Cancer Mortality Risk Among Workers at the Russian Nuclear Complex Mayak.

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1. Introduction

At present, radiation risk estimates used as a basis for radiation protection standards are generally derived from data on the experience of Japanese atomic bomb survivors who received a single exposure at high dose rates. However, health effects of protracted low-dose rate exposures are of primary interest for radiation protection. The first Russian nuclear complex for plutonium production, Mayak Production Association, began operation in 1948. A significant fraction of Mayak workers, especially those employed during the first decade of Mayak operation, accumulated doses of external γ-radiation in excess of 1 Gy. In addition, many workers hired in the early years had significant internal exposures to α-radiation from incorporated plutonium. Thus, these workers offer an opportunity to study the effects of protracted radiation exposures at cumulative doses that are sufficiently large to estimate risks with some degree of precision. The Mayak Worker Cohort includes almost 26,000 people hired at the main plants (nuclear reactors, radiochemical plant and plutonium production plant) and auxiliary plants (mechanical-repair and water processing plant) of the Mayak Production Association between 1948 and 1982. Procedures for creation of the cohort, vital status and cause of death ascertainment, and external and internal dosimetry are described in detail in Koshurnikova et al. 1999. Plutonium exposure has been clearly demonstrated to increase risks of cancers of the lung (Kreisheimer et al. 2003; Gilbert et al. 2004), skeleton (Koshurnikova et al. 2000), and liver (Gilbert et al. 2000), while external exposure has been linked to elevated mortality risks from all solid cancers combined and leukemia (Shilnikova et al., 2003). The current paper summarizes new analyses of external exposure based on an expanded cohort of workers and three additional years of follow-up.

2. Materials and methods

Recently, the Mayak worker cohort was expanded to include 4,382 workers who were first employed between 1973 and 1982. Some characteristics of the expanded cohort are summarized in the table. Workers at all the main plants had potential for external radiation exposure, primarily from γ-rays. Workers with potential for external exposure have worn film badges since the beginning of plant operations. Workers at the radiochemical and plutonium production plants also had a potential for internal exposures from inhaled radionuclides. The major component contributing to internal exposure was the α -particle emitting radionuclide ^{239}Pu (referred to as plutonium). Workers at the auxiliary plants generally had little or no potential for occupational radiation exposures. As indicated in the table, plutonium body burden measurements are available only for about 40% of the workers who had potential for plutonium exposure (workers at the radiochemical and plutonium production plants). To allow for the possible effects of internal exposure when we consider the risk of external exposure, and to make use of follow-up data for workers without plutonium measurements, we have developed a categorical surrogate index, which is defined in terms of occupational history data (Shilnikova et al. 2003). The surrogate index was used for periods during which there was no plutonium monitoring data while estimated plutonium body burden was used during post monitoring periods for monitored workers.

Analyses were based on Poisson regression methods and implemented with the software package EPICURE (Preston et al. 1993). Parameter estimates were computed with maximum likelihood methods, using excess relative risk models of the general form

$$(1) \quad \lambda_0(a,s,z)\cdot[1+ERR(d)],$$

where $\lambda_0()$ is the baseline hazard (rate) function, which varies with attained age (a), gender (s) and other covariates (z). *ERR(d)* is the excess relative risk function, in which d involves both external dose and internal exposure. The logarithm of the baseline hazard was modeled using gender-specific quadratic functions of log attained age.

3. Results

Solid cancer risks

In these analyses we considered all solid cancers and also two separate categories: cancers in the organs of primary plutonium deposition (lung, liver and skeleton) and all other solid cancers. As in our earlier analyses (Shilnikova et al. 2003), there was clearly an indication of a statistically significant effect of 5-year lagged external dose on the risk of all solid cancers ($P < .001$), cancers in the organs of primary plutonium deposition ($P<0.001$) and other solid cancers ($P=0.02$) in a linear dose-response model with adjustment for internal exposure. The estimated non-linearity in the external dose-response was not statistically significant ($P=0.09$ for all solid cancers). Modification of the external exposure effect was studied for all solid cancers. While there did not appear to be a gender difference in ERR ($P>0.5$) or heterogeneity in the risk with time since the dose was received ($P>0.5$), there was a significant ($P = 0.002$) decrease in the ERR with increasing age at hire (which can be considered a surrogate for age at first exposure).

There also was a significant association of the risk of all solid cancers ($P<0.001$), solid cancers in the organs of primary plutonium deposition ($P<0.001$) and other solid cancers ($P <0.001$) with internal exposure.

Leukemia risks

Risks of leukemia (other than chronic lymphocytic leukemia) increased significantly with increasing 2-year lagged external dose ($P < 0.001$). There was no evidence of significant effects of gender ($P>0.5$) or age at hire ($P=0.17$) on the risk of leukemia. In contrast to solid cancer risks, there was strong evidence of heterogeneity in the leukemia risk with respect to the time since the dose was received ($P < 0.001$), with the risk from doses received in the most recent two to five years being more than 10 times that from doses received more than five years ago. There was no evidence of significant non-linearity in the leukemia dose-response ($P=0.08$). It appears that about 50% of the non-CLL leukemia deaths were in excess of what one would expect. All the estimated radiation-associated leukemia deaths were attributed to external exposure. We found no association between leukemia and internal exposure ($P >0.5$).

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RÉSUMÉ

L'analyse faite dans une cohorte de presque 26,000 ouvriers de "Mayaque", une complexe nucleaire russe, a montré la liaison authentique du cancer solide et du leucosis avec l'irradiation gamma chronique. Les risques du cancer solide êtaient liés avec l'irradiation alpha interne du plutonium pendant qu'il n'y avait pas de liaison de l'irradiation alpha avec leucosis. On remarquait un effet authentique de l'âge au moment de l'embauchage sur les risques du cancer solide. On ne remarquait pas ni l'effet du sexe ni du temps depuis l'irradiation sur les risques du cancer solide. On remarquait l'effet authentique du temps dès le moment de la rèception de la dose sur les risques du leucosis. On ne remarquait pas ni l'effet du sexe ni l'âge au moment de l'embauchage sur les risques du leucosis.

Table. Characteristics of the Mayak worker cohort

	Plant				Total
	Auxiliary	Reactor	Radiochemical	Plutonium production	
Workers (% female)	3560 (18%)	5412 (22%)	9185 (26%)	7782 (27%)	25939 (24%)
Person-years	108,292	182,228	315,741	259,635	865,896
Average age at hire	23	24	23	24	24
Characteristics of External Radiation Exposure					
Monitored for external radiation (%)*	1,901 (53%)	4,833 (89%)	8,891 (97%)	4,787 (62%)	20,412 (79%)
Average cumulative whole-body external γ-ray dose (Gy)	0.13	0.55	1.06	0.39	0.69
Characteristics of Internal Radiation Exposure					
Monitored for Pu body burden	196 (6%)	228 (4%)	3,560 (39%)	3,120 (40%)	7,104 (27%)
Average Pu body burden (kBq)	0.60	0.21	0.96	2.57	1.63
Vital Status and Cause of Death Information (as of December 31, 2000)					
Known vital status (%)	3,295 (93%)	4,945 (91%)	8,317 (91%)	7,220 (93%)	23,777 (92%)
Deaths	1,001	1,960	3,206	2,662	8,829
Cancer deaths	201	493	804	730	2,228
Solid cancer deaths	190	461	742	693	2,086
Lung, liver and skeletal cancers	64	153	252	301	770
Leukemia	5	18	39	27	89
Unknown cause of death	69	57	102	67	295
Lost to follow-up	265 (7%)	467 (9%)	868 (9%)	562 (7%)	2,162 (8%)

*Unmonitored workers were believed to have little or no likelihood of external exposure.