among men in high-exposure occupations but in only one of the three high-exposure occupations, namely, electronics technicians in aviation squadrons (SMR = 2.2, 95% CI: 1.3, 3.7). Radar exposure had little effect on mortality in this cohort of US Navy veterans. *Am J Epidemiol* 2002;155:810–18.

leukemia, nonlymphocytic, acute; microwaves; mortality; neoplasms; veterans

There has been considerable public concern about the possible adverse health effects of both residential and occupational exposure to nonionizing electromagnetic radiation. Most attention has focused on extremely low frequency radiation (50–60 Hz), such as that associated with power lines and household electric appliances. Possible health effects have also been alleged for radiofrequency radiation, which occupies the portion of the electromagnetic spectrum ranging from 3,000 Hz to 300,000 MHz (i.e., between the extremely low frequency and infrared regions of the electromagnetic spectrum). These radiofrequencies are over five orders of magnitude below the frequency range of ionizing radiations, such as x-rays. Particular public concern has centered around the possible risk of brain cancer associated with microwave frequencies (i.e., frequencies from 300 MHz to 300,000 MHz), largely because of the increased use of cellular telephones, which operate in the frequency range from about 450 MHz to 2,000 MHz. Although some studies have suggested possible associations between radiofrequency radiation and brain cancer, leukemia, or testicular cancer, recent reviews have concluded that it is unlikely that such nonionizing radiation is carcinogenic (1–4). Studies published after these reviews also found no link between cellular telephone use and brain cancer (5–7) or leukemia (7), but these studies were limited in terms of both the duration of cellular telephone use and the length of follow-up of the study populations.

Radar waves fall in the microwave portion of the electromagnetic spectrum (table 1). One of the few previous studies of the health effects of occupational exposure to microwave frequencies was a cohort study of US Navy veterans who served during the Korean War (1950–1954) and had occupational exposure to radar (8). The mortality follow-up of the cohort for the original investigation extended through 1974 and identified no adverse effects attributable to microwave exposure, although lung cancer was elevated in men with the highest potential for radar exposure. Because of continuing public concern that exposure to microwave frequencies might lead to increased risk of disease, particularly cancer, a second mortality follow-up of the US Navy Veteran Cohort has been conducted. The extended follow-up period of more than 40 years permits an assessment of mortality effects with long latency periods.

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Abbreviations: BIRLS, Beneficiary Identification and Records Locator System; CI, confidence interval; ICD-8, *International Classification of Diseases*, Eighth Revision; ICD-9, *International Classification of Diseases*, Ninth Revision; ICDA-8, *International Classification of Diseases Adapted for Use in the United States*, Eighth Revision; SIR, standardized incidence ratio; SMR, standardized mortality ratio.

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TABLE 1. Sources of electromagnetic radiation from low frequency power lines to radar units

Frequency	Designation	Examples
0–30 Hz	Sub-extremely low frequency	Direct current power lines
30–300 Hz	Extremely low frequency	Alternating current power lines, audio, submarine communications
0.3–3 kHz	Voice frequency	Voice and audio
3–30 kHz	Very low frequency	Long-range communications, navigation, audio
30–300 kHz	Low frequency	Radio navigation, marine communications, long-range communications
0.3–3 MHz	Medium frequency	AM* radio, radio navigation, amateur radio, communications, marine radiophone, industrial equipment
3–30 MHz	High frequency	CB* radio, amateur radio, international communications, medical diathermy, industrial equipment
30–300 MHz	Very high frequency	Television, FM* radio, amateur radio, air traffic control, industrial equipment, police/fire/emergency radio
300–3,000 MHz	Ultra high frequency	Radar, television, CB radio, amateur radio, radio navigation, microwave ovens, medical diathermy, cell phones, industrial equipment, police/fire/emergency radio
3,000–30,000 MHz	Super high frequency	Radar, satellite communication, amateur radio, police/fire radio, taxi dispatchers
30,000–300,000 MHz	Extremely high frequency	Radar, satellite communications, amateur radio, police/fire radio

* AM, amplitude modulation; CB, citizens' band; FM, frequency modulation.

MATERIALS AND METHODS

Cohort definition

A cohort of 40,890 Navy personnel with high potential for radar exposure was assembled from Navy records (8). Graduates of Navy technical schools during the period from 1950 through 1954 were identified from six naval enlisted classifications of occupations. Based on consensus decisions by the Navy personnel involved in training and operations (8), a low microwave-exposure stratum was defined as men with job classifications of radioman, radarman, and aviation electrician's mate. Radar and radio operators generally worked below deck, far from radar pulse generators and antennae emitting microwave frequencies, and usually had radar exposures well below 1 mW/cm^2 (8). No information was provided in the original study on the radar exposure levels experienced by aviation electrician's mates, but they were likely to have had only casual exposure to radar waves. The high microwave-exposure stratum included men with the job classifications of electronics technician, aviation electronics technician, and fire control technician. Because they repaired and maintained gunfire control and search radar, the fire control and electronics technicians had the potential for exposures exceeding 100 mW/cm^2, even though their usual exposures were below 1 mW/cm^2 (8). The occupational standard at the time was 10 mW/cm^2 (9). The current study retained the original classification of exposure status by job classification.

Exposures other than radar were assessed by industrial hygienists using job descriptions in US Navy recruitment literature from the late 1940s (table 2). Electrical current on naval ships and at naval installations had a frequency of 60 Hz (10). All subjects in this study were exposed to extremely low frequency magnetic fields when they were around electrical equipment. Electrician's mates repaired wiring and may have had higher exposures to extremely low frequency fields, because they tended to operate in the environment in which the 60-Hz electrical power was generated, distributed, or transformed (10). No asbestos-covered wiring was used on naval ships. There were low levels of asbestos in the air from degradation of pipe wrapping, but there was no reason to expect differential asbestos exposure among occupations.

Radiomen and radarmen operated their respective equipment and did only minor or infrequent repairs. Electronics technicians maintained and repaired modular components in a variety of electronic equipment, including radio and radar. Fire control technicians performed tasks similar to those performed by electronics technicians, but they worked primarily on gunfire control radar and circuitry. They also repaired hydraulic and other mechanical equipment used to operate weapons. The four occupations involved primarily in maintenance and repair work were likely to have higher exposures to solder fumes, chlorinated solvents, and oils and greases (table 2). Exposures to these chemicals, however, were probably infrequent and would be considered as low in a typical occupational study.

Follow-up

Mortality data were obtained first from records of the Department of Veterans Affairs. The original study roster was matched against the Department of Veterans Affairs' computerized Beneficiary Identification and Records Locator Subsystem (BIRLS) using the military service number, which was available for every subject. For the subjects not found in BIRLS or found in BIRLS but lacking a date of birth, a manual search of the Veterans Administration

TABLE 2. Probable exposures for naval personnel in various occupations, US Navy Veteran Cohort, 1950–1997

Occupation	Exposures
Low radar exposure potential	
Radar operator	From video display unit: electromagnetic fields,* chlorinated solvents†
Radio operator	From duplicating machine: electromagnetic fields,* dyes or inks, chlorinated solvents,† solvents (methanol?, ketones?)
Aviation electrician's mate	Solder flux, lead, tin, silver, cadmium, electromagnetic fields,* chlorinated solvents,† depotting agents (minor: polycyclic aromatic hydrocarbons, polychlorinated biphenyls, metal dusts, hydraulic fluids, machining fluids, oils and greases, sulfuric acid, benzene, tetraethyl lead)
High radar exposure potential	
Aviation electronics technician	Solder flux, lead, tin, silver, cadmium, electromagnetic fields,* chlorinated solvents† (minor: polycyclic aromatic hydrocarbons, oils and greases, benzene, tetraethyl lead)
Electronics technician	Solder flux, lead, tin, silver, cadmium, electromagnetic fields,* chlorinated solvents† (minor: polychlorinated biphenyls, oils and greases, hydraulic fluids, sulfuric acid)
Fire control technician	Solder flux, lead, tin, silver, cadmium, electromagnetic fields,* chlorinated solvents† (minor: polycyclic aromatic hydrocarbons, oils and greases, hydraulic fluids)

* Extremely low frequency electromagnetic fields.

† The most likely solvent was carbon tetrachloride, which was probably replaced in the 1960s by trichloroethylene. Benzene use as a solvent was unlikely because of its flammability. Radar operators may have had higher intensity chlorinated solvent exposure than those in other occupations.

Master Index was performed to identify dates of birth. The subjects with newly found dates of birth from the Veterans Administration Master Index were then matched with BIRLS using interactive online interrogation of the BIRLS database. BIRLS has been shown to contain a high proportion (i.e., about 95%) of veteran deaths (11–13).

All subjects in the study cohort were then matched through 1997 against the Social Security Administration's Death Master File using the Social Security number, if known; those without a Social Security number (almost half) were matched using the name and date of birth. The final follow-up approach was a National Death Index search for deaths occurring in the years 1979 through 1997. The distribution of missing Social Security numbers was 40 percent for aviation electrician's mates, 42 percent for aviation electronics technicians, 42 percent for fire control technicians, 45 percent for electronics technicians, and 49 percent for radio and radar operators. We excluded 271 female subjects from our study, including 28 female deaths. These females were distributed fairly evenly among the six rating categories (about 0.3 percent of the subjects) except in the radio operators' class (2.0 percent). After additional exclusion of 36 duplicate records and two men who died in 1951 before graduation, the final cohort consisted of 40,581 men.

Cause-of-death coding

For each of the 8,393 deceased subjects identified, the cause of death was obtained from either a death certificate from a state vital statistics office or from the National Death Index Plus. Underlying causes of death were coded according to the *International Classification of Diseases*, Ninth Revision (ICD-9), for deaths in 1975 and later, and according to the *International Classification of Diseases Adapted for Use in the United States*, Eighth Revision (ICDA-8), for earlier deaths, by an experienced nosologist, who was unaware of the exposure information and job classification of study subjects. For the purposes of analysis, the *International Classification of Diseases*, Eighth Revision (ICD-8), and ICD-9 codes were "collapsed" into broader cause-of-death categories, such that the "fine" distinctions between ICD-8 and ICD-9 did not alter the broader classification of causes of death.

Imputation of missing and invalid dates

Each subject was deemed to have entered the cohort on January 1 of the year of graduation (1950–1954). The year of graduation was imputed to be 1952 for 5,140 subjects for whom it was missing. The original cohort list had the date of birth for only a small fraction of men (7), but we found many missing birth dates in the Veterans Administration Master Index search described above. For 16 men with questionable birth dates not verifiable using Social Security Administration files and for men with missing years of birth, the year of birth was assigned to 1930 for aviation electrician's mates; 1931 for fire control technicians, electronics technicians, and aviation electronics technicians; and 1932 for radar and radio operators, based on the average known years of birth for the men with those jobs. Thus, the year of birth was imputed for 3,402 men, distributed fairly evenly over the six rating categories (from 7.3 percent for the electronics technicians to 9.7 percent for the radio operators).

Statistical analysis

The Poisson regression program AMFIT, which is part of the computer package Epicure (14), was used to compute standardized mortality ratios and corresponding 95 percent confidence intervals based on age-specific US White male mortality rates from 1950 to 1997. Relative risks and 95 percent confidence intervals were also computed for specific causes of death using AMFIT, to compare the high-exposure stratum versus the low-exposure stratum and to compare four specific occupations versus the combined radio and radar operators group, while controlling for age at cohort entry and attained age. The person-years for each subject accrued from the date of graduation until the date of death or the end date of the study (December 31, 1997). We controlled for age at cohort entry (categorized as less than 20 years, 20–24 years, and 25 years or more) and attained age (categorized as less than 40 years, 40–44 years, 45–49 years, 50–54 years, 55–59 years, 60–64 years, and 65 years or more). The following time-related variables were also evaluated as possible confounders but were not included in the final model: year of graduation (1950, 1951, 1952, 1953, 1954), year of birth (1889–1926, 1927–1931, 1932–1936), and duration of follow-up from graduation to death or the end of the study (less than 25 years, 25–29 years, 30–34 years, 35–39 years, 40 years or more). Effect modification by age at cohort entry was assessed, particularly for causes of death with significant relative risks, but no effect modification was observed.

RESULTS

The high microwave-exposure stratum consisted of 20,021 sailors whose job classifications were electronics technician (n = 13,010), aviation electronics technician (n = 3,721), and fire control technician (n = 3,290). The low-exposure stratum consisted of 20,560 sailors with job classifications of radioman (n = 9,072), radarman (n = 10,079), and aviation electrician's mate (n = 1,409).

A total of 8,393 deaths were identified by the end of follow-up, resulting in a cumulative crude mortality rate of 20.7 percent after about 40 years. The overall standardized mortality ratios for the entire cohort were statistically significant at 0.74, demonstrating that the death rate in the cohort was significantly less than the US White male death rate (table 3). Standardized mortality ratios were less than one for most diseases and, specifically, for most cancers. The standardized mortality ratio for all external causes was significantly less than one, but the standardized mortality ratios were significantly greater than one for accidents involving air transportation and for war injuries. Except for esophageal cancer, breast cancer, and lymphocytic leukemia, all other cancer standardized mortality ratios were less than one. The overall standardized mortality ratio was 0.87 for deaths prior to 1955 and was even lower for deaths thereafter (standardized mortality ratios (SMRs) ranged from 0.62 to 0.78 when examined by 5-year intervals from 1955 through 1994). Thus, the healthy soldier effect (15) showed little diminution, even after more than 40 years.

The total standardized mortality ratio was significantly lower in the high-exposure occupations than the low-exposure occupations (table 3). The total standardized mortality ratios by occupation were as follows: radar and radio operators (SMR = 0.80), aviation electrician's mates (SMR = 0.83), electronics technicians (SMR = 0.65), aviation electronics technicians (SMR = 0.73), and fire control technicians (SMR = 0.83). There was no evidence of increased risk in the high-exposure stratum for brain cancer (SMR = 0.71, 95 percent confidence interval (CI): 0.51, 0.98) or testicular cancer (SMR = 0.60, 95 percent CI: 0.25, 1.43). Standardized mortality ratios for leukemia were slightly elevated in the high-exposure occupations but not significantly so.

The numbers of deaths in the high- and low-exposure strata, as well as the relative risks from internal comparisons of the high-exposure jobs with the low-exposure jobs, are shown in table 4. Slight differences in the numbers of deaths between tables 3 and 4 are due to minor differences in the coding of mortality for external rates used to calculate standardized mortality ratios (16) compared with the coding for internal comparisons. There were 6,869 deaths due to diseases (4,338 nonmalignant and 2,531 malignant), 1,200 due to injuries (816 accidental and 384 intentional), and 324 (3.9 percent) due to unknown causes. The high-exposure stratum had more injury deaths, particularly aviation accidents and war deaths, but fewer disease deaths, largely reflecting deficits of all malignant neoplasms, diabetes mellitus, and most circulatory and respiratory diseases.

In contrast to the suggestion in the first follow-up that high radar exposure was associated with lung cancer risk, there were significantly fewer lung cancer deaths in the high-exposure occupations (relative risk = 0.73, 95 percent CI: 0.63, 0.83) (table 4). There was a significant excess of nonlymphocytic leukemia in the high-exposure stratum (relative risk = 1.82, 95 percent CI: 1.05, 3.14). No significant excesses were seen for lymphoid malignancies (lymphoma, multiple myeloma, or lymphocytic leukemia) or for cancers of the brain or testes.

Occupation-specific relative risks for selected causes of death, using the combined radio and radar operators as the referent group, are presented in table 5. There were marked excesses of aviation-related deaths among the aviation electrician's mates, electronics technicians, and aviation electronics technicians. War deaths occurred excessively among aviation electronics technicians. Overall mortality and, in particular, total disease mortality were significantly decreased among electronics technicians (relative risk = 0.77, 95 percent CI: 0.73, 0.81) and aviation electronics technicians (relative risk = 0.79, 95 percent CI: 0.73, 0.87). Low disease mortality in these occupations was attributable to deficits in most major categories of disease, including vascular diseases, respiratory diseases (e.g., chronic obstructive pulmonary disease), diabetes mellitus, and malignant neoplasms (notably lung cancer). Lung cancer was decreased in electronics technicians (relative risk = 0.70, 95 percent CI: 0.59, 0.82) and aviation electronics technicians (relative risk = 0.66, 95 percent CI: 0.51, 0.86) but not in fire control technicians (relative risk = 1.02, 95 percent CI: 0.81, 1.29).

TABLE 3. Standardized mortality ratios, US Navy Veteran Cohort, 1950–1997

ICD-9* codes	Cause of death	Low radar exposure potential (*n* = 20,560)			High radar exposure potential (*n* = 20,021)			Total cohort (*n* = 40,581)		
		No.	SMR*	95% CI*	No.	SMR	95% CI	No.	SMR	95% CI
001–999	All causes, known and unknown	4,338	0.80	0.78, 0.82†	4,055	0.69	0.67, 0.71†	8,393	0.74	0.73, 0.76†
001–799	All diseases	3,626	0.80	0.77, 0.82†	3,243	0.65	0.63, 0.67†	6,869	0.72	0.70, 0.74†
140–208‡	All malignant neoplasms	1,352	0.91	0.86, 0.96†	1,182	0.73	0.69, 0.77†	2,534	0.81	0.78, 0.85†
140–149	Buccal cavity and pharynx cancer	32	0.81	0.58, 1.15	21	0.49	0.32, 0.76†	53	0.65	0.49, 0.85†
150.0–150.9	Esophagus cancer	50	1.14	0.87, 1.51	51	1.08	0.82, 1.42	101	1.11	0.91, 1.35
162.0–162.9	Trachea, bronchus, and lung cancer	497	0.87	0.79, 0.94†	400	0.64	0.58, 0.70†	897	0.75	0.70, 0.80†
175.0–175.9	Breast cancer	2	1.13	0.28, 4.54	2	1.05	0.26, 4.20	4	1.09	0.41, 2.91
186.0–186.9	Testicular cancer	4	0.46	0.17, 1.24	5	0.60	0.25, 1.43	9	0.53	0.28, 1.02
191.0–191.9	Brain cancer	51	1.01	0.77, 1.33	37	0.71	0.51, 0.98†	88	0.86	0.70, 1.06
200–203	Lymphoma and multiple myeloma	91	0.94	0.77, 1.16	91	0.89	0.72, 1.09	182	0.91	0.79, 1.06
204–208	All leukemias	44	0.77	0.58, 1.04	69	1.14	0.90, 1.44	113	0.96	0.80, 1.16
204.0–204.9	Lymphocytic leukemia	17	1.31	0.81, 2.11	16	1.12	0.69, 1.83	33	1.21	0.86, 1.70
205.0–207.7, 207.9	Nonlymphocytic leukemia	20	0.67	0.43, 1.04	39	1.24	0.90, 1.69	59	0.96	0.74, 1.24
250.0–250.9	Diabetes mellitus	67	0.66	0.52, 0.84†	39	0.36	0.26, 0.49†	106	0.50	0.42, 0.61†
390–459	All vascular diseases	1,539	0.77	0.73, 0.80†	1,458	0.65	0.62, 0.69†	2,997	0.71	0.68, 0.73†
410–414§	Ischemic heart disease	1,034	0.80	0.75, 0.85†	969	0.67	0.63, 0.72†	2,003	0.73	0.70, 0.76†
460–519	All nonmalignant lung diseases	201	0.71	0.62, 0.81†	167	0.51	0.44, 0.60†	368	0.60	0.54, 0.67†
490–496§	Chronic obstructive pulmonary disease	116	0.75	0.63, 0.90†	85	0.47	0.38, 0.58†	201	0.60	0.52, 0.69†
520–579	All diseases of the digestive system	199	0.68	0.60, 0.79†	179	0.58	0.50, 0.67†	378	0.63	0.57, 0.70†
571.0–571.8	Cirrhosis of the liver	126	0.68	0.57, 0.82†	116	0.61	0.50, 0.73†	242	0.64	0.57, 0.73†
800–999	All external causes of death	554	0.66	0.60, 0.71†	646	0.79	0.73, 0.85†	1,200	0.72	0.68, 0.76†
810–829	Motor vehicle accidents	214	0.70	0.61, 0.80†	181	0.62	0.53, 0.71†	395	0.66	0.59, 0.72†
840–845§	Accidents involving air transportation	24	1.10	0.74, 1.64	100	4.74	3.89, 5.76†	124	2.89	2.42, 3.44†
950–959	Suicide and self-inflicted injuries	149	0.79	0.68, 0.93†	152	0.81	0.69, 0.95†	301	0.80	0.72, 0.90†
960–969§	Homicide and other purposeful injuries	29	0.30	0.21, 0.44†	26	0.28	0.19, 0.42†	55	0.29	0.23, 0.38†
990–999§	Injuries resulting from operations of war	2	9.13	2.28, 36.5†	11	49.6	27.5, 89.6†	13	29.5	17.1, 50.8†
???	Deaths due to unknown causes	158			166			324		

* ICD-9, *International Classification of Diseases*, Ninth Revision; SMR, standardized mortality ratio; CI, confidence interval.
† The confidence interval for the SMR does not contain 1.
‡ Based on mortality rates since 1960.
§ Based on mortality rates since 1970.

TABLE 4. Relative risks for men with high radar exposure potential compared with men with low exposure potential, US Navy Veteran Cohort, 1950–1997

ICD-9* codes†	Cause(s) of death	No. with low radar exposure potential (*n* = 20,560)	No. with high radar exposure potential (*n* = 20,021)	Age adjusted	
				RR*	95% CI*
Total	All causes, known and unknown	4,338	4,055	0.87	0.83, 0.90‡
001–799	All diseases	3,626	3,243	0.81	0.77, 0.85‡
140–208	All malignant neoplasms	1,351	1,180	0.80	0.74, 0.87‡
140–149	Buccal cavity and pharynx cancer	32	21	0.62	0.35, 1.08
162.0–162.9	Trachea, bronchus, and lung cancer	497	400	0.73	0.63, 0.83‡
186.0–186.9	Testicular cancer	4	5	1.30	0.35, 4.89
191.0–191.9	Brain cancer	51	37	0.65	0.43, 1.01
200–203	Lymphoma and multiple myeloma	91	91	0.91	0.68, 1.22
204–208	All leukemias	44	69	1.48	1.01, 2.17‡
204.0	Acute lymphoid leukemia	5	4	0.87	0.23, 3.26
204.1	Chronic lymphoid leukemia	9	11	1.08	0.44, 2.66
205.0	Acute myeloid leukemia	11	22	1.81	0.87, 3.78
205.1	Chronic myeloid leukemia	5	8	1.55	0.50, 4.75
205.0–207.7, 207.9	Nonlymphocytic leukemia	20	39	1.82	1.05, 3.14‡
205.0, 206.0, 207.0, 207.2	Acute nonlymphocytic leukemia	14	28	1.87	0.98, 3.58
250.0–250.9	Diabetes mellitus	67	39	0.53	0.36, 0.80‡
391–459	All vascular diseases	1,539	1,458	0.86	0.80, 0.93‡
410–414	Ischemic heart disease	1,034	969	0.86	0.79, 0.94‡
460–519	All nonmalignant lung diseases	201	167	0.67	0.54, 0.83‡
490–496	Chronic obstructive pulmonary disease	116	85	0.59	0.44, 0.78‡
520–579	All diseases of the digestive system	199	179	0.83	0.67, 1.02
571.0–571.9	Cirrhosis of the liver	133	118	0.84	0.65, 1.08
800–999	All external causes of death	554	646	1.20	1.07, 1.35‡
810–829	Motor vehicle accidents	214	181	0.90	0.74, 1.10
840–845	Accidents involving air transportation	24	100	4.18	2.67, 6.54‡
950–959	Suicide and self-inflicted injuries	149	152	1.06	0.84, 1.33
960–969	Homicide and other purposeful injuries	29	26	0.97	0.57, 1.65
990–999	Injuries resulting from operations of war	2	11	5.66	1.24, 25.7‡
???	Deaths due to unknown causes	158	166	1.00	0.80, 1.24

* ICD-9, *International Classification of Diseases*, Ninth Revision; RR, relative risk; CI, confidence interval.
† Minor differences between tables 3 and 4 are due to small differences in coding of mortality in external rates (R. R. Monson, Comput Biomed Res 1974;7:325–32) compared with coding for internal comparisons.
‡ The confidence interval for the relative risk does not include 1.

In contrast to their reduced risk of solid tumors, the men who worked as aviation electronics technicians experienced a significantly increased risk of leukemia. This was largely attributable to a marked excess of nonlymphocytic leukemia (relative risk = 2.98, 95 percent CI: 1.41, 6.31) and, in particular, acute myeloid leukemia (relative risk = 3.85, 95 percent CI: 1.50, 9.84). The elevated relative risks of nonlymphocytic leukemia in the high-exposure occupations result, in part, from a lower than expected death rate in radio and radar operators. The standardized mortality ratios for nonlymphocytic leukemia by occupation were as follows: radar and radio operators (SMR = 0.69, 95 percent CI: 0.45, 1.07), aviation electrician's mates (SMR = 1.16, 95 percent CI: 0.38, 3.61), electronics technicians (SMR = 1.07, 95 percent CI: 0.71, 1.60), fire control technicians (SMR = 1.12, 95 percent CI: 0.50, 2.49), and aviation electronics technicians (SMR = 2.19, 95 percent CI: 1.30, 3.70). No significant excesses were seen for any job category for lymphoid malignancies, brain cancer, or testicular cancer.

DISCUSSION

This is the second follow-up of a cohort of US Navy veterans with possible microwave exposure from radar units aboard ships or in airplanes during the Korean War. All job classifications defining this Navy cohort were chosen because of their potential for occupational exposure to radar, with the possible exception of aviation electrician's mates. There is no evidence for increased disease risk in the entire cohort. Furthermore, the high microwave-exposure stratum had lower mortality rates than did the low-exposure stratum for most diseases and most types of cancer, including brain cancer.

Mortality rates for all diseases, chronic obstructive pulmonary disease, ischemic heart disease, diabetes mellitus, and lung cancer were lower in the stratum that was presumed a priori to have higher exposure to microwave frequencies. These differences in mortality between the high- and low-exposure strata may reflect different occupational exposures during naval service, or they may reflect a differ-

TABLE 5. Relative risks for men with occupations involved in repair of radar or electrical systems compared with radio and radar operators, US Navy Veteran Cohort, 1950–1997

ICD-9* codes†	Cause(s) of death	No. of radiomen and radarmen with low radar exposure (*n* = 19,151)	Aviation electrician mates (low exposure) (*n* = 1,409)			Electronics technician (high exposure) (*n* = 13,010)			Fire control technician (high exposure) (*n* = 3,290)			Aviation electronic technician (high exposure) (*n* = 3,721)		
			No.	RR*	95% CI*	No.	RR	95% CI	No.	RR	95% CI	No.	RR	95% CI
Total	All causes, known and unknown	3,952	386	1.02	0.91, 1.13	2,442	0.83	0.78, 0.87‡	787	1.00	0.93, 1.08	826	0.90	0.84, 0.97‡
001–799	All diseases	3,312	314	0.94	0.83, 1.05	1,945	0.77	0.73, 0.81‡	663	0.97	0.89, 1.06	635	0.79	0.73, 0.87‡
140–208	All malignant neoplasms	1,224	127	1.06	0.88, 1.28	721	0.78	0.71, 0.85‡	223	0.91	0.79, 1.06	236	0.82	0.71, 0.95‡
140–149	Buccal cavity and pharynx cancer	28	4	1.51	0.50, 4.57	14	0.69	0.36, 1.31	4	0.72	0.24, 2.12	3	0.47	0.14, 1.60
162.0–162.9	Trachea, bronchus, and lung cancer	443	54	1.20	0.90, 1.61	236	0.70	0.59, 0.82‡	93	1.02	0.81, 1.29	71	0.66	0.51, 0.86‡
186.0–186.9	Testicular cancer	4	0	0.00	0.00, 15.5	5	1.81	0.48, 6.80	0	0.00	0.00, 6.69	0	0.00	0.00, 5.83
191.0–191.9	Brain cancer	47	4	0.79	0.27, 2.26	21	0.59	0.35, 0.99‡	6	0.58	0.24, 1.39	10	0.85	0.42, 1.72
200–203	Lymphoma and multiple myeloma	83	8	0.99	0.47, 2.08	59	0.92	0.66, 1.29	11	0.67	0.35, 1.26	21	1.07	0.65, 1.75
204–208	All leukemias	40	4	1.12	0.39, 3.19	38	1.30	0.83, 2.03	8	1.04	0.48, 2.27	23	2.60	1.53, 4.43‡
204.0	Acute lymphoid leukemia	5	0	0.00	0.00, 11.4	2	0.59	0.11, 3.05	0	0.00	0.00, 3.92	2	2.52	0.48, 13.3
204.1	Chronic lymphoid leukemia	8	1	1.06	0.12, 9.25	7	1.13	0.41, 3.16	1	0.54	0.06, 4.55	3	1.41	0.35, 5.70
205.0	Acute myeloid leukemia	10	1	1.03	0.13, 8.35	10	1.33	0.55, 3.22	3	1.50	0.40, 5.61	9	3.85	1.50, 9.84‡
205.1	Chronic myeloid leukemia	5	0	0.00	0.00, 11.4	5	1.35	0.39, 4.70	1	1.16	0.13, 9.99	2	1.94	0.37, 10.1
205.0–207.7, 207.9	Nonlymphocytic leukemia	18	2	1.23	0.28, 5.43	21	1.58	0.84, 2.97	6	1.73	0.67, 4.44	12	2.98	1.41, 6.31‡
205.0, 206.0, 207.0, 207.2	Acute nonlymphocytic leukemia	12	2	1.92	0.42, 8.82	13	1.48	0.67, 3.26	5	2.23	0.77, 6.49	10	3.83	1.61, 9.10‡
250.0–250.9	Diabetes mellitus	65	2	0.30	0.07, 1.25	24	0.48	0.30, 0.76‡	9	0.67	0.33, 1.39	6	0.38	0.16, 0.89‡
391–459	All vascular diseases	1,421	118	0.83	0.68, 1.00	860	0.80	0.73, 0.87‡	309	1.06	0.93, 1.20	289	0.85	0.75, 0.97‡
410–414	Ischemic heart disease	959	75	0.79	0.62, 1.00	565	0.78	0.70, 0.87‡	209	1.06	0.91, 1.24	195	0.86	0.73, 1.00
460–519	All nonmalignant lung diseases	173	28	1.19	0.78, 1.81	96	0.66	0.51, 0.85‡	32	0.73	0.49, 1.08	39	0.75	0.52, 1.08
490–496	Chronic obstructive pulmonary disease	97	19	1.45	0.86, 2.45	51	0.62	0.44, 0.88‡	17	0.70	0.41, 1.20	17	0.59	0.34, 1.00
520–579	All diseases of the digestive system	177	22	1.26	0.79, 1.99	106	0.81	0.63, 1.03	41	1.13	0.79, 1.60	32	0.77	0.52, 1.13
571.0–571.9	Cirrhosis of the liver	115	18	1.76	1.05, 2.96‡	64	0.77	0.57, 1.05	28	1.28	0.83, 1.96	26	1.04	0.67, 1.60
800–999	All external causes of death	499	55	1.57	1.18, 2.08‡	382	1.13	0.99, 1.30	102	1.24	1.00, 1.54	162	1.74	1.45, 2.08‡
810–829	Motor vehicle accidents	195	19	1.48	0.92, 2.40	115	0.90	0.71, 1.13	39	1.26	0.89, 1.79	27	0.78	0.52, 1.17
840–845	Accidents involving air transportation	15	9	8.57	3.71, 19.8‡	35	3.45	1.88, 6.32‡	1	0.40	0.05, 3.04	64	22.7	12.8, 40.1‡
950–959	Suicide and self-inflicted injuries	138	11	1.14	0.61, 2.12	103	1.09	0.85, 1.41	25	1.11	0.72, 1.72	24	0.93	0.60, 1.45
960–969	Homicide and other purposeful injuries	27	2	1.22	0.29, 5.21	11	0.63	0.31, 1.26	11	2.71	1.33, 5.56‡	4	0.87	0.30, 2.51
990–999	Injuries resulting from operations of war	2	0	0.00	0.00, 48.2	3	2.25	0.38, 13.5	1	3.07	0.27, 34.5	7	19.1	3.88, 94.4‡
???	Deaths due to unknown causes	141	17	1.26	0.75, 2.13	115	1.12	0.88, 1.44	22	0.76	0.48, 1.21	29	0.90	0.60, 1.35

* ICD-9, *International Classification of Diseases*, Ninth Revision; RR, relative risk; CI, confidence interval.
† Minor differences between tables 3 and 5 are due to small differences in coding of mortality in external rates (R. R. Monson, Comput Biomed Res 1974;7:325–32) versus internal comparisons.
‡ The confidence interval for the relative risk does not include 1.

ence in lifestyle factors, in particular, tobacco use. There is no direct evidence that smoking rates were lower in the high-exposure occupations while the men were in the Navy. In fact, the lung cancer standardized mortality ratios in the original report were 0.85 for low-exposure jobs, 1.13 for electronics technicians, and 1.15 for fire control technicians and aviation electronics technicians (8). However, the lower death rates for smoking-related diseases among men in the high-exposure occupations may reflect lower smoking rates in civilian life. The high-exposure occupations had higher mortality from injuries, including war deaths and aviation accidents, as well as higher mortality from nonlymphocytic leukemia. Naval recruitment literature indicated that aviation electronics technicians and aviation electrician's mates were in the airman career path. Thus, persons with these jobs may later have held jobs that included extensive flight time. There is no obvious explanation for the excess of aviation-related deaths among the electronics technicians.

The increased leukemia mortality was observed primarily in aviation electronics technicians. The other high-exposure occupations had leukemia death rates close to those expected. Aviation electrician's mates did not have an increased risk of leukemia deaths, so it does not appear that exposures related to assignment to aviation squadrons led to the increased risk in aviation electronics technicians. It is conceivable that the aviation electronics technicians might have had more inadvertent or accidental radiofrequency exposure than did the other high-exposure occupations. This is because the aviation electronic technicians dealt primarily with mobile radar units (the aircraft), whereas the other groups dealt primarily with stationary radar units. Thus, the potential for aviation electronics technicians to get into the beam path of an operating radar may have been greater than for those dealing with ship-mounted radars. An attempt was made in the original study (7) to quantify the potential radar exposure in the three high-exposure occupations for men who had died from disease, homicide, or suicide ($n = 375$) and for a random sample of men alive at the end of 1974 ($n = 858$). A hazard number was calculated, taking into account the type and power of radar units and the number of months spent on the ships or in air squadrons to which a man was assigned. These hazard numbers indicated that aviation electronics technicians and fire control technicians had a greater potential for radar exposure than did the electronics technicians. Because of the difficulty and cost of finding and abstracting records, the loss of records for aviation squadrons, and the much larger numbers of deaths in the 40-year follow-up, an extension of the hazard number classification scheme to the current study was not feasible.

The results of previous studies of cancer among US military personnel exposed to electromagnetic fields have been inconclusive. A cohort study of leukemia in men on active duty in the Navy from 1974 through 1984 (10) reported a marginally significant excess of leukemia among electrician's mates (standardized incidence ratio (SIR) = 2.4, 95 percent CI: 1.0, 5.0); electrician's mates were deemed likely to have been exposed only to extremely low frequency fields (10). No other significant standardized incidence ratio was reported, but, interestingly, the highest standardized incidence ratio was observed for an aviation-related job; for aviation ordinancemen the leukemia standardized incidence ratio was 2.9 (95 percent CI: 0.8, 7.3). No evidence of increased leukemia risk was reported in that study for occupations in our study: aviation electronics technician (SIR = 0.3, 95 percent CI: 0.0, 1.9), electronics technician (SIR = 1.1, 95 percent CI: 0.4, 2.6), fire control technician (SIR = 0.5, 95 percent CI: 0.0, 2.5), aviation electrician's mate (SIR = 0.5, 95 percent CI: 0.0, 2.7), radioman (SIR = 1.1, 95 percent CI: 0.3, 2.8), and radarman (listed under a new job classification title, operations specialist) (SIR = 0.5, 95 percent CI: 0.0, 2.7) (10). A case-control study of brain cancer among US Air Force personnel (17) reported a marginally significant association (odds ratio = 1.39, 95 percent CI: 1.01, 1.90) for men who maintained or repaired radiofrequency- or microwave-emitting equipment.

A study of civilian employees of the Naval Weapons Center in China Lake, California, found significantly increased rates of leukopenia (defined as a total white blood cell count below 4,500 per ml) in employees of the Electronic Warfare Department (17). Within the Electronic Warfare Department, the rate of leukopenia was highest in the Microwave Development Division, where employees had the potential for routine exposure to low microwave levels; however, leukopenia rates were very low in employees of the Electronic Warfare Threat Environment Simulation Division of the Electronic Warfare Department, where workers probably were exposed to higher microwave levels than those in the Microwave Development Division (18). An evaluation of 48 leukopenic Naval Weapons Center employees found that 34 were lymphopenic and five were neutropenic, suggesting that lymphoid cells were decreased to a greater extent than were cells of myeloid origin (19).

Evaluation of laboratory experiments and animal studies has provided no support for a role of radiofrequency radiation in carcinogenesis (2, 3, 20–22). Comprehensive reviews of epidemiologic studies of possible adverse health effects of radiofrequency exposure have also concluded that the evidence supporting a role of microwave frequencies in the etiology of cancer is weak and inconsistent (1–3, 20, 21). Subsequent studies found no evidence of increased risk of brain cancer in cellular telephone users (5–7), although definitive evidence of the safety of these devices will require studies with cellular phone use of longer duration and with longer follow-up periods. Brain cancer rates were decreased in the high-exposure group in our study. Two recent studies have reported a possible association between microwave frequencies and intraocular melanoma (23, 24). A study of over 400,000 Danish subscribers to cellular telephones observed eight ocular cancers compared with 13.5 expected (7). One death from eye cancer was observed in our study, and it was in the low-exposure stratum.

The strengths of our study include its size and long duration of follow-up. The weaknesses of the study include the lack of dosimetry for microwave exposures and other occupational and environmental chemical exposures, misclassification of exposures due to the reliance on job titles, the absence of exposure information after naval duty, the lack of date of birth and year of graduation for many subjects, and the absence of the Social Security number for almost half the cohort. The ability to ascertain the deaths of military veterans in BIRLS using service numbers compensates somewhat for the absence of Social Security numbers (11–13). Nonetheless, the absence of Social Security numbers for half the cohort probably led to some underascertainment of deaths and perhaps a bit more for radar and radio operators than for the other job categories. In spite of this possible differential underascertainment of deaths, the overall standardized mortality ratios for the radar and radio operators were significantly higher than the standardized mortality ratios for electronics technicians and aviation electronics technicians, apparently related to decreased mortality from smoking-related conditions in the two electronics technicians groups. We inferred that the electronics technicians smoked less, because of their much lower mortality from lung cancer, chronic obstructive pulmonary disease, and ischemic heart disease. However, we lacked information about lifestyle risk factors to provide direct support for this inference. No information was available regarding smoking history, alcohol consumption, or the dietary habits of the subjects in this study.

Multiple comparisons may have led to chance significant findings, and thus the increased risk of nonlymphocytic leukemia in the aviation electronics technicians should be viewed with caution. If radar exposure caused leukemia, it would not be anticipated that increased risk would be observed in only one of the two occupations (i.e., aviation electronics technicians and fire control technicians) indicated by hazard numbers to have the highest potential radar exposure. Furthermore, the excess occurred in an occupational group with low overall mortality and with lower mortality from most specific causes other than injuries. It is unclear whether the increased leukemia risk is related to radar exposure, to some other exposure experienced by aviation electronics technicians, or to chance as a result of multiple comparisons.

For the occupations with high potential for radar exposure, no significant excesses were found for all malignant neoplasms combined, lymphoid malignancies, brain cancer, or testicular cancer. In fact, deaths from all cancers, lymphoid malignancies, and brain cancer were less common in the high microwave-exposure stratum than in the low-exposure stratum. Overall, it appears that radar exposure had very little effect on mortality in this cohort of US Navy veterans.

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