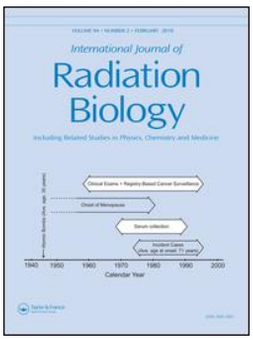

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ORIGINAL ARTICLE

Dosimetry associated with veterans who participated in nuclear weapons testing

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ABSTRACT

Background: This article summarizes the methodology, results, and challenges of the reconstruction of red bone marrow and male breast doses for a 1982-person sub-cohort of ~114,270 U.S. military veterans who participated in eight atmospheric nuclear weapons tests between 1945 and 1962. These doses are being used in an epidemiological investigation of leukemia and male breast cancer as part of a study of one million U.S. persons to investigate risk from chronic low-dose radiation exposure.

Methods: Previous doses to these veterans had been estimated for compensation and tended to be biased high but newly available documentation made calculating individual doses and uncertainties using detailed exposure scenarios for each veteran possible. The techniques outlined in this report detail the methodology for developing individual scenarios and accounting for bias and uncertainty in dose based on the assumptions made about exposure.

Results: Doses to the atomic veterans in this sub-cohort were relatively low, with about two-thirds receiving red bone marrow doses <5 mGy and only four individuals receiving a red bone marrow dose >50 mGy. The average red bone marrow dose for members of the sub-cohort was 5.9 mGy. Doses to male breast were approximately 20% higher than red bone marrow doses.

Discussion and challenges: Relatively low uncertainty was achieved as a result of our methodology for reconstructing exposures based on knowledge of the individual veterans' locations and activities from military records. Challenges did arise from use of military records to determine probability of participation in specific activities but accounted for in estimates of uncertainty.

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Atomic veterans; nuclear weapons tests; radiation dose assessment; uncertainty; nevada test site; pacific proving grounds

Background

This paper summarizes the methodology used to reconstruct radiation doses and associated uncertainties in an epidemiological analysis of military personnel who participated in the U.S. nuclear testing program. This cohort of atomic veterans is one component in a broader-scope study of about one million U.S. persons designed to investigate risk from chronic low-dose radiation exposure (Bouville et al. 2015; Boice et al. 2019). Military veterans participated in atmospheric nuclear weapons testing conducted by the United States between 1945 and 1963 and the reconstructed doses described here have been used in a case-cohort design to estimate the risk of leukemia and male breast cancer mortality resulting from chronic vs. acute radiation exposure (Boice et al. 2019). We also discuss some of the challenges and limitations of the methodology as well as opportunities for further research. Details of the methodology are reported by Till et al. (2014) and detailed doses are reported in Beck et al. (2017).

The U.S atmospheric weapons tests (DOE 2000) took place at:

- The Nevada Test Site (NTS) from 1951 through 1957 (Test series RANGER, BUSTER-JANGLE, TUMBLER-SNAPPER, UPSHOT-KNOTHOLE, TEAPOT, PLUMBBOB, and HARDTACK II). Military personnel participated in military maneuvers immediately following a nuclear test, observed tests, or provided support during test-related operations.
- The Pacific Proving Grounds[1] (PPG) from 1946 through 1962 (Test series CROSSROADS, SANDSTONE, GREENHOUSE, IVY, CASTLE, WIGWAM, REDWING, HARDTACK I, and DOMINIC). Military personnel were aboard ships or stationed on islands in the area during and following the tests.
- Alamogordo, NM, where the first nuclear test, TRINITY, took place on 16 July 1945.

The atomic veterans were primarily exposed to gamma and beta radiation from fission products resulting from nuclear weapons detonations. Many of the participants at the PPG were stationed on islands or ships impacted by fallout and thus received radiation exposure from fallout deposited on the ground or on ship surfaces as well as from

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descending fallout and re-suspended fallout. Other examples of activities that may have resulted in exposure include boarding contaminated target ships,[2] operating small boats in contaminated sea water, shore leave on fallout-contaminated islands, troop maneuvers at NTS during and following tests and observing tests at the NTS. Previous attempts to investigate disease among nuclear test participants in the U.S. have yielded mixed results, and these studies lacked the detailed dosimetry on individuals studied (Till et al. 2014).

Methods

The fundamental approach to dose estimation is to first determine the scenario of exposure for each veteran and then to assign a dose accounting for sources of bias and uncertainty. Because calculation of doses for all ~115,000 members of the cohort would have been prohibitive both from a cost and time perspective, an efficient epidemiologic study design, the case-cohort approach, was used that required detailed dose estimates for a smaller sub-cohort (Wacholder 1991). The sub-cohort in the current study included 1982 individuals, including all leukemia and male breast cancer cases and a 1% random comparison sample of the entire cohort.

Doses to U.S. military veterans were estimated previously under the Nuclear Test Personnel Review (NTPR) program directed by the Defense Threat Reduction Agency (DTRA)[3] within the Department of Defense (DOD). In 1988, legislation was passed that authorized a compensation program for veterans based on doses estimated by DOD personnel and their contractors. To estimate doses to veterans, the DOD undertook a comprehensive review of historical records and developed a dose reconstruction methodology that was designed to be high sided and favor veterans seeking compensation. The goal for this study was to estimate individual doses with uncertainties without the high-sided bias that was often introduced in the methodology developed during the veterans' compensation program.

Our approach built upon available film badge dosimetry and other measurement data recorded at the time of the tests and incorporated detailed scenarios of exposure for each veteran based on personal, unit, and other available historical records. Approximately, 25% of the military personnel had film badge records that accounted for at least 80% of their dose. These records were used to estimate specific organ doses to individuals wearing a badge and for groups of veterans performing similar duties at the same time and location. The distributions of film badge readings for individuals in specific military units with likely similar exposures were also used for estimating uncertainties.

One or more members of a unit performing similar duties were often issued a "cohort" film badge, which often could be used in estimating dose to the entire unit. The availability of film badge data varied over time. A relatively large percentage of individuals had film badge data for the later test series (e.g. PLUMBBOB-1957 and HARDTACK I-1958), while a relatively small percentage had film badge data for the earlier series (e.g. CROSSROADS-1946, GREENHOUSE-1951, and UPSHOT-KNOTHOLE-1953). In addition, while half of the CASTLE-1954 participants had reported badge exposures, the majority were based on a cohort badge wearer whose dose was assigned as a badge dose to other members of the cohort. For CASTLE in particular, the cohort badge assignments were determined to not necessarily reflect the activities an individual was involved in. Likewise, for REDWING, although many individuals wore badges, many of the badges were damaged from high heat and humidity and did not reflect the actual exposures received (NRC 1989).

Contributing to the total body of knowledge about an individual's potential for radiation exposure are documents related to military units, ships' logs, photographs of facilities, and activities at the NTS and the PPG; the indicator of military rate or rating (indicating an individual's job); and numerous other historical records. All available sources of information were incorporated into our methodology (Till et al. 2014).

Cancers studied and pathways of exposure

Leukemia and male breast cancer were selected as the focus of the study. Leukemia was selected because previous U.S. studies suggest a general pattern of increased leukemia risks (Seltzer and Jablon 1974; 1977; Caldwell et al. 1980; 1983; Robinette et al. 1985; Thaul et al. 2000), but these studies did not include individual dosimetry or uncertainty. Male breast cancer was chosen because a previous study of atomic veterans had reported a non-statistically significant increased risk of 39% (Thaul et al. 2000). The study of atomic bomb survivors (Ron et al. 2005) reported a statistical association of male breast cancer with radiation dose but based on small numbers, and the number of male breast cancers in our study, about 30, would be the largest study to date.

Veterans could have been exposed to both external and internal radiation. Based on conservative NTPR analyses as well as estimated doses to residents of the Marshall Islands, internal exposure to red bone marrow (organ of interest for leukemia) and male breast would almost always be no more than a few percent of the dose from external exposure (Goetz 1986; Phillips et al. 1985; Weitz et al. 2009). Other researchers have also concluded that when external and internal exposure exists from radioactive fallout of nuclear weapons, the primary exposure pathway for most organs other than thyroid is external (Bouville et al. 2010; Simon et al. 2010).

Criterion for detailed dose reconstruction

In reviewing the historical records such as film badge data, previous dose reconstructions, and other information describing a veteran's military unit and personal activities, if it could clearly be established that the dose was below a given level that did not merit a comprehensive dose reconstruction, then the dose reported by the NTPR program was used. This approach has been taken in similar studies where a decision level (also called "cutoff level") is chosen for the practical reasons of cost and feasibility (Boice et al. 2006).

Table 1. Examples of estimated bias or error[a] in NTPR dose assignments (Taken from Till et al. 2014; Table 4).

Source of exposure	NTPR source of bias or error	~ Range of bias or error[b]
Cohort badges at CASTLE	NTPR assigned doses based on random cohort assignments that resulted in errors due to both overestimating and underestimating doses to particular individuals	0.2–3.0
Film badge interpretation	NTPR assumed film badge reading equaled the whole body dose that resulted in all NTPR doses being biased high and did not correct for other known biases	1.2–2.0
Engine room duty	NTPR assumed high-sided dose (bias) and placed unlikely rates and ratings in the engine room (error).	1.2–10
Hull and seawater contamination	NTPR assumed all personnel worked and berthed below the water level where exposure would be highest resulting in errors in individual exposures	0.4–9.0
Bias correction for exposure to fallout on residence islands and ships	NTPR used available exposure rate measurements and model estimates of shielding that did not accurately reflect the true mean exposure. This generally biased high the mean dose to all those in a particular unit	0.5–6.0

[a]'Bias' refers to the tendency to systematically either overestimate or underestimate doses for a given exposure scenario. 'Error' refers to random errors in individual doses such as errors in assumed individual exposure scenario or errors in NTPR records. Random errors for a particular exposure scenario can be in either direction, while bias is always in the same direction.
[b]Range of ratios of NTPR to AVS doses.

Veterans with doses below the decision level were not excluded from the study and their estimated dose was still used in the analysis.

We selected a decision level of 5 mGy. We assigned an uncertainty to all NTPR doses clearly less than this level characterized by a geometric standard deviation (GSD) of 1.4, consistent with NTPR estimates of uncertainty in external exposure at those levels.

Process for dose estimation

In the first step of our methodology, we evaluated all information available in the Nuclear Test Review and Information Systems database (NuTRIS)[4] and NTPR literature on the veteran's potential sources of exposure along with the NTPR-estimated doses for each source. If the individual's exposure scenario was well established and the sum of all the NTPR doses was clearly less than the decision level of 5 mSv, the NTPR dose was converted to organ dose using appropriate organ dose coefficients and recorded in a database. If the total dose is not clearly less than the decision level, the doses recorded in NuTRIS were adjusted to provide a more realistic dose. These adjustments included

- Making use of more current information.
- Correcting obvious errors in the NuTRIS entries.
- Replacing suspect film badge data with reconstructed doses.
- Accounting for sources and time periods of exposure not included in NuTRIS.

More detailed custom dose reconstructions were performed when the probability of occurrence of a potential scenario needed to be estimated to calculate a dose, when there was no NTPR-estimated dose for a potential exposure, or when there was no generic NTPR dose reconstruction that applied to the particular source of exposure. About two-thirds of the cases with total dose deemed not clearly less than the decision level required some custom dose reconstruction.

Next, the uncertainty in our final dose estimate for each source of exposure was estimated. The final step was to total the exposures from all sources, convert to annual organ dose, and calculate a total uncertainty for each annual dose.

Scenarios of exposure

The scenario of exposure accounts for the time, duration, location, duties, and other factors that resulted in a veteran's exposure to radiation. Developing realistic scenarios of exposure was a key step toward estimating dose. Although individual scenario development was carried out during the NTPR program in support of claims for compensation, NTPR dose estimates for most of our cohort did not account for possible individual-specific activities and instead assumed the same generic exposure for all members of a unit.

Scenarios of exposure were divided by location, series, and type allowing for efficient consideration of the commonalities across the following broad categories:

- Ship-based scenarios at the PPG.
- Land-based scenarios at the PPG.
- Maneuvers, observers, and other activities at the NTS.

Broken down in this fashion, scenario similarities allowed for transfer of knowledge gained in one situation to be applied to similar situations. This categorization was particularly important for unique pathways that were appropriate for more than one type of individual.

Duties for most military personnel could be generally inferred from the branch of service, the unit, and the person's rate or pay grade (enlisted) or rank (officers).

Adjusting for bias and error in the NTPR dose

There are instances where the NTPR dose for a particular activity was known or believed to be systematically high-sided (biased) or where errors were made related to assumptions about exposures or model parameters. These instances were identified and adjusted to remove the effect of bias or error in the NTPR dose. Table 1 lists examples of several key instances of NTPR bias or error that required an adjustment to the NTPR dose and the approximate range of the adjustment. Detailed information about the methodology used to correct for errors and deliberate bias is provided in Till et al. (2014).

Accounting for uncertainty

A key component of dose estimation is the uncertainty. Our methodology separated uncertainty into two fundamental areas: uncertainty associated with defining the scenario of exposure and uncertainty in the dose for the given scenario.

Scenario uncertainty

Scenario uncertainty represents the degree to which an individual's location, responsibilities, and activities at a specific time are known. This uncertainty was first addressed separately in a qualitative manner for each potential source of exposure using the following three categories:

- A = individual's activities and duties are well known, or potential dose for the individual clearly falls below the dose reference level for the study, described previously.
- B = individual's activities and duties are less well known, but some aspects can be inferred from other information to estimate the probability of actually being exposed.
- C = individual could possibly have been exposed, but very little to nothing is known about the individual's activities and duties and, thus, very little can be inferred about the probability of actually being exposed.

These three categories of uncertainty were quantified by assigning estimated probabilities to the likelihood that each exposure occurred (Beck et al. 2017).

Individual variability in exposures

The uncertainty in an individual's dose depends both on the uncertainty in the mean exposure corrected for NTPR bias and on uncertainty due to individual variability. Any individual's dose will vary about the assigned mean dose, for example, due to differences between an individual's time spent shielded while indoors or below deck, spatial differences in exposure rates, and differences in specific duties within the unit. In some cases, we removed some of this uncertainty by applying corrections based on a crew member's rating and rank. For most cases, all members of a unit were assigned the same mean dose for a given activity by NTPR. In these cases, because we had no precise information on the actual location and specific duties of an individual crew member on an island or ship, it was important to include this variability as part of the total uncertainty in the veteran's exposure. The estimated coefficient of variance based on film badge readings on ships and islands varied from as little as 20% to as much as 70–80%.

Thus, for each source of exposure, the uncertainty in the exposure, assuming such exposure actually occurred, was estimated either from the mean and the dispersion in available film data if sufficient film data were available, from NTPR model calculations, or both. Of particular help was an initiative by NTPR to revise its previous high-sided uncertainty estimates for many scenarios to develop unbiased stochastic estimates of total uncertainty (Weitz et al. 2009). These stochastic estimates of uncertainty generally confirmed that most NTPR point estimates of upper-bound doses from external radiation exposure (95% CI) were less than about a factor of 3 above the estimated "unbiased" mean dose.

Probability of participating in specific activities

The NTPR generally assigned all individuals who could have participated in a particular activity a dose based on having participated, even if the probability of their participation was low. Examples are observing a particular shot at NTS, operating a small boat in contaminated water, boarding a target ship, or participating in rest and recreation on an island. This often resulted in a significant overestimate in the dose to some cohort members.

At the PPG, an activity that could have resulted in significant exposure was the re-boarding of target ships, usually by their original crews, for repairs, decontamination, or the retrieval of salvageable items (Till et al. 2014). In some cases, the ship's log notes which crew members participated in these boarding parties, along with the time a boarding party embarked and when it disembarked the target ship. In other cases, the ship's log notes a boarding party embarked but does not provide details about who participated. Knowledge about which crew members were most likely to re-board target ships was key to estimating uncertainty.

The probability of participating in any particular re-boarding was estimated by knowing the rank and rating of veterans who participated and the total number of these rank and ratings for the target ship crew. By combining available data from several types of ships, a general pattern emerged about which crew members were most likely to have participated in boarding parties and the probability of their boarding. This information allowed us to develop probabilities of boarding a target ship by rank and rating.

A similar approach was taken for calculating the probability of other activities. Based on all available data, the probability, p, of participation in a given activity was estimated, along with an uncertainty in this probability estimate. Often, the uncertainty in p was only crudely estimated due to lack of actual data. This estimated probability of participation, p, was combined with the uncertainty in the exposure, if the exposure actually occurred, to estimate the unconditional uncertainty in exposure. For example, if the probability of

boarding a target ship on a particular day was $p = .5$ and the uncertainty in the exposure, E, assuming it occurred, had a coefficient of variation of ~0.35–0.40, the coefficient of variation in the assigned exposure (0.5 * E) would be ~1.1.

Shared and unshared uncertainties

As for any estimate of risk based on dose for an epidemiological study, both the total uncertainty and the type of uncertainty are important. In particular, it is important to understand how much uncertainty is shared among individuals (Stram and Kopecky 2003). An example of shared uncertainty would be the uncertainty that arises if a single-dose estimate is assigned to all members of a unit participating in a maneuver after a detonation, since any error in the models and measurements used to calculate the estimate would be the same for all exposed. If a model overestimates the average dose by 50%, everyone's dose would be overestimated by an average of 50%. In contrast, the uncertainty in dose to two individuals exposed to fallout at different test series is unshared (uncorrelated) since the doses are based on completely different sets of measurements. Note that shared uncertainty, when present, can coexist with unshared uncertainties. Continuing the example, each member of a military unit had a certain probability of being absent from his unit's maneuver following a test detonation, and it is plausible that one person's absence was unrelated to the absence of anyone else in his unit. Similarly, each person's actual dose coefficient for a given organ differs from the mean value by an unknown amount, which is independent of everyone else's dose coefficient.

Consideration of classical (measurement) error as opposed to Berkson-type error is also important since classical-type errors can result in a reduction of the slope of the dose-response curve while unshared Berkson-type errors will not (Stram and Kopecky 2003; NCRP 2009). Our review of shared and unshared uncertainty in this study suggests there is, in the aggregate, relatively little shared uncertainty among members of the study group. This finding is due largely to the small number of study participants who served in the same unit at the same time and who were assigned a dose based on the same measurements. Most of the unshared uncertainty for members of the same unit is Berkson-type error. For example, although the same dose due to fallout is assigned to all unbadged personnel present on Enewetak island for a given time period, based on the mean of available film badge data for those badged, the uncertainty in any individual's "true" dose is due primarily to individual variations about this mean from variations in shielding (time indoors), location, and specific duties. The uncertainty in the mean itself, while shared classical type uncertainty, is usually small compared to the variability about the mean.

Total organ dose

The total radiation exposures from all sources are combined, and the total associated uncertainty was computed by combining the unconditional variances for all the individual's sources of exposure. The sum of all free-in-air exposures was then multiplied by a dose coefficient that converts the estimate of total exposure to organ dose, in this case to dose to red bone marrow (6.6 mGy R^{-1}) or male breast (7.9 mGy R^{-1}). Although a rotational incidence is generally more representative than an isotropic or other angular distribution (NCRP 2009) because the angular incidence will differ depending on activity and location (ship versus land), values between rotational and isotropic were adopted with a bias more toward the rotational (Beck et al. 2017). The conversion factors for converting from exposure to organ dose were assumed to have an uncertainty (GSD =1.2) which is due mainly to individual variations in actual angular incidence, in body and organ size, and in energy spectra of the incident gamma radiation.

Results

The doses to the atomic veterans in the sub-cohort were relatively low with about two-thirds of the atomic veterans receiving red bone marrow (RBM) doses <5 mGy and only a small fraction receiving doses >50 mGy. The average RBM dose for the cohort subset was 5.9 mGy. Each male breast dose is ~20% greater than the corresponding RBM dose. Detailed breakdowns of estimated doses and corresponding uncertainty by test series, test site, military service, and military rank are given in Beck et al. (2017).

The doses varied somewhat by test series with the highest doses to participants in the PPG CASTLE test series in 1954 due in a large part to the heavy fallout encountered by some naval vessels after the 1 March 1954, BRAVO test. Although 34% of the sub-cohort participated only in the 1946 CROSSROADS test series, a far greater percentage than for any other test series, their doses were low in comparison to those participating in most of the other later test series.

The mean uncertainty in the estimated doses, expressed in terms of the CV, was much lower for the REDWING, PLUMBBOB, and HARDTACK I test series than for earlier test series, primarily because almost all veterans participating in these test series were issued film badges.[5] Previously, only cohort badges were issued to one or two members of a unit performing similar duties or to individuals expected to receive a meaningful exposure. Although the mean CV for all test series was <0.5, the range of CV varied considerably with a few as high as CV =3.4.[6]

There was little variability in doses between test sites although the environmental characteristics and troop activities at the NTS and the PPG varied greatly. We also found no significant variation in dose between the branches of service (Air Force,[7] Army, Marines, and Navy) at each site. Although the mean dose was similar for those participating only in NTS tests or only in PPG tests, the maximum dose was greater at the PPG. Far more atomic veterans served at the PPG than at the NTS, again due to the large participation, mostly Navy, at the 1946 CROSSROADS test series. Approximately, 80% of the Army participation was at the NTS while almost all the Navy participation (~98%) was at the PPG. Air Force participation was greater at the PPG than

Table 2. Distribution of total red bone marrow (RBM) and male breast (MB) doses.

	This study – RBM		This study – male breast		NuTRIS[a]	
Dose range (mGy)	# of individuals	% of 1982 calculated doses	# of individuals	% of 1982 calculated doses	% of entire ~115,000 NuTRIS doses	% of entire ~115,000 adjusted NuTRIS doses
<5	1,312	66.2	1,257	63.4	55.7	68.4
5–10	304	15.3	304	15.3	17.5	15.0
10–20	214	10.8	216	10.9	12.6	9.8
20–50	148	7.5	195	9.8	12.5	6.3
50–100	3	0.15	8	0.4	1.5	0.36
[b]1–300	1	0	2	0.1	0.21	0.09
[b]>300	0	0	0	0	0.035[c]	0.02

[a]NuTRIS doses were reported as mean whole-body doses and thus would be comparable to red bone marrow doses and about 20% smaller than male breast doses.
[b]The maximum calculated RBM dose was 108 mGy. The maximum sub-cohort NuTRIS dose is 199 mGy.
[c]The maximum NuTRIS dose (entire cohort) is 908 mGy.

at the NTS, and the doses to Air Force personnel at the NTS were much smaller than at the PPG. The higher Air Force doses at the PPG were because Air Force personnel (as well as Army and some Navy and Marine) at the PPG were housed on islands that frequently were contaminated by fallout. Nevertheless, the average uncertainty (CV) is comparable for our reconstructions of NTS and PPG participants even though, as discussed in Till et al. (2014), the exposure scenarios at the NTS were often very different from the exposure scenarios at the PPG. The small number of individuals who participated in tests at both the NTS and PPG received, on average, much higher doses.

Although there were many more enlisted personnel than officers who participated in the tests, there was generally little difference in officer versus enlisted doses. Navy officers received slightly higher doses than enlisted personnel, due in part to the fact that officers almost always led the boarding parties that inspected and decontaminated target ships.

We also compared the calculated RBM doses from the current study with the corresponding NuTRIS doses (Beck et al. 2017). The RBM doses were generally 30–40% lower than those estimated by NTPR from their generic dose assessments. The overall correlation was quite good (RBM dose =0.64 * NuTRIS dose, 95% C.I. = 0.61–0.67), although there were some comparisons that deviated significantly from the general trend. The correlation was somewhat better for higher doses due primarily to the fact that many of those doses were based on film badge dosimetry and thus were more precise. The dose distributions of the calculated RBM and male breast doses are given in Table 2. The distribution of male breast doses differs slightly from the RBM distribution since each male breast dose is ~14% higher than the corresponding RBM dose. The distribution of NuTRIS doses for the entire ~115,000-person cohort is also shown, as well as the distribution after multiplying the cohort NuTRIS doses by the 0.64 ratio of NuTRIS to reconstructed doses described above. Because most of the calculated doses were for the randomly selected 1% of the entire cohort, the distributions of NuTRIS doses for the sub-cohort are very close to that of the NuTRIS doses for the entire 115,000-person cohort. However, while the maximum calculated RBM NuTRIS dose for this sub-cohort was 199 mGy (127 mGy after adjustment) and the maximum calculated RBM dose for this study was 108 mGy, the maximum NuTRIS dose for the entire cohort is ~900 mGy (580 mGy after adjustment). About 0.05% (~60) of the ~115,000 NuTRIS doses are >200 mGy.

Discussion

The average NuTRIS dose to the entire ~115,000-person cohort is 9.0 mGy, which if adjusted by the 0.64 ratio of NUTRIS to reconstructed RBM doses, results in an estimated cohort mean RBM dose of 5.8 mGy, very close to the mean dose for the sub-cohort calculated from the current study.

The uncertainty in most of the dose estimates was also small, averaging about CV =0.4–0.5.[8] The CV ranged from as low as 0.2, when most of the exposure was based on film data, to CV >3 when the exposure scenario was very uncertain. The CV was generally slightly less for the higher doses (mean CV=~0.3 for doses >30 mGy) due primarily to the fact that persons likely to receive significant exposure were more likely to have been issued a film badge.

The magnitude and the range of our uncertainties in organ dose are comparable to the estimated uncertainty in the reconstructed dose to the members of the Japanese Life Span Study (Young and Kerr 2005) and relatively small compared to those typically observed in most historical dose reconstructions of exposure from radionuclides in the environment, particularly studies involving significant internal dose (Beck et al. 2017).

The reasons for the relatively low and narrow range of uncertainty in our study include the availability of some film-badge data, detailed environmental monitoring data in fallout fields at test sites, and comparatively well-known exposure conditions based on knowledge of the individual veterans' locations and activities from military records. Furthermore, reconstructing doses from external exposure generally involves much lower uncertainty than when internal exposure needs to be considered since internal dose cannot generally be measured directly.

Limitations of methodology and opportunities for further study

One challenge in this study was to accurately estimate the exposure scenario for individuals who could have participated in a particular activity but it was not known if they did. This is, however, reflected in the estimated uncertainty.

Table 3. Organ doses (mGy) from external radiation exposure expressed as a ratio to the RBM dose (mGy).

Organ	Ratio to RBM[a]
Bone surface	1.10
Brain	1.11
Breast (male)	1.14
Heart	0.97
Liver	0.95
Prostate	0.92
Salivary gland	1.20
Testes	1.04
Thyroid	1.13

[a]RBM dose =1.0 (0.65 rad/R or 6.5 mGy/R).

Furthermore, estimating the probability of exposure to a given source along with the uncertainty in that exposure, if it occurred, was also a unique feature of this study compared with some of the other case–control studies discussed in this report where individual dose records were available for most participants.

Another limitation was the unavailability of original measurement data to validate various NTPR generic dose assessments. This limitation, coupled with limited availability of film badge data for some units, often made it difficult to estimate the bias in NTPR generic unit dose assessments for the individual unit members.

Assessing the validity of some of the reported film badge data also limited this study, particularly for test series where it was known some of the badge data was suspect.

An unexpected outcome of this study was the relatively good correlation between our reconstructed doses and the corresponding NTPR dose estimates. This suggests that it is possible to use the NuTRIS doses (which are available for the entire cohort), multiplied by an appropriate scaling factor (slope of the dose-reconstructed doses for the sub-cohort versus NuTRIS doses as determined in this study) to obtain estimates of risk from external radiation exposure for additional organs. The NuTRIS adjustment factor of 0.64 identified for RBM doses can be scaled by the respective ratios of exposure-to-dose coefficients for gamma rays for testes, brain, and heart to RBM (ICRP 2010) (Table 3) to estimate the corresponding organ-absorbed doses from external exposure. This assumption is supported by the fact that when the risk estimates for leukemia and male breast cancer based on the case-cohort study design are compared with corresponding risk estimates using the entire 115,000-person cohort with adjusted NuTRIS doses, nearly identical results are obtained (Boice et al. 2019). Comparison of our atomic veteran doses with NuTRIS doses for individual test series suggest the method may even be improved by using separate adjustment factors for each test series.

The dosimetry developed for the Atomic Veterans Study was designed to meet key criteria recommended for environmental dose reconstruction as described in NCRP Commentary 27 (NCRP 2018) and Till et al. (2017). These criteria include consideration of shared and unshared dosimetry, dose validation, and dose confounders among others. Therefore, with the large study size and generally low doses, the Atomic Veterans Study makes one of the largest cohorts with high quality dosimetry and low uncertainties available to researchers in the Million Person Study.

Only minimal additional effort would be required to estimate external dose for additional cancer cases for a more accurate case-cohort analysis. This is because external exposure in air for the 1% random selection component of the case-cohort has already been calculated. Adrenals, brain, kidneys, pancreas, spleen, testes, heart, and bladder are all organs where internal exposure to atomic veterans is also believed to have been negligible compared to external exposure (Weitz et al. 2009; Case et al. 2011). Internal dose to some organs for some veterans, although still generally less than external dose, could have been meaningful for the stomach, intestines, liver, lung, bone, and in particular, thyroid, and would require additional effort and resources to assess.

Although the doses to atomic veterans were found to be generally low, a key contribution of this project has been the development of a methodology to characterize exposure scenarios for any specific veteran in the absence of individual-specific dosimetry or individual interviews. The exposure scenario methodology, which comprises an essential component of the dosimetry, has provided a significant contribution to our understanding of the unique exposure circumstances encountered by these veterans and the likelihood that any individual participated in activities that resulted in his exposure. Previously, such detailed evaluations had only been completed for a small number of veterans filing a compensation claim.

Understanding the extent to which doses may have been overestimated is an important finding, not only for this epidemiologic study and to the veterans themselves but also to policy makers who may design and implement compensation programs in comparable situations.

Disclosure statement

No potential conflict of interest was reported by the authors.

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Notes

1. The Pacific Proving Grounds was renamed Enewetak Proving Ground prior to the HARDTACK I test series in 1958.
2. A large number of unmanned "target" ships were anchored close to surface zero during the CROSSROADS test BAKER. Some of these ships were later re-boarded to assess damage and to decontaminate if possible.
3. The predecessor of DTRA was the Defense Nuclear Agency (DNA) whose legacy goes back to the Manhattan Project, which directed the development of the first atomic weapons. The DTRA program has been ongoing since the early 1980s.
4. NuTRIS (Nuclear Test Review Information System) is a database developed and populated by NTPR that contains all of the pertinent information about each veteran including the dose estimated by NTPR.
5. Although, as discussed in Till et al. (2014), some of the film badges for REDWING suffered environmental damage, those doses were replaced by reconstructed doses and thus the uncertainties in total dose were not significantly impacted.
6. A CV of 0.5 would correspond to a geometric standard deviation (GSD) of 1.6 while a CV of 3.4 would correspond to a GSD of ~5, assuming the uncertainty distributions are approximately lognormal.
7. The Air Force was not a separate branch of service until 1947; thus, "Air Force" participants at TRINITY and CROSSROADS were actually in the Army Air Force.
8. Corresponding to GSD ~1.5–1.6, assuming an approximate lognormal distribution.

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