Recalculation of Age-specific Cancer Risk Due to Radiation Exposure Using the Recent Mortality Data of the Japanese Population

Michiya SASAKI*1, # and Takatoshi HATTORI*1

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After the Fukushima Dai-ichi nuclear power plant accident, one of the main issues was that the level of the radiation risk due to exposure, such as nominal risk coefficient, was difficult to understand. On the other hand, in the ICRP 1990 recommendation Annex C, the conditional and unconditional death probability rates, which can consider a plausible additional risk, were used as one of the referral premises for the judgement of the effective dose limits for members of the public and radiation workers. These conditional and unconditional death probability rates were illustrated as a function of the attained age and appear to be easily understandable to people concerned about the “time” and “level” of risk increment due to radiation exposure. In this study the conditional and unconditional death probability rates were updated by using recent Japanese statistical data in line with the methodology of the ICRP 1990 recommendation. Uncertainties associated with the selection of the statistical data for the Japanese population from 1985 to 2010 were also estimated to reveal the hidden variation of the prospective risk estimation. Variations in the estimated risk up to 10% order were found owing to the recent increase in life expectancy; however, the range of the variation over time is comparable to that obtained from prefecture data as of 2010.

KEY WORDS: age specific, radiation risk, ICRP, variation, statistical data.

I INTRODUCTION

After the Fukushima Dai-ichi nuclear power plant accident, the risk of radiation exposure become a major concern among the public. The Ministry of the Environment established an ambient dose equivalent rate criterion of 0.23 μSv/h to specify the deliberative decontamination action plan in the act for determining the requirements to identify the contamination waste management zone.1) The Ministry of Health, Labour and Welfare (MHLW) introduced new legislation for activity concentration in food in April 2012.2) In this promulgation, an annual effective dose of 1 mSv is considered since the CODEX3) uses the criterion of 1 mSv per year for international standards on food safety, and a continuous decrease in the detected activity of monitored foods had been observed over time after the Fukushima accident.

These countermeasures were essentially based on cabinet meeting decisions and views of Nuclear Safety Commission of Japan, which were grounded on the 2007 Recommendations of the International Commission on Radiological Protection (ICRP).4, 5) Even before this new legislation, a dose limit of 1 mSv per year for a member of the public had been adopted to regulate radiation safety and protection measures in normal operations; this number of the dose limit unfortunately appeared to acquire a high profile in the discussion on public safety, and thus the effect and the risk of radiation exposure became a major concern among the public during the aftermath of the disaster and the accident.

Regarding radiation risk quantification, ICRP gives age- and sex-specific additional death probability rates of a hypothetical population, assuming consistent annual exposure of 10 mSv to 50 mSv for workers and 1 mSv to 5 mSv for members of the public, in Appendix C “Basis for judging the significance of the effects of radiation” of ICRP Publication 60 (ICRP-60).6) This radiation risk was calculated on the basis of one epidemiological result and two sets of statistical data: risk coefficients for additive and multiplicative projection models reported in the 1988 UNSCEAR report7) originally from SHIMIZU et al.,8) the age- and sex-specific total death rates (survival data) for the Swedish population, and the age- and sex-specific background (irrespective of radiation exposure) death rates for leukaemia and non-leukaemia for the Japanese population.

According to NAKAMURA,9) there was no significant difference in the radiation risk indicators, such as loss of lifetime due to cancer death, when age- and sex-specific total death rates for the Japanese population were used in the calculation.

Recently, while life expectancy has been increasing owing to improved medical care and more healthy lifestyles,10) the radiation risk is now a major concern as mentioned before. The
nominal radiation risk is given as 5% Sv by ICRP; however, this numerical value is difficult to understand and thus ICRP Task Group (TG) 84 pointed out that efforts are necessary for good communication with stakeholders in more easily understood and transparent terms. Moreover, ICRP TG101 discussed the use of the effective dose and evaluated the age-specific lifetime attributable risk to provide risk information to patients treated by nuclear medicine. As radiation has been more recognized in our daily lives, it will be beneficial to revisit the basic data conclusively, and to recalculate the radiation risk and its uncertainty to promote understanding of the radiation risk itself for radiological protection measures.

The dose limit of 1 mSv, which was recommended in ICRP-60, is still valid in the latest ICRP 2007 recommendation and is providing an appropriate safety level of radiological protection. In this study, therefore, we first reproduced the age- and sex-specific death probability rates shown in ICRP-60, and then assessed the variation of the radiation risk estimation associated with statistical data for the Japanese population from 1985 to 2010 and statistical data by prefecture.

II REPRODUCTION OF RADIATION RISK IN ICRP 1990 RECOMMENDATION

2.1 Basic data and parameters

ICRP-60 estimated conditional and unconditional death probability rates for hypothetical populations using the following data:

- Risk coefficients for the additional and multiplicative models in the 1988 UNSCEAR report,
- Total death rate for the Swedish population,
- Background leukaemia and non-leukaemia death rates for the Japanese population.

Here, the conditional death probability rate can be calculated under the condition that the person is alive at that age, and vice versa for the unconditional death probability rate. As mentioned before, these risk coefficients are the absolute and relative risks from the report of Shimizu et al. The total death rate for the Swedish population was tabulated in ICRP-60.

On the other hand, background leukaemia and non-leukaemia death rates for the Japanese population refer the 1986 report of World Health Organization (WHO); however, numerical values were not available in ICRP-60 while approximation equations and corresponding parameters were provided.

Table 1 shows the deaths due to malignant neoplasms and leukaemia for the Japanese population cited from the 1986 report of WHO, as well as the calculated background leukaemia and non-leukaemia death rates.

ICRP-60 provided the following simple power function for the approximation of background death rates for leukaemia and non-leukaemia as shown in Fig. 1:

\[ B(u) = a \cdot u^b + c. \]  

where, \( u \) is age and \( a, b \) and \( c \) are fitting parameters. As Nakamura indicated in his paper, because the use of the fitting parameters for non-leukaemia in ICRP-60 led to poor agreement with the WHO data, we have determined these values ourselves (shaded values in Table 2).

![Fig. 1](image-url)  

Fig. 1 Fitting of the background age-specific death rates for non-leukaemia and leukaemia using equation (1). Data are cited from the WHO 1986 report, and the values of each fitting parameter are shown in Table 2.

### Table 1 Number of deaths due to malignant neoplasms and leukaemia and their rates for the Japanese population as of 1985 for different age intervals and each sex, cited from the WHO 1986 report.

| Age   | Population (in thousands) | Number of deaths at ages (in years) | Death rate |
|-------|---------------------------|-------------------------------------|------------|
|       | Males | Females | Males | Females | Malignant neoplasms (Non-leukaemia) | Leukaemia | Malignant neoplasms (Non-leukaemia) | Leukaemia |
| 0     | 735   | 706     | 25    | 30      | 7      | 4 | 3.401E-05 | 4.249E-05 | 9.524E-06 | 5.666E-06 |
| 1–4  | 3070  | 2946    | 133   | 107     | 44     | 48 | 4.332E-05 | 3.632E-05 | 1.433E-05 | 1.629E-05 |
| 5–14 | 9423  | 9041    | 420   | 308     | 226    | 148 | 4.457E-05 | 3.407E-05 | 2.398E-05 | 1.637E-05 |
| 15–24| 8729  | 8367    | 523   | 345     | 213    | 126 | 5.992E-05 | 4.123E-05 | 2.440E-05 | 1.506E-05 |
| 25–34| 8466  | 8322    | 1037  | 1220    | 208    | 145 | 1.225E-04 | 1.466E-04 | 2.457E-05 | 1.742E-05 |
| 35–44| 9882  | 9842    | 3993  | 4200    | 350    | 258 | 4.041E-04 | 4.267E-04 | 3.542E-05 | 2.621E-05 |
| 45–54| 7951  | 8111    | 12505 | 8574    | 422    | 335 | 1.573E-03 | 1.057E-03 | 5.308E-05 | 4.130E-05 |
| 55–64| 5740  | 6584    | 25179 | 14935   | 495    | 388 | 4.387E-03 | 2.268E-03 | 8.624E-05 | 5.893E-05 |
| 65–74| 3257  | 4441    | 33020 | 20898   | 562    | 384 | 1.014E-02 | 4.706E-03 | 1.726E-04 | 8.647E-05 |
| 75&+ | 1791  | 2862    | 33822 | 26437   | 456    | 360 | 1.888E-02 | 9.237E-03 | 2.546E-04 | 1.258E-04 |
Table 2  Fitting parameters of $a$, $b$, and $c$ in equation (1).

| Cancer type | Sex   | $a$   | $b$   | $c$   |
|-------------|-------|-------|-------|-------|
| Leukaemia   | Males | $4.4 \times 10^{-10}$ | 3.00  | $1.5 \times 10^{-5}$ |
|             | Females| $3.0 \times 10^{-10}$ | 2.90  | $1.5 \times 10^{-5}$ |
| Non-leukaemia | Males | $2.9 \times 10^{-10}$ | 5.14  | $4.0 \times 10^{-7}$ |
|             | Females| $3.9 \times 10^{-11}$ | 4.90  | $4.0 \times 10^{-7}$ |

### 2.2 Reproduction of conditional and unconditional death probability rates

In accordance with the calculation process in ICRP-60, conditional and unconditional death probability rates for leukaemia and non-leukaemia for males and females were reproduced assuming a hypothetical population of one million at age 0, radiation exposure over a lifetime for members of the public, and radiation exposure from ages 18 to 64 for workers. The conditional death probability rate $dp/dn$ and unconditional death probability rate $dr/dn$ at age $n$ can be computed as

\[
\frac{dp}{dn}(n) = R(n),
\]

\[
\frac{dr}{dn}(n) = R(n) \times \frac{N_e}{10^6}.
\]

Here, $N_e$ is the size of the hypothetical population at age $n$ at the beginning of the year. $R(n)$ is the death probability rate due to radiation exposure, which can be calculated using either additive or multiplicative models as follows:

\[
R(n) = \sum_{i=1}^{k} ((EAR_L + EAR_{Non-L}) \times D \times 1/DDREF) \times 10^6, \quad (3a)
\]

\[
R(n) = \sum_{i=1}^{k} ((ERR_L \times B_L + ERR_{Non-L} \times B_{Non-L}) \times D \times 1/DDREF) \times 10^6. \quad (3b)
\]

$B_L$ and $B_{Non-L}$ are the background death rates for leukaemia and non-leukaemia, and $EAR$ and $ERR$ are the excess absolute risk and excess relative risk, respectively. The values of $EAR$ and $ERR$ are expressed as functions of the age at exposure ($e$), and the attained age ($n$).\(^5\) $D$ is the annual dose and $DDREF$ (= 2) is the dose and dose-rate effectiveness factor.

In the calculation of the unconditional death probability rate, the annual decrease in the hypothetical population should be considered. In concrete, because a population of one million at the age of 0 is the initial condition in the calculation, the population can only decrease owing to the total background death rate, $B_{all}$, but initially there is no death due to radiation exposure because a two years latent period for leukaemia is assumed. At the age of 2, it is considered that deaths due to radiation exposure will start and the size of the population can be calculated as

\[
N_e = N_{e-1} - N_{e-1} \times \frac{dr}{dn}(n-1).
\]

In this study the conditional and unconditional death probability rates were calculated assuming chronic exposure. Thus, for example, the additional death rate due to radiation exposure at the age of 20 can be calculated as the sum of the attributable deaths due to the radiation exposure from ages 0 to 18, while taking latencies for leukaemia (2 years) and non-leukaemia (10 years) into account; therefore details are omitted but the risk related to the onset of the exposure period can be expressed using $\Sigma$ (See ICRP-60 for details).

Since the age- and sex-specific total death rates for Swedish population were tabulated as five-year age group, we estimated the total death rate for all ages by the spline compensation method. Figures 2 and 3 respectively show the results of reproducing the conditional and unconditional death probability rates for workers and members of the public, together with those in ICRP-60.

There were small discrepancies between our results and those in ICRP-60 values, especially when using the multiplicative risk model. This may be caused by the difference in the estimated parameters used for the approximation of the background non-leukaemia death rate for Japanese population as of 1985, as indicated in Table 2; however, reasonably good agreement with the results was confirmed.

### III VARIATION OF UNCONDITIONAL DEATH PROBABILITY RATE

As shown in Figs. 2 and 3, it is considered that the variation of the unconditional death probability rate will be much easier to identify since its curve has a clear peak around the age of 70–80. In addition, ICRP-60 provides unconditional death probability rates for use in the discussion of the dose limit for workers. Therefore, we decided to use the unconditional death probability rates to discuss the variation associated with the statistical data and to use the conditional death probability rates to provide informative material for understanding the meaning of the radiation risk. For all these calculations, Japanese statistical data from 1985 to 2010 were used.

#### 3.1 Variation associated with statistical data

(a) Fitting curve for background death rates for leukaemia and non-leukaemia

Japanese statistical data were obtained from a database available on the website of MHLW.\(^16\) As the age- and sex-specific total death rates are also provided by five year intervals, the spline compensation method was also adopted to estimate the age- and sex-specific total death rates for all ages.

For the background death probability rates for leukaemia and non-leukaemia for the whole Japanese population, statistical data were obtained from the information service website of National Cancer Center Japan.\(^15\) The ICD-9 code \(^{16}\) (204-208) was used for the data of 1985 and 1990, and the ICD-10 code \(^{17}\) (C91-95) was used for the data later than 1995 (i.e., 1995, 2000, 2005, and 2010) when counting the number of leukaemia deaths. To obtain the number of non-leukaemia deaths, number of leukaemia deaths was subtracted from the total number of malignant deaths (140-208 for ICD-9,
Fig. 2 Reproduction of the conditional death probability rate as a function of age in ICRP-60. Additive model was adopted for the members of the public (upper left) and for workers (upper right) by using Eqs. (2a) and (3a). Multiplicative model was adopted for the members of the public (lower left) and for workers (lower right) by using Eqs. (2a) and (3b). The data for calculation were cited from the references.6–8, 13)

Fig. 3 Reproduction of the unconditional death probability rate as a function of age in ICRP-60. Additive model was adopted for the members of the public (upper left) and for workers (upper right) by using Eqs. (2b), (3a) and (4). Multiplicative model was adopted for the members of the public (lower left) and for workers (lower right) by using Eqs. (2b), (3b) and (4). The data for calculation were cited from the references.6–8, 13)
C00-C97 for ICD-10). The background death probability rates for leukaemia and non-leukaemia were obtained by dividing each number of deaths by the corresponding population size.

Regarding the background death probability rates for leukaemia and non-leukaemia by prefecture, since only the numbers of all cancer death were available from the database, they were divided proportionally according to the ratio between the background death probability rates for leukaemia and non-leukaemia for the whole Japanese population as of 2010.

Although fitting equations for the background death rates for leukaemia and non-leukaemia were provided in ICRP-60, the values of the parameters differ significantly as shown in Table 1. In this study we devised a new fitting of a logistic regression curve and derived fitting parameters for the Japanese statistical data from 1985 to 2010 and for the 2010 data by prefecture. These parameters were also estimated using R software.\(^{16}\)

\[
\ln(B(u)) = \frac{a}{1 + b \exp(-cu)} - d, \quad (5)
\]

where, \(a\) is age and \(a, b, c\) and \(d\) are fitting parameters. As an example, Figure 4 shows the fitting results together with the background death rates for leukaemia and non-leukaemia as of 2010.\(^{15}\) Table 3 shows the parameter values when equation (5) was used to fit the Japanese statistical data from 1985 to 2010.

(b) Variation associated with statistical data: calendar year

The values of the risk coefficients EAR and ERR, the latent period, and the DDREF used in ICRP-60 were also used in the calculation in this study. The unconditional death probability rates for male and female member of the public are illustrated in Fig. 5, assuming chronic exposure of 1 mSv over a lifetime. 2010 statistical data\(^{15}\) using equation (5). The values of each parameter for years from 1985 to 2010 are shown in Table 3.

![Fig. 4 Results of fitting the background age-specific death rates for non-leukaemia and leukaemia from the Japanese 2010 statistical data\(^{15}\) using equation (5). The values of each parameter for years from 1985 to 2010 are shown in Table 3.](image)

| Cancer type      | Sex  | Year | \(a\)  | \(b\)  | \(c\)  | \(d\)  |
|------------------|------|------|--------|--------|--------|--------|
| Leukaemia        | Males| 1985 | 3.17E+00| 9.01E+01| 7.51E-02| 1.09E+01|
|                  |      | 1990 | 4.40E+00| 3.45E+01| 5.45E-02| 1.12E+01|
|                  |      | 1995 | 5.07E+00| 3.94E+01| 5.46E-02| 1.14E+01|
|                  |      | 2000 | 5.45E+00| 2.55E+01| 5.19E-02| 1.19E+01|
|                  |      | 2005 | 4.89E+00| 8.87E+01| 7.26E-02| 1.17E+01|
|                  |      | 2010 | 5.09E+00| 9.64E+01| 7.47E-02| 1.19E+01|
|                  | Females| 1985 | 2.61E+00| 6.42E+01| 7.43E-02| 1.12E+01|
|                  |      | 1990 | 3.19E+00| 4.65E+01| 6.66E-02| 1.14E+01|
|                  |      | 1995 | 4.22E+00| 3.47E+01| 5.59E-02| 1.18E+01|
|                  |      | 2000 | 5.04E+00| 2.40E+01| 5.07E-02| 1.22E+01|
|                  |      | 2005 | 4.63E+00| 7.84E+01| 6.75E-02| 1.20E+01|
|                  |      | 2010 | 4.98E+00| 8.04E+01| 6.65E-02| 1.21E+01|
| Non-leukaemia    | Males| 1985 | 6.38E+00| 3.24E+01| 8.09E-02| 1.08E+01|
|                  |      | 1990 | 6.55E+00| 3.35E+01| 8.05E-02| 1.08E+01|
|                  |      | 1995 | 6.82E+00| 3.49E+01| 8.00E-02| 1.09E+01|
|                  |      | 2000 | 7.01E+00| 3.52E+01| 8.02E-02| 1.10E+01|
|                  |      | 2005 | 7.23E+00| 3.37E+01| 7.90E-02| 1.11E+01|
|                  |      | 2010 | 7.46E+00| 3.30E+01| 7.87E-02| 1.13E+01|
|                  | Females| 1985 | 6.23E+00| 1.58E+01| 7.67E-02| 1.14E+01|
|                  |      | 1990 | 6.26E+00| 1.62E+01| 7.33E-02| 1.13E+01|
|                  |      | 1995 | 6.47E+00| 1.68E+01| 7.18E-02| 1.14E+01|
|                  |      | 2000 | 7.04E+00| 1.31E+01| 6.61E-02| 1.18E+01|
|                  |      | 2005 | 6.90E+00| 1.73E+01| 7.25E-02| 1.17E+01|
|                  |      | 2010 | 7.93E+00| 8.94E+00| 5.94E-02| 1.25E+01|
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Fig. 5 Unconditional death probability rate per million for males and females assuming exposure of 1 mSv/year over a lifetime using Japanese statistical data from 1985 to 2010 and different risk estimation models. Additive model was adopted for males (upper left) and for females (upper right) by using Eqs. (2b), (3a) and (4). Multiplicative model was adopted for males (lower left) and for females (lower right) by using Eqs. (2b), (3b) and (4). The data for calculation were cited from the references.6, 14, 15

Figure 6 shows the unconditional death probability rate obtained using the Japanese statistical data by prefecture as of 2010, in addition to the data for the whole Japanese population. For a few prefectures, there were several “zero” values for younger ages in the age- and sex-specific background leukaemia and non-leukaemia death rates. In such cases, the parameter values for equation (5) cannot converge and we excluded these values from the analysis.

3.2 Variation associated with statistical data by prefecture

As shown in Fig. 6, by comparing the peak values for each graph, some differences were also demonstrated: –6% – +4% for males and –3% – +3% for females using the additive model, and –29% – +47% for males and –36% – +31% for females using the multiplicative model.

3.3 Discussion

In Fig. 5, increases in the peak value for the unconditional death probability rate and the corresponding age were observed over time. This was caused by the increase in the hypothetical population over 40 years old owing to the recent increases in life expectancy, i.e., decreases in total, background leukaemia, and non-leukaemia death rates. Here, the additive model is
Fig. 6 Unconditional death probability rate per million for males and females assuming exposure of 1 mSv/year over a lifetime using different Japanese statistical data for the whole population and by prefecture as of 2010 and different risk estimation models. Additive model was adopted for males (upper left) and for females (upper right) by using Eqs. (2b), (3a) and (4). Multiplicative model was adopted for males (lower left) and for females (lower right) by using Eqs. (2b), (3b) and (4). The data for calculation were cited from the references.6, 14, 15)

only affected by the total background death rate. On the other hand, the multiplicative model is affected not only by the total background death rate, but also by the background death rates for leukaemia and non-leukaemia, which considerably vary depending on the calendar year as shown in Fig. 7.

Therefore, the extent of the variation depends on the risk model, and risk estimates based on the multiplicative model tend to have large variation.

For the multiplicative risk model, a decrease in the unconditional death probability rate was observed from 20 to 60 years old because the background death probability rate for non-leukaemia clearly decreased, especially below the age of 50 as indicated in Fig. 7. This was for several reasons: cancer control measures, progress in medical techniques and diagnostics to detect cancer at an earlier stage, and healthier lifestyles. It is presumed that the decrease in the background death rate for non-leukaemia was the main factor affecting the unconditional death probability rate in the multiplicative model.

In this study it was also revealed that the variation of the unconditional death probability rate by prefecture does not significantly differ from that with the calendar year over time (Fig. 6). This indicates that although the background death probability rate for non-leukaemia has been decreased (improved) for the whole Japanese population data from 1985 to 2010, its variation is still comparable to that for the prefecture data as of 2010. Consequently, it can be judged that the risk estimates, such as the conditional and unconditional death probability rates, given in ICRP-60 are still reasonably valid for the present Japanese population.
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IV CONDITIONAL DEATH PROBABILITY RATE AND TOTAL DEATH RATE

After the Fukushima Dai-ichi nuclear power plant accident, the risk of radiation exposure became a major concern for the public since the annual dose criterion of 1 mSv suddenly appeared in several radiological protection measures and regulations. During an emergency or an existing exposure situation after a nuclear disaster, reference levels are used for radiological protection measures, and ICRP stresses that the reference level does not indicate the boundary between safety and danger in the Recommendations. However, when this value is used as a visible and measurable criterion, such as the target dose for decontamination work, a high level of importance becomes attached to compliance with the level.

To compare the radiation risk objectively, the conditional death probability rate and the total death rate were plotted on the same scale since such comparison was also made in ICRP-60. Figure 8(a) shows the conditional death probability rates obtained with the additive and multiplicative models for males and females assuming the annual exposure of 5 mSv over a lifetime. Figures 8(b) and (c) show the total death rates obtained with the statistical data from 1985 to 2010 and from the prefecture data as of 2010, respectively. Comparing these estimations and the “raw” statistical data may be informative for understanding the extent of risk associated with radiation exposure of mSv order in a year.

V SUMMARY

We have revisited the age- and sex-specific radiation risks estimated in the ICRP 1990 recommendations as conditional and unconditional death probability rates assuming chronic exposure. Statistical data for the Japanese population from 1985 to 2010 were also used. Variations in the estimated risk up to 10% order were found owing to the recent increase in life expectancy; however, the range of the variation over time is comparable to that obtained from prefecture data as of 2010. In conclusion, the age- and sex-specific radiation risks

Fig. 7 Background age-specific and gender-specific death rates for non-leukaemia from 1985 to 2010 in Japan.

Fig. 8 (a) Change in the conditional death probability rate after exposure of 5 mSv/y over a lifetime, and change in the background age-specific and gender-specific total death probability rates (b) from 1985 to 2010 for the Japanese population and (c) by prefecture as of 2010.
in the ICRP 1990 recommendation are likely to still be valid in Japan. Here in this study, the risk of radiation exposure has been estimated, and goes no further than providing a prediction or mathematical expectation. As indicated in this study, the use of different statistical data may generate variation in the perceived radiation risk. We hope that our results will be helpful for promoting effective recovery actions in partnership with stakeholders as well as for understanding the implications of the radiation risk.

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