THE NCI STUDIES ON RADIATION DOSES AND CANCER RISKS IN THE MARSHALL ISLANDS ASSOCIATED WITH EXPOSURE TO RADIOACTIVE FALLOUT

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Abstract

The U.S. National Cancer Institute (NCI, National Institutes of Health) was requested by the U.S. Congress in 2004 to assess the number of radiation-related illnesses to be expected among the people of the Marshall Islands from nuclear tests conducted there during 1946-1958. A thorough analysis conducted by the NCI concluded that 20 of the 66 nuclear devices tested in or near the Marshall Islands resulted in measurable fallout deposition on one or more of the inhabited atolls of the Marshall Islands; all other tests deposited their fallout on the test site atolls and in the open ocean. In this work, the deposition densities (kBq m^{-2}) of the 63 radionuclides that are responsible for 98% of the doses received were estimated at each of the 32 atolls and separate reef islands of the Marshall Islands for each test. Those data along with reported measurements of exposure rates and bioassay results 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. The geographic pattern for total deposition of ^{137}Cs, external doses, internal organ doses, and cancer risks were similar with the large population of the southern atolls receiving the lowest doses and populations of atolls nearest the test sites that had not be relocated prior to testing receiving the highest doses. 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. 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. This paper summarizes the methods and results that are presented in a series of papers published in Health Physics in 2010 [1].

INTRODUCTION

From 1946 through 1958, 65 nuclear weapons tests, in seven series, were carried out by the U.S. at Bikini and Enewetak Atolls located at the northwestern end of the archipelago that makes up the Marshall Islands 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) [2, 3, 4], about 100 times the total yield of the atmospheric tests conducted at the Nevada Test Site. Radioactive debris from the detonations that was 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 [5, 6] indicate that radioactive debris from a number of tests traveled in other directions.

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 atoll populations that had not prior relocated prior to the testing.

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 [7, 8]. Those measurement data are the first known measurements of ^{131}I in urine after fallout and have provided the basis for estimating internal doses.

This report summarizes extensive efforts at the U.S. National Cancer Institute (NCI) to reconstruct radiation exposures and organ doses from exposure to radioactive fallout and to project cancer risks to the Marshall Islands population. Detailed information on the technical aspects of this work and on the results of all parts of the study have been published in Health Physics [1] and should be consulted for details:

- 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 [9];
- the estimation of doses from external irradiation [10];
- the estimation of the doses from internal irradiation [11];
- the estimation of the cancer risks [12];
- summary of all findings [13].

METHODS AND FINDINGS

A brief overview of methods of the NCI study and a summary of the findings is presented here.

The estimated total radiation absorbed doses include three components: (1) external exposure resulting from fallout deposited on the ground; (2) internal exposure from acute radionuclide intakes immediately or soon after fallout after each test; and (3) internal exposure from chronic (i.e., protracted) intakes of radionuclides resulting from the continuous presence of long-lived radionuclides in the environment. Sixty-three radionuclides 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 (^{55}Fe, ^{60}Co, ^{65}Zn, ^{90}Sr, and ^{137}Cs) were considered for the estimation of the internal doses from chronic intakes, including two radionuclides, ^{60}Co and ^{65}Zn, that were not considered in the calculation of the doses from acute intakes. Doses from acute and chronic intakes from cumulative deposition of $^{239+240}$Pu were also estimated.

Fallout Activity Deposited on the Ground

As discussed in [9], a thorough review of various historical and contemporary deposition-related data, some available only government laboratory reports and internal agency and laboratory memoranda, was used to make judgments on which tests deposited fallout in the Marshall Islands and to estimate fallout deposition density and fallout transit times, known as times-of-arrival (TOA). In some instances, it was necessary to use the results of a well-established model of atmospheric transport and deposition [14] to check our initial assumptions on the occurrence of fallout on particular atolls after certain tests.

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 $^{239+240}Pu$. Estimation of deposition densities relied on factors provided by Hicks [18, 19]. Examples of deposition densities of 24 of these radionuclides are presented in [9].

The estimated total ^{137}Cs activities deposited by all tests from this analysis, after appropriate decay to account for the effective decay rate (radiological plus weathering effects) and a correction for global fallout from non-Marshall Islands tests, were compared [9] with contemporary measurements (1978-1993) of the total ^{137}Cs activities remaining [15, 16, 17]. Comparisons indicated excellent agreement.

Our estimates for the ^{137}Cs deposition density and for the corresponding TOA at each atoll and for each of 20 individual tests are presented in [9]. As expected, the cumulative ^{137}Cs deposition densities were found to be much greater on northern atolls (e.g., Rongelap and Rongerik) than on mid-latitude atolls (e.g., Kwajalein) or southern atolls (e.g., Majuro).

Radiation Doses

Doses received by Marshallese 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. 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. 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 [10]:

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).

Annual and cumulative exposures were estimated [10] using the variation with time of the exposure rate calculated by Hicks [18, 19] modified to take fractionation into account 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. 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 [20]. 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 all organs in adults. Because the conversion factor depends on body size and shape (usually a function of age), our calculated doses for adults from external irradiation were increased by 30% for children less than 3 years of age and by 20% for children 3 years of age through 14 years [20]. Building shielding was estimated not to be important since houses at that time, made primarily out of palm tree 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.

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 [11, 21].

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 [9], (2) historical measurements of ^{131}I in pooled samples of urine collected from adults about two weeks after the Bravo test [7, 8]; and (3) assessment of appropriate values of gastrointestinal uptake for the radionuclides present in fallout particles [22]. The assessment of internal doses relied on the following six steps: (1) estimation of the intake of ^{131}I by populations on Rongelap, Ailinginae, and Rongerik following the Bravo test using historical bioassay data, (2) estimation of the intake of ^{137}Cs at the same three atolls based on the ratios of ^{137}Cs to ^{131}I [18, 19] but corrected for fractionation, (3) estimation of the deposition density of ^{137}Cs following each of 20 tests on all inhabited atolls, (4) estimation of the intake of ^{137}Cs 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 (red bone marrow, 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 [11].

Internal doses to the thyroid gland were much found to be 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 BRAVO test than for the residents of any other atoll [11]. The southern atolls, where about 73% of the population resided during the testing years, received the lowest organ doses from internal irradiation. The population of mid-latitude atolls, 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 internal doses intermediate in magnitude between the mid-latitude atolls and Rongelap, with thyroid doses about 35 times greater than the southern atolls [11]. 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 the acute intakes that followed the tests. While both types of intake 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 primarily resulted from 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 [11]. A previous assessment [23] showed that five radionuclides account for essentially all the internal dose from chronic intake: ^{55}Fe, ^{60}Co, ^{65}Zn, ^{90}Sr, and ^{137}Cs.

Available historical whole-body counting and bioassay measurements were used as a basis to estimate the chronic intakes since a complete dietary model does not exist that covers the many years after the tests when lifestyles became more westernized. Those whole-body and bioassay measurements were made on the Rongelap and Utrik evacuees for years after they returned to their respective home atolls [23] following their evacuation about two days after the BRAVO test. During the first few weeks after their return and until the 1980s, a Brookhaven National Laboratory team regularly conducted measurements of whole-body activity of ^{137}Cs, ^{60}Co and ^{65}Zn, as well as urinary concentrations of ^{90}Sr. Measurements of ^{55}Fe in blood were also performed, but only once [23].

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 ^{137}Cs deposition, (3) estimation of the chronic intakes by adults resulting from tests other than BRAVO, again based on relative ^{137}Cs 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 ICRP recommended dose coefficients.

Detailed information on the estimation of chronic intakes and resulting doses is presented in [11]. The doses from chronic intakes show the same geographical pattern as the doses resulting from acute intakes and ^{137}Cs deposition. 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, 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, ^{137}Cs was either the first or second most important contributor to internal dose from chronic intakes. For the evacuated Rongelap Island community, ^{137}Cs was the most important contributor to the chronic dose, whereas ^{65}Zn was the largest contributor to dose for the residents of all other atolls [11].

Summary of doses. 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 60 mGy on average, while the residents of the northern atolls received external doses in the hundreds to over 1000 mGy. Except for internal doses to the thyroid gland, external exposure was generally the major contributor to organ doses.

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 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.

We found that our estimated total doses at each atoll were 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. 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, 6 to 8 times as great as adults from Utrik.

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. Among the 4 representative population groups, cumulative thyroid doses ranged from 33 mGy for adults who lived on Majuro (southern atoll) at the time of testing to as high as 23,000 mGy for infants on Rongelap Island at the time of the BRAVO test.

For purposes of cancer risk projection [12], the annual organ doses were estimated. Children born in 1953 would have received the largest doses of any birth cohort.

Projected Cancer Risks

The annual doses from external irradiation and from internal irradiation were estimated for 25 Marshallese population groups according to birth year. Those estimates were combined with the population sizes and with age-dependent organ-specific risk coefficients to derive the corresponding cancer risk projections presented in [12]. 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.

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 are projected to occur after 2009 [12]. 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%.

CONCLUSIONS

The assessment conducted by the NCI on radiation doses and cancer risks to Marshallese from nuclear testing is the most comprehensive evaluation ever conducted for that population. A number of important lessons can be derived from that analysis. Here, it has been 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 from the test site, 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.

Acknowledgments

The contributors to this work and the 2010 publications included André Bouville, Charles Land, and Harold Beck, Dunstana Melo, Payne Harris, Shawki Ibrahim, Robert Weinstock, Iulian Apostoaei, and Brian Moroz. This research discussed here was supported by the Intra-Agency agreement between the National Institute of Allergy and Infectious Diseases and the National Cancer Institute, NIAID agreement #Y2-AI-5077 and NCI agreement #Y3-CO-5117. The author's participation in the 17th Annual Hiroshima Conference was supported by Hiroshima University.

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