ASSESSMENT OF RADIATION-INDUCED CANCER RISKS FROM THE CHERNOBYL FALLOUT IN FINLAND

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INTRODUCTION

Application of detailed radiation risk models to populations affected by radiation doses from the Chernobyl fallout allows forecasting and estimation of the consequences of the accident in countries far from the place of the accident, and comparison of the model estimates with epidemiological observations in low-dose conditions among large populations. Both tasks need time-dependent estimates of the radiation doses caused by the fallout, including future doses, and both have also severe problems and statistical limitations. Problems in the forecasting originate from the large uncertainties in the risk estimates, especially in the details and in the basic assumptions included in the models. In a large population, the predictions may show considerable numbers of exposure-induced cancers; the numbers may still remain under the statistically significant levels if they are a small fraction of all cancers in the population. One may ask whether it is too confusing to present such uncertain estimates of non-significant size. On the other hand, similar estimates are implicitly applied and generally used in radiation protection, and, even with the limitations, the model predictions may be the only piece of information available in advance while potential latent cancers are developing among the population during tens of years.

Epidemiological comparisons are possible already for leukaemia because of its short latency, and also for thyroid cancer. Now, ten years after the accident, the minimum latencies of all cancers begin to be over and, as time goes on, all late consequences of the Chernobyl accident can be used to test radiation risk models and estimates. Within the limits of relevant uncertainties, the radiation risk models should be compatible with epidemiological observations. The lack of statistical significance of the observations will then be a problem. In most cases it will be possible to set an upper limit to the risk but not a definite lower limit other than the zero risk level. In the following, some examples of model predictions are given, and a calculated estimate for childhood leukaemia is compared with an epidemiological study.

MATERIAL AND METHODS

In 1986 and 1987, doses from external radiation were determined by measuring the dose rate and the amounts of radionuclides deposited using a germanium gamma spectrometer and a Geiger-Müller tube [1–3]. The estimation of external doses in 1991 and 1994 was based on these measurements and on a survey performed using thermoluminescence dosemeters [4]. The doses for the intermittent years were estimated by interpolation. The estimation of internal doses from $^{134}$Cs and $^{137}$Cs was based on whole-body counter measurements of groups of children and adult men and women, representing the whole Finnish population. The group measured was chosen using stratified random sampling. The first sampling was done in 1986, and additional samplings later, to ensure that a sufficient number of people was measured annually. The group was measured once a year in 1986–1990 [5–8]. For 1991–1994, internal doses were estimated using measurements on a reference group, and its comparison with the population group in 1990. The effective doses in the future were estimated assuming an exponential decrease with an effective half-life of 5 years for internal doses and 22 years for external doses [9].

The modified relative risk model presented in the BEIR V report [10] includes cancer mortality functions for radiation-induced cancers, separately for leukaemia and breast cancer, cancers

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of respiratory and digestive organs and for all other cancers combined. For a single exposure to dose equivalent \( d \), the excess risk at age \( a \) is the product \( \gamma_0(a)f(d)g(\beta) \), where \( \gamma_0(a) \) is the age-specific baseline risk for unexposed population [11]. Function \( g(\beta) \) depends on sex, on the age at exposure, and on the time elapsed since exposure. The dose-dependent function \( f(d) \) is linear-quadratic for leukaemia, and linear for all other cancers. In our calculations, the dose rate effectiveness factor of \( \text{DREF} = 2 \) was used explicitly for non-leukaemic cancers. The risk of exposure-induced death (REID) and the loss of life expectancy (LLE) were calculated according to Thomas et al. [12]. The individual REID values, as calculated from the estimated annual fallout doses, were summed up to get the REID as the probability of death induced by the cumulative lifetime exposure to the Chernobyl fallout. Similarly, the individual LLE values from the annual doses were summed up for the cumulative loss of life expectancy. Further, the quotient of LLE/REID is the mean loss of life expectancy among people expected to die of radiation-induced cancers [12].

RESULTS

The mean annual effective doses caused by external radiation and by internal radiation from \( ^{134}\text{Cs} \) and \( ^{137}\text{Cs} \) for the whole population are 1.0 mSv (0.5 mSv internal and 0.54 mSv external) for the period of 10 years, and 1.7 mSv (0.63 mSv internal and 1.1 mSv external) for the period of 50 years from the Chernobyl accident [9]. The estimated annual effective doses for children and for adult men and women are presented in Fig. 1. If the internal doses from other radionuclides are added, the 50 years' dose is rounded up to 1.8 mSv. The radiocaesium isotopes give the same numerical value in about 70–80 years.

To illustrate the method of calculation, the REID of a single exposure, as a function of the age at exposure, is presented in Fig. 2. Assuming that the effective half-lives of the external and internal doses remain constant after 1994, the REID of the cumulative exposure, as a function of the time of birth, is presented in Fig. 3. Data included in Figs. 1 and 2 were used in the calculation. Taking the age distributions of the Finnish population (see Fig. 4) into account, the estimated number of fatal cancers induced by the Chernobyl fallout in Finland is about 240 cases for males and 220 cases for females (see Table I). The years of birth used in the calculation ranged from 1900 to 2080. The estimated number of exposure-induced fatal cancers, as a function of the time of birth, is presented in Fig. 5. The area under the curve is the expected number of exposure-induced deaths in the Finnish population, for any year of birth, and including all years and ages of death. As indicated in the figure, about 180 cases are expected for males and 150 cases for females born in 1986 or earlier, and about 60 cases are expected for males and 70 cases for females born after 1986.

Fig. 1. Estimated annual effective doses from the Chernobyl fallout in Finland [9].
Fig. 2. REID, calculated as the probability of death from cancer induced by a single exposure to a uniform dose of 1 mSv, presented as a function of the age at exposure.

Fig. 3. REID, calculated as the probability of death from cancer induced by cumulative exposure to the Chernobyl fallout in Finland, presented as a function of the time of birth.

Fig. 4. Age distributions of the male and female populations in Finland in 1986–1989 [11].
Table I  Expected consequences of the Chernobyl fallout in Finland: the estimated number of exposure-induced cancer deaths, and the mean loss of life expectancy per exposure-induced death (LLE/EID), for classified cancer groups.

<table>
<thead>
<tr>
<th>Cancer group</th>
<th>Number of exposure-induced deaths</th>
<th>Mean LLE/EID (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Males</td>
<td>Females</td>
</tr>
<tr>
<td>Leukaemia</td>
<td>41</td>
<td>29</td>
</tr>
<tr>
<td>Respiratory cancer</td>
<td>58</td>
<td>19</td>
</tr>
<tr>
<td>Digestive cancer</td>
<td>55</td>
<td>96</td>
</tr>
<tr>
<td>Breast cancer</td>
<td></td>
<td>11</td>
</tr>
<tr>
<td>Other cancers</td>
<td>81</td>
<td>61</td>
</tr>
<tr>
<td>Total (rounded)</td>
<td>240</td>
<td>220</td>
</tr>
</tbody>
</table>

Fig. 5. Estimated number of deaths from cancer induced by the Chernobyl fallout in Finland, as a function of the time of birth.

Figures 6 and 7 show more detailed REID curves for the groups of cancers classified according to the BEIR V report [10], separately for males and females. Curves of the loss of life expectancy (LLE) are not shown because their shapes seem to be very similar to the REID curves. The difference between LLE and REID can be seen indirectly in the curves showing the ratio, LLE/REID in Fig. 8. Figures 9 and 10 show the detailed LLE/REID curves for the classified cancers. Most LLE/REID curves are practically constant for people who were children or young adults in 1986 and for people who are born later. LLE/REID, the mean loss of life expectancy in case of exposure-induced cancer death, has a typical value for each classified cancer group, determined by the risk model and the cancer mortality statistics. The values are lower for elderly people who have, on average, less lifetime to be lost after the years of latency and cancer progress. The leukaemia curve differs clearly from the other curves because of the short latency and prominent steps in the age-dependence of the relative risk in the leukaemia model. A numerical summary of the expected consequences of the Chernobyl fallout in Finland is presented in Table I. The collective loss of life expectancy among the Finnish population is about 2700 years for males and 2800 years for females.
Fig. 6. REID in classified cancer groups among Finnish males. Otherwise, see Fig. 3 caption.

Fig. 7. REID in classified cancer groups among Finnish females. Otherwise, see Fig. 3 caption.

Fig. 8. LLE/REID, the mean loss of life expectancy among people who die from cancer induced by the Chernobyl fallout in Finland, presented as a function of the time of birth.
Fig. 9. LLE/REID in classified cancer groups among Finnish males. Otherwise, see Fig. 8 caption.

Fig. 10. LLE/REID in classified cancer groups among Finnish females. Otherwise, see Fig. 8 caption.

Fig. 11. Effects of effective half-life variations on the total REID among Finnish males. The numbers in parentheses indicate the internal and external half-life (in years) used in the calculation. The median curve (5, 22) is the same as shown in Fig. 3.
As an arbitrary example of uncertainties, Fig. 11 shows some effects that variations in the effective half-life have on the total REID. Compared with the median curve, the internal effective half-life estimate has been changed by ±50% or the external effective half-life to 30 years or to 10 years in the other curves. The measured or interpolated dose values from 1986–1994 were not changed in the example, and that is why the changes do not have more effect on the REID values and on the number of fatal cancers. A change of 50% in the external half-life has an effect of about 15% on the number of fatal cancers; for a change of 50% in the internal effective half-life the effect is less than 4%.

DISCUSSION

The Finnish population totals about 5 million; the proportion of females is 51.5%. According to the ICRP 1990 [13] risk factor of 0.05 Sv⁻¹, the total number of radiation-induced fatal cancers caused by the Chernobyl fallout in Finland is about 450, as estimated from the cumulative effective dose of 1.8 mSv over a period of 50 years, including also the internal doses from ⁹⁰Sr and ¹³¹I [9]. Our calculation for an extended period, without the internal doses from strontium and iodine, gives about 450–460 cases, depending on the actual period of time used in the calculation and on the rounding of the numbers of males and females. Thus, for the Finnish population, the ICRP risk factor applied to the cumulative effective dose, and the BEIR V model with DREF=2 give about the same total number of radiation-induced fatal cancers. The risk is the highest for people who were young or children at the time of the accident, or were born soon after it. The collective loss of life expectancy among the whole population is about 5500 years.

All annual doses and the cumulative effective dose are very low, thus allowing the use of the value of DREF=2 and the direct addition of the individual REID and LLE values calculated from the annual exposures. In Finland, the cumulative fallout dose over a period of 50 years (1.8 mSv) is comparable with the mean annual dose from natural radiation (about 3 mSv), and with the mean annual effective dose caused by the medical use of radiation (about 1 mSv). Thus, the risk to an individual seems to be very low. However, a low probability of death of an order of 10⁻⁴ applied to millions of people gives hundreds of deaths. In this case, one may think that the collective consequences arise from the high number of people exposed to radiation, rather than from the amount of radiation the people are exposed to. On the other hand, there are many substantial sources of uncertainty in the radiation risk estimates [10,12,13]. According to the BEIR V report (page 181), the range of uncertainty in the risk estimates should extend down to zero risk at low doses in the millisievert range because the possibility cannot be ruled out that there may be no risks from exposures to such low doses.

The mean annual number of all cancer deaths in Finland is about 10000, with a standard deviation of about 100 and a rising long-term trend of about 100 per year. Because the exposure-induced cases will be distributed over tens of years, it does not seem possible to show the effect statistically in the scale of the Finnish population, provided that the present risk estimates represent the correct order of magnitude. Curves like those shown in Figs. 2,3,5–7 may help in identifying groups suspected of having such effects. If any statistically significant effects can be linked reliably to the fallout exposure, they will lead to re-evaluation of radiation risk models and estimates.

In an epidemiological study on childhood leukaemia in Finland [14], no statistically significant effect on incidence of childhood leukaemia was detected during 1989–1992. The study yielded a point estimate of 1.3 cases per year, which is not significantly different from zero, and has an upper 95% confidence limit of eight extra cases per year. Calculations corresponding to Figs. 6 and 7 give a total of nine fatal leukaemia cases for children who were less than 15 years old during the period 1989–1992. According to the BEIR V model, the leukaemia deaths are evenly distributed over a period of about 15 years. Thus the expected average is about 0.6 cases per year which is well within the confidence limits of the epidemiological estimate.
REFERENCES


