Cancer Mortality Risk among Military Participants of a 1958 Atmospheric Nuclear Weapons Test

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ABSTRACT

Objectives. This study was undertaken to determine if Navy veterans who participated in an atmospheric nuclear test in 1958 were at increased risk of death from certain cancers.

Methods. Cancer mortality risk of 8554 Navy veterans who participated in an atmospheric nuclear test in the Pacific was compared with that of 14 625 Navy veterans who did not participate in any test. Radiation dosage information was obtained from film badges for 88% of the test participants.

Results. The median radiation dose for the test participants was 388 mrem (3.88 millisieverts [mSv]). Among participants who received the highest radiation dose (>1000 mrem, or 10 mSv), an increased mortality risk for all causes (relative risk [RR] = 1.23; 95% confidence interval [CI] = 1.04, 1.45), all cancers (RR = 1.42; 95% CI = 1.03, 1.96), and liver cancer (RR = 6.42; 95% CI = 1.17, 35.3) was observed. The risk for cancer of the digestive organs was elevated among test participants (rate ratio = 1.47; 95% CI = 1.06, 2.04) but with no significant dose–response trend. Many of the cancers of a priori interest were not significantly elevated in the overall test participant group or in the group that received the highest radiation dose.

Conclusions. Most of the cancers suspected of being radiogenic were not significantly elevated among the test participants. Nevertheless, increased risks for certain cancers cannot be ruled out at this time. Veterans who participated in the nuclear weapons tests should continue to be monitored. (*Am J Public Health.* 1995;85:523–527)

Introduction

From 1945 through 1962, the Manhattan Engineer District and its successor agency, the Atomic Energy Commission, conducted 235 atmospheric nuclear tests. The Department of Defense estimated that approximately 205 000 of its military and civilian personnel participated in the tests.[1] Film badge dosimeters were distributed to a representative sample of Defense Department personnel with exposure potential within each test site from 1945 to 1954 and to nearly all personnel with exposure potential in subsequent test series.[2] The film badges measured radiation exposure in millirem. (*Rem* is defined as the radiation absorbed, weighted by factors reflecting the biological effectiveness of the particular radiation.[3]) Most of the 205 000 test participants were exposed to low levels of radiation within the established federal limits of 5 rem (or 50 millisieverts [mSv]) per year.[4]

Studies of the mortality of A-bomb survivors indicate a significant dose–response relationship for leukemia; for cancers of the esophagus, stomach, colon, lung, breast, ovary, and bladder; and for multiple myeloma. Malignant lymphoma and cancers of the rectum, gallbladder, pancreas, uterus, and prostate were not found to be significantly increased.[5]

Analyses of combined mortality data on US nuclear industry workers who were exposed to chronic low doses of ionizing radiation at the Hanford site in Washington State, the Oak Ridge National Laboratory in Tennessee, and the Rocky Flats Nuclear Weapons Plant in Colorado pro vide no evidence of excess mortality from all cancers or from leukemia. Only one specific cancer, multiple myeloma, was found to be associated with radiation exposure.[6]

In 1979, the Centers for Disease Control presented a preliminary report indicating that the participants in a nuclear weapons test (SMOKY) conducted in Nevada in 1957 had an excess of leukemia cases based on age- and sex-specific general population rates.[7] Follow-up studies of the same cohort by Caldwell et al. and the National Academy of Sciences revealed further increases in leukemia incidence among the SMOKY participants.[8–10] However, deaths from leukemia and other radiogenic cancers were not elevated among participants in several other test series that were studied.[10] None of the studies of the test participants included a military nonparticipant control group for comparison purposes.

In light of the findings described above and of continuing concerns for the health of veterans who participated in the nuclear weapons tests, a study of the military participants of another test series was undertaken to determine whether they were at higher risk for dying from certain cancers. Hardtack I, a test series not included in previous studies, was selected because it had one of the highest proportions of participants with film dosimetry data.

Methods and Procedures

Identification of Study Subjects

A database of veterans who participated in nuclear weapons tests has been established by the Defense Department's

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TABLE 1—Cause-Specific Mortality among the Hardtack Participants Compared with the Nonparticipant Veterans

	Hardtack Participants (n = 8554)		Nonparticipant Veterans (n = 14 625)			
	Observed No. of Deaths	Crude Death Rate[a]	Observed No. of Deaths	Crude Death Rate[a]	Crude Rate Ratio	95% Confidence Interval
All causes	1083	40.00	1695	36.52	1.10	1.02, 1.19
All cancers	264	9.75	396	8.53	1.14	0.98, 1.33
Digestive organs	66	2.44	77	1.66	1.47	1.06, 2.04
Esophagus	10	0.37	15	0.32	1.16	0.52, 2.58
Stomach	4	0.15	12	0.26	0.58	0.19, 1.80
Large intestine	20	0.74	27	0.58	1.28	0.72, 2.28
Liver	5	0.18	4	0.09	2.00	0.54, 7.45
Pancreas	14	0.52	14	0.30	1.73	0.82, 3.63
Respiratory system	97	3.58	159	3.43	1.04	0.81, 1.34
Lung	94	3.47	151	3.25	1.07	0.83, 1.38
Skin	4	0.15	11	0.24	0.63	0.20, 1.98
Prostate	15	0.55	18	0.39	1.41	0.71, 2.80
Bladder	1	0.04	5	0.11	0.36	0.04, 3.08
Non-Hodgkin's lymphoma	6	0.22	7	0.15	1.47	0.49, 4.37
Multiple myeloma	2	0.07	6	0.13	0.54	0.11, 2.68
Leukemia	6	0.22	15	0.32	0.69	0.27, 1.78

[a]Per 10 000 person-years.

Defense Nuclear Agency.[1] Information on test participants was gathered from sources such as ship logs, muster rolls, military service records, medical records, morning reports, and outreach programs.

Operation Hardtack I (1958) included 35 Pacific nuclear detonations mainly at Enewetak and Bikini atolls and 2 detonations above Johnston Island.[11] Radiation dosage information on the Hardtack I database was determined by individual film badges for 88% of the veterans. Estimated doses were calculated for the remaining unbadged individuals by using the film badge levels of those who served in the same military unit or occupation.[1]

Of the 13 910 verified participants of the Hardtack I test series, 13 713 served in the military and 197 were civilian personnel. A total of 2382 of the veterans who served in multiple test series were excluded from the study cohort because of the difficulty in determining the contributory effect of their participation in other nuclear tests. Of the remaining 11 331 veterans, 2777 served in branches of the military other than the Navy and were excluded. The resulting 8554 Navy veterans were included in the study cohort. They had a median gamma level of 388 mrem.

A nonparticipant Navy veteran group was determined from *Jane's Fighting Ships for 1957–1958* and the list of ships that were active in 1958.[12–13] A total of 49 aircraft carriers and heavy cruisers were identified as active and not stationed in the Pacific, and the microfilmed ship logs of 41 of those ships were obtained from the Bureau of Naval Personnel. Nine of the 41 ships were excluded because they had participated in other nuclear tests, their ship logs contained only a partial list, their ship logs contained no officer list, their enlisted lists were undated, or the microfilm was of poor quality. After the remaining 32 ships were randomly sorted, the name, rank, and military service number were abstracted for 15 000 enlisted personnel and officers from the first 10 ships. The file was then matched to the Nuclear Test Personnel Review file, and 375 of the 15 000 were excluded from the study because they had served in atmospheric nuclear tests. This left 14 625 for the nonparticipant Navy veteran group. There were no women in either the participant group or the nonparticipant group.

Vital Status Determination for Mortality Analysis

Each of the Navy Hardtack I participants and the nonparticipant veterans was followed for vital status from September 1, 1958, the month after the last Hardtack I test, until his date of death or September 1, 1991, whichever occurred first. Vital status was determined by matching the subjects' names and military service numbers against those in the Department of Veterans Affairs (VA) Beneficiary Identification and Record Locator Subsystem (BIRLS). The expected completeness of veteran deaths reported to the VA and entered in BIRLS is approximately 90%.[14] The source of vital status follow-up was limited to BIRLS because social security numbers of veterans were not available from the ship logs.

Of the 8554 Hardtack participants, 1083 (12.7%) were identified in BIRLS as deceased while 1695 (11.6%) of the 14 625 nonparticipant Navy veterans were identified as deceased. The underlying cause of death for each subject was coded by a qualified nosologist according to the rules in effect at the time of death but using the rubrics of the *International Classification of Diseases*, 9th edition (ICD-9).[15] Cause of death was unknown for 81 Hardtack (7.5%) and 109 nonparticipant veterans (6.4%). Participation in the Hardtack nuclear test was unknown to the nosologist.

The differential completeness of BIRLS as a vital status source was evaluated using the National Death Index as a reference source. Random samples of 1000 Hardtack participants and 1000 nonparticipant veterans whose social security numbers were known to the VA were selected from each group and matched against the index for vital status. Of the Hardtack participants who were found on the index, 84% were also recorded as deceased on BIRLS. Among the nonparticipant veterans, 89% of those found on the index were also found on BIRLS.

Statistical Methods

The analysis of mortality data was approached in three stages. In stage 1, a simple comparison of the relative frequency of overall deaths as well as of specific causes of death was made between the Hardtack participants and the nonparticipant Navy veterans based on person-years at risk. This was done without adjusting for any other variables. Unadjusted rate ratios (RRs) were generated from crude death rates, and 95% confidence intervals (CIs) were calculated.[16]

In stage 2, the Cox proportional hazards model was used to estimate mortality risk among overall Hardtack participants as well as among a specific exposure group relative to the mortality

TABLE 2—Cause-Specific Mortality (Adjusted for Military Rank) among the Hardtack Participants Compared with the Nonparticipant Veterans, by Gamma Dose Category

	Gamma Dose = 0 to 250 mrem (n = 3345)			Gamma Dose = 251 to 1000 mrem (n = 4115)			Gamma Dose >1000 mrem (n = 1094)		
	Observed No. of Deaths	RR[a]	95% Confidence Interval	Observed No. of Deaths	RR[a]	95% Confidence Interval	Observed No. of Deaths	RR[a]	95% Confidence Interval
All causes	417	1.09	0.98, 1.21	513	1.08	0.98, 1.19	153	1.23	1.04, 1.45
All cancers	101	1.12	0.90, 1.39	121	1.08	0.88, 1.32	42	1.42	1.03, 1.96
Digestive organs	29	1.64	1.07, 2.52	29	1.32	0.86, 2.03	8	1.39	0.67, 2.89
Esophagus	7	2.15	0.88, 5.28	3	0.72	0.21, 2.48	0	0.00	0.00, 0.00
Stomach	1	0.36	0.05, 2.79	3	0.89	0.25, 3.16	0	0.00	0.00, 0.00
Large intestine	10	1.58	0.76, 3.29	8	1.04	0.47, 2.29	2	0.99	0.24, 4.19
Liver	1	1.20	0.13, 10.74	2	1.70	0.31, 9.34	2	6.42	1.17, 35.33
Pancreas	4	1.32	0.43, 4.00	9	2.32	1.00, 5.35	1	1.00	0.13, 7.64
Lung	38	1.10	0.77, 1.57	43	1.01	0.72, 1.41	13	1.16	0.66, 2.05
Skin	1	0.42	0.05, 3.24	3	0.97	0.27, 3.48	0	0.00	0.00, 0.00
Prostate	5	1.24	0.46, 3.40	8	1.54	0.66, 3.57	2	1.46	0.34, 6.31
Non-Hodgkin's lymphoma	2	1.22	0.25, 5.89	3	1.51	0.39, 5.83	1	1.90	0.23, 15.42
Leukemia	2	0.54	0.12, 2.37	2	0.45	0.10, 1.98	2	1.73	0.39, 7.56

[a]Relative risk (RR) calculated by the Cox proportional hazards model adjusting for military rank.

risk among the nonparticipant veterans, adjusting for military rank.[17] The Hardtack group was categorized into three groups according to degree of radiation exposure: low-dose radiation was defined as 250 mrem or less, medium-dose radiation was 251 to 1000 mrem, and high-dose radiation was more than 1000 mrem.

In stage 3, cause-specific number of deaths in both groups of veterans were compared with the number of expected deaths based on age and calendar-year–specific proportions of deaths for each cause among US males. Differences between observed and expected number of deaths for each cause were summarized in the form of the proportionate mortality ratio (PMR).[18]

Of a priori interest were those categories of cancers that prior research has found to be possibly radiogenic and that have most likely developed in sufficient numbers to allow for the computation of mortality rate ratios. Furthermore, any cancers included in the VA's statutory list for adjudicating compensation claims filed by atomic veterans were also evaluated whenever there were sufficient numbers. Studies suggested that chronic lymphocytic leukemias were generally not radiogenic,[19] so a separate analysis of leukemia excluding chronic lymphocytic leukemia was planned.

The study cohort was large enough to provide a statistical power of 95% to detect a 2.0-fold increase in risk for lung cancer among the Hardtack I participants compared with the nonparticipants. However, the study had limited statistical power to detect moderate increases in risk from rare causes such as multiple myeloma and leukemia.

TABLE 3—Cause-Specific Mortality among the Hardtack Participants and Nonparticipant Veterans Compared with the US Male Population

	Hardtack Veterans			Nonparticipant Veterans		
	Observed No. of Deaths	PMR[a]	95% Confidence Interval	Observed No. of Deaths	PMR[a]	95% Confidence Interval
All causes	1083	1.00		1695	1.00	
All cancers	264	1.12	0.99, 1.27	396	1.08	0.97, 1.19
Buccal cavity and pharynx	7	1.07	0.43, 2.20	12	1.15	0.59, 2.00
Digestive organs	66	1.24	0.96, 1.57	77	0.92	0.73, 1.16
Esophagus	10	1.72	0.83, 3.17	15	1.66	0.93, 2.73
Stomach	4	0.53	0.14, 1.35	12	1.00	0.51, 1.74
Large intestine	20	1.05	0.64, 1.63	27	0.92	0.61, 1.34
Liver	5	1.46	0.47, 3.40	4	0.75	0.20, 1.92
Pancreas	14	1.25	0.69, 2.11	14	0.80	0.44, 1.34
Respiratory system	97	1.08	0.88, 1.32	159	1.14	0.97, 1.33
Lung	94	1.10	0.89, 1.34	151	1.13	0.95, 1.32
Skin	4	0.52	0.14, 1.33	11	0.88	0.44, 1.58
Prostate	15	1.88	1.05, 3.10	18	1.60	0.95, 2.53
Bladder	1	0.27	0.00, 1.51	5	0.90	0.29, 2.10
Non-Hodgkin's lymphoma	6	1.57	0.57, 3.42	7	1.15	0.46, 2.37
Multiple myeloma	2	0.66	0.07, 2.39	6	1.28	0.47, 2.78
Leukemia	6	0.60	0.22, 1.30	15	0.94	0.52, 1.55

[a]PMR = proportionate mortality ratio.

A 10% random sample of the Hardtack participants (n = 855) and nonparticipant (n = 1462) veterans was selected to determine whether dates of birth were comparable between the two groups. Date of birth information was unavailable from ship logs for the nonparticipant veterans, so an extensive manual search of veterans' records was conducted against the BIRLS, the Veterans Administration Master Index, and the National Personnel Records Center database. Date of birth information was thus found for 761 of 855 participants (89%) and for 1286 of 1462 nonparticipants (88%). For both groups, the mean year of birth was 1933, and the age distribution was almost identical. Additionally, among the test participants, age distribution of the three exposure groups (0 to 250, 251 to 1000, and >1000 mrem) was comparable with the mean age of each (26.9, 26.6, 26.7, respectively) at the beginning of the follow-up.

Results

Comparing the Hardtack participants against the nonparticipant group, we find that the total number of accumulated person-years at risk was 270 727 versus 464 113, the average number of years of follow-up was 31.6 vs 31.7, the average age at death was 52 years vs 51 years, and the percentage who were enlisted was 91.7% vs 94.4%, respectively.

There was a significant excess of deaths among the Hardtack participants from all causes (RR = 1.10; 95% CI = 1.02, 1.19) (Table 1). Mortality from cancer of the digestive organs was also significantly elevated among the Hardtack participants compared with the nonparticipant veterans (RR = 1.47; 95% CI = 1.06, 2.04). However, mortality rates from all cancers combined and from many other a priori cancers of interest were not statistically elevated. Further analysis of leukemia excluding chronic lymphocytic leukemia was conducted, and, again, no significant difference was found. None of the Hardtack participants and only two nonparticipant veterans died from chronic lymphocytic leukemia.

Adjusting for military rank yielded results similar to the crude comparisons. Mortality from cancer of the digestive organs continued to be statistically significant, with a relative risk of 1.47 (95% CI = 1.05, 2.04) for Hardtack participants compared with the nonparticipant Navy veterans. Mortality rates from the other site-specific cancers were not significantly elevated.

The Hardtack participants in each radiation gamma dose category were compared with the nonparticipant veterans using the proportional hazards model (Table 2). Statistically significant relative risks were observed only for all causes, all cancers, and liver cancer in the high-dose (>1000 mrem) group, for pancreatic cancer in the medium-dose (251 to 1000 mrem) group, and for cancer of the digestive organs in the low-dose (0 to 250 mrem) group. The number of deaths due to liver cancer was small: five among the Hardtack participants and four among the nonparticipant veterans.

When both groups were compared with the general US population, the only risk that was significantly elevated was that for prostate cancer among the Hardtack participants (PMR = 1.88; 95% CI = 1.05, 3.10) (Table 3).

Discussion

Unadjusted rate ratios from all causes of death and from cancer of the digestive organs were significantly elevated for Hardtack participants compared with the nonparticipant veterans. Cancer of the digestive organs includes cancer of the esophagus, stomach, small intestines, colon, rectum, liver, bile ducts, and pancreas. Many of these site-specific cancers are known to be radiogenic and are defined as service connectable under the VA guidelines for compensation related to radiation exposure. After adjusting for military rank, cancer of the digestive organs continued to be significantly elevated among Hardtack participants.

As noted above, cancer of the prostate was significantly elevated among the Hardtack participants compared with US men. The risk for prostate cancer was higher among the participants compared with the nonparticipants, but it was not statistically significant (RR = 1.41; 95% CI = 0.71, 2.80) (Table 1). Previous research has suggested a weak association between prostate cancer and radiation.[20-22] However, the risk for prostate cancer did not show a significant increase with radiation dose in Japanese A-bomb survivors[5] and in US nuclear industry workers.[6]

Estimates of the external radiation doses for the participants were reported to be so low (<0.5 rem for most veterans) that no detectable increase in cancer risk would have been expected on the basis of cancer risk estimates derived from high-dose studies. For example, the Institute of Medicine Committee on the Biological Effects of Ionizing Radiation estimated that an acute whole-body dose of 0.1 Sv (10 rem) among 100 000 males of all ages would result in 500 to 1200 additional cancer deaths.[19] Thus, an equivalent number for the 8554 Hardtack participants under a linear low-dose extrapolation would be fewer than 6 excess cancer deaths. There were an estimated 32 (95% CI = −5, 66) excess cancer deaths in the study (RR = 1.14; 95% CI = 0.98, 1.33) (Table 1). Therefore, the cancer risk observed in the Hardtack participants is about five to six times larger than the projected magnitude of risk. A recent mortality study of workers at the Oak Ridge National Laboratory also reported a dose-response relationship that is 10 times higher than estimates based on A-bomb survivors.[23]

There are several possible explanations for this. First, the observed excess risk among Hardtack participants may have been a spurious association due to statistical aberrations including multiple comparisons. Many of the known radiogenic cancers, including leukemia, were not significantly elevated among the participants, and a significant dose–response relationship was not observed for cancer of the digestive organs or prostate. Second, the risk estimates become very uncertain when applied to very low doses. If there were substantial departures from a linear model at low doses, the risk estimate could have been much different. However, a recent study shows that the risk estimates obtained by extrapolation from the studies of Japanese A-bomb survivors exposed to high doses are unlikely to be substantially in error.[24] Third, the Defense Nuclear Agency's estimates of radiation exposure levels for the Hardtack participants might have been much lower than the actual exposure levels; the accuracy of those estimates has been questioned especially when the dose levels were reconstructed without measurements from film badges. However, exposure data for the Hardtack participants should be considered more reliable than data for participants of other test series because exposure levels from a higher percentage (88%) of Hardtack participants were determined from film badges.

Among the several limitations of the study is the reliance on death certificates rather than on medical records for information on cause of death. Death certificates are dependable documents establishing the fact of a person's death, but their accuracy of recording cause-specific mortality is somewhat variable.[25] However, because of the historical nature of the exposure, which occurred almost 35 years ago, death certificates may be the only practical and consistently available source of data on cause of death in this regard. Second, no information is available on potential confounders, such as the smoking and drinking habits of the veterans and their postservice exposure to known occupational carcinogens. It is also not known whether the participants and nonparticipants have similar smoking histories. However, these veterans were selected for the study in such a way as to minimize their differences in most regards (i.e., branch of service, age, rank, sex, time of service, and duty) except for participation in the nuclear weapons test. Third, the study veterans as a group were still relatively young, and more than 87% of them were still alive at the end of the follow-up period. Further follow-up of these veterans for their cancer mortality is warranted. Fourth, the slightly lower death ascertainment for Hardtack participants could lead to a bias toward an underestimate of overall mortality risk as well as of specific cancer risk in contrast to the nonparticipant Navy veterans.

The major advantage of this study is the inclusion of a Navy veteran comparison group. Such a comparison group will address potential problems related to the "healthy soldier effects," which arise when a military cohort is compared with the general US population.[26,27]

In summary, although reported radiation doses for the Hardtack participants were generally under 500 mrem, the possibility that the veterans who participated in the atmospheric nuclear test may be at an increased risk of death from certain cancers cannot be ruled out at this time. This group of veterans should continue to be monitored for their mortality outcomes. □

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