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Long-Term Effects of the Rain Exposure Shortly after the Atomic Bombings in Hiroshima and Nagasaki

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The "black rain" that fell after the atomic bombings of Hiroshima and Nagasaki has been generally believed to contain radioactive materials. During 1949–1961 the Atomic Bomb Casualty Commission conducted surveys that included a query about exposure to the rain that fell a short time after the bombings. This article presents the first report of those data in relation to possible adverse health outcomes. This study looked at Life Span Study subjects who were in either city at the time of bombing and had an estimated direct radiation dose from the bombs (n = 86,609). The mortality data from 1950–2005 and cancer incidence data from 1958–2005 were used. Excess relative risks (ERRs) of subjects who were exposed to rain compared to those who reported no rain exposure were calculated using a Poisson regression model. In Hiroshima 11,661 subjects (20%) reported that they were exposed to rain, while in Nagasaki only 733 subjects (2.6%) reported rain exposure. To avoid outcome dependent biases (i.e., recall of exposure after a health outcome has already occurred), the primary analyses were based on events that occurred during 1962–2005. No significant risks due to rain exposure were observed for death due to all causes, all solid cancer or leukemia in Hiroshima. In Nagasaki there was no significantly elevated rain exposure-associated risks for 1962–2005, however, for 1950–2005 there was a weak association for all-cause mortality (ERR = 0.08; 95% confidence interval 0.00006, 0.17; $P = 0.05$). For incidence of solid cancer and leukemia, no significantly elevated rain exposure risks were observed in either city. These results failed to show deleterious health effects from rain exposure. While these data represent the most extensive set of systematically collected data on rain exposure of the atomic bomb survivors, they are limited by substantial uncertainties regarding exposures and missing individual data, so cautious interpretation is advised. © 2014 by Radiation Research Society

INTRODUCTION

Shortly after the atomic bombings in Hiroshima and Nagasaki, it was reported that rain fell widely in the cities out to areas several kilometers from the hypocenter. Since much of the rain was dirty with soot and ash, it was called ''black rain''. The rain likely originated from the ascending air currents of both the fireball from the atomic bomb explosion and the widespread fires that burned throughout the cities after the bombings. It has been generally believed that this rain contained radioactive materials, though the degree of radioactivity probably varied considerably depending on how much the rain was associated with the radioactive plume. Increased amounts of ground level radioactivity due to rain fallout were observed: a small increase (~45 μR/h) at Koi-Takasu in western Hiroshima and a large increase (~1.8 mR/h) at Nishiyama in eastern Nagasaki (*1*), though rainfall was widely reported in the other areas, especially Hiroshima (*2–4*). Although measurements made within a few months after the bombing did not indicate that rain contained significant radioactivity in areas other than Koi-Takasu and Nishiyama (*1*), the public perception has been that all black rain was highly radioactive, and therefore its health effects have long been a public concern.

Information about ''fallout rain'' exposure was gathered from several surveys conducted by the Atomic Bomb Casualty Commission (ABCC), the predecessor of the Radiation Effects Research Foundation (RERF), in the early period after the bombings. However, these data were thought to be inadequate for quantitative risk analyses because it was not possible to estimate individual doses, given the dichotomous nature of the exposure information, absence of location-specific data on the radioactivity concentration of the rain, lack of information on the

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evacuation routes used by most subjects and paucity of individual information regarding shielding from fallout radiation and/or ingestion of radioactive substances present in the rain. The data were further limited because no information on exposure to fallout rain was available for a considerable proportion of the subjects, and for those who responded that they had been exposed, the location at which exposure occurred was often unavailable. From a dosimetric perspective, it is also unclear whether survivors who reported that they were exposed to the rain were actually in contact with rainwater or were merely in an area where rain fell, and there was no information on the extent of body surface area, duration of skin contact with the rainwater, protective effect of clothing, or other factors related to either internal or short-range external exposure to radiation from any radioactive material that might have been in the rain. However, upon reconsideration and re-evaluation of the ABCC/RERF records on fallout rain exposure along with the RERF mortality and cancer incidence data, it was decided this information may be of interest in light of public concerns. Therefore, we investigated whether subjects who reported exposure to fallout rain have higher long-term health risks compared to those whose survey response indicated that they had not been exposed to rain.

METHODS

The ABCC/RERF Life Span Study (LSS) is a prospective study of a fixed cohort of atomic bomb survivors followed since 1950. The ABCC conducted several baseline surveys to document the survivors' situations at the time of bombing and shortly thereafter with various primary objectives and inclusion criteria between 1949–1961. Questions about exposure to the rain were included in the two major interview surveys: the Migration Questionnaire (MQ), conducted in 1955–1956, and the Master Sample Questionnaire (MSQ), conducted in 1956–1961. The MQ questions were, ''Was the person caught in Fallout Rain?'' (Yes or No) plus ''Where'' and ''Time'' with boxes for free-form description. The MSQ questions were, ''Was the person caught in Fallout Rain?'' (Yes, No or Unknown) and ''Where'' with a box for a free-form description. The words ''Fallout Rain'' were used in the questions written in English. However, a more accurate translation of the question as asked in Japanese was ''Were you caught in rain just after the atomic bombing?'' The rain exposure status of subjects was classified as ''yes'', ''no'' or ''unknown'' based on the questionnaires. If the reported rain exposure status was inconsistent between the MQ and MSQ, the exposure status recorded in the MSQ was given higher priority because the MSQ was conducted for more subjects and is considered the most reliable baseline survey. Questions regarding exposure to the rain were not included in any of the other baseline surveys: the Radiation Census, the Radiation Questionnaire, and the Nonmedical Radiation History, which were conducted in 1949–1953, 1953–1955 and 1951–1954, respectively. However, infrequently information about exposure to the rain was described in the margins of these surveys. For subjects who did not participate in either the MQ or MSQ (10% of the subjects in this study), if information about rain exposure was obtained from another survey conducted by the ABCC, that information was used. Subjects whose questionnaires were left blank for questions regarding fallout rain [Hiroshima; 16,442 (28%), Nagasaki; 3,053 (11%)] were included in the ''unknown'' category, although reasons for leaving these questions blank remain unclear. Eligible subjects for this study were defined as LSS cohort members who were in either city at the time of the bombing and had an estimated DS02 (*5*) radiation dose ($n = 86{,}609$). The date of entry for the mortality study was 1 October 1950, which is also the date that comprehensive mortality follow-up was initiated. The date of entry into the cancer incidence study was 1 January 1958, which is the date that population-based tumor registries were established in Hiroshima and Nagasaki. Follow-up data on mortality and cancer incidence until 31 December 2005 were used in the analysis. Mortality data were derived from Japan's mandatory family registry system (*koseki*), while cancer incidence was derived from the Hiroshima and Nagasaki population-based cancer registries. Analyses for solid cancer and leukemia incidence were adjusted to allow for migration. Detailed descriptions about the definition of the study population, follow-up of vital status, cause of death, cancer incidence and migration rate adjustments have been reported elsewhere (*6–8*).

Mortality and cancer incidence follow-up data overlapped with the time the fallout exposure data were being gathered (late 1940s to 1961). Furthermore, the computerized data do not contain the dates that the questionnaire information was ascertained or who supplied the primary information. Therefore, it could not be determined whether those who were incapacitated by cancer or other severe disease, or who died before 1962, may have been more likely to have missing data or have unknown/inaccurate responses from surrogates. Thus, two sets of analyses were performed, one for the entire follow-up period (potentially influenced by concurrent data acquisition, particularly by surrogates) and the other beginning in 1962 after all questionnaires had been completed. We consider the analyses for the period beginning in 1962 to be the primary analyses; the results from the analyses using the entire follow-up period are shown for comparison with results from other LSS reports.

The effects of exposure to rain were estimated by city because meteorological conditions and fallout materials contained in the rain were assumed to be different between Hiroshima and Nagasaki. The dependent variables examined were mortality rate (all cause, all solid cancer and leukemia) and cancer incidence rate (all solid cancer and leukemia). Using a Poisson rate regression, we modeled the rate of each end point by the form,

$$\lambda_0(c,s,b,a)[1 + (\beta_1 d + \gamma rain_{hiro\_yes} + \delta rain_{naga\_yes}) \cdot exp(\tau e + \upsilon ln(a)) \cdot \sigma s + \varepsilon rain_{hiro\_unk} + \zeta rain_{naga\_unk}].$$

This model estimates excess relative risk (ERR) above the baseline risks (λ_0), which are described nonparametrically using stratification by city (c), sex (s), birth year (b) with 10-year categories and attained age (a) with 10-year categories. We included the effects of caught-in-rain status ($rain_{hiro\_yes}$, $rain_{naga\_yes}$, $rain_{hiro\_unk}$, $rain_{naga\_unk}$) as an addition to the model of the direct radiation dose (d), where the effect of total radiation (both direct and rain) could be modified by age at exposure (e), sex and attained age.

As in previous reports (*6, 7*), we used the linear model ($\beta_1 d$) for the direct radiation dose response in all but analyses for leukemia outcomes. A linear-quadratic model for direct radiation dose ($\beta_1 d + \beta_2 d^2$) was used for both leukemia mortality and incidence, because previous LSS reports indicated that a linear-quadratic model is more appropriate for leukemia among the LSS subjects.

In the above model, both direct and fallout exposures are treated in a biologically consistent manner, i.e., as potentially additive radiation doses with parallel modification by age at exposure, attained age and sex (''common effect modification model''). In addition, we tested another model assuming that the rain effects did not vary with sex, age at exposure and attained age (''no rain effect modification model''). For leukemia incidence, estimates based on the no rain effect modification model are shown in Table 2, because the common effect modification model did not converge. Full results from supplemental analyses using the no effect modification model (''direct exposure only model'') are available in the supplementary materials (http://dx.doi.org/10.1667/RR13822.1.S1).

TABLE 1
Distribution of Subjects by Caught-in-Fallout Rain Status

Items	Caught in fallout rain? No n	No (%)	Yes n	Yes (%)	Unknown n	Unknown (%)	Total n	Total (%)
Hiroshima								
	29,254		11,661		17,577		58,492	
Sex								
Male	11,835	(40.5)	4,606	(39.5)	7,523	(42.8)	23,964	(41.0)
Female	17,419	(59.5)	7,055	(60.5)	10,054	(57.2)	34,528	(59.0)
Age at the time of bombing (years)								
0–9	5,354	(18.3)	2,213	(19.0)	3,420	(19.5)	10,987	(18.8)
10–19	5,686	(19.4)	2,091	(17.9)	3,146	(17.9)	10,923	(18.7)
20–29	3,748	(12.8)	1,580	(13.5)	2,246	(12.8)	7,574	(12.9)
30–39	4,548	(15.5)	1,951	(16.7)	2,466	(14.0)	8,965	(15.3)
40–49	5,005	(17.1)	1,983	(17.0)	2,738	(15.6)	9,726	(16.6)
Over 50	4,913	(16.8)	1,843	(15.8)	3,561	(20.3)	10,317	(17.6)
Mean age	29.84		29.49		29.29		29.54	
(SD)	(18.82)		(18.48)		(18.79)		(18.70)	
Weighted absorbed colon dose (Gy)								
0–0.004	13,646	(46.6)	2,869	(24.6)	5,181	(29.5)	21,696	(37.1)
0.005–0.09	10,908	(37.3)	4,706	(40.4)	7,118	(40.5)	22,732	(38.9)
0.1–0.4	3,436	(11.7)	2,851	(24.4)	3,817	(21.7)	10,104	(17.3)
0.5–0.9	770	(2.6)	794	(6.8)	809	(4.6)	2,373	(4.1)
1–	494	(1.7)	441	(3.8)	652	(3.7)	1,587	(2.7)
Nagasaki								
	23,664		733		3,720		28,117	
Sex								
Male	9,799	(41.4)	299	(40.8)	1625	(43.7)	11,723	(41.7)
Female	13,865	(58.6)	434	(59.2)	2095	(56.3)	16,394	(58.3)
Age at the time of bombing (years)								
0–9	6,069	(25.6)	165	(22.5)	610	(16.4)	6,844	(24.3)
10–19	5,353	(22.6)	233	(31.8)	1,055	(28.4)	6,641	(23.6)
20–29	2,752	(11.6)	92	(12.6)	473	(12.7)	3,317	(11.8)
30–39	2,808	(11.9)	85	(11.6)	411	(11.0)	3,304	(11.8)
40–49	3,253	(13.7)	91	(12.4)	434	(11.7)	3,778	(13.4)
Over 50	3,429	(14.5)	67	(9.1)	737	(19.8)	4,233	(15.1)
Mean age	27.88		22.91		25.68		26.23	
(SD)	(18.02)		(15.93)		(17.51)		(17.58)	
Weighted absorbed colon dose (Gy)								
0–0.004	14,655	(61.9)	351	(47.9)	1,806	(48.5)	16,812	(59.8)
0.005–0.09	6,065	(25.6)	210	(28.6)	953	(25.6)	7,228	(25.7)
0.1–0.4	1,694	(7.2)	85	(11.6)	447	(12.0)	2,226	(7.9)
0.5–0.9	712	(3.0)	57	(7.8)	282	(7.6)	1,051	(3.7)
1–	538	(2.3)	30	(4.1)	232	(6.2)	800	(2.8)

Model fits were compared based on the likelihood ratio tests (at significance level $\alpha = 0.05$) for nested models or the Akaike Information Criteria (AIC) (*9*) for non-nested models. The ERRs of rain exposure were estimated as the increase in the relative risk compared to those who were not exposed to rain but had the same estimated direct radiation dose. Parameter estimation and testing were performed using the Epicure program (*10*).

RESULTS

Among the 86,609 eligible LSS subjects, 42,050 (72%) subjects in Hiroshima and 25,064 (89%) subjects in Nagasaki had "yes", "no" or "unknown" rain exposure information available from the baseline surveys (the balance had missing information). In Hiroshima, 11,661 subjects (20%) reported that they were exposed to rain, while only 733 subjects (2.6%) in Nagasaki reported rain exposure (Table 1). The distribution of subjects by age at the time of the bombings was relatively similar in Hiroshima. In Nagasaki, the distribution was skewed, where 48% of the respondents were less than 20 years old at the time of the bombing. In Hiroshima, the proportion of survivors who reported rain exposure was nearly the same in all age groups while teens in Nagasaki had the highest proportion of reported rain exposure (3.5% vs. the city average of 2.6%). The percentage of subjects whose rain exposure was unknown was relatively high among the teenage group in Nagasaki, as well as those over 50 years old in both cities. Subjects who reported no rain exposure tended to have lower direct radiation doses (i.e., they were more distally located at the time of the bombing).

TABLE 2
Excess Relative Risks for Exposure to Fallout Rain with 95% Confidence Intervals for All Causes of Death, Solid Cancer Death, Leukemia Death, Solid Cancer Incidence and Leukemia Incidence

Outcomes	Fallout rain status	Hiroshima			Nagasaki		
		No. of cases	ERR[a]	95% CI[b]	No. of cases	ERR	95% CI
1962–2005							
All cause of death	No	15,997	0.00	Reference group	10,865	0.00	Reference group
	Yes	6,381	–0.03	(−0.06, −0.01)	349	0.08	(−0.008, 0.18)
	Unknown	7,941	0.004	(−0.02, 0.03)	1,348	0.02	(−0.04, 0.08)
Solid cancer death	No	3,573	0.00	Reference group	2,654	0.00	Reference group
	Yes	1,483	–0.04	(−0.08, 0.01)	106	0.15	(−0.003, 0.36)
	Unknown	1,892	–0.01	(−0.07, 0.05)	353	–0.03	(−0.15, 0.09)
Leukemia death	No	89	0.00	Reference group	65	0.00	Reference group
	Yes	49	0.05	(−0.36*, 0.56)	2	–0.18	(−1.39,* 1.02*)
	Unknown	47	–0.13	(−0.44, 0.30)	13	0.35	(−0.40, 1.63)
Solid cancer incidence	No	5,653	0.00	Reference group	3,849	0.00	Reference group
	Yes	2,283	–0.06	(−0.10, −0.03)	106	–0.09	(−0.19,* 0.03)
	Unknown	3,026	–0.02	(−0.07, 0.03)	459	–0.19	(−0.27, −0.10*)
Leukemia incidence[#]	No	79	0.00	Reference group	46	0.00	Reference group
	Yes	46	0.26	(−0.21, 1.05)	1	–0.79	(−1.71, 2.03)
	Unknown	45	–0.03	(−0.39, 0.47)	11	0.48	(−0.44, 2.15)
1950–2005							
All cause of death	No	18,322	0.00	Reference group	13,060	0.00	Reference group
	Yes	7,294	0.01	(−0.02, 0.04)	394	0.08	(0.00, 0.17)
	Unknown	11,315	0.26	(0.23, 0.29)	2,289	0.43	(0.36, 0.49)
Solid cancer death	No	3,970	0.00	Reference group	2,937	0.00	Reference group
	Yes	1,633	–0.02	(−0.06, 0.04)	109	0.14	(−0.01, 0.33)
	Unknown	2,460	0.19	(0.13, 0.25)	451	0.15	(0.03, 0.27)
Leukemia death	No	111	0.00	Reference group	79	0.00	Reference group
	Yes	69	0.06	(−0.15,* 0.32)	3	–0.03	(−0.07,* 0.02*)
	Unknown	68	–0.13	(−0.41, 0.24)	20	0.74	(−0.10, 2.05)
1958–2005							
Solid cancer incidence[#]	No	5,982	0.00	Reference group	4,045	0.00	Reference group
	Yes	2,430	–0.03	(−0.08, 0.02)	106	–0.21	(−0.36, −0.04)
	Unknown	3,196	–0.006	(−0.05, 0.04)	475	–0.19	(−0.27, −0.10)
Leukemia incidence[#]	No	91	0.00	Reference group	53	0.00	Reference group
	Yes	51	0.11	(−0.30, 0.70)	1	–0.90	(−1.53,* 1.63)
	Unknown	50	–0.10	(−0.42, 0.36)	12	0.35	(−0.49, 1.85)

[a] Excess relative risk.
[b] 95% confidence interval.
* Likelihood-based estimation algorithm failed to identify an interval. A Wald-type confidence interval was calculated.
[#] Estimates are based on the no effect modification for rain model, because the common effect modification model did not converge.

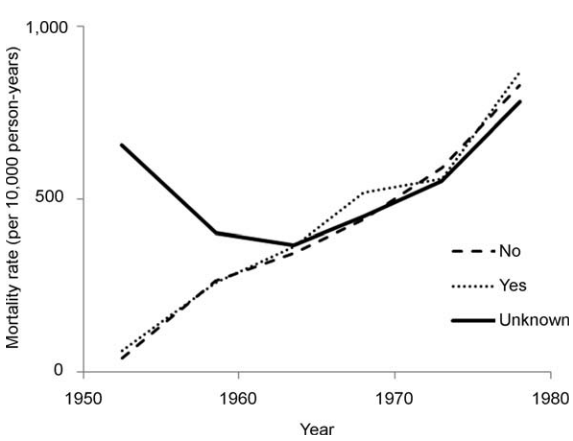

FIG. 1. Sex-averaged mortality rate adjusted for birth year by calendar year and caught-in-rain status.

Sex-averaged mortality rates adjusted for birth cohort (10-year birth cohorts) by caught-in-rain status and calendar year are shown in Fig. 1. This figure shows standardized mortality rates calculated for calendar years 1950–1980. After 1980, standardized rates became unstable due to sparse data for the earliest birth cohorts. Among those with unknown rain exposure, the mortality rate was considerably higher in the years during which the baseline surveys were conducted (1950–1961) but it was similar to those of other rain status groups thereafter. This suggests that surrogate interviewees probably were more likely to report unknown rain exposure at the time of the survey if the actual bomb survivor had already died.

Table 2 shows, by rain exposure status, the estimates of all-cause mortality and both mortality from and incidence for all solid cancer and leukemia. The number of leukemia incidence cases was smaller than those of leukemia death

TABLE 3
Excess Relative Risks for Exposure to Fallout Rain with 95% Confidence Intervals for All Causes of Death, Solid Cancer Death and Leukemia Death among Subjects Who Have Less than 5 mGy Weighted Absorbed Colon Dose

Cause of death	Fallout rain status	Hiroshima			Nagasaki		
		No. of deaths	ERR[a]	95% CI[b]	No. of deaths	ERR	95% CI
1962–2005							
All causes of death	No	7,498	0.00	Reference group	6,640	0.00	Reference group
	Yes	1,584	–0.03	(−0.09, 0.02)	161	0.01	(−0.07,* 0.15)
	Unknown	2,204	0.03	(−0.02, 0.08)	621	0.08	(−0.01, 0.17)
Solid cancer	No	1,644	0.00	Reference group	1,557	0.00	Reference group
	Yes	378	–0.001	(−0.00,* 0.00*)	43	0.05	(−0.11,* 0.20*)
	Unknown	517	0.02	(−0.07, 0.12)	155	0.02	(−0.14, 0.20)
Leukemia	No	36	0.00	Reference group	15	0.00	Reference group
	Yes	5	–0.36	(−0.78, 0.48)	0		NA
	Unknown	17	0.47	(−0.19, 1.32*)	5	0.35	(−0.60, 2.43)
1950–2005							
All causes of death	No	8,573	0.00	Reference group	8,085	0.00	Reference group
	Yes	1,795	–0.02	(−0.04,* 0.01*)	182	–0.01	(−0.04,* 0.02*)
	Unknown	3,442	0.38	(0.33, 0.43)	1,114	0.54	(0.45, 0.64)
Solid cancer	No	1,822	0.00	Reference group	1,730	0.00	Reference group
	Yes	409	–0.001	(−0.01,* 0.00*)	44	0.05	(−0.10,* 0.21*)
	Unknown	710	0.27	(0.16, 0.38)	203	0.21	(0.04, 0.39)
Leukemia	No	42	0.00	Reference group	34	0.00	Reference group
	Yes	9	–0.01	(−0.54, 0.71*)	0		NA
	Unknown	19	0.41	(−0.20, 1.17*)	7	1.08	(−0.16, 3.44)

[a] Excess relative risk.
[b] 95% confidence interval.
* Likelihood-based estimation algorithm failed to identify an interval. A Wald-type confidence interval was calculated.

cases for 1962–2005. This is driven by differences in the ascertainment of events: deaths and cause of death are obtained throughout Japan, while cancer incidence information is obtained only from Hiroshima and Nagasaki tumor registry catchment areas.

In Hiroshima, no significantly increased risks from rain exposure were observed for death due to all causes, all solid cancers or leukemia, or for the incidence of all solid cancers or leukemia. This was true for both the 1962–2005 and 1950–2005 analyses.

In Nagasaki, rain exposure showed no significantly increased risk for any of the cancer outcomes or for all-cause mortality for the 1962–2005 period. Although the risk estimate for leukemia incidence could not be calculated properly due to the small number of cases among persons exposed to rain in Nagasaki, the number of cases did not appear to be elevated. For 1950–2005 a marginal association was suggested for death due to all causes (ERR = 0.08; 95% CI 0.00006, 0.17; $P = 0.05$) (Table 2 and Supplementary Table S1; http://dx.doi.org/10.1667/RR13822.1.S1). The magnitudes of the risk estimates due to direct radiation were equivalent to previously published analyses (*6, 7*).

To determine whether the rain exposure effect may have been masked by the direct radiation effects, analyses limited to subjects with estimated weighted absorbed colon dose less than 5 mGy were carried out (Table 3). The direct radiation term was omitted from these low-dose analyses. All subjects were more than 2.2 km from the hypocenter at the time of the bombing. No significantly increased risks for persons exposed to rain were observed for deaths due to all causes, all solid cancer or leukemia in either city. Significant increased risks were observed for all-cause and solid cancer death among those with unknown rain exposure during 1950–2005.

Parameter estimates and model fit summary information based on the models with and without variables of rain exposure are shown in Supplementary Tables S1–S5 (http://dx.doi.org/10.1667/RR13822.1.S1). Over the full observation period, model fits for all-cause mortality, solid cancer mortality and solid cancer incidence were significantly improved by adding variables of rain exposure ($P < 0.001$). However, the improved fits for the entire follow-up period did not result from significant increases of risk for those with rain exposure; rather, those with unknown rain exposure had significantly higher risks of death (*6, 7*). The ERRs for death due to all causes and solid cancer significantly increased among those with unknown rain exposure in the full follow-up period. However, these risks were not significant when the analysis period was limited to the years after 1961. This tendency was observed in both cities. Thus, the improvements of model fit for the entire follow-up period and the elevated risk of death before 1962 appear to be related to the adjustment of those dying in the earliest period who predominantly had unknown/missing rain exposure status.

In summary, in the period 1962–2005, which represents estimates from data with suspected biases removed, there were no statistically significant increased risks associated with rain exposure for any of the outcomes examined: all-cause mortality, all solid cancer mortality, leukemia mortality, all solid cancer incidence or leukemia incidence. For the period 1950–2005 (or 1958–2005 for cancer incidence), all-cause mortality showed a marginal excess in Nagasaki.

DISCUSSION

This is the first report that addresses the possibility of the long-term risks of mortality and cancer incidence among LSS cohort members due to the rain that fell in the cities shortly after the atomic bombings.

In Hiroshima, the results consistently indicated that exposure to rain was not significantly associated with increased mortality or incidence for any end points: total mortality, cancer mortality, solid cancer incidence or leukemia incidence. Conversely, increased ERRs for rain exposure were observed in Nagasaki for all-cause death in 1950–2005 (Table 2 and Supplementary Table S1; http://dx.doi.org/10.1667/RR13822.1.S1) and for all solid cancer death in 1962–2005 in the analysis using a model which ignores effect modification (by sex, age at exposure and attained age) for rain effects [ERR = 0.25; 95% CI: 0.01, 0.53; $P = 0.038$ (Supplementary Table S2)], but these findings were inconsistent between models as well as observation periods. There are several reasons that the positive finding may be spurious. First, only 733 subjects (2.6%) in Nagasaki reported that they had been ''caught in rain'', which may be too few to provide reliable statistical inference. Note that no positive association of rain exposure with any outcome was observed in Hiroshima, which had far greater statistical power to detect possible effects because of the much larger number who indicated rain exposure. Second, the association of direct radiation exposure with cancer death is much stronger than that of noncancer death (*7*) and many other studies have had similar findings. Therefore, one would expect the risk of rain exposure would be higher for cancer death compared to all-cause deaths, yet they were similar (Table 2). Third, radiation is known to elevate risks of both cancer mortality and incidence, yet there was no increased risk of cancer incidence after rain exposure in any model or city (Table 2). Finally, leukemia is often taken to be a ''sentinel'' indicator of radiation effects, but neither mortality nor incidence of leukemia was significantly elevated in either city.

Elevated risks of leukemia and cancer due to direct radiation exposure were evident in this study and those effects were consistent between the results for mortality and incidence outcomes (Supplementary Tables S1–S5; http://dx.doi.org/10.1667/RR13822.1.S1). The parameter estimates of the risk of direct radiation did not vary after inclusion of the rain exposure term for any of the examined models, which indicates no important confounding of direct radiation dose for reported rain exposure.

Using the three available rain exposure categorizations, the risks of mortality for all causes and solid cancer were significantly higher during 1950–2005 among the people who had unknown rain exposure information compared to those who reported no rain exposure in both cities. However, no such elevated ERRs were observed for analyses limited to the years 1962–2005 (Table 2). The MQ and MSQ surveys that provided the information on rain exposure were conducted from 1955–1961. Hence, subjects who died before the survey may often have had their survey conducted by proxy, which may have raised their apparent risks due to recall bias. The fact that the mortality rate of the ''unknown'' group decreased after the baseline surveys finished and later increased in parallel with the other rain exposure groups as the cohort aged supports this supposition of an outcome-dependent bias; i.e., ''reverse causation''.

While the questionnaires were the same in both cities, there is evidence that the procedures may have been different between cities, as the percentage of the subjects who left the question for rain exposure blank was higher in Hiroshima compared with Nagasaki. Unfortunately, questions about the intensity of rainfall (heavy or light) or quantitative evaluation of exposure to rain were not generally asked. Although more detailed information on rainfall was recorded during 1954–1958, the questions were presented to only a small fraction of the cohort and the answers were narrative rather than quantitative (*11*). Since there are no records remaining on the methods by which the surveys were conducted, it is not possible to determine the exact way in which investigators asked survivors about their rain exposure status. The MSQ records suggest an English translation of the question could be written as follows: ''Were you caught in the rain just after the atomic bombing?'' Unfortunately, the definition of ''just after'' is not clear, so it is not possible to determine how individual survivors interpreted the question. Although the most likely interpretation of ''the rain just after'' would be rain that fell several minutes to several hours after the bombing, subjects might have reported rain that fell up to several days later.

Throughout this article, we used reported exposure to rain that fell just after each bombing as a simple surrogate for radiation dose. While estimated doses may be preferable, they are difficult to derive for a number of reasons, which include: 1. lack of location-specific data on the radioactivity concentration of the rain; 2. spatial discrepancy between the survivor's location at the time of bombing and the location where they may have had any reported exposure to the rain, which is poorly documented; and 3. lack of individual information about variables that would relate the radioactivity content of the rain at a given location to the external and internal radiation doses that a survivor would have received. Each of these points is discussed briefly.

First, it is theoretically possible to estimate the total radionuclide inventory that was deposited on the ground in the known fallout areas of Koi-Takasu in Hiroshima and Nishiyama in Nagasaki by making assumptions about the fractionation of the bomb debris and using the gamma-ray exposure-rate measurements of early surveys that were done in 1945 (*12*). However, the lack of data on the amount of rainfall precludes a calculation of the radioactivity concentration of the rain. The few direct measurements of black rain from preserved stained walls in Hiroshima do not provide sufficient information to estimate the radioactivity concentration of the rain (*13*).

Second, the nomenclature ''fallout rain'' has been used very generally, and while rain fell in many areas throughout the cities, documented radioactive fallout was concentrated in a few geographic locations. Hence, there is confusion about the distinction between ''black rain'' and rain that truly contained fallout. Because the areas of known fallout in Koi-Takasu and Nishiyama are both around 3 km from their respective hypocenters, it may be possible for calculations of approximate dose to be made for people who were in those areas at the times of the bombings and exposed to the rain, assuming that they either did not evacuate or received the majority of dose before they evacuated (*1*), however, that would not be possible for those at other locations.

Third, if the radioactivity content of the rain were known, calculations of close-range external exposure to gamma rays and beta particles from rain itself would be possible only if additional information were available, including individual information about posture, clothing and whether any material adhered to skin or clothing. Calculation of dose from internal exposure would require assumptions about routes of entry into the body. Due to this limited information, it is not possible to accurately estimate radiation dose due to rain exposure.

The purpose of this study was to establish whether or not there was a risk from exposure to rain that fell shortly after the bombings. There were other potential sources of exposure to residual radioactivity, such as induced radiation from activated soil. However, expert consensus indicates that additional fallout due to gravitational settling was not possible in the absence of rain since the residual bomb materials that condensed in the atmosphere were very small and would have been dispersed by the winds (*14*).

Controversy has erupted in recent years over the idea that there may have been undocumented fallout in distal areas to the northwest in Hiroshima on the premise that the bomb debris cloud was moving to the northwest. Early surveys to measure residual radiation were not done because the areas were mountainous and inaccessible. However, no significant levels have been detected there despite new and innovative efforts to overcome the effects of time and interference from global fallout in later years (*15, 16*). Furthermore, the current cohort is not appropriate for use in these studies because there were virtually no members of the LSS in that sparsely populated area.

Despite the discussed limitations, these data represent the most extensively and systematically collected data on rain exposure in the atomic bomb survivors and therefore may help address public concerns about health effects from black rain exposure. It has been recently reported (*17*) that those exposed to black rain have physical/mental health afflictions similar to those directly exposed to the atomic bomb compared to those who were not exposed to either the atomic bomb or black rain. However, those results were collected by cross-sectional survey in 2008. The long period of time between exposure and survey date, the retrospective nature of the study, as well as the many deaths and out-migration that occurred prior to the survey raise concerns regarding possible biases from cohort selection and recall. In contrast, our data were collected during the 1950s and early 1960s, which indicates that most of the follow-up was prospective rather than retrospective.

Based on systematically collected data, we failed to find deleterious health effects from rain exposure, though the data have limitations. We believe that these results align with the claim that health effects induced by fallout rain exposure are not as great as those observed in survivors who were directly exposed proximally to the atomic bomb. However, due to the limitations of the data, deleterious health effects from rain exposure immediately after the atomic bombing cannot be completely ruled out.

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REFERENCES

1. Okajima S, Fujita S, Harley JH. Radiation doses from residual radioactivity. In: Roesch WC, editor. US-Japan joint reassessment of atomic bomb radiation dosimetry in Hiroshima and Nagasaki. Hiroshima, Japan: Radiation Effects Research Foundation; 1987.
2. Uda M, Sugahara H, Kita I. Meteological conditions related to the atomic bomb explosion in Hiroshima. Collection of reports on investigations of the atomic bomb casualties. Tokyo, Japan: Science Council of Japan; 1953.
3. Masuda Y. Re-investigation about ''black rain'' after Hiroshima A-bomb. Tenki (Weather) 1989; 35:69–79.
4. Ohtaki M. Re-construction of spatial-time distribution of 'black rain' in Hiroshima based on statistical analysis of witness of survivors from atomic bomb. In: Aoyama M, Oochi Y, editors. Revisit the Hiroshima A-bomb with a database: latest scientific view on local fallout and black rain. Hiroshima: Hiroshima City; 2011.

5. RERF DS02: A revised system for atomic bomb survivor dose estimation. Hiroshima: Radiation Effects Research Foundation; 2005.
6. Preston DL, Ron E, Tokuoka S, Funamoto S, Nishi N, Soda M, et al. Solid cancer incedence in atomic bomb survivors: 1958–1998. Radiat Res 2007; 168:1–64.
7. Ozasa K, Shimizu Y, Suyama A, Kasagi F, Soda M, Grant EJ, et al. Studies of the mortality of atomic bomb survivors, Report 14, 1950–2003: an overview of cancer and noncancer diseases. Radiat Res 2012; 177:229–43.
8. Sposto R, Preston DL. Correcting for catchment area non-residency in studies based on tumor registry data. Hiroshima: Radiation Effects Research Foundation; 1992.
9. Akaike H. A new look at the statistical model identification. Automatic Control 1974; 6:716–23.
10. Preston DL, Lubin JH, Pierce DA, McConney ME. EPICURE: User's guide. Seattle, WA: HiroSoft International Corporation; 1993.
11. A review of Yamada-Jones report at the Oak Ridge National Laboratory. Commentary and review series CR1-12. Hiroshima: Radiation Effects Research Foundation; 2012.
12. Endo S, Tanaka K, Shizuma K, Hoshi M, Imanaka T. Estimation of beta-ray skin dose from exposure to fission fallout from the Hiroshima atomic bomb. Radiat Prot Dosimetry 2012; 149:84–90.
13. Shizuma K. Estimation of cumulative exposure from radioactive fallout. In: Hasai, H., Shibata S., Imanaka T., editor. Proceedings of the workshop ''New Radiation Dosimetry System DS02 for the Atomic Bombings in Hiroshima and Nagasaki''. Kyoto, Japan: Research Reactor Institute, Kyoto University; 2005.
14. Kerr GD, Egbert SD, Al-Nabulsi I, Beck HL, Cullings HM, Endo S, et al. Workshop report on atomic bomb dosimetry-residual radiation exposure: recent research and suggestions for future studies. Health Phys 2013; 105:140–9.
15. Sakaguchi A, Kawai K, Steier P, Imanaka T, Hoshi M, Endo S, et al. Feasibility of using 236U to reconstruct close-in fallout deposition from the Hiroshima atomic bomb. Sci Total Environ 2010; 408:5392–8.
16. Yamamoto M, Hoshi M, Zhumadilov K, Endo S, Sakaguchi A, Imanaka T, et al. Estimation of close-in fallout ^{137}Cs deposition level due to the Hiroshima atomic bomb from soil samples under houses built 1–4 years after the explosion. In: Aoyama M, Oochi, Y. editors. Revisit the Hiroshima A-bomb with a database. Hiroshima: Hiroshima City; 2013.
17. Survey on atomic bombing exposure in Hiroshima city - Report on health awareness survey of people who experienced the atomic bombing. Hiroshima; 2010. (in Japanese)