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RADIATION DOSES AND CANCER RISKS IN THE MARSHALL ISLANDS ASSOCIATED WITH EXPOSURE TO RADIOACTIVE FALLOUT FROM BIKINI AND ENEWETAK NUCLEAR WEAPONS TESTS: SUMMARY

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Abstract

Nuclear weapons testing conducted at Bikini and Enewetak Atolls during 1946–1958 resulted in exposures of the resident population of the present-day Republic of the Marshall Islands to radioactive fallout. This paper summarizes the results of a thorough and systematic reconstruction of radiation doses to that population, by year, age at exposure, and atoll of residence, and the related cancer risks. Detailed methods and results are presented in a series of companion papers in this volume. From our analysis, we concluded that 20 of the 66 nuclear tests conducted in or near the Marshall Islands resulted in measurable fallout deposition on one or more of the inhabited atolls of the Marshall Islands. In this work, we estimated deposition densities (kBq m^{-2}) of all important dose-contributing radionuclides at each of the 32 atolls and separate reef islands of the Marshall Islands. Quantitative deposition estimates were made for 63 radionuclides from each test at each atoll. Those estimates along with reported measurements of exposure rates at various times after fallout were used to estimate radiation absorbed doses to the red bone marrow, thyroid gland, stomach wall, and colon wall of atoll residents from both external and internal exposure. Annual doses were estimated for six age groups ranging from newborns to adults. We found that the total deposition of ^{137}Cs, external dose, internal organ doses, and cancer risks followed the same geographic pattern with the large population of the southern atolls receiving the lowest doses. Permanent residents of the southern atolls who were of adult age at the beginning of the testing period received external doses ranging from 5 to 12 mGy on average; the external doses to adults at the mid-latitude atolls ranged from 22 to 59 mGy on average, while the residents of the northern atolls received external doses in the hundreds to over 1,000 mGy. Internal doses varied significantly by age at exposure, location, and organ. Except for internal doses to the thyroid gland, external exposure was generally the major contributor to organ doses, particularly for red bone marrow and stomach wall. Internal doses to the stomach wall and red bone marrow were similar in magnitude, about 1 mGy to 7 mGy for permanent residents of the southern and mid-latitude atolls. However, adult residents of Utrik and Rongelap Island, which are part of the northern atolls, received much higher internal doses because of intakes of short-lived

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radionuclides leading to doses from 20 mGy to more than 500 mGy to red bone marrow and stomach wall. In general, internal doses to the colon wall were four to ten times greater than those to the red bone marrow and internal doses to the thyroid gland were 20 to 30 times greater than to the red bone marrow. Adult internal thyroid doses for the Utrik community and for the Rongelap Island community were about 760 mGy and 7,600 mGy, respectively. The highest doses were to the thyroid glands of young children exposed on Rongelap at the time of the Castle Bravo test of 1 March 1954 and were about three times higher than for adults. Internal doses from chronic intakes, related to residual activities of long-lived radionuclides in the environment, were, in general, low in comparison with acute exposure resulting from the intakes of radionuclides immediately or soon after the deposition of fallout. The annual doses and the population sizes at each atoll in each year were used to develop estimates of cancer risks for the permanent residents of all atolls that were inhabited during the testing period as well as for the Marshallese population groups that were relocated prior to the testing or after it had begun. About 170 excess cancers (radiation-related cases) are projected to occur among more than 25,000 Marshallese, half of whom were born before 1948. All but about 65 of those cancers are estimated to have already been expressed. The 170 excess cancers are in comparison to about 10,600 cancers that would spontaneously arise, unrelated to radioactive fallout, among the same cohort of Marshallese people.

Introduction

The Marshall Islands atolls were administered by the United States as a United Nations Trust Territory from 1947 until 1986 when the Republic of the Marshall Islands was established as a sovereign nation in free association with the United States. Previous to those years, the Marshall Islands were administered by Japan under a League of Nations mandate, and were the site of many important battles of the Pacific during World War II. After World War II, the United States established the Pacific Proving Grounds for testing nuclear weapons. From 1946 through 1958, 65 nuclear weapons tests, in seven series, were carried out by the United States at Bikini and Enewetak Atolls located at the northwestern end of the archipelago that makes up the Marshall Islands (Fig. 1) and one additional test was carried out 100 km to the west of Bikini. The total explosive yield of the 66 tests was approximately 100 Mt (equivalent to 100 million tons of trinitrotoluene or TNT) (U.S. DOE 2000; Simon and Robison 1997; Simon 1997), about 100 times the total yield of the atmospheric tests conducted at the Nevada Test Site. Radioactive debris from the detonations, dispersed in the atmosphere, was generally blown by the predominantly easterly winds towards the open ocean west of the Marshall Islands, though various historical reports (e.g., Breslin and Cassidy 1955; DNA 1979) indicate that radioactive debris from a number of tests traveled in other directions. The radioactive debris generated by the tests that eventually fell to the ground is termed fallout and was the single source of the exposures of the Marshallese people described in this report. According to our analysis, twenty of the 66 tests that were carried out in or near the Marshall Islands resulted in measurable fallout in the Marshall Islands (Table 1). Of special significance was the largest test conducted in the Marshall Islands, code-named Castle Bravo, a 15-Mt thermonuclear device tested on 1 March 1954. As a result of unexpected wind shear conditions, heavy fallout of debris from Bravo on atolls east of the Bikini Atoll test site resulted in high radiation doses to the populations of nearby atolls.

While the populations of Bikini and Enewetak were relocated before the testing began, other populations were evacuated following the Bravo test. Within about two days following the detonation of the Bravo test and the unexpected fallout on atolls to the east, the resident populations of Rongelap (including some Rongelap residents temporarily present on Ailinginae) and Utrik, as well as American military weather observers on Rongerik, were evacuated to avert continued exposure, to be decontaminated, and to receive immediate medical care for conditions of acute exposures (Cronkite et al. 1997).

In the month after the Bravo test, ^{131}I, an important radionuclide in fallout, was measured in urine collected about two weeks after the Bravo event from adults exposed on Rongelap, Ailinginae, and Rongerik (Harris 1954; Harris et al. 2010). Those measurement data have proved to be of significant value for reconstruction of internal dose for those groups. For example, Brookhaven National Laboratory used the activity measurements in urine as well as other data and assumptions to estimate internal thyroid dose for persons exposed on Rongelap, Ailinginae, and Utrik (Lessard et al. 1985). Internal doses from long-lived radionuclides on Rongelap and Utrik also were estimated by Lessard et al. (1984) using whole-body and bioassay data collected years after the Bravo test.

The U.S. Government through Brookhaven National Laboratory and other institutions has provided decades of medical care, health surveillance, and documentation of health effects among the highly exposed Marshallese from Rongelap/Ailinginae and Utrik (see for example, Conard et al. 1970, 1980; Cronkite et al. 1997), but only two epidemiologic studies have ever been conducted, one of benign thyroid disease (Hamilton et al. 1987) and one of benign thyroid disease and thyroid cancer (Takahashi et al. 1997, 2001). To date, there has not been a broad epidemiologic study of the Marshallese to determine the total numbers of cancers and other serious illnesses resulting from exposure to radioactive fallout. Nor has there been reliable diagnoses and recording of cancers among the general Marshallese population over the years since the nuclear testing ended that would now permit comparing their cancer rates with rates at other locations worldwide.

In 2004, the Senate Committee on Energy and Natural Resources asked the National Cancer Institute (NCI) for its “expert opinion” on the estimated number of baseline cancers ‡ and radiation-related illnesses from nuclear weapons testing in the Republic of the Marshall Islands. The Division of Cancer Epidemiology and Genetics (DCEG) of the NCI was tasked with developing a response because of its robust research program in radiation epidemiology and many years of experience in reconstruction of fallout-related doses and in cancer risk estimation. For that purpose, we developed unrefined estimates of radiation doses and numbers of radiation-induced cancers (DCEG 2004), based on: (1) 1954 measurements of ^{131}I in the urine of adults exposed on two atolls, Rongelap and Ailinginae, collected after the test Bravo in 1954; (2) measurements made in 1957–1977 of the contents of ^{137}Cs and other radionuclides in the bodies of inhabitants of Rongelap and of Utrik who returned to their atolls in 1957 and 1954, respectively; and (3) measurements of total ^{137}Cs and plutonium in soil from each atoll obtained for all atolls from the Marshall Islands-sponsored radiological survey completed in 1994 (Simon and Graham 1997). We combined those elements using a simple analytic approach to develop crude estimates of the number of cancers likely to be radiation-induced among those living in 1954. This was, to our knowledge, the first time radiation doses and numbers of radiation-induced cancers had been estimated in a systematic manner over the entirety of the territory of the Marshall Islands. Our unrefined estimates were generally conservative and were intended to avoid under-estimation of the number of cancers that might occur. These initial results were presented during joint hearings of the House of Representatives Committee on Resources and the Committee on International Relations in May 2005 (United States 2005). Following these joint hearings, we improved the models and data analysis to derive more realistic estimates of external and internal radiation dose by year, atoll, and age, as well as improved estimates of cancer risks. Those estimates and the methods on which they are based are the subject of this Summary paper and its companion papers.

The purpose of this group of papers is to present, in the peer-reviewed literature, a summary of the most important data that are available and that are useful for dose reconstruction, a detailed analysis of fallout deposited on each of the atolls of the Marshall Islands from nuclear weapons tests at Bikini and Enewetak, improved estimates of radiation doses, and improved estimates of cancer risks resulting from exposure to the fallout. These estimates are based on a much deeper analysis of the available data than in DCEG (2004) and on models developed especially for this study. Although numerous studies have been conducted over the past decades to monitor the Marshall Islands and people, to develop land remediation strategies, and to assess contemporary and possible future doses that might be received by inhabitants of certain atolls in the Marshall Islands, the focus was more often on radiological monitoring, and on the northern Marshall Islands in particular. Many of those studies were chronicled in a special issue of Health Physics (Simon and Vetter 1997). The current study, however, is the first comprehensive effort to estimate the deposition of all the important radionuclides contributing to dose and to estimate the doses and associated cancer risks to the population of the Marshall Islands.

Detailed information on the technical aspects of this work and on the results of all parts of the study are provided in the seven companion papers in this volume, including:

- the estimation of the amounts of fallout that were deposited on the ground over each atoll and separate reef island of the Republic of the Marshall Islands (Beck et al. 2010);
- the estimation of doses from external irradiation (Bouville et al. 2010);
- the estimation of the doses from internal irradiation (Simon et al. 2010);
- the estimation of the cancer risks (Land et al. 2010);
- bioassay data important to internal dose estimation (Harris et al. 2010) and interpretation of intake-related dosimetric factors (Ibrahim et al. 2010); and
- a model of atmospheric transport and deposition that was used to provide confirmation of the reliability of some of the estimated depositions (Moroz et al. 2010).

The present paper summarizes the purposes and methods of the overall study and the estimated radiation doses and related cancer risks, as well as presents data that are common to all of the above papers, including the nuclear tests, the radionuclides considered, and the population sizes and their movements during the testing period.

SCOPE OF THE STUDY

The overall purposes of this study were to derive an internally consistent set of radiation absorbed doses to Marshallese alive during and after the years of nuclear testing in the Marshall Islands and to provide a thorough description of methods used in the dose reconstruction, to estimate the number of cancers that had already occurred and that could be attributed to radiation exposure, and to estimate the number of radiation-related cancers yet to occur. The dose and risk assessment includes all Marshallese population groups and takes into account the size of the population of each atoll community, the baseline cancer risks (i.e., cancers unrelated to fallout exposure), and all of the Bikini and Enewetak nuclear tests that resulted in fallout over the territory of the Marshall Islands.

As indicated in Beck et al. (2010), we estimated that, of the 66 nuclear tests detonated in or near the Marshall Islands from 1946 through 1958, 20 tests deposited measurable fallout in the Marshall Islands excluding the atolls on which the test sites were located (Fig. 1). These tests were: Yoke in 1948; Dog and Item in 1951; Mike and King in 1952; Bravo, Romeo, Koon, Union, Yankee, and Nectar in 1954; Zuni, Flathead, and Tewa in 1956; and Cactus, Fir, Koa, Maple, Redwood, and Cedar in 1958. The characteristics of these 20 tests are presented in Table 1. Each of these 20 tests was taken into account in the estimation of radiation doses and cancer risks.

There are 30 atolls and four separate reef islands in the Marshall Islands. Ground deposition densities were estimated for 63 radionuclides plus 239,240Pu for all the atolls and separate reef islands except the two atolls where the testing sites were located (Bikini and Enewetak). However, some of the atolls were not inhabited during all or part of the testing period either because they were historically used only for gathering food (Ailinginae, Bikar, Erikub, Jabat, Jemo Island, Knox, Taka, and Taongi) or because the residents were relocated for safety reasons (Bikini and Enewetak) or evacuated due to unexpected exposures (Ailinginae, Rongelap, Rongerik, Utrik). Thus, radiation doses were estimated for 26 population groups, including the residents of the 23 atolls and islands that were inhabited during the years of nuclear testing (Table 2), and three other groups: persons from Rongelap who were on Ailinginae at the time of the Bravo test, persons from Rongelap who were visiting the southern atolls at the time of the Bravo test, and U.S. military weather observers on Rongerik. For the consideration of cancer risks, only the 25 Marshallese population groups were considered. Both the dose and cancer risk assessment explicitly included members of the six Marshallese groups that were relocated or evacuated during the testing period: (1) 64 persons evacuated from Rongelap Atoll after the Bravo test; (2) 18 persons from Rongelap evacuated from Ailinginae Atoll after the Bravo test; (3) 117 persons from Rongelap who were visiting the southern atolls at the time of the Bravo test; (4) 157 persons from Utrik Atoll evacuated after the Bravo test; and the populations that normally resided on (5) Enewetak Atoll and (6) Bikini Atoll but who had been relocated to Ujelang Atoll and Kili Island, respectively, before the testing program began. Population data for all atolls and reef islands of the Marshall Islands at various times including the years of the nuclear testing period are presented in Table 2. Information on the dates of evacuation and on the places of relocation is provided in Table 3.

Radiation absorbed doses to the thyroid, red bone marrow (RBM), stomach wall, and colon wall were estimated for members of the 25 Marshallese population groups by age group (children under 1 y, 1–2 y, 3–7 y, 8–12 y, 13–17 y, and adults) and for the U.S. military personnel on Rongerik. Those specific organs and tissues were selected because they are expected to give rise to the largest number of cancers for reasons noted below:

- The thyroid gland, far more than any other organ, concentrates radioiodine, which is amply produced by detonations of nuclear weapons;
- Irradiation of the blood-forming cells in the RBM was caused mainly by external exposure to gamma-emitting radionuclides but also by internal exposure to radiostrontiums, and would be expected to have increased the risk of leukemia, which has shown an especially strong relationship with radiation exposure in many epidemiologic studies; and
- The stomach and colon walls can be highly exposed after ingestion of fallout because many of the radionuclides produced by nuclear fission are highly insoluble, even in the gastrointestinal tract, thereby irradiating the stomach and colon as they pass through it.

The skin was also a tissue potentially exposed to fallout radiation. Marshallese who received significant amounts of fallout directly onto their body, e.g., at Rongelap where skin “burns” were documented, would have received high skin doses primarily from beta particles emitted during radioactive decay. In this analysis, we have not estimated the dose to skin or the number of skin cancers that might be produced as a consequence of exposure to fallout, primarily for two reasons: (1) there are no baseline non-melanoma skin cancer data reported by the Surveillance, Epidemiology and End Results (SEER) program and other U.S. cancer registries, and the baseline risks are an essential part of the calculation to estimate the number of cancers, and (2) the number of personal injury claims awarded by the Marshall Islands Nuclear Claims Tribunal indicates that, among the 2,046 awards made through June 2004, there were 72 awards for skin burns, but only one award for skin cancer (Marshall Islands NCT 2004). Hence, it appears that, despite potentially high doses to the skin to at least a small subset of the Marshallese, there is little evidence that the risk of skin cancer is great among Marshallese.

Estimated doses were derived for “representative” persons, that is, for persons who could be described to have habits, lifestyles, diet, and anthropometric characteristics typical of the Marshall Islands population for their age and sex (except in the case of military servicemen on Rongerik). Doses were assessed on a yearly basis for exposures occurring from 1948, the year in which the first relevant test took place, to 1970, when the residual environmental contamination had reached negligible levels on most atolls. These estimated annual organ doses were necessary input data for the cancer risk calculations.

The estimated total radiation absorbed doses include three components: (1) doses from external irradiation emitted by fallout deposited on the ground; (2) doses from internal irradiation from acute radionuclide intakes immediately or soon after fallout after each test; and (3) doses due to internal irradiation from chronic (i.e., protracted) intakes of radionuclides resulting from the continuous presence of long-lived radionuclides in the environment. Sixty-three radionuclides, listed in Table 4, were considered in the estimation of internal doses from acute intakes of fallout radionuclides from each test. Based on screening estimates, these 63 radionuclides were estimated to account for over 98% of the internal dose to any organ from acute intakes. In addition, five long-lived radionuclides (55Fe, 60Co, 65Zn, 90Sr, and 137Cs) were considered for the estimation of the internal doses from chronic intakes, including two radionuclides, 60Co and 65Zn, that were not considered in the calculation of the doses from acute intakes. Doses from acute and chronic intakes from cumulative deposition of 239+240Pu were also estimated.

Risks of radiation-induced leukemia and cancer of the thyroid, stomach, and colon, as well as all other cancer types combined, were assessed for the 25 Marshallese population groups on the basis of the estimated radiation doses. Two time periods were considered: from 1948 through 2008 for the assessment of the radiation-induced cancers that have been expressed thus far, and from 2009 onwards for the prediction of cancers that remain to be expressed. For comparison purposes, the numbers of baseline cancers, that is, those unrelated to fallout exposure, are also reported.

SUMMARY OF METHODS AND FINDINGS

A brief overview of methods of the study and a summary of the findings are presented here. Detailed information can be found in individual companion papers. Throughout this section and elsewhere, we discuss findings relative to four groups of atolls or communities. Within each group, resident populations were exposed to similar levels of fallout as a consequence of the dispersion patterns of the nuclear debris clouds. The southern atoll group is well represented by Majuro, which is the national capital today and was home to about one-third of the population of the southern atolls in 1958, while the mid-latitude atolls are best represented by Kwajalein, which was home to about one-quarter of the total Marshall Islands population during the testing years. Our radiological findings for the southern atolls and mid-latitude atolls along with our radiological findings for the Utrik community and for the Rongelap Island community (both from the northern atolls) capture the range of exposures received by Marshallese at all atolls. In the case of Utrik and Rongelap, we define the “community” to be those exposed to fallout from the Bravo test on Utrik and Rongelap, respectively, and who were evacuated after the Bravo test. Our findings illustrate the geographic pattern as well as provide atoll and atoll-group estimates of contamination, organ dose, and cancer risk as well as the dependence on age at exposure.

Fallout activity deposited on the ground

As discussed in Beck et al. (2010), a complete review of various historical and contemporary deposition-related data, some available only in gray literature (e.g., government laboratory reports and internal agency and laboratory memoranda, supplemented by meteorological analyses) was used to make judgments regarding which tests deposited fallout in the Marshall Islands and to estimate fallout deposition density and fallout transit times, otherwsie known as times-of-arrival (TOAs). In some instances, it was necessary to use the results of a well-established model of atmospheric transport and deposition (Moroz et al. 2010) to corroborate or contradict our initial assumptions on the occurrence of fallout on particular atolls after certain tests. The various types of data reviewed for estimating deposition included measurements of 137Cs and other radionuclides in soil (both historical and contemporary), historical measurements of exposure rate following individual tests derived from aerial surveys, ground surveys and continuous-reading monitoring devices (strip-chart recorders), and historical measurements of beta activity collected on gummed film during the years of nuclear testing.

For each atoll, fallout TOAs and the estimated fractionation of fallout were used to estimate deposition density for 63 activation and fission products from each nuclear test, plus the cumulative deposition over all tests of 239+240Pu. Examples of deposition densities of 24 of these radionuclides are presented in Beck et al. (2010).

The estimated total 137Cs activities deposited by all tests from this analysis, after appropriate decay to account for the effective decay rate (radiological plus weathering) in the Marshall Islands and a correction for global fallout from non-Marshall Islands tests, were compared with contemporary measurements of the total 137Cs activities remaining in the soil as measured by investigators in 1978 (Tipton and Meibaum 1981; Robison et al. 1997) and in 1991–1993 (Simon and Graham 1997). This comparison was used to demonstrate the validity of our estimates of total 137Cs deposition density. Our atoll-specific cumulative 137Cs estimates were found to be in excellent agreement with contemporary measurements of 137Cs in soil (Beck et al. 2010).

Our estimates for the 137Cs deposition density and for the corresponding TOA at each atoll and for each of 20 individual tests are presented in tabular form by Beck et al. (2010). Our best estimates of the cumulative 137Cs deposition density from all tests, with 90% uncertainty ranges, are presented in Table 5 and the geographic pattern of total fallout deposition is illustrated in Fig. 2. The cumulative 137Cs deposition densities are much greater on northern atolls (e.g., Rongelap and Rongerik) than on mid-latitude atolls (e.g., Kwajalein) or southern atolls (e.g., Majuro). Table 5, as can be noted, also provides estimates of deposition separately for southern and northern islands in Kwajalein Atoll and in Rongelap Atoll. The deposition densities differed by about 20% between south and north islands of Kwajalein but more than three times between islands of south and north Rongelap Atoll (Table 5), reflecting differences in deposition due either to the large size of the atoll (Kwajalein), or, in the case of Rongelap, to the position of the Bravo debris cloud trajectory relative to location of individual islands in the atoll.

The estimates of radionuclide deposition density, fractionation, and transit times reported in Beck et al. (2010) allowed estimations of both external and internal dose to representative persons as described in companion papers.

Radiation doses

As noted earlier, the estimated doses came from three sources of exposure: (1) external irradiation from fallout deposited on the ground; (2) internal irradiation from acute radionuclide intakes immediately or soon after deposition of fallout from each test; and (3) internal irradiation from chronic intakes of radionuclides resulting from the continuous presence of long-lived radionuclides in the environment.

External doses

The doses from external irradiation arose from gamma rays emitted during radioactive decay of the fallout radionuclides during the passage of the radioactive cloud or after deposition on the ground. Doses received during the passage of the radioactive cloud are generally insignificant compared to those delivered after deposition of fallout on the ground. Exposure during cloud passage was implicitly included by integration of the exposure rate from the initial time of fallout arrival rather than from the time when the exposure rate was at its peak.

The doses from external irradiation were estimated in three basic steps (Bouville et al. 2010):

1. estimation of the outdoor exposure rates at 12 h after each test and of the variation in the exposure rates with time at each atoll after each test;
2. estimation of the annual exposure from 1948 through 1970 and of the total exposure from TOA to infinity, obtained by integrating the estimated exposure rates over time; and
3. estimation of the annual and cumulative absorbed doses to tissues and organs of the body by applying conversion factors from free-in-air (outdoor) exposure to tissue absorbed dose and by assuming continuous residence on the atoll (with corrections for temporarily resettled populations).

The outdoor exposure rates at each atoll were assessed in one of two ways depending on whether reliable measurements of exposure rates were available for a particular nuclear test and atoll combination. If measurement data were available, they were assessed and a best estimate of the average exposure rate at 12 h post detonation (termed E12) on the atoll or reef island was made. If no reliable exposure rate data were available to estimate E12 directly, then the assessment of E12 was derived from the estimates of 137Cs deposition densities and TOA provided in Beck et al. (2010) for each atoll and each test. The method relating the estimates of 137Cs deposition densities and TOA to E12 was developed by the Off-Site Radiation Exposure Review Project (ORERP) for estimating external whole-body dose from fallout originating at the Nevada Test Site (Hicks 1982).

The annual and cumulative exposures derived from the estimate of E12 were estimated by Bouville et al. (2010) using the variation with time of the exposure rate calculated by Hicks (1981, 1984), but modified to take fractionation into account, where necessary, as well as the “weathering effect” which reflects the gradual decrease of the exposure rate caused by the migration of the deposited activity into deeper layers of soil.

The conversion factors from free-in-air (outdoor) exposure to tissue absorbed dose depend on the energy distribution of the gamma rays that are incident on the body and on the organ for which the dose is being estimated. However, for most of the fission and activation products that are created during a nuclear explosion, the gamma-ray energies resulting in external exposure are a few hundred keV or more and the variation in photon energy results in at most a few percent difference in dose per unit incident fluence for the various organs considered in this study (Jacob et al. 1990). Thus, energy and organ dependence in dose conversion factors were not taken into consideration; a single conversion factor, 6.6 × 10–3 mGy per mR, was used for adults for all organs. However, the conversion factor does depend on the age of the person, or, more precisely, her or his body size and shape. Thus, based on calculations using anthropomorphic phantoms that represented different ages (Jacob et al. 1990), our calculated doses to adults from external irradiation were increased by 30% for children less than 3 y of age and by 20% for children 3 y of age through 14 y. While age and body size were important for the estimation of external dose to the organs considered, sex was not. Building shielding was estimated not to be important since houses at that time, made primarily out of palm fronds, did not provide any substantial reduction of gamma ray intensity.

Annual absorbed doses from external irradiation from all important tests were estimated for the time period from 1948 through 1970; that is, until the annual doses had decreased to very low levels in comparison to the peak values observed in 1954. These annual doses were estimated for the relocated populations and for the populations continuously resident on all inhabited atolls of the Marshall Islands in three age categories (infants, children, and adults). The doses reported for the relocated populations include, where appropriate, contributions from exposures received before evacuation, during the period of resettlement, and following return to the atoll of origin (Table 3). Annual doses to adults from external irradiation are presented in Bouville et al. (2010) along with estimated uncertainties; the doses were highest during the years of atmospheric testing in the Marshall Islands, after which they decreased to values that were, in 1970, less than 0.1% of the peak values observed in 1954. Our best estimates of the total external doses (mGy) from all tests and of the 90% uncertainty ranges are presented in Table 5 for representative adults of all 26 population groups. The geographic pattern of total external doses received is the same as for the deposition of 137Cs illustrated in Fig. 2 and, as described, is much higher in the northern atolls than in the central and southern atolls.

Internal doses from acute intakes of radionuclides

The internal radiation doses resulting from acute intakes, defined as those that occurred during or soon after fallout deposition, were assumed to be primarily a consequence of ingesting radionuclides in, or on, debris particles that contaminated food surfaces, plates and eating utensils, the hands and face, and, to a lesser degree, drinking water (Lessard et al. 1985; Simon et al. 2010). Internal doses from other pathways of exposure, in particular, inhalation, were much lower than those due to ingestion and have not been explicitly estimated in this assessment. Fallout particles at northern atolls were typically large (tens to more than one hundred micrometers in diameter) resulting in generally low intakes by inhalation. Fallout deposited at southern atolls, even though generally composed of smaller sized particles, was often deposited with rainfall which significantly reduced the availability of the particles to be inhaled. Annual rainfall rates are three to four times greater in the southern atolls compared to the northern atolls (Arnow 1954).

The methods used in this study for estimating acute intakes of fallout radionuclides and resulting doses are based on: (1) the estimates of test-, atoll-, and radionuclide-specific deposition densities discussed in Beck et al. (2010); (2) historical measurements of 131I in pooled samples of urine collected from adults about two weeks after the Bravo test (Harris 1954; Harris et al. 2010); and (3) assessment of appropriate values of gastrointestinal uptake for the radionuclides present in fallout particles (Ibrahim et al. 2010). The assessment of internal doses was composed of the following six steps: (1) estimation of the intake of 131I by populations on Rongelap, Ailinginae, and Rongerik, following the Bravo test using historical bioassay data; (2) estimation of the intake of 137Cs at the same three atolls based on the ratios of 137Cs to 131I calculated by Hicks (1981, 1984) but corrected for fractionation; (3) estimation of the deposition density of 137Cs following each of 20 tests on all inhabited atolls; (4) estimation of the intake of 137Cs at all inhabited atolls assuming that the ratio of intake to deposition was the same at all atolls; (5) estimation of intakes of all radionuclides considered at all inhabited atolls following each nuclear test; and (6) estimation of annual and cumulative radiation absorbed doses to four organs (RBM, thyroid, stomach, colon) of representative persons for all relevant birth years.

Detailed information on the acute intakes and resulting doses, as well as the estimated uncertainty in these dose estimates, is presented in Simon et al. (2010). The population of the southern atolls had acute intakes estimated to be much smaller than those experienced by the more highly exposed Rongelap and Utrik populations. For example, adult Majuro residents had intakes of about 6% and 9% of the 131I and 137Cs (cumulative over all tests), respectively, of adult Utrik community members, and about 1%, and 2%, respectively, of the intakes of Rongelap community members exposed to Castle Bravo fallout on Rongelap Island (see Table 8, Simon et al. 2010).

Doses to the thyroid gland were much greater than those to the other organs and tissues, and were much greater for the Marshallese who resided on Rongelap and Utrik Atolls at the time of the Castle Bravo test than for the residents of any other atoll (Table 10, Simon et al. 2010). The southern atolls, where about 73% of the population resided during the testing years, received the lowest organ doses. The population of mid-latitude atolls (Kwajalein and others, see Fig. 2), home to about 23% of the total Marshall Islands population during the testing years, received organ doses that were about three times greater than at the southern atolls. The population of Utrik received doses intermediate in magnitude between the mid-latitude atolls and Rongelap, with thyroid doses about 35 times greater than the southern atolls (Table 10, Simon et al. 2010). The Rongelap Island community received the highest doses, with thyroid doses about 350 to 400 times greater than those received in the southern atolls.

Internal doses from chronic intakes of radionuclides

Following the deposition of radionuclides on the ground, chronic (i.e., protracted) intakes took place at rates much lower than those due to the acute intakes. While both acute and chronic intakes were primarily a result of ingestion, the environmental transport processes leading to chronic intakes were substantially different from those that gave rise to acute intakes. Chronic intakes were primarily a function of the consumption of seafood and of locally grown terrestrial foodstuffs internally contaminated with long-lived radionuclides via root uptake and, to a lesser degree, inadvertent consumption of soil (Simon 1998; Simon et al. 2010). A previous assessment (Lessard et al. 1984) showed that five radionuclides account for essentially all the internal dose from chronic intake: 55Fe, 60Co, 65Zn, 90Sr, and 137Cs.

The available historical whole-body counting and bioassay measurements were used as a basis to estimate the chronic intakes since a suitable dietary model covering the many years after the tests, when lifestyles became more westernized, does not exist. Those whole-body and bioassay measurements were made on the Rongelap and Utrik evacuees for years after they returned to their respective home atolls (Lessard et al. 1984). The Rongelap and Utrik populations, who were evacuated within about two days following the detonation of the Castle Bravo test on 1 March 1954, were returned to their home atolls in June 1957 and June 1954, respectively (Table 3). During the first few weeks after their return and until the 1980's, a Brookhaven National Laboratory team regularly conducted measurements of whole-body activity of 137Cs, 60Co and 65Zn, as well as urinary concentrations of 90Sr. Measurements of 55Fe in blood were also performed, but only once (Lessard et al. 1984).

The steps used to estimate the doses from chronic intakes of radionuclides were: (1) estimation of the chronic intakes by Rongelap and Utrik adult evacuees due to the Bravo test; (2) estimation of the chronic intakes resulting from the Bravo test by adults of all other atolls, based on the relative 137Cs deposition; (3) estimation of the chronic intakes by adults resulting from tests other than Bravo, again based on relative 137Cs deposition; (4) estimation of the chronic intakes by children; and (5) estimation of the doses from chronic intakes from all tests and all population groups using International Commission on Radiogical Protection recommended dose coefficients.

Detailed information on the estimation of chronic intakes and resulting doses is presented in Simon et al. (2010). The doses from chronic intakes show the same geographical pattern as the doses resulting from acute intakes and 137Cs deposition (Fig. 2). However, because of the absence of short-lived iodine isotopes which dominated the thyroid dose from the acute intakes, the thyroid doses from chronic intakes were not much greater than the doses to other organs and tissues. Similar to the situation for acute intakes (Simon et al. 2010), only a few radionuclides contributed most of the organ absorbed dose. For all organs and for all four of the atoll and population groups discussed, 137Cs was either the first or second most important contributor to internal dose from chronic intakes. For the evacuated Rongelap Island community, 137Cs was the most important contributor to the chronic dose, whereas 65Zn was the largest contributor to dose for the residents of all other atolls (Table 15, Simon et al. 2010).

The cumulative thyroid doses (mGy) to representative adults on each atoll from both acute and chronic intakes of radionuclides in fallout from all tests with 90% uncertainty ranges are presented in Table 5 and have the same geographic pattern as for 137Cs deposition that is illustrated in Fig. 2.

Comparison of doses by mode of exposure

Table 6 compares estimated cumulative internal doses to representative adults of four population groups as reported in Simon et al. (2010) with the external doses for those same population groups as reported in Bouville et al. (2010). As elsewhere in this paper and companion papers, those persons of adult age (>18 y) at the time of the first test with significant deposition (Yoke test, 1 May 1948) are considered as adults in this assessment. In addition, all dose estimates presented are best estimates based on an analysis of all available data.

With respect to the components of the internal dose, the dose from chronic intake exceeded the dose from acute intake for RBM and stomach wall, for all populations groups except the Rongelap Island community. For the Rongelap Island community, the acute doses for all organs exceeded the chronic doses. Because of the exposure to radioiodines in fallout, the absorbed dose to the thyroid gland from acute intakes exceeded the chronic dose to the thyroid, regardless of the population group. Acute doses to colon wall were also greater than the corresponding chronic doses for all four population groups.

With respect to the total internal dose relative to the external dose, external doses were much greater than the internal doses to RBM and stomach wall, regardless of the population group, but were comparable to the internal doses to the colon wall (greater by two-fold at the southern and mid-latitude atolls, and about one-half for the Utrik and Rongelap Island communities). Internal doses to the thyroid were significantly greater than external doses, regardless of the population group.

Total doses

Total (external plus internal) organ absorbed doses can be presented in various ways to demonstrate the spatial and time-dependence of exposures received across the Marshall Islands and the dependence on age at exposure. As discussed earlier, Fig. 2 illustrates the groups of the atolls within the Marshall Islands with similar degrees of deposition. In parallel, Table 7 presents population-weighted total doses to adults within each of the four geographic areas. We found that our estimated total doses are relatively comparable within each of the four population groups: residents of southern atolls, residents of mid-latitude atolls, the Utrik community, and the Rongelap Island/Ailinginae/Rongerik evacuees (Table 5). Here, as elsewhere in this paper and companion papers, both Fig. 2 and Table 7 demonstrate that adults in mid-latitude atolls received cumulative organ doses approximately four times as great as adults in the most southern atolls. Similarly, adults of the Utrik community received cumulative organ doses four to seven times as great as adults from the mid-latitude atolls. Adults among the Rongelap Island/Ailinginae/Rongerik evacuees received the largest cumulative doses, six to eight times as great as adults from Utrik.

Recognizing that the doses within each of the four areas in Fig. 2 can be represented by the doses to Majuro residents, Kwajalein residents, the Utrik community, and the Rongelap Island community, Table 8 provides cumulative radiation doses (external plus internal) at those atolls for all birth years from 1930 to 1958. Those born in or before 1930 would be of adult age at the time of the first tests and would have received approximately equal doses regardless of the birth year.

We found that our estimates of total organ radiation absorbed doses (sum of external and internal) varied by year of birth. Persons who were adults at the beginning of the testing period (born in 1930 or earlier) received relatively low thyroid doses from the large tests in 1954 compared to those who were very young at the time of those tests (Table 8). Among the four representative population groups, cumulative thyroid doses ranged from 33 mGy for adults who lived on Majuro at the time of testing to as high as 23,000 mGy for infants on Rongelap Island at the time of the Bravo test.

The dose contributions from the six tests that resulted in the highest total doses (external plus internal) to adults of the four representative atolls and for the four organs and tissues that are considered (RBM, thyroid, stomach wall, and colon wall) are provided in Table 9. Bravo was by far the most important contributor to the total dose for the Utrik and Rongelap Island communities, but less important than Yankee, Yoke, Koon, Romeo, and Flathead for the Kwajalein residents, and less important than Koon and Romeo for the Majuro residents.

For purposes of cancer risk projection (Land et al. 2010), the annual organ doses are required. Annual doses were greatest in the years with large yield nuclear tests, i.e., 1954, 1956, and 1958. Fig. 3 shows the temporal pattern of total dose (external plus internal) received on an annual basis to the thyroid gland of children born in 1953 in each of four population groups (Majuro residents, Kwajalein residents, Utrik community, and Rongelap Island community). Children born in 1953 would have received the largest doses of any birth cohort.

Uncertainties of estimated doses

Estimated doses and the uncertainties associated with those estimates varied by location, fallout event, calendar year, and age at time of exposure. The precision of our dose reconstruction is better for exposures received on Rongelap and Ailinginae than on Utrik, primarily because of the availability of historical urine bioassay data and large amounts of environmental monitoring data (both historical and contemporary), and both are more reliable than the estimated doses for persons exposed on the mid-latitude and southern atolls.

Of the exposure pathways examined, determination of dose from external sources was the most direct and, therefore, the most precise. An analysis was conducted to evaluate the uncertainty in the annual doses from external irradiation for each year of testing. Annual and cumulative exposures were often estimated from historical measurements or from relatively simple conversions from fallout deposition density. We determined that the uncertainty of doses from external irradiation could be characterized by lognormal distributions with geometric standard deviations (GSDs) of approximately 1.2 for exposure on Rongelap and Ailinginae, 1.5 for exposure on Utrik, and 1.8 for exposures on the other atolls (Bouville et al. 2010). As can be seen, the overall GSDs were smallest for the communities where the greatest doses were received from the 1954 tests. Conversely, the GSDs were largest for communities with the lowest doses from the 1954 tests.

In comparison to estimates of external dose, estimates of dose from internal irradiation are substantally more uncertain. Based on an analysis accounting for uncertainties in the most relevant and sensitive parameters involved in the internal dose assessment, we found that the uncertainty of doses from internal irradiation could be characterized by lognormal distributions with GSDs of approximately 2.0 for exposure on Rongelap and Ailinginae, 2.5 for exposure on Utrik, and 3.0 for exposures on the other atolls (Simon et al. 2010). Doses from chronic intake of radionuclides result from a more complex exposure situation and are more uncertain than the doses from acute intakes. However, doses from chronic intakes were small and refinements to the estimation of the uncertainty associated with them would contribute little to the overall dose uncertainty.

Projected cancer risks

The annual doses from external irradiation and from internal irradiation that were estimated for the 25 Marshallese population groups according to birth year were combined with the population sizes and with age-dependent organ-specific risk coefficients to derive the corresponding cancer risk projections presented in Land et al. (2010). Risk estimates were presented in terms of the number of cancers by organ site projected to occur among Marshallese as a consequence of exposure to fallout from regional nuclear tests. The cancer risks were based on an estimated population of 12,175 residents of the Marshall Islands born before 1948 and another 12,608 born in the years 1948 through 1970, giving a total potentially exposed population of 24,783. Projected lifetime numbers of baseline and radiation-related (excess) cancers are shown in Table 10 by cancer type: leukemia, thyroid, stomach, and colon.

In addition, the numbers of “all other solid cancers” has been estimated using the colon dose as representative of the dose to most other organs and tissues of the body. The projected number of baseline (non-radiation related) cancers among the 24,783 Marshallese in all organs totals 10,600, while the projected number of excess (radiation-related) cancers is 170, including 65 that have yet to occur (Land et al. 2010). In comparison to our 2004 estimates, which also are presented in Table 10, the numbers of projected radiation-related thyroid and colon cancers are much smaller as a result of a much more realistic dose assessment.

When the entire population of the Marshall Islands is considered, the estimated fraction of cancers that has occurred or will occur and that can be attributed to exposure to radioactive fallout, expressed as a percentage, is about 20% for thyroid and about 5% for leukemia. These percentages can be compared to all other cancers, for which the attributable fractions are on the order of 1%. The attributable fractions, as expected, were much higher among the most heavily exposed population groups (Land et al. 2010). A breakdown of the estimated number of cancer attributable to exposure to fallout radiation according to population group and time period, as well as estimation of the uncertainties in the projected number of cancers, is discussed in detail by Land et al. (2010). The attributable fractions (%) of all cancers from exposure to fallout radiation within each of the four atoll groups with 90% uncertainty ranges are presented in Table 11 and have the same geographic pattern as for 137Cs deposition illustrated in Fig. 2. Because of the small numbers of projected cases on some atolls (resulting in highly uncertain estimates), the cancer risk projections are shown only for groups of atolls rather than for individual atolls.

CONCLUSIONS

The methods and findings described in this paper and the seven companion papers represent the most comprehensive retrospective evaluation ever conducted of exposure of Marshallese and the related cancer risks from regional nuclear testing. This effort, in response to a Congressional request, will provide information useful to U.S. Congressional committees as well as to health authorities both in the U.S. and in the Marshall Islands. However, the methods are also illustrative of methods that may be useful in broader circumstances, some of which might occur in the future. Though nuclear testing in the atmosphere is not likely to be revived, nuclear detonations that would result in exposure of the public might occur in the future due to accidents or intentional actions in wartime or by terrorists. A number of important lessons can be derived from this analysis. Here, we have confirmed that exposure to radioactive fallout, particularly soon after detonation of a large device, can result in high exposures and substantial increases in cancer risk. At distances of more than a few hundred kilometers, however, exposures and related cancer risks are likely to be highly diminished due to dilution of the radioactive debris in the atmosphere (depending on the meteorological conditions) and radioactive decay during transit. Lifestyles that are dependent on storing and preparing food outdoors are particularly susceptible to transmitting radioactive contamination to man. Reconstruction of radiation doses many years after exposure can be an intensive effort and underscores the need for dependable data of various types. The amount of data necessary to make reliable estimates of radiation dose and cancer risks is significant and the collection of that information should not be overlooked following nuclear events, but should be, in fact, a high priority.

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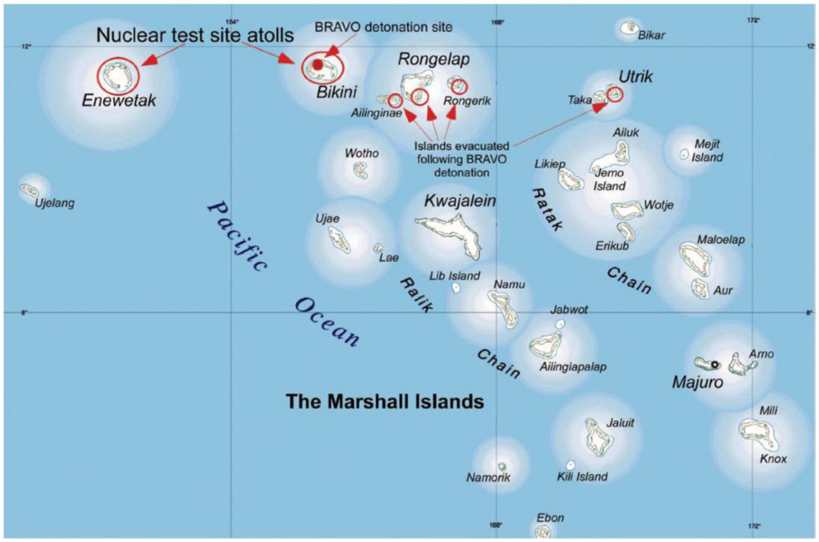

Fig. 1.

Atolls and reef islands of the Republic of the Marshall Islands, and locations of nuclear test sites and of evacuated populations.

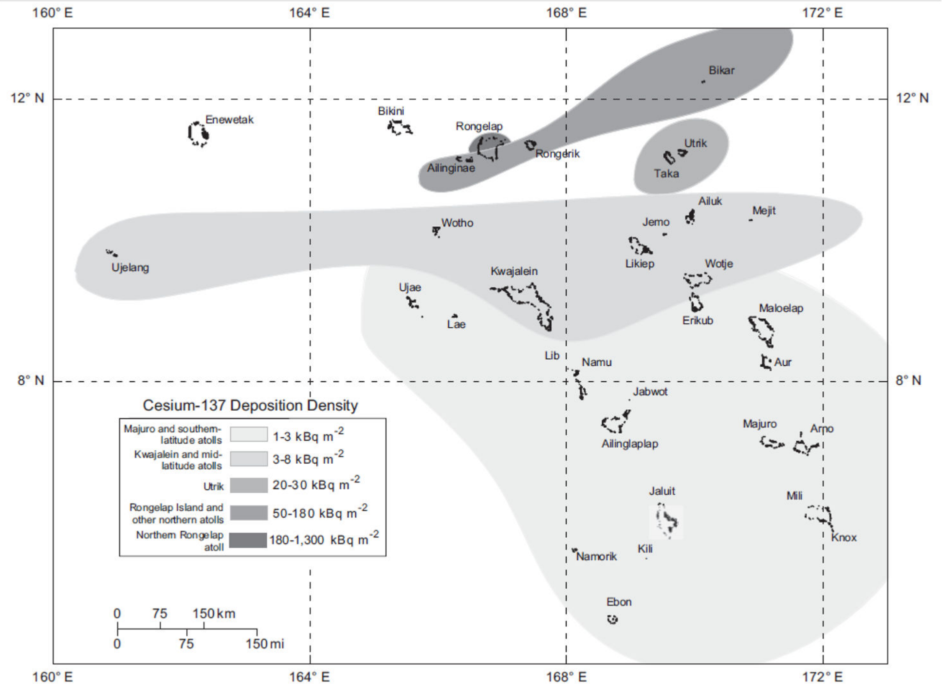

Fig. 2.

Geographical variation of total (cumulative) ^{137}Cs deposited (kBq m^{-2}) from all Marshall Islands nuclear tests (see Table 5) illustrating four areas with similar deposition. Taongi Atoll, located beyond the boundaries of the map at 14° 32′ north latitude, is not shown and not included in the range of depositions shown in the key for the northern atolls. Shaded areas also describe groups of atolls with similar values of organ dose (Table 5) and cancer risk (Table 11).

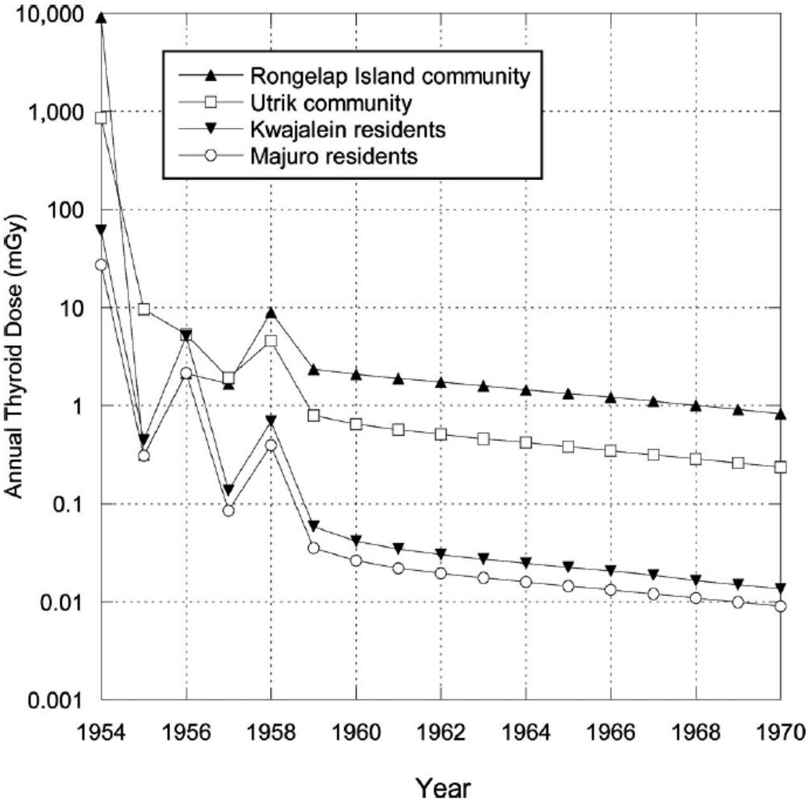

Fig. 3.

Annual thyroid doses (mGy) to representative children born in 1953 on four atolls (Majuro, Kwajalein, Utrik and Rongelap Island) that are representative of exposures across all of the Marshall Islands: sum of external dose plus internal acute and chronic doses. Rongelap and Utrik estimates account for evacuations and relocations of communities.

Table 1

Nuclear tests estimated to have deposited measurable fallout in the Marshall Islands.

Test name	**Operation**	**Test site atoll**	**Local date (mm/dd/yyyy)**	**Total yield (Mt)[a]**	**Fusion yield (Mt)[a]**
Yoke	Sandstone	Enewetak	05/01/1948	0.049	0
Dog	Greenhouse	Enewetak	04/08/1951	0.08	0
Item	Greenhouse	Enewetak	05/25/1951	0.05	0
Mike	Ivy	Enewetak	11/01/1952	10.4	4.7
King	Ivy	Enewetak	11/16/1952	0.5	0.25
Bravo	Castle	Bikini	03/01/1954	15	6
Romeo	Castle	Bikini	03/27/1954	11	3.7
Koon	Castle	Bikini	04/07/1954	0.11	0.04
Union	Castle	Bikini	04/26/1954	6.9	2.3
Yankee	Castle	Bikini	05/05/1954	13.5	4.5
Nectar	Castle	Enewetak	05/14/1954	1.7	0.85
Zuni	Redwing	Bikini	05/28/1956	3.5	2.25
Flathead	Redwing	Bikini	06/12/1956	0.37	0.18
Tewa	Redwing	Bikini	07/21/1956	5	2.7
Cactus	Hardtack I	Enewetak	05/06/1958	0.018	0
Fir	Hardtack I	Bikini	05/12/1958	1.4	0.7
Koa	Hardtack I	Enewetak	05/13/1958	1.4	0.7
Maple	Hardtack I	Bikini	06/11/1958	0.21	0.07
Redwood	Hardtack I	Bikini	06/28/1958	0.41	0.14
Cedar	Hardtack I	Bikini	07/03/1958	0.22	0.07

[a] UNSCEAR (2000).

Table 2

Populations[a] of the atolls and separate islands of the Marshall Islands over 45 y and population groups for which doses were estimated in this study.

		Population size				
Atoll/Island	**Doses computed for resident populations**	**1935**	**1958**	**1967**	**1973**	**1980**
Ailinginae[b]	—	na	—	—	—	—
Ailinglaplap	✓	na	1,288	1,195	1,100	1,385
Ailuk	✓	na	419	384	335	413
Arno	✓	na	1,037	1,273	1,120	1,487
Aur	✓	na	241	361	300	444
Bikar	—	—	—	—	—	—
Bikini	—	na	__[c]	__[c]	75	__[c]
Ebon	✓	na	819	836	740	887
Erikub	—		—	—	—	—
Enewetak	—	na	__[d]	__[d]	__[d]	542
Jabat	—	—	—	—	70	72
Jaluit	✓	na	1,098	1,113	925	1,450
Jemo Island	—	—	—	—	—	—
Kili Island[c]	✓	na	267	309	360	489
Knox	—	—	—	—	—	—
Kwajalein[e]	✓	na	1,284	3,540	5,469	6,624
Lae	✓	na	165	131	154	237
Lib island	✓	na	44	142	98	98
Likiep	✓	na	636	430	406	481
Majuro	✓	na	3,415	5,249	10,290	11,791
Maloelap	✓	na	454	494	432	614
Mejit Island	✓	na	346	320	271	325
Mili	✓	na	412	582	538	763
Namorik	✓	na	513	547	431	617
Namu	✓	na	482	547	493	654
Rongelap[f]	✓	na	264	189	165	235

Atoll/Island	Doses computed for resident populations	Population size				
		1935	1958	1967	1973	1980
Rongerik[g]	—	—	—	—	—	—
Taka	—	—	—	—	—	—
Taongi	—	—	—	—	—	—
Ujae	✓	na	167	191	209	309
Ujelang[d]	✓	na	172	251	342	*d*
Utrik	✓	na	198	269	217	336
Wotho	✓	na	71	61	85	101
Wotje	✓	na	361	396	425	535
Residence not stated	—	—	—	—	19	—
Total	—	10,446	14,163	18,860	25,050	30,889

[a] Data obtained from 1999 Marshall Islands Yearbook (see http://marshall.csu.edu.au/Marshalls/html/STATS/RMIYearbook1998-99.pdf).

[b] There was no continuously resident population on Ailinginae. Eighteen Rongelap community members were exposed to Bravo fallout there.

[c] The Bikini community was relocated to Kili Island prior to the nuclear testing.

[d] The Enewetak community was relocated to Ujelang Atoll prior to the nuclear testing; they returned in 1980.

[e] Excluding non-Marshallese residents of Kwajalein Missile Range.

[f] This group includes the 64 persons who were present on Rongelap Island at the time of the Bravo test (Rongelap Island community), the 18 persons exposed on Ailinginae to Bravo fallout, and 117 persons who were visiting the southern atolls at the time of the Bravo test (Rongelap control group).

[g] There was no resident population on Rongerik. Twenty-eight U.S. military weather observers were exposed to Bravo fallout there.

Table 3

Locations of relocated communities on dates of the 20 nuclear tests considered and estimates of move dates (see footnotes).

		Populations and locations of exposures						
Test	**Date of test**	**Rongelap Island community**[a]	**Rongelap group exposed on Ailinginae**[b]	**Rongelap control group**[c]	**U.S. Military weather observers**[d]	**Utrik community**[e]	**Bikini community**[f]	**Enewetak community**[g]
Yoke	04/30/1948	Rongelap Island	Rongelap Island	Rongelap Island	—	Utrik	Kwajalein	Ujelang
Dog	04/08/1951	Rongelap Island	Rongelap Island	Rongelap Island	—	Utrik	Kili	Ujelang
Item	05/25/1951	Rongelap Island	Rongelap Island	Rongelap Island	—	Utrik	Kili	Ujelang
Mike	11/01/1952	Rongelap Island	Rongelap Island	Rongelap Island	—	Utrik	Kili	Ujelang
King	11/16/1952	Rongelap Island	Rongelap Island	Rongelap Island	—	Utrik	Kili	Ujelang
Bravo	02/28/1954	Rongelap Island	Ailinginae	Majuro	Rongerik	Utrik	Kili	Ujelang
Romeo	03/27/1954	Kwajalein	Kwajalein	Majuro	—	Kwajalein	Kili	Ujelang
Koon	04/07/1954	Kwajalein	Kwajalein	Majuro	—	Kwajalein	Kili	Ujelang
Union	04/26/1954	Kwajalein	Kwajalein	Majuro	—	Kwajalein	Kili	Ujelang
Yankee	05/05/1954	Kwajalein	Kwajalein	Majuro	—	Kwajalein	Kili	Ujelang
Nectar	05/14/1954	Majuro	Majuro	Majuro	—	Kwajalein	Kili	Ujelang
Zuni	05/28/1956	Majuro	Majuro	Majuro	—	Utrik	Kili	Ujelang
Flathead	06/12/1956	Majuro	Majuro	Majuro	—	Utrik	Kili	Ujelang
Tewa	07/21/1956	Majuro	Majuro	Majuro	—	Utrik	Kili	Ujelang
Cactus	05/06/1958	Rongelap Island	Rongelap Island	Rongelap Island	—	Utrik	Kili	Ujelang
Fir	05/12/1958	Rongelap Island	Rongelap Island	Rongelap Island	—	Utrik	Kili	Ujelang
Koa	05/13/1958	Rongelap Island	Rongelap Island	Rongelap Island	—	Utrik	Kili	Ujelang
Maple	06/11/1958	Rongelap Island	Rongelap Island	Rongelap Island	—	Utrik	Kili	Ujelang
Redwood	06/28/1958	Rongelap Island	Rongelap Island	Rongelap Island	—	Utrik	Kili	Ujelang
Cedar	07/03/1958	Rongelap Island	Rongelap Island	Rongelap Island	—	Utrik	Kili	Ujelang

[a] In May 1946, Rongelap population was evacuated temporarily to Lae Atoll, where no exposure occurred. On 3 March 1954, following the Bravo test, the population was evacuated from Rongelap Island (~H+51 h) to Kwajalein where they remained until ~5 May 1954 at which time they moved to Majuro. In June, 1957, the population returned to Rongelap where they remained until 1985, after which they moved to Kwajalein and Majuro.

[b] Group of 18 Rongelap Island community members visiting Ailinginae at the time of the Bravo test on 1 March 1954. They were assumed lo be on Rongelap prior to the Bravo test. The group was evacuated from Alinginae on 3 March 1954, (~H+51 h) to Kwajalein. They returned to Rongelap in 1957 with rest of Rongelap Island community.

[c] Group of approximately 117 members of the Rongelap Island community who were absent from Rongelap at the time of Bravo. They were assumed to be on Majuro and to have remained there until 1957 when they rejoined the rest of the community. The term “control” group was derived from Brookhaven National Laboratory reports (BNL 1958).

[d] Twenty-eight U.S. military weather observers were stationed on Eniwetak Island. Rongerik Atoll prior to Bravo; they were evacuated on 3 March 1954, and did not return.

[e] Following deposition of Bravo fallout, on 3 March 1954 (~H+67 h), the Utrik population was evacuated to Kwajalein; they returned 2 June 1954.

[f] The Bikini people were evacuated to Rongerik in March, 1946. In March, 1947, they were moved from Rongerik to Kwajalein. In early November, 1948, they were moved to Kili Island where most still live today.

[g] In December 1947, the Enewetak community was moved to Ujelang. In 1980, some returned to Enewetak.

Table 4

List of radionuclides considered in estimates of deposition and of internal doses from acute intakes for the 20 tests considered in this study (all are fission products unless otherwise noted).

Nuclide	Half-life
^{55}Fe[a]	2.7 a
^{64}Cu[a]	13 h
^{77}As	39 h
^{83}Br	2.4 h
^{88}Rb	18 min
^{89}Sr	51 d
^{90}Sr	29 a
^{90}Y	64 h
^{91}Sr	9.6 h
^{91m}Y	50 min
^{92}Sr	2.7 h
^{92}Y	3.5 h
^{93}Y	10 h
^{95}Zr	64 d
^{95}Nb	35 d
^{97}Zr	17 h
^{97m}Nb	53 s
^{99}Mo	66 h
^{99m}Tc	6.0 h
^{103}Ru	39 d
^{103m}Rh	56 min
^{105}Ru	4.4 h
^{105}Rh	35 h
^{106}Ru	370 d
^{109}Pd	14 h
^{112}Ag	3.1 h
^{115}Cd	53 h
^{117}Cd	2.5 h
^{117m}In	2.0 h
^{121}Sn	27 h
^{125}Sb	2.8 a
^{127}Sn	2.1 h
^{127}Sb	3.9 d
^{129}Te	70 min
^{129}Sb	4.4 h
^{131m}Te	30 h

Nuclide	**Half-life**
^{131}I	8.0 d
^{132}Te	78 h
^{132}I	2.3 h
^{132m}Te	55 min
^{133}I	21 h
^{135}I	6.6 h
^{137}Cs	30 a
^{139}Ba	83 min
^{140}Ba	13 d
^{140}La	1.7 d
^{141}La	3.9 h
^{141}Ce	33 d
^{142}La	91 min
^{143}Ce	33 h
^{143}Pr	14 d
^{144}Ce	280 d
^{144}Pr	17 min
^{145}Pr	6.0 h
^{147}Nd	11 d
^{149}Pm	53 h
^{149}Nd	1.7 h
^{151}Pm	28 h
^{153}Sm	46 h
^{237}U[a]	6.8 d
^{240}U[a]	14 h
^{240m}Np[a]	7.2 min
^{239}Np[a]	2.4 d
$^{239+240}$Pu[b]	24,000/6,600 a

[a] Activation product.

[b] Fuel material. Only cumulative depositions and intakes over all tests were estimated.

Table 5

Estimated total ^{137}Cs deposition (Bq m^{-2}), external dose (mGy), and internal dose (mGy, sum of acute + chronic) to red bone marrow (RBM), thyroid, stomach, and colon of representative adults of all population groups. Values in table are best estimates and 90% uncertainty range (5%–95%) as discussed in text. All entries are rounded to two significant digits.

Community/Atoll by geographic grouping	Total ^{137}Cs, kBq m^{-2} (5%–95%)	External dose, mGy (5%–95%)	Internal dose to RBM, mGy (5%–95%)	Internal dose to thyroid, mGy (5%–95%)	Internal dose to stomach wall, mGy (5 %–95%)	Internal dose to colon, mGy (5%–95%)
Southern latitude group						
Ailinglaplap	1.5 (0.73–2.8)	6.9 (1.8–18)	0.80 (0.051–3.8)	20 (1.3–93)	0.84 (0.054–4.0)	4.3 (0.27–20)
Arno	2.2 (1.1–3.8)	10 (2.7–28)	1.2 (0.07–5.2)	25 (1.6–120)	1.1 (0.07–5.2)	5.6 (0.36–26)
Aur	2.0 (1.2–3.1)	9.9 (2.6–26)	1.1 (0.068–5.1)	25 (1.6–120)	1.1 (0.070–5.2)	5.7 (0.36–27)
Ebon	1.4 (0.95–2.0)	5.3 (1.4–14)	0.74 (0.047–3.5)	12 (0.76–56)	0.67 (0.042–3.2)	2.7 (0.17–13)
Erikub[a]	2.4 (1.7–3.4)	—	—	—	—	—
Jabal[a]	1.7 (0.81–3.0)	—	—	—	—	—
Jaluit	1.5 (0.80–2.5)	6.6 (1.8–18)	0.78 (0.050–3.7)	14 (0.91–68)	0.74 (0.047–3.5)	3.3 (0.21–15)
Kili Island[b]	1.5 (0.89–2.3)	11 (2.8–28)	1.1 (0.071–5.3)	27 (1.7–130)	1.2 (0.074–5.5)	6.1 (0.39–29)
Knox	1.6 (0.95–2.5)	—	—	—	—	—
Lae	2.0 (0.76–4.5)	10 (2.7–27)	1.1 (0.070–5.2)	28 (1.8–130)	1.2 (0.074–5.5)	6.2 (0.39–29)
Lib Island	2.4 (0.97–4.9)	12 (3.2–33)	1.3 (0.081–6.0)	34 (2.2–160)	1.4 (0.088–6.6)	7.3 (0.45–34)
Majuro	2.0 (1.4–2.9)	9.8 (2.6–26)	1.1 (0.069–5.1)	23 (1.5–110)	1.1 (0.068–5.1)	5.4 (0.34–25)
Maloelap	2.4 (1.4–3.8)	12 (3.3–33)	1.3 (0.083–6.1)	32 (2.0–150)	1.4 (0.086–6.4)	7.1 (0.45–33)
Mili	1.6 (0.95–2.5)	7 (1.9–19)	0.84 (0.054–4.0)	17 (1.1–80)	0.82 (0.052–3.9)	3.9 (0.25–18)
Namorik	1.3 (0.75–2.1)	5.5 (1.5–15)	0.68 (0.043–3.2)	12 (0.76–56)	0.63 (0.040–3.0)	2.7 (0.17–13)
Namu	2.0 (0.82–4.1)	11 (2.8–28)	1.1 (0.068–5.1)	29 (1.8–140)	1.2 (0.074–5.5)	6.1 (0.39–29)
Ujae	1.6 (0.53–3.7)	8.6 (2.3–23)	0.87 (0.055–4.1)	22 (1.4–100)	0.92 (0.058–4.3)	4.9 (0.31–23)
Rongelap control group[c]	2.8 (1.7–4.5)	22 (15–31)	21 (1.3–97)	53 (3.4–250)	17 (1.1–82)	27 (1.7–129)
Mid-latitude group						
Ailuk	7.5 (3.8–14)	59 (16–160)	5.8 (0.37–27)	160 (10–760)	7.1 (0.45–33)	44 (2.8–210)
Jemo Island[a]	5.2 (2.5–9.5)	—	—	—	—	—
Kwajalein south	3.6 (2.2–5.5)	22 (5.8–58)	1.9 (0.12–9.2)	67 (4.3–320)	2.4 (0.15–11)	14 (0.88–65)
Kwajalein north[a]	4.3 (1.9–8.1)	—	—	—	—	—

Community/Atoll by geographic grouping	**Total ^{137}Cs, kBq m^{-2} (5%–95%)**	**External dose, mGy (5%–95%)**	**Internal dose to RBM, mGy (5%–95%)**	**Internal dose to thyroid, mGy (5%–95%)**	**Internal dose to stomach wall, mGy (5 %–95%)**	**Internal dose to colon, mGy (5%–95%)**
Likiep	5.5 (2.5–11)	39 (10–100)	3.5 (0.22–16)	110 (7.0–520)	4.3 (0.27–20)	25 (1.6–120)
Mejit Island	6.6 (3.3–12)	49 (13–130)	4.5 (0.29–21)	120 (7.7–580)	5.3 (0.34–25)	31 (2.0–150)
Ujelang[d]	4.0 (1.8–7.8)	25 (6.6–66)	2.2 (0.14–10)	86 (5.4–400)	3.0 (0.19–14)	18 (1.1–84)
Wotho	4.0 (2.4–6.4)	23 (6.2–62)	2.2 (0.14–10)	77 (4.9–360)	2.8 (0.18–13)	15 (0.96–71)
Wotje	5.2 (2.6–9.4)	31 (8.2–82)	2.8 (0.18–13)	80 (5.1–380)	3.1 (0.20–15)	17 (1.1–82)
Utrik group						
Utrik[e]	29 (15–50)	130 (53–260)	35 (3.8–138)	760 (83–3,000)	41 (4.4–160)	210 (23–830)
Taka[a]	20 (11–33)	—	—	—	—	—
Northern latitude group						
Ailinginae[f]	54 (24–110)	470 (125–1,300)	25 (1.6–120)	2,600 (160–1,200)	232 (15–1,100)	940 (60–4,500)
Bikar[a]	68 (26–150)	—	—	—	—	—
Rongelap north[a]	560 (180–1,300)	—	—	—	—	—
Rongelap Island community[g]	180 (100–280)	1,600 (1,100–2,200)	42 (8.4–130)	7,600 (1,500–23,000)	550 (110–1,700)	2,800 (560–8,500)
Rongerik[h]	120 (45–250)	940 (390–1,900)	11 (0.71–52)	3,900 (250–19,000)	200 (13–940)	1,200 (77–5,700)
Taongi[a]	1.2 (4.0–2.8)	—	—	—	—	—

[a] No dose entry indicates an atoll or island that was not traditionally inhabited.

[b] Deposition pertains to the total ^{137}Cs deposited on Kili Island from all tests. Doses pertain to Bikini community.

[c] Rongelap control group refers to 117 Rongelap community members who were not on Rongelap Island at the time of the Bravo test and were assumed in this work to have been on Majuro at that time. Deposition pertains to the sum of the ^{137}Cs deposited on Majuro in 1954 and 1956, and on Rongelap Island for the other years. Doses account for the entire residence history of this group (see Table 3).

[d] Deposition pertains to the total ^{137}Cs deposited on Ujelang Atoll from all tests. Doses pertain to Enewetak community.

[e] Deposition pertains to the total ^{137}Cs deposited on Utrik Atoll from all tests. Doses pertain to Utrik community.

[f] Deposition pertains to the total ^{137}Cs deposited on Sifo Island, Ailinginae Atoll. Doses, however, pertain solely to 18 members of Rongelap community exposed to Bravo fallout on Sifo Island, but exposed to fallout from all other tests at the same locations as the Rongelap Island community (see Table 3 for relocation history).

[g] Deposition pertains to the total ^{137}Cs deposited on Rongelap Island from all tests. Doses, however, account for evacuations and relocations of the community (see Table 3 for relocation history).

[h] Deposition pertains to the total ^{137}Cs deposited on Rongerik Atoll. Doses pertain only to the acute exposure from Bravo fallout received by U.S. military weather observers.

Table 6

Comparison of best estimates of cumulative internal and external dose (mGy) to adults of four representative population groups for four organs. All dose estimates rounded to two significant digits.

	Population group			
Organ/Mode of exposure	**Majuro residents**	**Kwajalein residents**	**Utrik community**	**Rongelap Island community**
Thyroid				
Acute internal	22	66	740	7,600
Chronic internal	0.76	1.3	25	14
Total internal	23	67	760	7,600
RBM				
Acute internal	0.11	0.25	2.3	25
Chronic internal	0.98	1.7	33	17
Total internal	1.1	2.0	35	42
Stomach wall				
Acute internal	0.32	1.1	16	530
Chronic internal	0.75	1.3	24	14
Total internal	1.1	2.4	40	540
Colon				
Acute internal	44	12	180	2,800
Chronic internal	0.99	1.7	32	17
Total internal	5.4	14	210	2,800
Whole body (external dose)	9.8	22	130	1,600

Table 7

Population-weighted average total dose (external plus internal, mGy) to adults of four groups of atolls and/or communities (see Fig. 2). Grouping is based on similar levels of deposition of total ^{137}Cs (see Fig. 2). Input data derived from Tables 2 and 5. Range in parentheses represents the minimum and maximum total dose within the group of atolls or communities. All values rounded to two significant digits.

Atoll or population group	Atolls of exposure	Total dose to RBM, mGy (range)	Total dose to thyroid, mGy (range)	Total dose to stomach wall, mGy (range)	Total dose to colon, mGy (range)
Southern latitude	Ailinglaplap, Arno, Aur, Ebon, Jaluit, Kili Island[a], Lae, Lib Island, Majuro[b], Maloelap, Mili, Namorik, Namu, Ujae	10 (6.1–43)	30 (17–75)	10 (6.0–39)	14 (8.0–49)
Mid-latitude	Ailuk, Kwajalein, Likiep, Mejit Island, Ujelang[c], Wotho, Wotje	37 (24–65)	130 (89–220)	38 (24–66)	56 (36–100)
Utrik community	Utrik and atoll of relocation[d]	160	890	170	340
Rongelap Island/Ailinginae/Rongerik evacuees	Rongelap, Ailinginae, Rongerik, and atolls of relocation[d]	1,000 (500–1,600)	5,900 (3,000–9,200)	1,400 (700–2,100)	2,800 (1,400–4,400)
All	All	29 (6.1–1,600)	124 (17–9,200)	32 (6.0–2,100)	56 (8.0–4,400)

[a] Primary residence location of Bikini community during test years.

[b] Includes Majuro permanent residents and Rongelap control group (see Table 3).

[c] Primary residence location of Enewetak community during testing years.

[d] See Table 3 for atolls of relocation.

Table 8

Total radiation absorbed doses (mGy) to four tissues and organs of representative persons by birth year (< 1931 through 1958): sum of external and internal irradiation: all values rounded to two significant digits. Doses for Utrik and Rongelap Island communities account for relocations.

	Majuro residents				Kwajalein residents				Utrik community				Rongelap Island community			
Birth year	**RBM**	**Thyroid**	**Stomach**	**Colon**	**RBM**	**Thyroid**	**Stomach**	**Colon**	**RBM**	**Thyroid**	**Stomach**	**Colon**	**RBM**	**Thyroid**	**Stomach**	**Colon**
<1931	11	33	11	15	24	89	24	36	160	890	170	340	1,600	9,200	2,100	4,400
1931	11	33	11	15	24	93	24	36	160	890	170	340	1,600	9,200	2,100	4,400
1932	11	33	11	15	24	93	24	36	160	890	170	340	1,600	9,200	2,100	4,400
1933	11	33	11	15	24	93	24	36	160	890	170	340	1,600	9,200	2,100	4,400
1934	11	33	11	15	24	93	24	36	160	890	170	340	1,600	9,200	2,100	4,400
1935	11	34	11	15	25	95	25	37	160	890	170	340	1,600	9,200	2,100	4,400
1936	11	34	11	15	25	95	25	37	160	890	170	340	1,600	9,200	2,100	4,400
1937	11	39	11	16	25	109	25	38	160	1,000	170	360	1,600	11,000	2,200	4,700
1938	11	39	11	16	25	109	25	38	160	1,000	170	360	1,600	11,000	2,200	4,700
1939	11	40	11	16	25	110	25	39	160	1,000	170	360	1,600	11,000	2,200	4,700
1940	11	40	11	16	25	111	25	39	160	1,000	170	360	1,600	11,000	2,200	4,700
1941	13	42	13	18	28	121	28	42	190	1,000	190	380	2,000	12,000	2,500	5,000
1942	13	43	13	18	28	123	29	44	190	1,000	200	420	1,900	12,000	2,500	5,600
1943	13	43	13	19	28	124	29	44	200	1,000	200	430	1,900	12,000	2,500	5,600
1944	13	43	13	19	28	124	29	44	200	1,000	200	430	1,900	12,000	2,500	5,600
1945	13	44	13	19	29	125	29	45	200	1,000	200	430	2,000	12,000	2,500	5,600
1946	13	44	13	19	29	135	30	47	200	1,000	200	430	2,000	12,000	2,500	5,600
1947	13	53	13	19	29	160	30	48	200	1,500	210	460	1,900	17,000	2,600	6,000
1948	13	53	13	19	25	139	26	40	200	1,500	210	460	1,900	17,000	2,600	6,000
1949	13	54	13	19	23	121	23	36	200	1,500	210	460	1,900	17,000	2,600	6,000
1950	13	55	13	20	23	122	23	36	200	1,500	210	460	1,900	17,000	2,600	6,000
1951	13	55	13	20	22	122	23	36	200	1,500	200	460	1,900	17,000	2,600	6,000
1952	14	68	14	23	24	157	25	43	210	2,000	230	600	2,100	23,000	3,100	8,200
1953	13	61	13	21	23	148	24	42	210	2,000	230	600	2,100	22,000	3,100	8,200
1954	5	25	5	7	11	74	11	15	93	550	85	130	500	5,600	630	960
1955	1.5	5.6	1.3	2.3	3.1	13	3.0	4.9	32	31	24	34	30	38	26	37

Birth year	Majuro residents				Kwajalein residents				Utrik community				Rongelap Island community			
	RBM	**Thyroid**	**Stomach**	**Colon**	**RBM**	**Thyroid**	**Stomach**	**Colon**	**RBM**	**Thyroid**	**Stomach**	**Colon**	**RBM**	**Thyroid**	**Stomach**	**Colon**
1956	0.88	4.0	0.80	1.2	1.9	8.6	1.8	2.4	18	21	14	21	30	41	27	40
1957	0.41	1.0	0.36	0.60	0.82	1.6	0.74	1.1	13	16	10	17	35	40	29	44
1958	0.30	0.62	0.26	0.40	0.55	1.0	0.49	0.70	10	11	8.2	13	30	31	26	38

Table 9

Proportion (%) of total organ dose to adults of each of four communities from the six tests contributing most to the total dose.

Majuro residents		Kwajalein residents		Utrik community		Rongelap Island community	
Nuclear test	**Proportion (%)**	**Nuclear test**	**Proportion (%)**	**Nuclear test**	**Proportion (%)**	**Nuclear test**	**Proportion (%)**
Thyroid							
Koon	29	Yankee	37	Bravo	93	Bravo	94
Romeo	29	Yoke	21	Yankee	3	Romeo	2
Bravo	23	Koon	18	Koon	2	Koon	2
Flathead	6	Romeo	8	Romeo	0.8	Union	0.8
Mike	5	Flathead	5	Fir	0.4	Yankee	0.5
King	3	Bravo	5	Union	0.3	Zuni	0.1
Cumulative	95	*Cumulative*	92	*Cumulative*	~100	*Cumulative*	~100
Red Bone Marrow							
Romeo	33	Yankee	36	Bravo	94	Bravo	83
Koon	31	Yoke	21	Romeo	2	Romeo	7
Bravo	19	Koon	14	Koon	1	Koon	6
Flathead	5	Romeo	11	Yankee	1	Union	2
Mike	4	Flathead	5	Union	0.7	Yankee	1
Union	3	Bravo	4	Fir	0.5	Zuni	0.3
Cumulative	95	*Cumulative*	91	*Cumulative*	~100	*Cumulative*	~100
Stomach							
Romeo	33	Yankee	36	Bravo	94	Bravo	85
Koon	31	Yoke	21	Romeo	2	Romeo	6
Bravo	20	Koon	14	Koon	1	Koon	5
Flathead	5	Romeo	11	Yankee	1	Union	2
Mike	4	Flathead	5	Union	0.7	Yankee	1
Union	3	Bravo	4	Fir	0.5	Zuni	0.3
Cumulative	96	*Cumulative*	91	*Cumulative*	~100	*Cumulative*	~100
Colon							
Romeo	31	Yankee	36	Bravo	95	Bravo	90
Koon	30	Yoke	22	Yankee	2	Romeo	4

Majuro residents		Kwajalein residents		Utrik community		Rongelap Island community	
Nuclear test	**Proportion (%)**	**Nuclear test**	**Proportion (%)**	**Nuclear test**	**Proportion (%)**	**Nuclear test**	**Proportion (%)**
Bravo	21	Koon	15	Koon	1	Koon	3
Flathead	6	Romeo	10	Romeo	1	Union	1
Mike	5	Flathead	5	Union	0.5	Yankee	0.8
King	2	Bravo	4	Fir	0.4	Zuni	0.2
Cumulative	95	*Cumulative*	92	*Cumulative*	~100	*Cumulative*	~100

Table 10

Projected number of lifetime baseline and excess cancers for the entire population of the Marshall Islands by cancer type and comparison with the results of the NCI preliminary study (DCEG 2004).

	Preliminary study (DCEG 2004)			This study (Land et al. 2010)			
Cancer type	**Baseline number of cancers**[a]	**Excess number of cancers**	**Total number of cancers**	**Baseline number of cancers**[a]	**Projected excess number of cancers 1948–2008**	**Projected excess number of cancers from 2009 onwards**	**Rounded total number of cancers**
Leukemia	123	5	128	140	6.0	1.4	147
Thyroid	127	262	389	190	35	15	240
Stomach	326	15	341	570	3.1	3.6	577
Colon	470	157	627	930	7.2	9.3	946
All other solid cancers	4,550	93	4,643	8,800	54	36	8,890
Rounded total number of cancers	5,600	530	6,100	10,600	105	65	10,800

[a] The 2004 preliminary analysis assumed the population size obtained by the 1958 census, while the present study is based upon the total number of people exposed anytime between 1948 and 1970, which is projected to be about twice the size of the 1958 population.

Table 11

Lifetime Attributable Fraction (%) of projected cancers according to geographic grouping plus entire Marshall Islands: best estimate and 90% uncertainty range in parentheses (5%–95%).

	Leukemia	Thyroid	Stomach	Colon	All other solid cancers	Total
Southern latitude atolls[a]	2.2 (0.41–6.0)	12 (2.5–27)	0.47 (0.069–1.3)	0.69 (0.23–1.4)	0.48 (0.11–1.0)	0.76 (0.16–1.8)
Mid-latitude atolls[b]	8.4 (1.7–20)	25 (6.1–45)	1.9 (0.26–5.7)	2.3 (0.73–4.8)	1.4 (0.34–2.9)	2.2 (0.50–4.8)
Utrik community	19 (4.3–45)	71 (32–86)	4.8 (0.64–14)	9.4 (3.2–19)	6.7 (1.5–14)	10 (2.4–22)
Rongelap Island and Ailinginae community[c]	78 (39–91)	95 (87–97)	48 (11–73)	64 (36–78)	43 (20–54)	55 (28–69)
Entire Marshall Islands[c]	5.1 (0.96–12)	21 (6.0–39)	1.2 (0.17–3.4)	1.7 (0.59–3.4)	1.0 (0.27–2.0)	1.6 (0.41–3.4)

[a] Includes Kili Island where Bikini Atoll community resided.

[b] Includes Ujelang where Enewetak Atoll community resided.

[c] Does not include the U.S. military weather observers exposed to Bravo fallout on Rongerik.