Epidemiology of Accidental Radiation Exposures

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Much of the information on the health effects of radiation exposure available to date comes from long-term studies of the atomic bombings in Hiroshima and Nagasaki. Accidental exposures, such as those resulting from the Chernobyl and Kyshtym accidents, have as yet provided little information concerning health effects of ionizing radiation. This paper will present the current state of our knowledge concerning radiation effects, review major large-scale accidental radiation exposures, and discuss information that could be obtained from studies of accidental exposures and the types of studies that are needed. — Environ Health Perspect 104(Suppl 3):643–649 (1996)

Key words: radiation, cancer, risk estimation, accidents, low-dose, atomic bomb survivors, nuclear workers, Chernobyl

Introduction

Ionizing radiation is one of the agents in our environment for which genetic and cancer risks have been best studied and characterized to date. This is mainly due to two facts: large populations have been exposed and followed for decades and, compared to many other environmental agents, radiation exposures are relatively easy to reconstruct on an individual level, at least for exposures received at high exposure rates and high levels.

The information available to date on radiation risks comes from several sources. Epidemiological studies of large populations that have received relatively high doses of \( \gamma \) or X radiation at a high dose rate (atomic bomb survivors, patients treated by radiotherapy for malignant or benign diseases, occupational exposures in the early years of medical exposures) or high doses of \( \alpha \) particles in a protracted fashion over many years (hard rock, particularly uranium, miners) have been carried out (1–3). More recently, there have also been large-scale epidemiological studies of populations that have received low doses in a protracted fashion as a result of occupation, mainly in the nuclear industry (4,5). Large-scale animal experiments have been carried out in order to understand the effects of different radiation types, exposure levels, patterns of exposure, and modifying factors (1–3). There have also been cytogenetic, molecular, and genetic studies aimed at understanding the mechanisms of radiation-induced carcinogenesis (1,6).

Nonroutine environmental exposure to ionizing radiation of large populations has occurred through accidents but also through acts of war and war-related activities. Such exposures can be divided into two types: those that affect only a limited number of persons (mainly workers at the location of the accident) and those that involve large groups of the general population. Accidents limited to a few exposed persons are much more frequent than those yielding global environmental contamination and may go unreported. Most of the known accidents resulted in relatively high doses to small numbers of persons (7). Table 1 summarizes the main events that have resulted in large-scale radiation exposures. They vary substantially in terms of the size of the populations exposed and the level and type of exposures. Most of these have as yet provided little information concerning the carcinogenic and genetic effects of ionizing radiation. The exception is the study of survivors of the atomic bombings in Hiroshima and Nagasaki, which is the primary basis for radiation protection for X and \( \gamma \) radiation today.

Current Basis for Radiation Risk Estimates—The Atomic Bomb Survivors Study

Background

On 6 August and 9 August 1945, respectively, atomic bombs were dropped on the cities of Hiroshima and Nagasaki in Japan, bringing about, in a matter of days, the end of the Second World War in the Pacific. The bombs, by today's standards, were small, with yields between 10 and 20 kT of trinitrotoluene (TNT). Most of the resulting exposure was to \( \gamma \) rays and to some neutrons, and most of the dose to those who were in the cities at the time of the bombing was almost instantaneous (8). Follow-up of the health of the survivors started soon after the bombings; however, it was not until 1950, at the time of the national census, that an exhaustive list of the survivors was made by introducing a question in the census questionnaire concerning presence in Hiroshima or Nagasaki at the time of the bombings (12). Among the 195,000 survivors thus identified, a random sample of approximately 99,000, stratified on distance from the epicenter, and a sample of 26,000 who were not in the city were drawn in the early 1950s—the Life Span Study sample—and have been followed since then for mortality and cancer incidence. Subsamples of this population were drawn for clinical and reproductive history follow-up, and a sample of the offspring of the survivors was drawn for genetic follow-up.

Individual radiation dose was reconstructed for members of the Life Span Study and for children in utero at the time of the bombing, taking into account the location and position of the subjects at the moment of the bombing, the shielding situation, the weather, and results of atmospheric weapons tests and leakage experiments.
Doses among the study subjects ranged from 0 up to 6 Gy; the distribution of doses was skewed, with the majority of survivors receiving less than 200 mGy. In all, about 12,500 persons received doses of 1 Gy or above (9), and those tended to be the subjects who were closest to the epicenters. Several versions of the dose estimates have been derived over time. Those currently used are based on the Dosimetry System 86 (DS86) (8). The neutron component of the dose is currently being reevaluated (13), but this is unlikely to have a substantial impact on the risk estimates (14).

Because of the size of the exposed population, the availability of individual dose estimates, and the distribution of ages and sexes in the population of survivors, the Life Span Study is at present the most informative single study of radiation effects; it is the main basis for radiation risk estimates and radiation protection standards today (1,2,15,16).

Table 1. Characteristics of main large-scale accidental or nonroutine radiation exposures.

| Name (reference) | Location          | Exposure circumstances                                   | Date       | Number of exposed persons | Exposure type         | Dose estimate                                                                 |
|------------------|-------------------|----------------------------------------------------------|------------|---------------------------|-----------------------|-------------------------------------------------------------------------------|
| Hiroshima and Nagasaki (9,10) | Japan | War, atomic bombing                                      | 1945       | 195,000                   | Whole body to \(\gamma\) and neutrons | Range = 0–6 Gy  
Average = 0.16 Gy  
2,500 persons, > 1 Gy |
| Marshall Islands, Bikini atoll (6) | Pacific Ocean | Accidental exposures from thermonuclear test           | 1954       | 267 on atolls              | Whole body, to \(\gamma\) and \(\beta\)  
Thyroid to \(^{131}\)I  
Whole body | Range = 1–2 Gy  
Range = 3–15 Gy  
Range = 2–6 Gy |
| Kyshtym (6,10) | Southern Urals: Chelyabinsk, Sverdlovsk, and Tyumensk Provinces | Explosion of radioactive waste storage tank          | 1957       | 270,000                    | Whole body \(\gamma\) rays  
Internal | Range = 0–600 mSv  
Range = 0–520 mSv  
Average CEDE = 5–600 mSv  
7,300 persons, = 600 mSv |
| Techa River, Lake Karachay (6,10) | Southern Urals | Routine discharge of radio-chemical production waste in river basin and lake | 1949–1956 | 124,000 on river banks  | Whole body to \(\gamma\)  
Internal to \(^{85}\)Sr, \(^{137}\)Cs | Total average marrow dose:  
Range = 0–4 Gy  
2,000 > 1 Gy  
Range AEDE = 35–1,700 mSv  
Range = 0–4,000 mSv  
Rest = 7 mSv |
| Hanford† | Washington State | Release of radioactive iodine                           | 1944–1947 | 270,000  
1,400 most exposed‡ | Marrow  
External | Thyroid to \(^{131}\)I  
95% < 0.3 Gy  
Range = 0.15–6.5 Gy  
Median = 0.7 Gy |
| Juarez (6) | Mexico | \(^{60}\)Co radiotherapy head opened                    | 1983–1984 | 4,000                      | 700 persons, 0.005–0.25 Gy  
80 persons, 0.25+ Gy  
5 persons, 3–7 Gy  
< 1 mSv  
100–2500 \(\mu\)Sv |
| Windscale (6) | United Kingdom | Fire in reactor opened                                 | 1957       | 135,000 evacuees from 30 km zone | Whole body to \(\gamma\) rays  
Children | Range = 30–500 mSv  
Average = 120 mSv  
Average = 0.3 Gy  
Range = 0.1–2.5 Gy  
Average = 60 mSv  
4%, > 100 mSv  
800 persons, > 200 mSv  
Range = 0.1–10 Gy |
| Chernobyl (6,11) | Ukraine | Destruction of reactor core                            | 1986       | 270,000 in strict control zones | Thyroid to \(^{131}\)I,  
children  
CEDE from \(\gamma\) rays  
children | 600,000 clean-up workers  
75 million in European part of USSR  
200 evacuated  
128 exposed  
Whole body to \(\gamma\)  
Range = 0–5.3 Sv |

AEDE, annual effective dose equivalent. †Life Span Study cohort with DS86 dose estimates (9). ‡Committed effective dose equivalent estimated for the 30 years after the accident. §Personal communication. ¶Infants and children drinking milk from cows in pasture.
Results
The early effects of the bombings have been extensively described: they included thermal, mechanical, and radiation (in particular radiation-induced bone-marrow depletion) injuries (17). Late effects observed among the survivors were cataracts (18) and increased cancer risk (9), as well as microcephalus and mental retardation in those exposed in utero (19). There was no apparent effect on life shortening and aging (20) and on the incidence of most noncancerous diseases (21). There was also no evidence of genetic effects (22,23).

Among cancers, the first increase was observed in leukemia mortality, which peaked in the period between 1950 and 1954 (9). Increases were observed for all leukemia subtypes except chronic lymphocytic leukemia (CLL) (24), a disease virtually unknown in Japan, and adult T-cell leukemia. Although the relative risk has decreased since then, it is still significantly elevated (24). The increased leukemia risk was the main long-term effect of radiation observed until 1970. Leukemia mortality is best described by a linear excess relative risk model of the form:

$$RR = 1 + \beta \alpha d$$

where \(d\) denotes the radiation dose, \(t\) attained age, \(e\) the age at exposure and \(s\) the sex of the subject (25,27). In this model, the cancer mortality among the exposed is proportional to that of the nonexposed and the latent period is independent of dose and age at exposure.

It is noteworthy that the total number of cancer deaths attributable to radiation among the atomic bomb survivors is relatively small: about 10% of the 6,000 solid cancer deaths and 55% of the 200 leukemia deaths observed to the end of 1985 (9). In the higher dose categories, however, most of the cancer deaths are attributable to radiation exposure. Despite this fact, this study is the most informative single study on radiation effects in humans. If no effort had been made to carry out a complete and systematic individual follow-up of the Life Span Study cohort with individual dose reconstruction, it may have been very difficult to detect the excess cancer risk.

Open Questions in Radiation Protection: What Can Be Learned from Other Exposure Circumstances?

Radiation protection today is primarily concerned with low-dose protracted exposures to ionizing radiation (such as are received by the general population from environmental sources or by occupational groups from their work with radiation), with host and environmental factors that may modify radiation-induced risks and with the effect of different types of radiation. The study of atomic bomb survivors alone cannot provide information to answer these questions for several reasons:

- Because of the nature of the exposure, the follow-up of the atomic bomb survivors provides little information on the risk related to low doses—of the order of 0.1 to 0.2 Gy—and no information on the effect of exposure protraction.
- The study population may be a selected sample of all survivors present in Hiroshima and Nagasaki at the time of the bombings because it was identified from a list of those alive in 1950. How large an impact this initial selection effect may have on the estimation of cancer risk 40 to 50 years after the bombing is a subject of debate.
- The study subjects are Japanese, exposed during wartime. It is possible that host and environmental factors modify the risk of radiation-induced cancer; thus, the choice of model to extrapolate risk estimates to populations with different background incidence and mortality rates of cancer is uncertain.
- The size of the study population is still small for the study of relatively rare malignancies.

It is therefore important to obtain complementary information on radiation risks from the study of other populations with different patterns of radiation exposure and different host and environmental characteristics. Studies of large numbers of patients irradiated for therapeutic purposes (for cancer or benign diseases) in Western Europe, North America and Israel have been carried out [for a detailed review, see (1,2)]. Overall, the results of these studies are consistent with those of the atomic bomb survivors, although studies of second cancer risk among patients having received radiotherapy for a first cancer appear to indicate a slightly lower risk of cancer per unit of radiation dose (28).

To extrapolate risks to exposure situations resulting in low doses received in a protracted fashion, most committees and regulatory bodies have chosen to divide estimates derived by linear extrapolation from atomic bomb survivors data by a factor ranging from 2 to 5, the dose/dose-rate effectiveness factor (DDREF), to account for the sparing effect of exposure protraction (1,2,15,16). There is much controversy about the appropriateness of this approach, however, with some scientists claiming that risks are in fact much higher and others that protracted low-dose exposures may reduce the risk of cancer. Studies of populations having received low-dose, low dose-rate exposures are now providing direct estimates of risk from such exposures.

Direct Estimates of the Effects of Low Doses and Dose Rates—Studies of Nuclear Workers

Studies of cancer risk among workers in the nuclear industry around the world are particularly well suited for the direct estimation of the effects of low doses and dose rates of ionizing radiation. This is because large numbers of workers have been employed by this industry since its beginning in the early to mid-1940s, because these populations are relatively stable, and because, by law, individual real-time monitoring of potentially exposed personnel has been carried out in most countries, at least for external higher energy exposures, and the measurements have been kept.

Published studies have covered cohorts of nuclear industry workers in the United
States, the United Kingdom, and Canada (29–54). Most of these studies have provided little evidence of dose-related increases in all cancer mortality, although statistically significant associations between mortality from all cancers combined and cumulative radiation dose were observed in two studies of Oak Ridge National Laboratory employees in the United States (49) and of the employees of the Atomic Weapons Establishment in the United Kingdom (40). The statistical power of individual studies was, however, low and in most cohorts the confidence intervals of the risk estimates were compatible with a range of possibilities, from negative effects to risks an order of magnitude greater than those on which current radiation protection recommendations are based. Combined analyses of data from some of these studies have therefore been carried out at the national and international levels (4,5,55–57) specifically to test the adequacy of existing risk extrapolations.

Table 2 presents the results of the International Agency for Research on Cancer (IARC) international combined analyses (5), carried out on 96,000 workers, and compares them to estimates obtained from IARC reanalyses of the atomic bomb survivors data. As in the latter study, a dose-related increase in leukemia mortality has been observed among nuclear industry workers; the estimate of risk per unit of radiation dose is intermediate between the linear and linear-quadratic extrapolations from atomic bomb survivors data (the latter estimate is one of the bases for current radiation protection recommendations). Given the width of the confidence interval, however, the workers' estimate is also compatible with a reduction of risk and with risks twice the linear extrapolation from atomic bomb survivors. The estimate for all other cancers combined is close to zero, but, like the leukemia estimate, the confidence interval includes the extrapolation from atomic bomb survivors.

The size of the estimated risk for low-dose protracted exposures is relatively small: the excessive relative risk (ERR) of 2.18/Sv for leukemia corresponds to a 22% increased risk of dying from leukemia for a dose of 100 mSv received in a protracted fashion. For comparison, although the current recommendations of the International Commission for Radiation Protection (15) are to limit doses to 100 mSv over 5 years for workers (and 1 mSv/year for the public), only 8% of the 96,000 workers in the combined data set received 100 mSv over their entire careers. The estimated number of leukemia deaths attributed to radiation exposure in this study was 9.7 (i.e., 8% of all leukemia deaths).

The estimates presented here from the combined analyses of worker studies (5) are the most comprehensive and precise direct estimates obtained to date. Although they are lower than the linear estimates obtained from studies of atomic bomb survivors, they are compatible with a range of possibilities, from a reduction of risk at low doses to risks twice those on which current radiation protection recommendations are based. Overall, however, the results of this study do not suggest that current radiation risk estimates for cancer at low levels of exposure are appreciably in error.

There remains uncertainty concerning the exact size of this risk, as indicated by the width of the confidence intervals presented. Further follow-up of these cohorts and careful studies of additional cohorts, such as those underway currently in 14 countries as part of the International Collaborative Study of Cancer Risk among Radiation Workers in the Nuclear Industry (58,59), are needed to reduce the uncertainty further.

### Studies of Accidental and Nonroutine Exposures

Studies of other exposed populations, particularly the populations exposed accidentally, could also provide important information to answer the outstanding scientific and radiation protection questions. The effects of protracted exposures could be examined in studies of Chernobyl emergency accident workers and in populations living along the Techa River or exposed as a result of the Kyshtym accident. The effects of relatively low doses, such as those resulting from environmental exposures in areas contaminated by the Chernobyl accident; effects of exposure to different radionuclides and different types of radiation; and effects of factors that may modify radiation induced risks could also be studied.

To be informative, studies of accidentally exposed populations must, like the atomic bomb survivor and the nuclear worker studies, fulfill several important criteria: they must cover very large numbers of exposed subjects, the follow-up must be complete and nonselective, and precise and accurate individual dose estimates (or markers of exposure that are sensitive and specific) must be available.

Several papers in the current session cover aspects of the Chernobyl follow-up. Given the levels of environmental exposure of the general population (Table 1), the population movements that have taken place since the accident, and in the absence of systematic individual exposure estimates, it is unlikely that a follow-up of the general population living in contaminated territories will be very informative for radiation risk estimation.

The observation of an early and dramatic increase in the number of thyroid cancer cases in children (Table 3) in Belarus, Ukraine and, more recently, in Russia (60), however, may give important information about host and environmental factors that may modify the risk of radiation-induced cancer, in particular a possible genetic predisposition and stable iodine status (61). Studies are being set up to investigate this hypothesis.

Another potentially informative population exposed to radiation as a result of the Chernobyl accident is that of the clean-up or emergency accident workers (Table 1). Provided adequate estimates of individual exposure can be derived, either by questionnaire from official dosimetry records or by sensitive and specific biological markers, studies of emergency accident workers could provide important information on the effect of exposure rate and of different radionuclides (62). Large-scale analytic epidemiological studies of cancer risk

### Table 2. Comparison of estimates of excess relative risk (ERR) per Sv (and 90% CI) between nuclear workers and atomic bomb survivors.

| Population | All cancers except leukemia | Leukemia excluding CLL |
|------------|-----------------------------|------------------------|
| ERR/Sv     | 90% CI                      | ERR/Sv                 | 90% CI                 |
| Nuclear workers data | -0.07 (-0.39,0.30) | 2.18 (0.13,5.7) |
| Atomic bomb, linear | 0.18 (0.05,0.34) | 3.67 (2.0,5.5) |
| Atomic bomb, L-Q | — | 1.42 (<0.65) |

Data from Cardis et al. (5). *Adjusted for age, socioeconomic status, facility, and calendar time. *Simulated confidence interval. *Atomic bomb survivors data adjusted for age, city, and calendar time; analyses carried out at IARC (5). *Based on the linear term of a linear-quadratic (L-Q) dose–response model in the atomic bomb survivors data.

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among these workers are now under way in Baltic countries and are starting in Belarus, Russia, and in the Ukraine.

Studies of populations environmentally exposed in the southern Urals (Table 1) are also underway (63,64). Given the size of the exposed populations and levels of exposures, if cohort ascertainment and follow-up can be systematic and complete and if reliable individual dose estimates can be obtained, these studies will provide very valuable information on the effects of dose protraction at different exposure levels and for different radionuclides.

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