Paper

HEALTH EFFECTS FROM FALLOUT

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Abstract—**This paper primarily discusses health effects that have resulted from exposures received as a result of above-ground nuclear tests, with emphasis on thyroid disease from exposure to ^{131}I and leukemia and solid cancers from low dose rate external and internal exposure. Results of epidemiological studies of fallout exposures in the Marshall Islands and from the Nevada Test Site are summarized, and studies of persons with exposures similar to those from fallout are briefly reviewed (including patients exposed to ^{131}I for medical reasons and workers exposed externally at low doses and low dose rates). Promising new studies of populations exposed in countries of the former Soviet Union are also discussed and include persons living near the Semipalatinsk Test Site in Kazakhstan, persons exposed as a result of the Chernobyl accident, and persons exposed as a result of operations of the Mayak Nuclear Plant in the Russian Federation. Very preliminary estimates of cancer risks from fallout doses received by the United States population are presented.**
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INTRODUCTION

As DISCUSSED in the two previous papers (Bouville et al. 2002; Simon and Bouville 2002), fallout from atmospheric nuclear tests has resulted in exposure to persons throughout the world. These include large exposures to selected populations living in the vicinity of the test sites, and epidemiological studies of some of these populations have been conducted. In several cases, substantial efforts have been devoted to estimating doses, and additional efforts are underway. In addition, both doses and health effects for the United States population as a whole are being evaluated. In this paper, we start by summarizing the results of epidemiological studies of populations exposed as a result of fallout and also studies of other populations with exposures similar to those from fallout. We then discuss promising new studies of populations exposed in countries of the former Soviet Union. Finally, we discuss the basis for current estimates of risks in exposed populations, and present preliminary estimates of cancer risks from fallout doses received by the United States population.

EPIDEMIOLOGICAL STUDIES OF POPULATIONS EXPOSED TO FALLOUT

Below we discuss primarily epidemiological studies of people that were near nuclear test sites when the tests were conducted. These studies were conducted both because of concern for the exposed groups and to increase our scientific knowledge of radiation-induced health effects, especially our understanding of risks of thyroid disease from exposure to radioactive iodines. Simon and Bouville (2002) provide additional information on dosimetry for these studies. Studies of people who were exposed from tests conducted at the Semipalatinsk Test Site are discussed in a later section, "Emerging Studies in Countries of the Former Soviet Union."

Marshall Islanders

Misjudgments in weather predictions and bomb yield led to contamination of inhabited islands in Rongelap, Ailinginae, and Utrik Atolls from the BRAVO test conducted in 1954 on the Bikini Atoll. Exposures in the Marshall Islands are the subject of a special issue of *Health Physics* (1997); studies of thyroid disease in the Marshall Islands are reviewed in detail in Takahashi et al. (2001). Acute effects were observed among Rongelap subjects and among a group of Japanese fishermen who were nearby. Estimated external gamma doses in air were 1.9 Sv for people evacuated from Rongelap, 1.1 Sv for people evacuated from Ailinginae, and 0.11 Sv for people evacuated from Utrik (Lessard et al. 1985). For people on Rongelap, average thyroid doses have been estimated to be 12 Gy for adults, 22 Gy for a 9-y-old child, and 52 Gy for a 1-y-old child. These dose estimates are very uncertain, but are nevertheless the best presently available.

By the end of 1990, 29 of the 86 people from Rongelap or Ailinginae (34%) had developed thyroid nodules, clearly higher than the rate of 4% observed in a comparison group of 227 Rongelap people who were not living on Rongelap at the time of the BRAVO test. Six of the twenty-nine cases in Rongelese were thyroid cancers. Twenty-six of 167 people (16%) from Utrik developed thyroid nodules by the end of 1990 (Howard et al. 1997). The combined population of Rongelap, Ailinginae, and

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Utrik (253 people) is too small to have demonstrated increases in leukemia or other cancers. However, the single case of leukemia that has been observed, an acute myeloblastic leukemia in a 19-y-old Rongelap male who was exposed to 1.9 Gy at 1 y of age, can probably be attributed to radiation exposure (Conard 1980). Dose to the Marshall Islanders was mainly from external radiation and ingestion of short-lived radioisotopes with a small component from ^{131}I (Lessard et al. 1985). These studies are important in that they provide the first evidence of increased risk of thyroid disease from exposure to radioactive iodines but may be limited in providing quantitative information on the specific effects of exposure to ^{131}I.

Contemporary measurements of radioactivity in the environment (Simon and Graham 1997) indicate that Marshallese living on many other atolls received some exposure from the bomb tests although doses are estimated to be much smaller (Takahashi et al. 2001). Hamilton et al. (1987) studied persons on 12 atolls that previously had been thought to be unexposed and found that the prevalence of palpable nodules decreased with increasing distance from Bikini.

In the Marshall Islands Nationwide Thyroid Study more than 5,000 people born before 1965 were clinically evaluated for both palpable thyroid nodules and nodules diagnosed by ultrasound (Takahashi et al. 2001). Approximately 3,700 of these people were born before 1 March 1954 and are designated as the BRAVO cohort. In analyses based on people exposed on atolls other than Rongelap and Ailinginae, the prevalence of thyroid cancer was inversely related to distance from Bikini ($p =$ 0.09), and positively related to two proxy measures of dose ($p < 0.001$ and $p = 0.06$). However, none of these relationships approached statistical significance when Utrik was excluded, and none of these relationships were found for the prevalence of all benign nodules or of all palpable nodules (including thyroid cancer). In fact, benign nodules and palpable nodules were positively related to distance ($p = 0.08$ and 0.05, respectively) (Takahashi et al. 2001). These results are counter to the earlier results of Hamilton et al. (1987) and provide little evidence of fallout-related thyroid disease on atolls other than Rongelap, Ailinginae, and Utrik. Further evaluation based on improved estimates of thyroid dose to individual Marshallese is planned (Takahashi et al. 1999).

Nevada Test Site exposures

In the period 1951 to 1962, nearly 100 atmospheric tests were conducted at the Nevada Test Site (NTS), with the maximum exposures occurring in the years 1952, 1953, 1955, and 1957 (NCI 1997). Several studies have evaluated the possibility of adverse health effects among those living near the NTS in Utah or Nevada, as discussed by Land (1996). Here we primarily discuss two major undertakings that included individualized radiation dosimetry. Although the relatively low doses in these studies limit the conclusions that can be drawn, these studies may serve as a model for the study of radiation exposures in other environmental settings.

Several thousand school children who were exposed to NTS fallout in southwestern Utah, southeastern Nevada, and southeastern Arizona were clinically evaluated for thyroid disease in the period 1965 to 1970. Subjects who still resided in the three-state areas were re-evaluated in 1985 to 1986. Extensive efforts were made to estimate doses to the thyroid for individual subjects and made use of data on milk drinking habits that were obtained by interview. Mean doses to the thyroid were 0.17, 0.05 and 0.013 Gy, respectively, for the Utah, Nevada, and Arizona subjects with a maximum dose of 4.6 Gy (Till et al. 1995). Among the nearly 2,500 subjects included in the final analysis, eight thyroid cancers and 11 non-malignant thyroid neoplasms were ascertained (Kerber et al. 1993). A non-statistically significant association (one-tailed $p = 0.096$) with dose was found for thyroid cancer, and the resulting ERR Gy^{-1} was 7.9. The association became statistically significant (one-tailed $p = 0.019$) when malignant and benign thyroid neoplasms were combined with an estimated ERR Gy^{-1} of 7.0. These estimates are similar (but uncertainly estimated) to the estimate of 7.7 Gy^{-1} obtained from the pooled analyses of subjects exposed externally during childhood (Ron et al. 1995). Further follow-up of this cohort is underway.

Several studies have investigated leukemia in relation to NTS fallout in Utah. Early reports were based on comparisons of rates of leukemia (and other cancers) by place of residence at the time of disease diagnosis and time period, and did not take account of changes in residence, and did not include estimates of doses to individuals. These deficiencies were remedied in a leukemia case-control study (Stevens et al. 1990), which included 1,177 persons who had died of leukemia (cases), and 5,330 persons who had died of other causes (controls). Residential histories and fallout deposition rates were used to estimate dose to the bone marrow for each subject. The median dose for all subjects was 3.2 mGy, whereas the mean dose for subjects who lived in Washington county (closest to the NTS) throughout the fallout period was 19 mGy (Simon et al. 1995). When all subjects were included, a weak but non-significant dose-response relationship was found with an estimated relative risk for those with doses exceeding 6 mGy of 1.7 (95% CI: 1.0 to 2.8). However, statistically significant associations were found for those who died under age 20 y (one-tailed $p = 0.02$), those dying in the period 1952 to 1957 (one-tailed $p = 0.04$), and for acute lymphocytic leukemias (one-tailed $p = 0.009$); these are all subgroups for which risks might be expected to be especially large based on findings from Japanese atomic-bomb survivors. The estimated risks from this study were about double those that would be predicted by the BEIR V leukemia model (NAS/NRC 1990) but did not differ significantly from BEIR V predictions.

In 1997, the National Cancer Institute (NCI 1997) published estimates of thyroid doses for the American public resulting from ^{131}I exposure from nuclear weapons tests conducted at the NTS. In an ecological study, Gilbert et al. (1998) related age-, calendar year-, sex-, and county-specific thyroid cancer mortality and incidence rates for the United States to the estimated ^{131}I doses from NTS fallout estimates taking geographic location, age at exposure, and birth cohort into account. The analyses included 4,602 thyroid cancer deaths and 12,657 incident cases of thyroid cancer, and made use of mean doses for 3,053 counties, seven time periods, and seven age-at-exposure categories. An association was found for dose received before 1 y of age, based on either the mortality or incidence data. However, neither cumulative dose nor dose received between 1 and 15 y of age was associated with thyroid cancer mortality or incidence, a finding that is not consistent with evidence from studies of children exposed externally. This inconsistency may result from the limitations and biases inherent in ecological studies, particularly the error introduced when studying a mobile population. Meaningful quantitative risk estimation was not possible in this study.

In summary, none of the epidemiological studies of NTS exposures provide definitive evidence of excess risks from fallout exposures, but suggest increased risks that are of the magnitude that might be predicted from studies of persons exposed externally.

Studies of nuclear test participants

Studies have been conducted of United States military personnel who participated in nuclear tests either at the NTS or in the Pacific (Robinette et al. 1985; Johnson et al. 1996; Thaul et al. 2000) and also of test participants from other countries (Darby et al. 1993; Pearce et al. 1997). These cohorts may have been exposed to some prompt radiation (neutron and gamma) and may have been subject to bodily contamination with radioactive debris making their exposures somewhat different from exposures to the public from NTS and global fallout. Some studies (Darby et al. 1993; Pearce et al. 1997; Thaul et al. 2000) have suggested that leukemia mortality rates may be elevated relative to those of specially selected comparison groups. These studies were conducted largely to obtain direct information on health effects for concerned military veterans, and none had adequate dosimetry to allow evaluation of dose-response relationships.

EPIDEMIOLOGICAL STUDIES OF PERSONS WITH EXPOSURES SIMILAR TO THOSE FROM FALLOUT

In addition to the studies discussed in the previous section, other populations have been exposed to ^{131}I and/or other external and internal sources of radiation at low dose rates. Although these studies do not involve fallout exposures from nuclear-bomb tests, the exposures are sufficiently similar that the studies provide pertinent information for estimating health effects from fallout. These studies may be especially important for evaluating health effects for fallout doses to the general population, where it is generally not feasible to study effects directly. Current models for estimating health effects from radiation exposure are based primarily on Japanese atomic-bomb survivors and medically exposed populations, with exposures from external sources at high dose rates.

^{131}I exposures from the Hanford Nuclear Site

A draft report describes results of a study of persons exposed as children in the 1940's to ^{131}I releases from the Hanford Nuclear Site in southeastern Washington State, in which 3,193 persons were clinically evaluated for thyroid disease (Davis et al. 1999). No evidence of dose-response relationship was found for thyroid cancer (19 cases), benign thyroid nodules (249 cases), or any of the other nine categories of thyroid disease that were evaluated. Although extensive efforts were made to estimate individual doses to the thyroid, the large degree of uncertainty in these estimates may still be a major limitation of the study. The final report has not yet become available.

Medical exposures to ^{131}I

There are several studies of persons exposed to ^{131}I for diagnostic and therapeutic medical reasons. However, these studies primarily involve exposure in adulthood, whereas evidence of increased thyroid cancer risks from external exposure has been limited almost entirely to exposure in childhood. In a large study of over 34,000 patients administered ^{131}I for diagnostic purposes in Sweden, there was no evidence of excess thyroid cancer when analyses were limited to those who were examined for reasons other than suspected thyroid cancer (Hall et al. 1996). A strength of the study is that it included individual estimates of thyroid doses, but there was no evidence of a dose response. Among the 1,800 patients in this study who were under the age of 20 y at exposure (most were between 15 and 20) and who were not being examined because of suspected thyroid cancer, two thyroid cancers were observed resulting in a standardized incidence ratio of 1.4 (95% CI = 0.17 to 5.0). In a study of 3,500 United States patients who received diagnostic examination with ^{131}I at ages younger than 20, 4 thyroid cancers were identified leading to a relative risk of 3.0 (95% CI = 0.3 to 70) (Hamilton et al. 1989; Chiacchierini 1990). Clearly the latter two studies are too limited to allow reliable quantification of risks.

Three studies of therapeutic exposures to ^{131}I used to treat hyperthyroidism in Sweden (Hall et al. 1992), the United States (Ron et al. 1998), and England (Franklyn et al. 1999) showed elevated risks of thyroid cancer, although the excess was not statistically significant in the Swedish study. Some of the excess in these studies could be due to the underlying thyroid disease. Doses to the thyroid were probably in the range of 60 to 100 Gy.

External exposure at low doses and dose rates

Studies of persons exposed to low doses of external radiation either occupationally or environmentally have been reviewed elsewhere (IARC 2000; UNSCEAR 2000). Here we briefly discuss only studies of nuclear workers who were individually monitored for radiation exposure using personal dosimeters. Among low dose studies, these studies are the most promising for quantitative risk assessment and have generally confirmed the appropriateness of risk estimates based on atomic-bomb survivor data. Specifically, the International Agency for Research on Cancer (IARC) analyzed combined data from studies of nuclear workers in the United States, United Kingdom, and Canada (Cardis et al. 1995). This analysis resulted in a statistically significant response for leukemia, but there was no evidence of a dose-response relationship for the combined category of cancers other than leukemia. Risk estimates for both leukemia and cancers other than leukemia had wide confidence intervals (CI) indicating that they were compatible with those based on atomic-bomb survivor data. With the generally small doses received by workers, the increased cancer risk from radiation is very small relative to the baseline cancer risk, so that random fluctuation and the strong potential for confounding make it difficult if not impossible to detect or estimate risks precisely. Possibly this situation will be improved by a collaborative study of about 600,000 nuclear workers in 17 countries that is being coordinated by IARC (Cardis and Esteve 1992).

EMERGING STUDIES IN COUNTRIES OF THE FORMER SOVIET UNION

Most of the studies discussed above are limited by the fact that doses were not large enough to yield risk estimates of reasonable precision. In addition, with studies at low doses and accompanying small risks, even a small amount of bias from confounding can seriously bias resulting estimates per unit of dose (Gilbert 1996, 2001). Promising cohorts in countries of the former Soviet Union may allow direct evaluation of health effects from exposure to ^{131}I and from low dose rate external exposure at doses that are high enough to yield reasonable statistical power. With the exception of studies involving exposures from the Semipalatinsk Nuclear Test Site, the exposures in these studies are not from nuclear-bomb tests but are sufficiently similar to such exposures to provide relevant information.

The success of these studies in providing useful quantitative risk estimates will depend on developing reliable dose estimates for individual subjects; establishing appropriate comparison groups; and developing data on health endpoints that are reasonably accurate, complete, and not biased by exposure status. In all of the studies discussed below, both dosimetry and other kinds of data are still being developed or improved, and, thus, reliable quantitative risk estimates are not yet available.

Exposures from the Semipalatinsk Nuclear Test Site

From 1949 to 1962, more than 100 atmospheric nuclear tests were conducted by the former Soviet Union at the Semipalatinsk Test Site (STS) in Kazakhstan. Exposure was primarily from the first test, in August 1949, affecting the Altai and northern Semipalatinsk regions, and two subsequent tests, a plutonium bomb in 1951, and the Soviet Union's first thermonuclear-bomb test in 1953, affecting locations in the Semipalatinsk region southeast of the STS. In a summary of published doses provided in Bouville et al. (2000), it is estimated that the average dose from external and internal sources among about 7,900 persons in nine villages near the STS exceeds 1 Sv. Doses to the thyroid for those exposed in childhood are likely to be an order of magnitude larger. Among fallout-exposed populations, persons exposed from the STS appear to offer the greatest potential for direct evaluation of health effects, particularly thyroid disease from exposure to ^{131}I.

Burkart et al. (2000) summarize preliminary investigations of cancer incidence in selected parts of Kazakhstan (near and distant from the STS) and of mortality and prevalence of chronic non-malignant diseases in the Altai region of the Russian Federation. Although some results suggest health effects from STS exposures, insufficient information on study methods and data quality make these findings difficult to interpret. Results of epidemiological studies that include estimated doses to individuals have not yet been reported.

A promising study of thyroid disease prevalence is being conducted by the National Cancer Institute in collaboration with the Research Institute for Radiation and Medical Ecology in Semipalatinsk, the Semipalatinsk Medical Academy, and the University of New Mexico. In August 1998, about 3,000 current residents of six heavily exposed and two lightly exposed villages in Kazakhstan near the STS were screened for thyroid disease. Of the 3,000, about 2,000 had been exposed as children, and 1,000 had not been present in the period 1949 to 1953; the two groups were of similar age. Screening included the use of ultrasound to detect nodules and fine needle aspiration biopsy to detect malignancy. To obtain information needed for dose estimation, subjects were interviewed with respect to residential history and childhood sources and amount of milk and other food involved in the intake of fallout-derived ^{131}I. A group of women who were familiar with children's diets at that time were also interviewed. Results have not yet been reported.

Exposures resulting from the Chernobyl accident in 1986

Large increases in thyroid cancer incidence have occurred in Belarus, Ukraine, and Russia among persons under 20 y of age who were exposed to ^{131}I as a result of the Chernobyl accident (Demidchik et al. 1996; Tsyb et al. 1996; Tronko et al. 1999). At first it was thought that this might be explained by thyroid screening that has been conducted in the affected areas, but it was later determined that most of the cancers were sufficiently aggressive that they would not likely have been missed with usual reporting methods (Bleuer et al. 1997).

In addition, both a case-control study in Belarus (Astakhova et al. 1998) and several geographic correlation studies in Belarus, Russia and the Ukraine (Jacob et al. 1999; UNSCEAR 2000) have demonstrated exposure-response relationships. Although Astakhova et al. do not attempt to estimate risk per unit of dose, the study is the first case-control study with dose estimates for individual subjects to demonstrate a dose-response relationship. Jacob et al. provide an estimate of the excess absolute risk (EAR) of 2.4 10^{-4} Gy^{-1} with a 95% CI of 1.4 to 3.8, and an estimate of the excess relative risk (ERR) of 22 to 90 Gy^{-1} (depending on the geographic area evaluated). Although these estimates must be regarded tentatively, the EAR is lower than the estimate of 4.4 10^{-4} Gy^{-1} from a study of persons exposed externally in childhood (Ron et al. 1995) while the ERR is much larger than the ERR of 7.7 Gy^{-1} from Ron et al. These differences might have resulted because subjects in the Chernobyl study developed their thyroid cancers while still young and baseline risks were low, whereas most of the subjects in the externally exposed groups were followed much longer and developed their thyroid cancers as adults.

Studies of Chernobyl exposures have already contributed by firmly establishing that exposure to ^{131}I in childhood can increase the risk of thyroid cancer. The contribution is likely to be increased by several case-control studies that are currently underway. These studies include extensive efforts to estimate thyroid doses for individual subjects and should make it possible to quantify the risk as a function of dose although understanding the role of both screening effects and iodine deficiency will be important if these data are to be useful for evaluating risks in other populations. Because the number of people exposed as a result of the Chernobyl accident far exceeds the number of people in studies of thyroid cancer from external exposure, the potential for new information is enormous. It is important to continue investigations to allow the evaluation of long-term risks, particularly whether or not the large risks observed thus far continue into adulthood.

The most promising Chernobyl-exposed subjects for evaluating health effects other than those due to ^{131}I are the 600,000 to 800,000 workers who participated in clean up after the accident (UNSCEAR 2000). These workers probably received external doses in the order of 0.1 Gy, whereas others, such as those residing in contaminated areas, usually received doses that were an order of magnitude or so smaller. Analyses reported thus far have primarily involved comparing mortality rates for these workers with those of the general population (Buzunov et al. 1996; Cardis et al. 1996; Okeanov et al. 1996; Ivanov et al. 1997a; Rahu et al. 1997). Increased incidence of leukemia has been reported in Belarussian, Russian, and Ukrainian clean-up workers, but not in the small Estonian cohort. However, the estimated increases could be strongly biased by greater intensity of follow-up for the workers than for the general population, and, in some cases, failure to confirm leukemia cases. This conclusion is supported by a case-control study, nested in a cohort of 156,000 Russian clean-up workers, where internal comparisons by dose showed little evidence of a dose-response relationship (Ivanov et al. 1997b); this cohort was one of those indicating an excess based on external comparisons (Ivanov et al. 1997a). To date, no evidence of excess solid cancers in the clean-up worker cohorts has been found, but this may not be surprising considering latency and the small excess relative risks expected for these cancers. The clean-up workers may eventually provide useful risk estimates if sufficient attention is given to individual dose estimates, to appropriate comparison groups, and to analyses based on combined data from the several cohorts that are now being evaluated. The potential and problems of evaluating leukemia risks from Chernobyl exposures are discussed in an editorial by Boice (1997).

Exposures resulting from operations of the Mayak Nuclear Facility

The production of plutonium at the Mayak Facility in Ozyorsk, Russian Federation, which began operations in 1948, exposed both workers and nearby populations to external and internal radiation including large releases of ^{131}I. Thyroid cancer incidence was evaluated in about 19,500 cohort members who lived in Ozyorsk as children during the years of highest potential ^{131}I exposure and who still lived in Ozyorsk. Twenty-nine cancers were ascertained, and preliminary analyses suggest that these subjects had higher rates of thyroid cancer than predicted by Russian national incidence rates (Koshurnikova et al. 2000). In a pilot thyroid screening study of 894 (581 exposed, 313 unexposed) of these subjects, several thyroid disease endpoints were evaluated, and the results suggest that the prevalence of thyroid nodules was higher in the exposed than in the unexposed subjects (Mushkacheva et al. 2000). The study may be expanded to include additional subjects and estimates of ^{131}I doses to the thyroid.

During the early 1950's, the Techa River was severely contaminated with radioactive wastes from the Mayak Plant. About 28,000 inhabitants of the riverbank villages who received significant exposure are being studied. Subjects were exposed to ^{137}Cs and ^{90}Sr; thus this study may be especially relevant for addressing the effects of global fallout, which includes a strontium component. The mean red bone-marrow dose was originally estimated to be 0.4 Gy, but doses are currently being re-evaluated, and preliminary results suggest that the original estimates may be reduced. Initial analyses suggest a leukemia dose response and an increased risk of all solid cancers combined (Kossenko and Degteva 1994; Kossenko et al. 1997). Follow-up of this cohort has been challenging, but has been greatly improved in the last few years; cancer incidence data as well as mortality data are being collected. This cohort could potentially provide useful direct information on strontium exposure and on protracted exposure in general. Leukemia is the most promising endpoint, both because of its larger relative risk and because bone-marrow doses are higher than doses to other organs (due to the strontium component).

Workers at the Mayak Plant were exposed to both external (primarily gamma) radiation and to plutonium at doses much higher than those of similar workers in other countries (Koshurnikova et al. 1999). The average cumulative external dose for workers initially hired in the years 1948 to 1958 was 1.1 Gy, and significant relationships with external dose have been demonstrated for both leukemia and all solid cancers (Shilnikova et al. 2000). Although the Mayak workers are not as relevant for fallout exposures as other cohorts in the former Soviet Union, they may provide useful direct estimates of protracted external doses that can supplement those from the atomic-bomb survivors.

QUANTITATIVE ESTIMATES OF CANCER RISKS FROM FALLOUT IN THE UNITED STATES

In addition to special populations that received relatively large doses from fallout, health risks from exposures to the general public are of interest. As discussed by Bouville et al. (2002), the National Cancer Institute (NCI 1997) published estimates of thyroid doses for the American public resulting from ^{131}I exposure from nuclear weapons tests conducted at NTS. Recently, these efforts have been expanded, and preliminary estimates of doses to the thyroid and red bone marrow that include contributions from both NTS and global fallout and that also include contributions from both external and internal exposure to more than 20 radionuclides are now available (DHHS 2001). Preliminary estimates of health effects from these doses are also given in the DHHS report.

Because direct study of very large populations with very small risks is not feasible, risks must be estimated using models based on data from studies of other exposed populations. From the discussion in the previous sections, it can be seen that epidemiological data on populations that have been exposed to fallout or to exposures similar to those from fallout have not yet provided reliable quantitative estimates of risk. Thus, risk estimates must be based on data from atomic-bomb survivors and medically exposed cohorts.

Below we summarize risk estimates from the DHHS (2001) report. These estimates include estimates for thyroid cancer resulting from ^{131}I exposures from the NTS, and very preliminary estimates for leukemia and solid cancers resulting from external exposure from both NTS and global exposure. It should be kept in mind that doses and risks from fallout vary substantially by year of birth, geographic location, and other factors. From a public health standpoint, the extent to which those with especially large risks can be identified is important. Most of the estimates are based on a very simple approach, and, in particular, do not take detailed account of changes in population size over time, year of birth, and age at exposure. They should, therefore, be regarded as very preliminary.

The DHHS report did not attempt to quantify health effects other than cancer. Extensive study of the Japanese atomic-bomb survivors and of a large number of medically exposed cohorts have made it clear that cancer is the most important health effect of exposure to radiation at moderate or small doses (NAS/NRC 1990; UNSCEAR 2000). Benign tumors are also a possible effect of fallout exposure, but difficulties in studying these tumors and limitations in data on baseline risks preclude quantifying risks (DHHS 2001). Non-neoplastic diseases have been linked with radiation exposure at high doses, but it is unclear whether or not these effects would occur at lower doses (IOM/NRC 1999; Shimizu et al. 1999; DHHS 2001).

Thyroid cancer

Ron et al. (1995) evaluated thyroid cancer risks using data on atomic-bomb survivors and six studies of medically exposed persons. A pooled analysis of those exposed under age 15 in the five cohort studies was conducted, and resulted in an overall ERR Gy^{-1} of 7.7 (90% CI: 2.1 to 28.7). The confidence limits were calculated to reflect heterogeneity among the studies, which was substantial. Linear models were found to provide a good fit both to the pooled data, and to data from individual studies. Even among those exposed under age 15, the ERR Gy^{-1} showed a strong decrease with increasing age at exposure. There was no clear evidence of exposure-related risk among subjects exposed in adulthood, but only two studies included such subjects. The ERR Gy^{-1} was highest about 15 y after exposure, but still in excess 40 or more years after exposure.

Because exposure from ^{131}I differs from external exposure both in dose rate and the distribution of energy deposition within the thyroid gland, it may be less effective than external exposure in causing thyroid cancer. Thus, if data on external exposure are to be used to estimate health effects from fallout, it is necessary to consider the relative biological effectiveness (RBE) of ^{131}I. Ron (1999) briefly reviews experimental evidence regarding the RBE. More recent studies, including a meta-analysis of experimental and epidemiological data (Laird 1987), support the use of an RBE in the range 0.66 to 1. Lower values have been used in the past (NCRP 1985), but these were largely based on studies of persons exposed to ^{131}I for medical reasons in adulthood (where there is little evidence of risk from external exposure) and on early animal experiments with very large doses.

Land (IOM/NRC 1999) estimated the number of thyroid cancers from NTS fallout by applying age-specific risk coefficients from Ron et al. (1995) and making various assumptions about the RBE. With an assumed RBE of 0.66, Land estimated that about 49,000 thyroid cancers would be expected to occur from NTS exposures. He further estimated that about 45% of the cancers would already have occurred, and about 75% would be in persons exposed under 5 y of age. Land calculated an approximate 95% CI of 11,300 to 212,000, which includes both statistical uncertainties and uncertainties in the estimated average dose; the interval does not include uncertainty in the RBE and other model assumptions. IOM/NRC (1999) noted that various epidemiological analyses suggest that the excess is probably in the lower part of the range.

Leukemia and solid cancers other than thyroid

Several scientific committees and groups have provided models for estimating risks of leukemia and solid cancers (NAS/NRC 1990; ICRP 1991; EPA 1994, 1999; UNSCEAR 2000). These models are based primarily on the Japanese atomic-bomb survivor cancer mortality data, although the recent UNSCEAR report also derives estimates based on cancer incidence data. DHHS used the ICRP lifetime risk estimate of 5% Sv^{-1} for mortality from all cancers (including leukemia) and the lifetime risk estimate of 0.5% Sv^{-1} for leukemia alone. These estimates were obtained by reducing linear coefficients based on the atomic-bomb survivor data by a dose and dose rate effectiveness factor (DDREF) of two. If cancer mortality estimates for the United States population from the recent UNSCEAR report (2000) were reduced by a DDREF of two, they would be similar in magnitude to the ICRP estimates.

A preliminary estimate of the average external dose from NTS and global fallout received by a person residing in the United States over the period 1951 to 2000 is 1.2 mGy (DHHS 2001). The population dose would then be about 217,000 person-Gy based on the assumption that the population was 163 million (1960 population) for the years 1951 to 1972, and 250 million (1990 population) for the years 1973 to 2000. DHHS applied the ICRP (1991) coefficient of 5% Gy^{-1} for total cancer mortality to the population dose, and estimated that about 11,000 extra cancer deaths would be predicted among the United States population alive during the years of fallout.

This estimate is subject to several sources of uncertainty, which include uncertainties in the epidemiological data (statistical variation, random and systematic errors in atomic-bomb survivor dosimetry, diagnostic misclassification in atomic-bomb survivor data), uncertainties in extrapolating risk estimates from high to low doses and dose rates, transfer of risk estimates from Japanese atomic-bomb survivors to the United States population, and projection of risks beyond the time period covered by data. If uncertainties in the ICRP lifetime risks are assumed to be as evaluated by NCRP (1997), and if the average dose is assumed to have a 90% credibility interval that extends from a factor of three below the estimate to a factor of three above the estimate, the predicted number of excess cancer deaths might range from 1,700 to 32,500 (90% credibility interval).

These deaths would be spread out over the period from the 1950's through much of the 21st century. For comparison, it is noted that 500,000 cancer deaths occurred in the United States in 1990 alone, and that about 40 million cancer deaths might be predicted to occur over a 75-y period. If nonfatal cancers were included, the numbers above would be approximately doubled. Although the number of extra incident cancer cases (22,000) predicted from external fallout exposure is small compared to the number that would occur for other reasons, it is about half the predicted number of thyroid cancers from NTS ^{131}I exposure (49,000). The number of cancer deaths (11,000) from external exposure is likely to exceed the number of thyroid cancer deaths, since thyroid cancer has a low fatality rate (less than 10%).

Doses received from fallout and the ages at which they are received depend strongly on birth cohort. For this reason, DHHS evaluated risks for persons born in 1931, 1951, and 1971. Both doses and risks would likely be largest for persons born in 1951. For such a person, the risk of fatal cancer from external fallout dose would be less than 1 in 4,000, or a small fraction of a percent. This can be compared with the risk of fatal cancer in the absence of fallout, which would be about 1 in 5 or 20%. For persons born in 1931 or 1971, risks from fallout would be much smaller.

Estimates of leukemia risks from external and internal exposure can also be made by applying the ICRP risk coefficient of 0.5% Sv^{-1}. For external exposure, about 10% of the total cancer deaths (1,100 of the 11,000) would be estimated to be leukemia deaths. DHHS also estimated an additional 550 leukemias from internal exposure, primarily from ^{90}Sr.

Estimates for risks of site-specific solid cancers (other than thyroid) resulting from external exposure from fallout could be estimated using various models (ICRP 1991; EPA 1994, 1999; UNSCEAR 2000). For internal exposure, doses vary considerably by organ. Preliminary data indicate that the organs likely to receive the largest internal doses (in addition to the thyroid and red bone marrow) are colon, kidney, liver, and bone surfaces. Because estimates of doses to specific organs are generally less than those from external exposure, and because most organs receive very little dose from internal sources, the total risk from internal exposure to organs other than the thyroid and red bone marrow is likely to be considerably less than the total risk from external exposure. Risk estimates for site-specific cancers are more uncertain than estimates of risks for all cancers because statistical variation in risk coefficients is larger and because of the need to transfer risk coefficients from atomic-bomb survivors to a United States population. Differences in baseline risks between the United States and Japan are often much greater for site-specific cancers than for all cancer.

CONCLUSION

Excess thyroid disease from fallout has clearly been demonstrated among the highly exposed Marshall Islanders. Extensive studies that include dose estimates for individuals suggest excesses of both thyroid disease and leukemia in populations exposed to the much smaller doses from tests conducted in Nevada; the magnitude of these excesses is compatible with predictions based on studies of persons exposed externally. With regard to exposures to the general United States population, preliminary estimates of risks of developing cancer from fallout have been made, but are subject to large uncertainties in both estimated doses and in the risk models, which are based on indirect data. In spite of the uncertainties, it can be concluded that it is likely that there is an increased risk of cancer from fallout in the United States, and that this risk is very small relative to the usual risk of cancer in the absence of fallout exposure.

An important source of uncertainty in estimating the health effects from fallout is that current risk models are based primarily on high dose rate external exposure, whereas fallout exposures are protracted over time and include internal as well as external exposure. The uncertainty in estimating risks from exposure to ^{131}I is especially important because it is the main source of radiation to the thyroid from fallout exposure. Several epidemiological studies in countries of the former Soviet Union include people exposed to ^{131}I and to protracted doses from other sources that are large enough to provide risk estimates of reasonable statistical precision, and thus may help to reduce uncertainties. Obtaining reliable individual dose estimates will be critical to the success of these studies.

REFERENCES

Astakhova LN, Anspaugh LR, Beebe GW, Bouville A, Drozdovitch VV, Garber V, Gavrilin YI, Khrouch VT, Kuvshinnikov AV, Kuzmenkov YN, Minenko VP, Moschik KV, Nalivko AS, Robbins J, Shemiakina EV, Shinkarev S, Tochitskaya SI, Waclawiw MA. Chernobyl-related thyroid cancer in children of Belarus: A case-control study. Radiat Res 150:349–356; 1998.

Bleuer JP, Averkin YI, Okeanov AE, Abelin T. The epidemiological situation of thyroid cancer in Belarus. Stem Cells 15:251–254; 1997.

Boice JD, Jr. Leukaemia, Chernobyl and epidemiology (invited editorial). J Radiol Prot 17:129–133; 1997.

Bouville A, Anspaugh L, Balonov MI, Gordeev KI, Kiselev VI, Loborev VM, Luckyanov NK, Pauli E, Robison WL, Savkin M, Suldakov VV, Zelentsov S. Estimation of doses. In: Warner F, Kirchmann RJC, eds. Nuclear test explosions: Environmental and human impacts. Chichester, England: John Wiley & Sons Ltd; 2000: 179–228.

Bouville A, Simon SL, Miller CW, Beck HL, Anspaugh LR, Bennett BG. Estimates of doses from global fallout. Health Phys 82:690–705; 2002.

Burkart W, Kellerer AM, Bauer S, Harrison JR, Land C, Shoikhet YN, Kiselev VI, Simon SL, Tsukatani T, de-Vathaire F. Health effects. In: Warner F, Kirchmann RJC, eds. Nuclear test explosions: Environmental and human impacts. Chichester, England: John Wiley & Sons Ltd.; 2000: 179–228.

Buzunov V, Omelyanetz N, Strapko N, Ledoschuk B, Krasnikova L, Kartushin G. Chernobyl NPP accident consequences clearing up participants in Ukraine—health status epidemiologic study—main results. In: Karaoglou A, Desmet G, Kelly GN, Menzel HG, eds. The radiological consequences of the Chernobyl accident, Proceedings of the First International Conference, Minsk, Belarus. Luxembourg: Office for Official Publications of the European Communities; EUR 16544; 1996: 871–878.

Cardis E, Esteve J. International collaborative study of cancer risk among nuclear industry workers, I-Report of the feasibility study. Lyon, France: International Agency for Res on Cancer; Internal Report No 92/001; 1992.

Cardis E, Gilbert ES, Carpenter L, Howe G, Kato I, Armstrong BK, Beral V, Cowper G, Douglas A, Fix J, Fry SA, Kaldor J, Lave C, Salmon L, Smith PG, Voelz GL, Wiggs LD. Effects of low doses and low dose rates of external ionizing radiation: cancer mortality among nuclear industry workers in three countries. Radiat Res 142:117–132; 1995.

Cardis E, Anspaugh L, Ivanov VK, Likhtarev IA, Mabuchi K, Okeanov AE, Prisyazhniuk AE. Estimated long term health effects of the Chernobyl accident. In: One decade after Chernobyl: Summing up the consequences of the accident, Proceedings of an International Atomic Energy Agency Conference. Vienna: International Atomic Energy Agency; 1996: 241–279.

Chiacchierini RP. Iodine-131 exposure and neoplasia. Radiat Res 124:359–360; 1990.

Conard RA. Review of medical findings in a Marshallese population twenty six years after accidental exposure to radioactive fallout. Upton, NY: Brookhaven National Laboratory; BNL 51261; 1980.

Darby SC, Kendall GM, Fell GM, Doll R, Goodill AA, Conquest AJ, Jackson DA, Haylock RG. Further follow up of mortality and incidence of cancer in men from the United Kingdom who participated in the United Kingdom's atmospheric nuclear weapon tests and experimental programmes. Br Med J 307:1530–1535; 1993.

Davis S, Kopecky KJ, Hamilton TE, Amundson B. Hanford thyroid disease study. Seattle: Hanford Nuclear Site; Draft final report; 1999.

Demidchik EP, Drobyshevskaya IM, Cherstvoy LN, Astakhova LN, Okeanov AE, Vorontsova TV, Germenchuk, M. Thyroid cancer in children in Belarus. In: Karaoglou A, Desmet G, Kelly GN, Menzel HG, eds. The radiological consequences of the Chernobyl accident. Luxembourg: EUR 16544 EN; 1996: 677–682.

Department of Health and Human Services. A feasibility study of the health consequences to the American population of nuclear weapons tests conducted by the United States and other nations. Atlanta, GA: Centers for Disease Control and Prevention; Draft technical report; 2001.

Environmental Protection Agency. Estimating radiogenic cancer risks. Washington, DC: EPA; 402-R-93-076; 1994.

Environmental Protection Agency. Estimating radiogenic cancer risks. Addendum: uncertainty analysis. Washington, DC: EPA; 402-R-99-003; 1999.

Franklyn JA, Maisonneuve P, Sheppard M, Betteridge J, Boyle P. Cancer incidence and mortality after radioiodine treatment for hyperthyroidism: A population-based cohort study. Lancet 353:2111–2115; 1999.

Gilbert ES. Combined analysis of studies of nuclear workers. In: Implications of New Data on Radiation Cancer Risk. Bethesda, MD: National Council on Radiation Protection and Measurements; NCRP Proceedings No. 18; 1996: 97–112.

Gilbert ES. Invited commentary: Studies of workers exposed to low dose of radiation. Am J Epid 153:319–322; 2001.

Gilbert ES, Tarone R, Bouville A, Ron E. Thyroid cancer rates and 131I doses from Nevada atmospheric nuclear bomb tests. J Natl Cancer Inst 90:1654–1660; 1998.

Hall P, Berg G, Bjelkengren G, Boice JD, Jr, Ericsson UB, Hallquist A, Lidberg M, Lundell G, Tennvall J, Wiklund K, Holm LE. Cancer mortality after iodine-131 therapy for hyperthyroidism. Intl J Cancer 50:886–890; 1992.

Hall P, Mattsson A, Boice JD, Jr. Thyroid cancer after diagnostic administration of iodine-131. Radiat Res 145:86–92; 1996.

Hamilton TE, Van Belle G, LoGerfo JP. Thyroid neoplasia in Marshall Islanders exposed to nuclear fallout. J Am Med Assoc 258:629–635; 1987.

Hamilton PM, Chiaccierini RP, Kaczmarek RG. A follow-up study of persons who had iodine-131 and other diagnostic procedures during childhood and adolescence. Washington DC: U.S. Department of Health and Human Services; HAS Publication FDA 89–8276:1989.

Howard JE, Vaswani A, Heotis P. Thyroid disease among the Rongelap and Utirik population—an update. Health Phys 73:190–198; 1997.

Institute of Medicine/National Research Council. Exposure of the American people to iodine-131 from Nevada nuclear-bomb tests. Review of the National Cancer Institute report and public health implications. Washington, DC: National Academy Press; 1999.

International Agency for Research on Cancer. IARC monographs on the evaluation of carcinogenic risk to humans. Vol 75: Ionizing radiation, Part 1: X- and gamma-radiation and neutrons. Lyon, France: IARC; 2000.

International Commission on Radiological Protection. 1990 recommendations of the International Commission on Radiological Protection. New York: Elsevier Science; ICRP Publication 60: Ann. ICRP21(1–3); 1991.

Ivanov VK, Tsyb AF, Gorsky AI, Maksyutov MA, Rastopchin EM, Konogorov AP, Korelo AM, Biryukov AP, Matyash VA. Leukaemia and thyroid cancer in emergency workers of the Chernobyl accident: Estimation of radiation risks (1986–1995). Radiat Environ Biophys 36:9–16; 1997a.

Ivanov VK, Tsyb AF, Konogorov AP, Rastopchin EM, Khait SE. Case-control analysis of leukaemia among Chernobyl accident emergency workers residing in the Federation, 1986–1993. J Radiol Prot 17:137–157; 1997b.

Jacob P, Kenigsberg Y, Zvonova I, Goulko G, Buglova E, Heidenreich WF, Golovneva A, Bratilova AA, Drozdovitch V, Kruk J, Pochtennaja GT, Balonov M, Demidchik EP, Paretzke HG. Childhood exposure due to the Chernobyl accident and thyroid cancer risk in contaminated areas of Belarus and Russia. Br J Cancer 80:1461–1469; 1999.

Johnson JC, Thaul S, Page WF, Crawford H. Mortality of veteran participants in the CROSSROADS nuclear test. Washington, DC: National Academy Press; 1996.

Kerber RA, Till JE, Simon SL, Lyon JL, Thomas DC, Preston-Martin S, Rallison ML, Lloyd RD, Stevens WS. A cohort study of thyroid disease in relation to fallout from nuclear weapons testing. J Am Med Assoc 270:2076–2082; 1993.

Koshurnikova NA, Shilnikova NS, Okatenko PV, Kreslov VV, Bolotnikova MG, Sokolnikov ME, Khokhriakov VF, Suslova KG, Vassilenko EK, Romanov SA. Characteristics of the cohort of workers at the Mayak nuclear complex. Radiat Res 152:352–363; 1999.

Koshurnikova NA, Shilnikova NS, Petrushkina NP, Okatendo PV, Privalov VA, Iaitsev SV, Preston D, Ron E. Thyroid cancer incidence among people who lived in Ozyorsk (Chelyabinsk-65) as children. Presented at IRPA-10, May 14–19; 2000.

Kossenko MM, Degteva MO. Cancer mortality and radiation risk evaluation for the Techa river population. Sci Total Environ 142:73–90; 1994.

Kossenko MM, Degteva MO, Vyushkova OV, Preston DL, Mabuchi K, Kozheurov VP. Issues in the comparison of risk estimates for the population in the Techa River and atomic bomb survivors. Radiat Res 148:54–63; 1997.

Laird NM. Thyroid cancer risk from ionizing radiation: a case study in the comparative potency model. Risk Anal 7:299–309; 1987.

Land CE. Epidemiological studies of downwinders. In: Environmental dose reconstruction and risk implications. Bethesda, MD: National Council on Radiation Protection and Measurements; NCRP Proceedings No. 17; 1996: 311–328.

Lessard E, Miltenberger R, Conard R, Musolino S, Naidu J, Moorthy A, Schopfer C. Thyroid absorbed dose for people at Rongelap, Utirik, and Sifo on March 1, 1954. Upton, NY: Brookhaven National Laboratory; BNL-51882; 1985.

Mushkacheva GS, Rabinovich EI, Preston DL, Privalov VA, Schneider AB, Hall P, Povolotskaja SV, Rizhova EF, Masharova EI, Ron E. Thyroid abnormalities associated with protracted childhood I-131 exposure from atmospheric emissions from the Mayak Nuclear Plant in Russia. Presented at the 12th International Thyroid Congress; 2000.

National Academy of Sciences/National Research Council. Committee on the Biological Effects of Ionizing Radiation. Health effects exposure to low levels of ionizing radiation (BEIR V Report). Washington, DC: National Academy Press; 1990.

National Cancer Institute. Estimated exposures and thyroid doses received by the American people from Iodine-131 in fallout following Nevada atmospheric nuclear bomb tests. Bethesda, MD: National Cancer Institute; 1997.

National Council on Radiation Protection and Measurements. Induction of thyroid cancer by ionizing radiation. Bethesda, MD: National Council on Radiation Protection and Measurements; NCRP Report No 80; 1985.

National Council on Radiation Protection and Measurements. Uncertainties in fatal cancer risk estimates used in radiation protection. Bethesda, MD: National Council on Radiation Protection and Measurements; NCRP Report No 126; 1997.

Okeanov AE, Cardis E, Antipova SI, Polyakov SM, Sobolev AV, Bazulko NV. Health status and follow-up of the liquidators in Belarus. In: Karaoglou A, Desmet G, Kelly GN, Menzel HG, eds. The radiological consequences of the Chernobyl accident, proceedings of the first international conference, Minsk, Belarus, March 1996. Luxembourg: Office for Official Publications of the European Communities; EUR 16544; 1996: 851–859.

Pearce N, Winkelmann R, Kennedy J, Lewis S, Purdie G, Slater T, Prior I, Fraser J. Further follow-up of New Zealand participants in United Kingdom atmospheric nuclear weapons tests in the Pacific. Cancer Causes Control 8:139–145; 1997.

Rahu M, Tekkel M, Veidebaum T, Pukkala E, Hakulinen T, Auvinen A, Rytomaa T, Inskip PD, Boice JD, Jr. The Estonian study of Chernobyl cleanup workers: II. Incidence of cancer and mortality. Radiat Res 147:653–657; 1997.

Robinette CD, Jablon S, Preston DL. Mortality studies in nuclear weapons tests participants. In: Medical follow-up agency, National Research Council. Washington, DC: National Academy Press; 1985: 1–47.

Ron E. Radiation effects on the thyroid: Emphasis on iodine-131. In: Radiation protection in medicine: Contemporary issues. Bethesda, MD: National Council on Radiation Protection and Measurements; NCRP Proceedings No. 21; 1999: 201–226.

Ron E, Lubin JH, Shore RE, Mabuchi K, Modan B, Pottern L, Schneider AB, Tucker MA, Boice JD, Jr. Thyroid cancer after exposure to external radiation: a pooled analysis of seven studies. Radiat Res 141:259–277; 1995.

Ron E, Doody MM, Becker DV, Brill AB, Curtis RE, Goldman MB, Harris BS, Hoffman DA, McConahey WM, Maxon HR, Preston-Martin S, Warshauer ME, Wong FL, Boice JD, Jr. Cancer mortality following treatment for adult hyperthyroidism. Cooperative thyrotoxicosis therapy follow-up study group. J Am Med Assoc 280:347–355; 1998.

Shilnikova NS, Preston DS, Gilbert ES, Ron E, Koshurnikova NA. Cancer risk among workers at the Russian Nuclear Complex Mayak. In: Moriarty M, Mothersill C, Seymour C, Edington M, Ward JF, Fry RJM, eds. Proceedings of the 11th International Congress of Radiation Research, Volume 2. Lawrence, KS: Allen Press; 2000: 766–769.

Shimizu Y, Pierce DA, Preston DL, Mabuchi K. Studies of the mortality of atomic bomb survivors. Report 12, Part II. Noncancer mortality: 1950–1990. Radiat Res 152:374–389; 1999.

Simon SL, Bouville A. Radiation doses to local populations near nuclear weapons test sites worldwide. Health Phys 82:706–725; 2002.

Simon SL, Graham JC. Findings of the first comprehensive radiological monitoring program of the Republic of the Marshall Islands. Health Phys 73:66–85; 1997.

Simon SL, Till JE, Lloyd RD, Kerber RL, Thomas DC, Preston-Martin S, Lyon JL, Stevens W. The Utah leukemia case-control study: dosimetry methodology and results. Health Phys 68:460–471; 1995.

Stevens W, Thomas DC, Lyon JL, Till JE, Kerber RA, Simon SL, Lloyd RD, Elghany NA, Preston-Martin, S. Leukemia in Utah and radioactive fallout from the Nevada test site. A case-control study. JAMA 264:585–591; 1990.

Takahashi T, Simon SL, Trott KR, Fujimori K, Nakashima N, Arisawa K, Schoemaker MJ. A progress report of the Marshall Islands Nationwide Thyroid Study: An international cooperative scientific study. Tohoku J Exp Med 187:363–375; 1999.

Takahashi T, Trott KR, Fujimori K, Nakashima N, Ohtomo H, Schoemaker MJ, Simon SL. Thyroid disease in the Marshall Islands, findings from 10 years of study. Sendai, Japan: Tohoku University Press; 2001.

Thaul S, Page WF, Crawford H, O'Maonaigh H. The five series study: Mortality of military participants in U.S. nuclear weapons tests. Washington, DC: National Academy Press; 2000.

Till JE, Simon SL, Kerber R, Lloyd RD, Stevens W, Thomas DC, Lyon JL, Preston-Martin S. The Utah thyroid cohort study: analysis of the dosimetry results. Health Phys 68:472–483; 1995.

Tronko MD, Bogdanova TI, Komissarenko IV, Epstein OV, Oliynyk V, Kovalenko A, Likhtarev IA, Kairo I, Peters SB, LiVolsi VA. Thyroid carcinoma in children and adolescents in Ukraine after the Chernobyl nuclear accident: Statistical data and clinicomorphologic characteristics. Cancer 86:149–156; 1999.

Tsyb AF, Parshkov EM, Shakhtarin VV, Stepanenko VF, Skvortsov VF, Chebotareva IV. Thyroid cancer in children and adolescents of Bryansk and Kaluga regions. In: Karaoglou A, Desmet G, Kelly GN, Menzel HG, eds. The radiological consequences of the Chernobyl accident. Luxembourg: EUR 16544 EN; 1996: 691–697.

United Nations Scientific Committee on the Effects of Atomic Radiation. Sources, effects and risks of ionizing radiation. 2000 Report to the general assembly, with annexes. New York: United Nations; 2000.

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