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REGULAR ARTICLE

Hiroshima survivors exposed to very low doses of A-bomb primary radiation showed a high risk for cancers

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Abstract
Objectives The aim of this study was to compare the risk for cancers of A-bomb survivors in the ongoing life span study (LSS) with unexposed groups consisting of the entire populations of Hiroshima prefecture and neighboring Okayama prefecture.
Methods The subjects consisted of the Hiroshima group reported in LSS report 12 (LSS-H group) and a control group (the entire populations of Hiroshima and Okayama—HPCG and OPCG, respectively). We estimated the expected number of deaths due to all causes and to cancers of various causes among the exposed survivors of the Hiroshima bombing in the LSS report 12 who died in the follow-up interval at ages similar to those of people in Hiroshima and Okayama prefectures who were aged 0–34 years at the time of the bombing in 1945. We compared the standardized mortality ratio (SMR) of the LSS-H group to that of the HPCG and OPCG (SMR-H and SMR-O, respectively).
Results Even at low and very low dose categories, the SMR-H and SMR-O were significantly high for all deaths, all cancers, solid cancers, and liver cancers in male subjects, and for uterus and liver cancers in female subjects, respectively. The results show that, if the dose estimations of the dosimetry system 1986 (DS86) are correct, there are significantly increased risks of cancer among even survivors exposed to the very low dose level.
Conclusions The dose assumptions of DS86 have been criticized for underestimating doses in areas distant from the hypocenter. The contribution of residual radiation, ignored in LSS, and that of neutrons, underestimated by DS86, is suggested to be fairly high.

Keywords Atomic bomb · Cancer · Hiroshima survivors · Radiation · SMR

Introduction

The life span study (LSS) conducted by the Radiation Effects Research Foundation (RERF) is an epidemiological investigation of deaths among people exposed to the Hiroshima and Nagasaki atomic bombs. The exposure dose for the LSS cohort is estimated based on the primary radiation dose defined by dosimetry system 1986 (DS86) [1–3]. The residual radiation that the entire LSS group may have been exposed to was excluded from the general analysis of the LSS. For this reason, it is intrinsically difficult to examine the level of the exposure risk based on residual radiation. All LSS reports after report 8 have estimated the risk of radiation exposure among A-bomb survivors using regression analyses. These analyses, however, did not show the results for A-bomb survivors in comparison with an unexposed group (NIC; not in the city at the time of bombing) [4]. (LSS reports use the term "unexposed group", but this category of survivors was actually exposed to very low-dose primary radiation.)

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It is questionable, therefore, whether unbiased estimates of the risk of radiation-induced disease can be obtained from these data. Francis et al. [5] have reported that in the event of the delayed effects of radiation, in which dosage is not a major contributory factor, the association between the radiation and any subsequent effects could be overlooked in the absence of a non-exposed control group for comparison. While it is difficult to obtain an ideal control group for A-bomb survivors, the comparison of A-bomb survivors with a truly unexposed group is needed due to recent and growing concerns regarding exposure, particularly internal exposure, by residual radiation.

In the study reported here, we estimated all deaths as well as the number of deaths expected from various kinds of cancers among the exposed survivors of the Hiroshima bombing included in LSS 12 who died in the follow-up interval at ages similar to those of people in Hiroshima and Okayama prefectures who were aged 0–34 years at the time of the bombing in 1945. The numbers of deaths were classified according to sex, radiation dose, and disease. We then calculated and compared standardized mortality ratio (SMR).

Materials and methods

The subjects in our study comprised the Hiroshima group (LSS-H group) reported in LSS report 12 (LSS 12) [4] and a control group consisting of the entire populations of Hiroshima prefecture (HPCG) and neighboring Okayama (OPCG). Data for both the LSS-H group and the control groups were collected and categorized by sex and age at the time of the bombing (in 5-year age groups) to calculate the SMR. We obtained the number of cause-specific deaths and population by age group from the vital statistics database of the respective prefectures [6–8]. We defined the years 1971–1990 (divided into five intervals) as the follow-up interval for LSS 12 and as the observation period for the present study. The reason we chose to start the observation period in 1971 was simply that this was the first year of Hiroshima and Okayama prefecture mortality data that were available to us. Therefore, the subjects in this study, whom we could follow during the years 1971–1990, were aged 0–34 years old in 1945 (in 1971 the population of Hiroshima prefecture consisted of about 560,000 males and 590,000 females, and the population of Okayama prefecture was about 378,000 males and 416,000 females [6–8]). The reason we did not use the latest LSS 13 data is that in LSS 13 the disease categories were changed; for example "leukemia" became "all hematopoietic cancers", making it difficult to link with our data. Using the data on exposed survivors from LSS 12, we initially calculated the observed person–years as well as the observed number of deaths (O) according to follow-up interval, sex, age at exposure (0–34 years old), colon radiation dose (three levels; see below), and cause of death. We then calculated the mortality rate by cause of death in the HPCG and OPCG, respectively, according to follow-up interval, sex, and age in 1945 (in 5-year age groups). The expected number of deaths (E) was calculated for each category (sex, age at exposure, colon radiation dose, and cause of death) of the LSS-H group using an indirect method based on observed person–years. This expected number of deaths was calculated in two ways: (1) with the HPCG as the standard; (2) with the OPCG as the standard. These O and E values were then used to calculate the SMR. We estimated the 95% confidence interval (CI) of SMR using the following formula: lower confidence limit $= 1/(2E)\chi^2_{0.025}(2O + 2)$ and upper confidence limit $= 1/(2E)\chi^2_{0.975}(2O)$, where $\chi^2_{0.975}(2O)$ is the value obtained when the upper probability of the chi-square value with 2O degrees of freedom is 0.975. In this study, the colon radiation dose (Sv) was divided into three categories: under 0.005 (very low), more than 0.005 and under 0.1 (low), and more than 0.1 (but less than 4.0) (high), respectively. This colon radiation dose was the estimated radiation dose when the distance from the hypocenter and the radiation shielding provided by buildings (based on DS86) [4] had been taken into effect. Deaths were categorized as all deaths and as those from all cancers (specifically, leukemia, solid cancers, stomach cancer, colon cancer, liver cancer, lung cancer, female breast cancer, and uterine cancer).

Results

For all deaths and deaths due to all cancers, the SMRs of the LSS-H group in comparison with the HPCG and OPCG (SMR-H and SMR-O, respectively) were shown to be significantly high in the high dose category in all sex and dose level categories (Tables 1, 2). In addition, SMRs for LSS-H males in the low and very low dose categories were also significantly high in relation to all deaths and deaths from all cancers. The SMR-Os of deaths in the female low dose category due to all deaths and all cancers were significantly high.

Both the SMR-H and SMR-O of deaths due to leukemia were estimated to be three or more in the very low and high dose categories for males, and around three in the high dose category for females. All of these SMRs are significantly high.

The SMR-H and SMR-O for solid cancers among males were significantly high in all dose categories and increased with the radiation dose. The SMR for females for death due to solid cancers was significantly high in the high dose category (SMR-H 1.64, 95% CI 1.44–1.87; SMR-O 1.71, 95% CI 1.50–1.94). The SMR-O was also significantly

Table 1 The standardized mortality ratio (SMR) according to colon doses and selected cancers: Hiroshima, both sexes, age 0–34 years at time of bomb, 1971–1990

Cause of death	Dose categories (Sv)															
	<0.005 (very low)				0.005–0.1 (low)				≧0.1 (high)				Total			
	O[a]	E[b]	SMR[c] (95% CI)	*P* value[d]	O[a]	E[b]	SMR[c] (95% CI)	*P* value[d]	O[a]	E[b]	SMR[c] (95% CI)	*P* value[d]	O[a]	E[b]	SMR[c] (95% CI)	*P* value[d]
Males																
All deaths	682	571.5	1.193 (1.107–1.285)	0.000	715	651.5	1.097 (1.020–1.179)	0.013	403	324.1	1.243 (1.128–1.368)	0.000	1,800	1547.1	1.163 (1.111–1.218)	0.000
All cancers	242	195.0	1.241 (1.094–1.402)	0.001	263	220.6	1.192 (1.057–1.341)	0.004	161	110.5	1.456 (1.249–1.690)	0.000	666	526.1	1.266 (1.173–1.364)	0.000
Leukemia	16	5.1	3.150 (1.950–4.871)	0.000	9	5.9	1.538 (0.820–2.694)	0.274	9	2.9	3.069 (1.635–5.376)	0.001	34	13.9	2.453 (1.759–3.343)	0.000
Solid cancers	218	184.6	1.181 (1.035–1.343)	0.014	250	208.6	1.198 (1.059–1.351)	0.004	147	104.6	1.406 (1.196–1.642)	0.000	615	497.7	1.236 (1.142–1.335)	0.000
Stomach	65	55.4	1.174 (0.922–1.476)	0.195	73	62.6	1.167 (0.929–1.449)	0.187	33	31.5	1.049 (0.749–1.436)	0.852	171	149.4	1.145 (0.986–1.323)	0.077
Colon	12	9.0	1.334 (0.769–2.187)	0.404	12	10.3	1.170 (0.675–1.919)	0.698	9	5.1	1.757 (0.936–3.078)	0.136	33	24.4	1.354 (0.966–1.853)	0.100
Liver	55	31.7	1.733 (1.333–2.219)	0.000	61	36.3	1.679 (1.308–2.125)	0.000	48	17.8	2.692 (2.033–3.506)	0.000	164	85.9	1.909 (1.639–2.212)	0.000
Lung	30	29.9	1.005 (0.705–1.395)	0.948	38	33.4	1.138 (0.831–1.527)	0.477	15	16.9	0.886 (0.540–1.387)	0.728	83	80.2	1.035 (0.836–1.269)	0.753
Females																
All deaths	701	651.7	1.076 (0.999–1.157)	0.054	745	733.2	1.016 (0.946–1.090)	0.662	519	409.1	1.269 (1.164–1.380)	0.000	1,965	1794.0	1.095 (1.048–1.144)	0.000
All cancers	244	234.8	1.039 (0.917–1.173)	0.550	286	261.1	1.095 (0.976–1.226)	0.124	241	146.6	1.644 (1.449–1.858)	0.000	771	642.6	1.200 (1.118–1.286)	0.000
Leukemia	6	7.0	0.858 (0.402–1.668)	0.851	6	7.8	0.772 (0.362–1.501)	0.648	12	4.4	2.755 (1.589–4.519)	0.001	24	19.1	1.255 (0.846–1.805)	0.317
Solid cancers	228	220.3	1.035 (0.909–1.174)	0.602	269	244.9	1.099 (0.975–1.234)	0.123	226	137.5	1.644 (1.443–1.865)	0.000	723	602.6	1.200 (1.116–1.289)	0.000
Stomach	43	59.9	0.718 (0.534–0.948)	0.034	56	67.1	0.834 (0.643–1.067)	0.175	57	37.6	1.518 (1.173–1.936)	0.002	156	164.6	0.948 (0.811–1.102)	0.505
Colon	14	14.2	0.985 (0.590–1.563)	0.941	13	15.5	0.836 (0.492–1.348)	0.604	13	8.7	1.487 (0.876–2.398)	0.204	40	38.5	1.039 (0.764–1.385)	0.873
Liver	30	15.9	1.889 (1.326–2.622)	0.001	29	17.5	1.656 (1.156–2.311)	0.009	16	9.9	1.615 (0.999–2.507)	0.076	75	43.3	1.733 (1.384–2.147)	0.000
Lung	21	21.0	1.002 (0.658–1.474)	0.920	38	23.8	1.599 (1.167–2.146)	0.005	27	13.2	2.039 (1.405–2.878)	0.000	86	58.0	1.484 (1.202–1.813)	0.000
Female breast	21	17.0	1.235 (0.811–1.816)	0.397	22	18.5	1.189 (0.788–1.736)	0.485	30	10.4	2.876 (2.019–3.993)	0.000	73	45.9	1.589 (1.265–1.974)	0.000
Uterus	27	15.3	1.767 (1.218–2.493)	0.004	35	16.8	2.087 (1.503–2.833)	0.000	21	9.5	2.204 (1.447–3.241)	0.000	83	41.6	1.996 (1.611–2.448)	0.000

[a] Observed number of deaths (person-years)

[b] Expected number of deaths (person-years)

[c] Risk among Hiroshima survivors in the life span study (LSS) relative to population of Hiroshima prefecture

[d] Chi-square test

Table 2 The SMR according to colon doses and selected cancers: Okayama, both sexes, aged 0–34 years at time of bomb, 1971–1990

Cause of death	Dose categories (Sv)															
	<0.005 (very low)				0.005–0.1 (low)				≧0.1 (high)				Total			
	O[a]	E[b]	SMR[c] (95% CI)	*P* value[d]	O[a]	E[b]	SMR[c] (95% CI)	*P* value[d]	O[a]	E[b]	SMR[c] (95% CI)	*P* value[d]	O[a]	E[b]	SMR[c] (95% CI)	*P* value[d]
Males																
All deaths	682	560.8	1.216 (1.128–1.309)	0.000	715	641.3	1.115 (1.037–1.199)	0.004	403	318.7	1.265 (1.146–1.390)	0.000	1,800	1520.7	1.184 (1.130–1.239)	0.000
All cancers	242	181.5	1.334 (1.179–1.511)	0.000	263	205.9	1.277 (1.132–1.436)	0.000	161	102.9	1.565 (1.340–1.814)	0.000	666	490.3	1.358 (1.260–1.464)	0.000
Leukemia	16	5.1	3.139 (1.981–4.948)	0.000	9	5.9	1.527 (0.799–2.627)	0.283	9	2.9	3.066 (1.598–5.254)	0.001	34	13.9	2.441 (1.741–3.310)	0.000
Solid cancers	218	169.8	1.284 (1.123–1.458)	0.000	250	192.6	1.298 (1.145–1.461)	0.000	147	96.2	1.528 (1.303–1.788)	0.000	615	458.6	1.341 (1.238–1.448)	0.000
Stomach	65	50.7	1.281 (1.001–1.602)	0.045	73	57.6	1.268 (1.002–1.563)	0.042	33	28.8	1.145 (0.812–1.558)	0.492	171	137.1	1.247 (1.075–1.442)	0.004
Colon	12	7.6	1.574 (0.865–2.460)	0.160	12	8.7	1.379 (0.769–2.187)	0.343	9	4.4	2.056 (1.199–3.941)	0.049	33	20.7	1.594 (1.121–2.151)	0.010
Liver	55	23.0	2.395 (1.839–3.063)	0.000	61	26.5	2.305 (1.828–2.970)	0.000	48	13.0	3.702 (2.788–4.808)	0.000	164	62.4	2.629 (2.271–3.065)	0.000
Lung	30	31.0	0.969 (0.679–1.344)	0.932	38	34.7	1.094 (0.792–1.457)	0.637	15	17.5	0.855 (0.508–1.305)	0.625	83	83.2	0.997 (0.807–1.226)	0.979
Females																
All deaths	701	610.0	1.149 (1.067–1.236)	0.000	745	687.3	1.084 (1.009–1.164)	0.029	519	382.8	1.356 (1.244–1.474)	0.000	1,965	1680.1	1.170 (1.119–1.222)	0.000
All cancers	244	224.2	1.088 (0.961–1.230)	0.186	286	249.1	1.148 (1.023–1.285)	0.021	241	139.8	1.724 (1.518–1.945)	0.000	771	613.1	1.258 (1.172–1.348)	0.000
Leukemia	6	5.6	1.069 (0.469–1.945)	0.962	6	6.3	0.952 (0.469–1.945)	0.937	12	3.5	3.456 (2.307–6.561)	0.000	24	15.4	1.560 (1.079–2.301)	0.039
Solid cancers	228	211.5	1.078 (0.949–1.225)	0.256	269	234.8	1.146 (1.016–1.285)	0.028	226	131.8	1.714 (1.503–1.942)	0.000	723	578.1	1.251 (1.163–1.344)	0.000
Stomach	43	59.5	0.722 (0.533–0.946)	0.038	56	66.0	0.849 (0.654–1.085)	0.243	57	37.1	1.537 (1.190–1.965)	0.001	156	162.6	0.959 (0.818–1.113)	0.604
Colon	14	14.1	0.994 (0.600–1.588)	0.913	13	15.9	0.818 (0.478–1.310)	0.548	13	8.8	1.473 (0.850–2.329)	0.216	40	38.8	1.031 (0.754–1.367)	0.912
Liver	30	11.3	2.651 (1.915–3.786)	0.000	29	12.5	2.317 (1.557–3.113)	0.000	16	7.1	2.269 (1.415–3.534)	0.001	75	30.9	2.429 (1.932–2.997)	0.000
Lung	21	19.1	1.100 (0.726–1.626)	0.746	38	21.5	1.771 (1.321–2.429)	0.001	27	11.9	2.265 (1.550–3.175)	0.000	86	52.5	1.639 (1.340–2.021)	0.000
Female breast	21	14.3	1.466 (0.985–2.206)	0.103	22	15.5	1.422 (0.972–2.140)	0.125	30	8.8	3.420 (2.340–4.628)	0.000	73	38.6	1.893 (1.490–2.325)	0.000
Uterus	27	15.4	1.755 (1.240–2.540)	0.005	35	17.0	2.061 (1.483–2.795)	0.000	21	9.6	2.177 (1.379–3.089)	0.000	83	42.0	1.975 (1.595–2.423)	0.000

[a] Observed number of deaths (person-years)

[b] Expected number of deaths (person-years)

[c] Risk among Hiroshima survivors in LSS relative to population of Okayama prefecture

[d] Chi-square test

high in the low dose category (SMR 1.15, 95% CI 1.02–1.29).

Stomach cancer SMR-O was significantly high in the low dose category for males (SMR 1.27, 95% CI 1.00–1.56) and in the high dose category for females (SMR 1.54, 95% CI 1.19–1.97). The SMR-O for colon cancer among males was significantly high in the high dose category (SMR 2.06, 95% CI 1.20–3.94). The SMR-H for death due to liver cancer was significant in all classes except the high dose category for females, with significantly high SMR-H and SMR-O for both sexes in all other dose classes, with an SMR range of 1.6–3.7. Male SMR for deaths due to lung cancer did not show any significant differences, while SMR-H and SMR-O for females were significantly high in both the low and high dose categories (low: SMR-H 1.60, 95% CI 1.17–2.15; SMR-O 1.77, 95% CI 1.32–2.43; high: SMR-H 2.04, 95% CI 1.41–2.88; SMR-O 2.27, 95% CI 1.55–3.18).

The SMR-H and SMR-O of female breast cancer were significantly high in the high dose category (SMR-H 2.88, 95% CI 2.02–3.99; SMR-O 3.42, 95% CI 2.34–4.63). Uterine cancer SMR-H and SMR-O were significantly high in all dose categories (SMR 1.8–2.2), with the SMR having a positive correlation with increasing radiation dose.

Discussion

In this study, we calculated the SMR for all causes of death and for various types of cancer by comparing the actual number of deaths among the LSS-H group with the expected number of deaths during the follow-up period among the cohort aged 0–34 years in 1945 in Hiroshima and Okayama. We found that the SMRs of survivors subjected to high exposure levels were significantly high for about three-quarters of the causes of death. The SMRs of survivors subjected to low exposure were also significantly high for about half of causes of death.

Two possibilities should be noted here. First, there is the possibility of observational bias: individuals of the LSS-H group are examined more frequently than those in the HPCG and OPCG, possibly making the diagnosis of cancer easier. Second, there is the possibility of measurer bias, in which the diagnosis of physicians would tend toward cancer for individuals in the LSS-H group. While it is difficult to know the accuracy of diagnoses at the time the people were exposed to radiation, it is also possible that the discovery rate was higher in the LSS-H group than in HPCG and OPCG, and so these biases may have led to an overestimation in our results.

However, since we used the causes of death recorded on the death certificate, the accuracy of the death certificates is vital to the reliability of the results in this study. From a comparison of reports based on the LSS autopsy program with information on the cause of death as recorded on the death certificate, the LSS reported that about 20% of cancer deaths are misclassified as non-cancer on the death certificate, while about 3% of non-cancer deaths are misclassified as cancer [9–11]. Thus, evidence has also been reported for the underestimation of cancer deaths in the LSS-H group.

Significant increases in the SMRs for disease (total) were seen. The results of this study would seem to indicate a higher attribute risk (the value of the RR reciprocal subtracted from one than in previous LSS reports) [4].

There are two possible reasons for the difference in risk as reported in the LSS reports and that reported here: (1) differences in non-radiation-related factors, such as lifestyle, and (2) differences related to radiation, such as differences between genuine non-exposed groups and non-exposed control groups that in fact included people exposed to considerable levels of radiation.

With regard to the first possibility, the following point should be considered. Geographically, Hiroshima City is located within Hiroshima prefecture, while Okayama prefecture lies next to Hiroshima prefecture. Both prefectures are located along the Seto Inland Sea and have similar geographical conditions. There are no specific differences in lifestyle that could be given as a reason for different incidences of illness or death between the two. In fact, when adjusted for population and age, both prefectures reflect similar trends in terms of overall causes of death in relation to the standard figures for 1985, and the residents of these prefectures can therefore be considered appropriate for use as controls [12]. The basic conditions required for comparison are therefore met.

Among the LSS-H group, those who were further away from the hypocenter (in the suburbs of Hiroshima) at the time of the bombing have experienced a higher mortality than those exposed to the same low dose near the hypocenter (the center of Hiroshima city), but who were shielded by buildings, etc. It has also been suggested that the SMR tends to increase with distance from the hypocenter (a test for this trend indicates that it is statistically significant at $P < 0.001$). In addition, it is possible that the people exposed to radiation were mainly city residents, whereas HPCG and OPCG include many residents of rural areas. In this framework, Cologne and Preston [13] reported that since people distant from the epicenter lived in rural areas, appropriate subjects for regression analysis were those living within a radius of 3 km from the explosion. However, it is also said that there is not a large difference in risk when the subjects of the study are limited to people within 3 km of the epicenter and when they are within 10 km. The fact that there is not a large difference regardless of whether or not these people are included would seem to indicate that there is not a large difference in risk in the disease structure in urban and rural areas.

Variation in mortality rates with distance in the zero-dose survivor group could be due to geographic differences in lifestyle, socioeconomic status, regional differences in health care, and/or occupation [13]. Since there is little reported evidence on possible differences in other causes of exposure, such as lifestyle, these factors will need to be studied in the future.

A population migration occurs between HPCG and OPCG in this study since these groups are retrospectively followed every year using vital statistics. The LSS-H group is the population of A-bomb Hiroshima survivors followed-up in LSS. However, the LSS-H group was also estimated to have migrated somewhat, although the effect of migration was adjusted using the LSS cancer incidence data [14]. Considerable care is needed when interpreting the findings in this study because the HPCG and OPCG, which are large populations, are thought to contain a higher proportion of suburban residents than the LSS-H group. Unless all subjects in the LSS-H group migrated from Hiroshima prefecture, the HPCG would have contained A-bomb survivors. However, the impact of overlap between the LSS-H group and HPCG is estimated to be low since the populations of HPCG and OPCG (the number of people in Hiroshima and Okayama prefectures who were aged 0–34 years at the time of the bombing in 1945 was about 1,150,000 and 795,000, respectively, in 1971 [6–8]) were sufficiently large in relation to that of LSS-H group (about 58,000 people [4]). In addition, the high mortality rates of A-bomb survivors may have made the control group's mortality rate appear higher than it actually is, although we estimate that the inclusion of A-bomb survivors in HPCG had a modest influence on our results. Therefore, this would not make the significant difference we found any less important.

In order to guarantee compatibility, the control group should be established without any selection bias, but this is very difficult. If there were any selection biases, one must consider whether the biases function to shift the results toward overestimation or in the opposite direction. In our study, it is possible that since the control group may have included some people who were at high risk, the SMR obtained for the LSS-H group may be smaller than the actual ratio.

With regard to possibility (2) above—that there is a radiation-related reason for the difference between the LSS risk and the risk indicated in this study—the following should be considered.

The LSS reports from no. 8 onwards did not use genuine non-exposed control groups, rather they calculated risk by obtaining background risk using regression analysis from data relating to deaths among those exposed to radiation. Analysis of the level of exposure to radiation used DS86, which only looked at the initial radiation and does not take residual radiation into account. As a result, when people in the lowest radiation dose category within the LSS group were exposed to significant risk from radiation, the LSS report calculated the background risk as higher than it actually was and, consequently, calculated the SMR as being lower than it actually was.

The results of our study would seem to confirm this: even people in the lowest dose category were shown to be subject to a significantly higher level of risk than those in the control group. The significant difference in risk between the two groups is thought to be due either to a difference in the evaluation of risks from initial radiation or (perhaps in addition to) to a difference in the evaluation of risks from residual radiation, and it can be explained as follows. If DS86 underestimated the level of radiation to which survivors were exposed in more remote areas, then those survivors included in the very low and low categories must have in fact received a higher initial dose of radiation than was formerly considered. This would explain the high SMR among the very low category within the LSS group. Assuming, on the other hand, that the assumptions relating to initial radiation doses in DS86 were correct, this would indicate that the initial radiation in the very low dose category in fact carried an increased risk, over and above that which could be assumed based on the high radiation area data. Additionally, the evaluations in DS86 do not take into account residual radiation, which could be the basic reason for the disparity. It cannot be denied that even survivors in the very low category may have been subject to additional radioactive fallout and may have breathed in or swallowed induced radioactive substances in the vicinity of the hypocenter [15–18].

Large differences were not necessarily seen in the SMR of leukemia and malignant tumors of the digestive organs. The cause of leukemia is thought to lie in the pattern of onset originating with A-bomb radiation. In this study, we used data collected since 1971, but it has also been reported by RERF that leukemia in people exposed to the A-bomb occurred relatively soon after the exposure; consequently, looking at data only for more recent years, the number of cases does not seem particularly high [3]. For solid cancers, on the other hand, the absolute risk increases with the age of the exposed person, and these cancers become easier to detect [4]. Therefore, since the follow-up period in this study began 25 years after the initial exposure, it is likely that the influence of A-bomb radiation is becoming smaller in terms of leukemia. In addition, the prognosis of leukemia is poor, and it is fairly simple to identify leukemia as the cause of death. Thus, it is unlikely that it is easy to monitor leukemia in people exposed to radiation but difficult to monitor it in those who were not exposed. In terms of digestive system cancer, such as stomach cancer, patterns of death differ, depending on the category of radiation dosage. Confounding factors, such as smoking

and drinking alcohol, may also affect the distribution, but there were also more males than females involved in the rescue efforts subsequent to the bombing, and these males may therefore have been active in areas with residual radiation [15, 17].

In addition, a strong correlation was seen, especially with liver cancer, even with low dosage in both men and women, and no dose–response relationship was seen between very low dosages (less than 0.005 Sv) and low dosages (0.005–0.1 Sv). Since the hepatitis virus is involved in the majority of liver cancers, causes other than radiation (e.g., iatrogenic factors) cannot be ruled out.

With regard to doses from the initial radiation, studies by RERF have found that there is a linear dose–response relation for solid cancers. However, that was from the results of multiple regression analysis with the exposed group. The dose response was not linear in HPCG and OPCG, and the group thought to consist of people in LSS-H exposed to very low doses showed a considerably higher SMR with solid cancers than did the control group. Therefore, given the possible involvement of radiation that is not considered part of the initial dose (radioactive fallout), it would seem impossible to detect a dose–response relationship. In studies at RERF, dose–response relationships are not ruled out, even in the range of very low dosages of initial radiation, and it would be difficult to say that this is a threshold value even in the present study.

One more trend worth noting is that within the very low radiation dosage category, there are certain illnesses for which the SMR seems to be higher than that for the low category and—sometimes—even for the high category.

The illnesses that display these trends have not been subjected to genuine SMR assessments since epidemiological studies carried out by RERF did not include a genuine non-exposed control group comparison. It is therefore difficult to disprove a link with radiation. The fact that such illnesses seem to display a high SMR within the very low radiation category may instead indicate a contribution of residual radiation that was not included in the exposure evaluation [11].

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