Calculating Disability-Adjusted Life Years (DALY) as a Measure of Excess Cancer Risk Following Radiation Exposure

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Abstract

This paper has proposed that disability-adjusted life year (DALY) can be used as a measure of radiation health risk. DALY is calculated as the sum of years of life lost (YLL) and years lived with disability (YLD). This multidimensional concept can be expressed as a risk index without a probability measure to avoid the misuse of the current radiation detriment at low doses. In this study, we calculated YLL and YLD using Japanese population data by gender. DALY for all cancers in Japan per 1 Gy per person was 0.84 year in men and 1.34 year in women. The DALY for all cancers in the Japanese baseline was 4.8 in men and 3.5 in women. When we calculated the ICRP detriment from the same data, DALYs for the cancer sites were similar to the radiation detriment in the cancer sites, excluding leukemia, breast and thyroid cancer. These results suggested that the ICRP detriment overestimate the weighting fraction of leukemia risk and underestimate the weighting fraction of breast and thyroid cancer. A big advantage over the ICRP detriment is that DALY can calculate the risk components for non-fatal diseases without the data of lethality. This study showed that DALY is a practical tool that can compare many types of diseases encountered in public health.

Keywords

DALY, Radiation risk, Cancer, Japan, ICRP, Detriment

Introduction

Lifetime cancer mortality, incidence rate, and lives lost have been the previous indices of health risk associated with radiation protection[1]. ICRP defined the detriment in Publication 60 by considering non-fatal cancers and the number of lives lost due to the difference in latent

times [2]. The detriment has been used in estimating tissue-weighting factors and detriment-adjusted nominal risk coefficients [3] and has been a measure of radiation risk used for radiation protection. However, the detriment has the disadvantage that it can neither be appropriately interpreted nor used. Behind invention of the detriment, there are some historical reasons on estimation of the cancer risk for radiation protection. The cancer incidence data has been available to estimate the risk rather than the mortality risk[2]. It has become evident that non-fatal cancers such as breast and thyroid cancers can be susceptibly increased by radiation exposure[2].

For radiation protection, a multi-dimensional concept has been emphasized as a measure of radiation risk. In particular, the question was the comparison of risks between fatal and non-fatal cancers. ICRP (2007) considered the lethality and quality of life. Furthermore, ICRP considered the length of life lost when evaluating the detriment of leukemia. As the other components, a social judgment is involved when inferring the detriment in addition to the scientific information. A modifying factor is used for calculating the detriment by considering the quality of life (QOL) for non-fatal cancer. ICRP judges that cancers should be weighted not only by lethality but also for pain, suffering, and any adverse effects of cancer treatment [2].

The concept of the detriment can be only used for comparison purposes between different doses. The number of radiation-induced cancer deaths has been sometimes incorrectly inferred using the detriment-adjusted nominal risk coefficient multiplied by the size of the population that received radiation exposure. Since the detriment is a multi-dimensional risk index, the detriment-adjusted nominal risk does not mean the number of radiation-induced cancer deaths. The calculated detriment expresses only a relative numerical value in an exact sense. In addition, the detriment does not mean the risk of a population considered since it is calculated in a hypothetical population with both sexes, different ages and ethnic diversity [2]. The detriment is given as risk coefficients like a probabilistic quantity. These issues would be brought by the definition specific to radiation-related cancer risk.

It appears that the misuse partly occurred due to the probabilistic quantity and that the multidimensional concept as a measure of health risk failed to be properly communicated with people because ICRP defined the relative quantity specific to radiation protection. Risk comparison does not work appropriately when one compares with other health risks that are expressed by cancer incidence or mortality. Based on these reasons, it can be said that the detriment as a risk measure has some disadvantages, if the detriment will be used not only for risk comparison and but also for understanding of radiation risk.

After the Fukushima accident, the key issues regarding the use of detriment-adjusted nominal risk coefficients have been identified [4]. Further, a misunderstanding of radiation risk may occur from methods of determining low-dose risk and from the interpretation of the meaning. In

particular, the probability measure of the detriment-adjusted nominal risk coefficients would have led to misuse and misinterpretation in the Fukushima accident. The essential lessons learned are that people want to quantitatively know whether future health effects will occur. The cautionary notice that health effect calculation should be avoided would be not effective from the viewpoints of risk communication. Risk quantification of radiation would be required so as to easily compare with other risk. The same method would be desirable as radiological protection purpose

In common public health, measuring disease burden in a population requires a composite metric for both premature mortality and the prevalence and severity of illness [5]. As a risk measure of both common health and environmental health [6], there is a disability-adjusted life year (DALY) that is developed from concepts of life lost. DALY is defined as the number of years lost due to ill-health, disability, and/or early death. DALY was developed by Harvard University in 1990 and was further adopted to establish an order of priority for health issues by the World Health Organization (WHO) [7, 8]. In this study, we calculated DALY to estimate radiation cancer risk and compared this with the radiation detriment to discuss the effectiveness of DALY.

Calculation methods of DALY for cancer risk following radiation exposure

DALY is a measure of overall disease burden, expressed as the number of healthy years lost due to premature death and disability by disease or unexpected accidents. To use *DALY*, mortality and morbidity are combined into a single, common metric. Therefore, mortality can be compared with morbidity by *DALY*. The basic formula of *DALY* is expressed as the following equations[9]:

$$DALY=YLL+YLD \quad (1)$$

$$YLL=N_m \times LE \quad (2)$$

$$YLD=N_i \times DW \times YD \quad (3)$$

DALY: Disability adjusted life year (year)
YLL: Years of life lost due to premature mortality (year)
YLD: Years lived with disability (year)
N_m: Number of deaths (person)
LE: Standard life expectancy at age of death (year/person)
N_i: Number of incident cases (person)
DW: Disability weight
YD: Mean years of disability (year/person)

YLL due to be exposed to radiation is expressed with the following equations [10]:

$$YLL(e,d) = CYLL(e,d) / N(e) \quad (4)$$

$$CYLL(e,d) = \int_{e+L}^{g} M_i(e,d,a) \cdot RC(a) \cdot N(a) \cdot S(a)/S(e) \cdot LE(a) da \quad (5)$$

$$YLL(d) = \sum_0^g YLL(e,d) \cdot N(e) / \sum_0^g N(e) \quad (6)$$

e: Age at exposure

d: Radiation dose (Gy)

a: Attained age (the age at which a cancer might occur)

CYLL: Collective year of life lost (person·year)

g: Standard life expectancy at birth is set at 80 years for men and 86 for women

L: Minimum latent period (year)

S: The probability of surviving

M_i: The excess absolute risk of cancer incidence exposed

RC: Ratio of cancer mortality per incidence

N: Age population distribution (person)

In DALY's calculation, life expectancy is defined as one which occurs before the age to which the dying person could have expected to survive if they were a member of a standardized model population with a life expectancy at birth equal to that of the world's longest-surviving population, Japan.[8] In this calculations, life expectancy at birth was set 86 years for women and 80 years for men using the Japanese life table as a reference. The minimum latent period *L* was set at five-years for solid cancers and was set at two-years for leukemia [10]. For calculating *LE*, the survival rates, *S* (*t*), were used in Equation 7:

$$LE(x) = T(x)/S(x), \; T(x) = \int_x^{\infty} S(t) dt \quad (7)$$

Next, *YLD* due to be exposed to radiation was expressed as the following equations:

$$YLD(e,d) = CYLD(e,d)/N(e) \quad (8)$$

$$CYLD(e,d) = DW \cdot YD \cdot \int_{e+L}^{g} M_i(d,e,a) \cdot N(a) \cdot S(a)/S(e) \, da \quad (9)$$

$$YLD(d) = \sum_0^g YLD(e,d) \cdot N(e) / \sum_0^g N(e) \quad (10)$$

CYLD: Collective years lived with disability (person·year)

DW: Disability weight

YLL and *YLD* for a population are calculated as a weighted average of the age-at-exposure specific M_i. The weights are proportional to the number of people, $N(e)$, who would be exposed at age *e*.

The mean years of disability (*YD*) were calculated from the survival fraction exceeding 5 years (*SF*) as following equation (See Appendix. A):

$$YD = \log 2 \,/\, -0.2 \times \log SF \tag{11}$$

We separately calculated the excess absolute risk for cancer incidence M_i based on the Excess Relative Risk (ERR) and Excess Absolute Risk (EAR) models and then combined the results using an arithmetic mean [11, 12]. The parameters of these models were established in the Tables A4.6 and 4.7 in ICRP Pub.103 [3]. The dose and dose rate effective factor was set at 2 for solid cancers referencing ICRP.

The ratio of cancer mortality per incidence (*RC*) was expressed as the following equation:

$$RC(a) = \lambda_m(a) / \lambda_i(a) \tag{12}$$

λ_m: Cancer mortality baseline rate of Japanese
λ_i: Cancer incidence baseline rate of Japanese

Cancer-specific incidence, mortality rates, and the survival fractions exceeding 5 years have been based on data from the National Cancer Center in Japan. The cancer-specific incidence and mortality rate statistics were from 2010 in Japan [13]; the survival fractions exceeding 5 years were from 2003 to 2005 in Japan [14]. These baseline incidence and mortality rates were obtained using spline interpolation from per 5 years to per 1 year. *N* was the number of people, based on census data, in the Japanese population at age "*e*" for a reference year (2010) [15]. Figure 1 shows the age distribution of the Japanese population in 2010(*N*). For calculating survival probabilities (*S*), the Japanese life tables for the year 2010 were used (Figure 2).

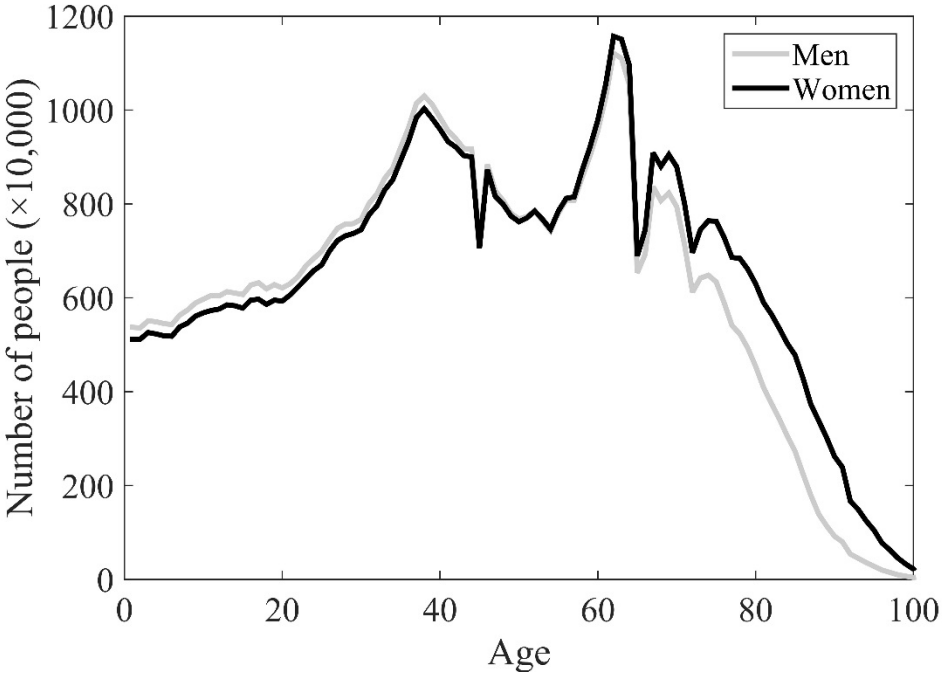

Figure 1. Age population distribution in Japan in 2010

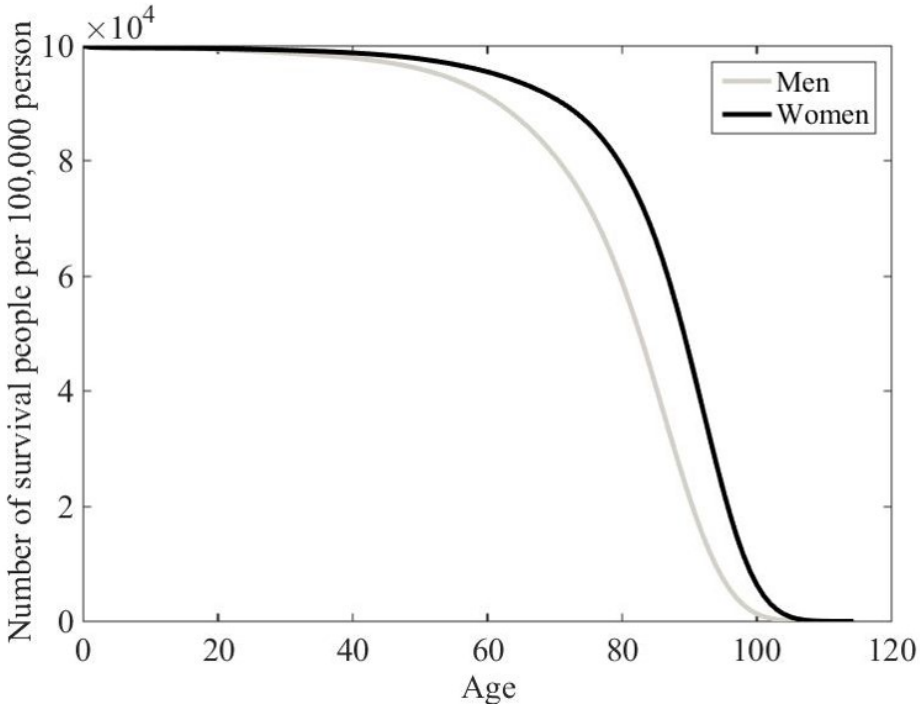

Figure 2. Number of surviving people per 100,000 in Japan in 2010

We used disability weights (DW) of cancer according to stage diagnosis/therapy in the WHO table [16]. We established the DW of all cancer sites shown in Table 1.

Table 1. Disability Weight (DW) of each cancer site

Cancer site	DW
All Solid	0.2
Stomach	0.2
Colon	0.2
Liver	0.2
Lung	0.15
Breast	0.09
Bladder	0.09
Leukemia	0.09
Other Solid	0.09

Calculation results of DALY for cancer at single exposure to 1 Gy

Table 2 illustrates the results of DALY for each cancer site for Japanese after exposure at 1 Gy dose per person. Furthermore, the ratio of DALY for each cancer site per DALY for all cancers and the ratio of YLL per DALY for each cancer are shown in Table 2. Furthermore, in these calculations, we used the classification of cancer sites where they had the ERR or EAR model parameters from the Tables A.4.6 and A.4.7 of ICRP Pub.103. In ICRP Pub.103, leukemia is expressed as marrow. The other solid sites were set by subtracting the sum of each solid cancer site from all solid cancers.

Table 2. Calculation results of DALY for each cancer in the Japanese population exposed at 1 Gy, the attributable fraction (%) of DALY for each cancer site in DALY for all cancers, and those of YLL in DALY for each cancer

Cancer Sites	Men			Women		
	DALY per men	% of total DALY	% of YLL in DALY	DALY per women	% of total DALY	% of YLL in DALY
All Sites	0.84	100%	88%	1.34	100%	85%
All Solid Sites	0.73	87%	87%	1.25	93%	84%
Esophagus	0.004	0.5%	97%	0.01	0.4%	97%
Stomach	0.094	11%	81%	0.16	12%	85%
Colon	0.102	12%	74%	0.056	4.2%	80%
Liver	0.082	9.7%	97%	0.042	3.1%	97%
Lung	0.11	13%	98%	0.22	16%	96%
Breast	-	-	-	0.36	27%	80%
Ovary	-	-	-	0.036	2.7%	96%
Bladder	0.026	3.1%	77%	0.061	4.6%	90%
Thryoid	0.031	3.7%	81%	0.15	12%	56%
Other Solid Sites	0.28	33%	87%	0.15	11%	94%
Leukemia	0.11	13%	98%	0.09	7.1%	98%

DALY for all cancer sites in the Japanese population exposed at 1 Gy was 0.84 per men. In men, lung cancer had the largest proportion at 13% of total DALY, followed by leukemia at 13% and colon cancer at 12%. In women, DALY for all cancer sites in Japan at 1 Gy per women was 1.34. In women, breast cancer had the largest proportion at 27% of total DALY, followed by lung cancer at 16% and stomach cancer at 12%.

Compare calculation results of DALY with detriment

We have also discussed the validity of the calculation of DALY for radiation exposure. The validity of these calculations was demonstrated by the comparison of the calculation results with the ICRP detriment for the same condition. Note that there is a difference of calculations between the ICRP detriment and YLD. The lethality fraction of cancer is used to represent QOL in the calculation of ICRP detriment. On the other hand, YLD are able to consider QOL with DW instead of the lethality fraction of cancer.

Radiation detriment for a tissue D_T is calculated using Eqs.(13) , (14) and (15) .[3]

$$D_T = R_T\big(k_T + q_T(1-k_T)\big)l_T \tag{13}$$

$$q_T = q_{min} + k_T(1-q_{min}) \tag{14}$$

$$R_T = \Big(\int_0^g S(e)\cdot \int_{e+L}^{g} M_i(e,a)\cdot S(a)/S(e)\,da\Big)\Big/\int_0^g S(e) \tag{15}$$

where、R_T is the lifetime risk of excess absolute cancer incidence for a tissue exposed. In this paper, in order to compare between DALY and ICRP detriment, we used R_T which was calculated based on the Japanese baseline incidence data of cancer instead of the nominal risk coefficients that are averaged across seven western and Asian populations. k_T is the lethality fraction for a tissue. These values of k_T are used on the table 3. q_T is a non-fatal weight (between 0 and 1) reflecting the reduced quality of life associated with living with a serious illness, q_{min} is 0.1 without thyroid cancer, q_{min} of thyroid cancer is 0.2[3] and l_T is the average life lost due to the disease relative to normal life expectancy, expressed relative to the average over all cancers. These values of l_T are used on the Table 4. [3] Table5 shows the results of detriment for each cancer site for Japanese exposed at 1 Gy.

Table 3. Calculation results of the lethality fraction for a tissue of cancer mortality per incidence (k_T) in Japan

Cancer site	Men	Women
All Solid sites	42%	43%
Esophagus	54%	57%
Stomach	35%	43%
Colon	32%	40%
Liver	67%	71%
Lung	65%	58%
Breast	-	46%
Ovary	-	48%
Bladder	26%	46%
Thyroid	13%	11%
Leukemia	33%	69%

Table 4. The values of relative life lost l_T from ICRP pub103, Table A4.5[3]

Cancer site	l_T
Esophagus	0.87
Stomach	0.88
Colon	0.97
Liver	0.88
Lung	0.8
Breast	1
Thyroid	1.29
Marrow (Leukemia)	1.63
Other solid sites	1.03

Table 5. The results of ICRP detriment for each cancer site in the Japanese population exposed at 1 Gy and the ratio of the detriment in each cancer site per detriment for all cancers

Cancer site	Men		Women	
	Detriment	% of total Detriment	Detriment	% of total Detriment
All sites	622.6	100%	755.6	100%
All solid sites	428.2	68.8%	594.8	78.7%
Esophagus	13.5	2.2%	10.8	1.4%
Stomach	47.8	7.7%	60.8	8.1%
Colon	60.6	9.7%	28.7	3.8%
Liver	27.4	4.4%	15.9	2.1%
Lung	78.0	12.5%	152.9	20.2%
Breast	-	-	107.9	14.3%
Ovary	-	-	12.7	1.7%
Bladder	26.3	4.2%	35.8	4.7%
Thryoid	5.4	0.9%	22.5	3.0%
Other solid sites	169.3	27.2%	146.8	19.4%
Leukemia	194.4	31.2%	160.7	21.3%

In these calculations, leukemia was the highest of cancer sites in the detriment due to radiation exposure. Figures 3 and 4 show comparisons of the attributable fraction of the DALY and ICRP detriment. The descending order for the detriment was almost same from that of DALY without leukemia, breast and thyroid cancer. In men, leukemia showed the largest proportion at 31.2% of the total detriment, followed by lung cancer at 12.5%, colon cancer at 9.7%, and stomach cancer at 7.7%. The percentage for leukemia in the detriment was higher than in the DALY. In women, the detriment of leukemia had the largest proportion at 21.3% of the total detriment, followed by lung cancer at 20.2% and breast cancer at 14.3%. The percentages of leukemia in the detriment were higher than in DALY. On the other hand, breast and thyroid cancers in the detriment were lower than in DALY.

These results supported the concept that DALY can show similar results as the ICRP detriment without leukemia in men. This could be because of the value of relative life lost (l_T). The leukemia value of l_T is largest value in cancer sites in Table.4. Then, D_T of leukemia is effected by the correction of l_T. In women, these results suggested that the ICRP detriment underestimated the weighting fraction of breast and thyroid cancer risk in total if one compared it with DALY. This may have been because breast and thyroid cancer are non-fatal cancer.

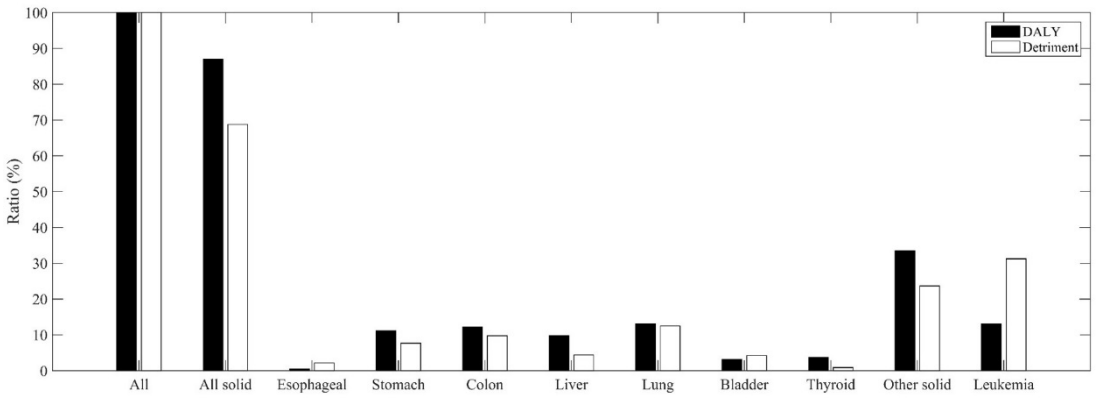

Figure 3. Comparisons of the attributable fraction of DALY and ICRP detriment for men

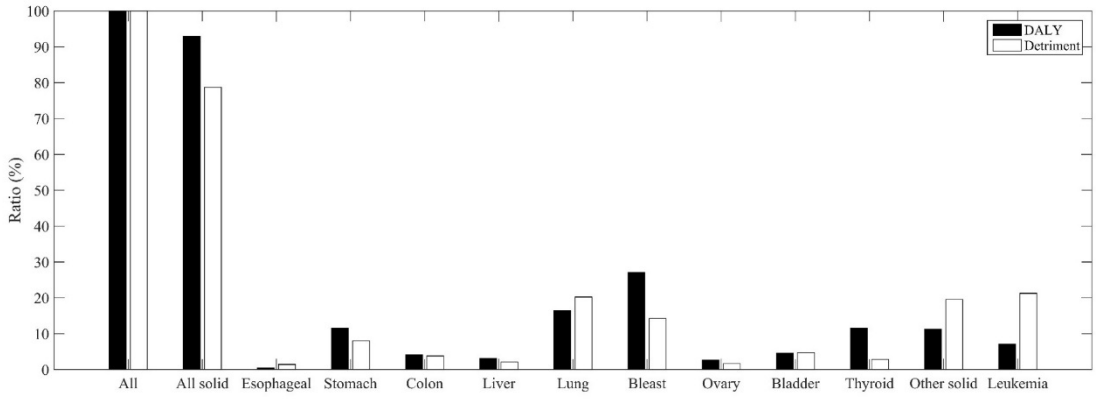

Figure 4. Comparisons of the attributable fraction of DALY and ICRP detriment for women

Fraction of YLL in DALY

We have discussed the fraction of YLL in DALY. In Table.2, the fractions of YLL in DALY of the cancer sites was almost higher than 70%. Only the fraction for thyroid cancer of women was smaller than for other cancer sites. These results reflected the survival fraction exceeding 5 years. Table 6 shows the survival fraction exceeding 5 years of each cancer site in Japan and the mean years of disability calculated using Eq. (11). With higher survival fractions exceeding 5 years of cancer site, there were smaller fractions of YLL in DALY.

Table 6. The survival fraction exceeding 5 years and the mean years of disability for each

cancer site in Japan

Cancer site	Men		Women	
	The survival fraction exceeding 5 years (%)	The mean years of disability (year)	The survival fraction exceeding 5 years (%)	The mean years of disability (year)
All solid sites	55.4	5.9	62.9	7.5
Esophagus	32.3	3.1	41.3	3.9
Stomach	64.2	7.8	61.5	7.1
Colon	72.2	10.6	67.9	9.0
Liver	28.7	2.8	26.2	2.6
Lung	25.0	2.5	41.0	3.9
Breast	-	-	89.1	30.0
Ovary	-	-	55.0	5.8
Bladder	76.5	12.9	64.4	7.9
Thyroid	87.0	24.9	93.7	53.3
Other solid sites	55.4	5.9	62.9	7.5
Leukemia	35.4	3.3	39.8	3.8

A major advantage over the ICRP detriment was that DALY can calculate the risk components for non-fatal diseases. In DALY, the YLD component can be calculated using DW and YD that were defined through public health. Therefore, it is obvious that DALY is a practical tool that can compare many types of diseases encountered in common public health

Effects of DW values on DALY

In Table 1, we used DW values in the stages of diagnosis and treatment. DW values that were established by WHO were 0.75 for the metastatic stage and 0.81 for the terminal stage depending on the stage of cancer. Here, we calculated the DALY of each cancer with varying DW values from 0.3 to 0.7 depending on the cancer stage and the DW values based on human subjects. These results are shown in Figures 5 and 6 with respect to the different DW for both the diagnosis and treatment stages (DW = WHO).

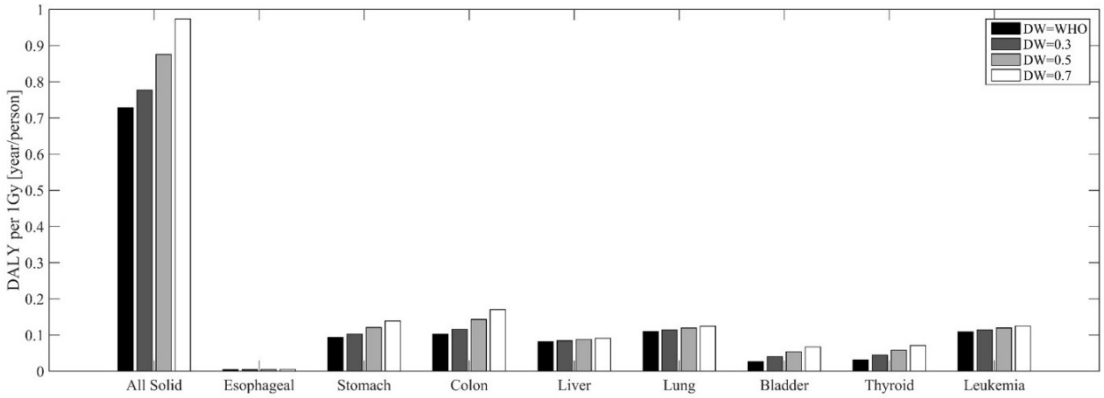

Figure 5. DALY with different DW values (Japanese Men)

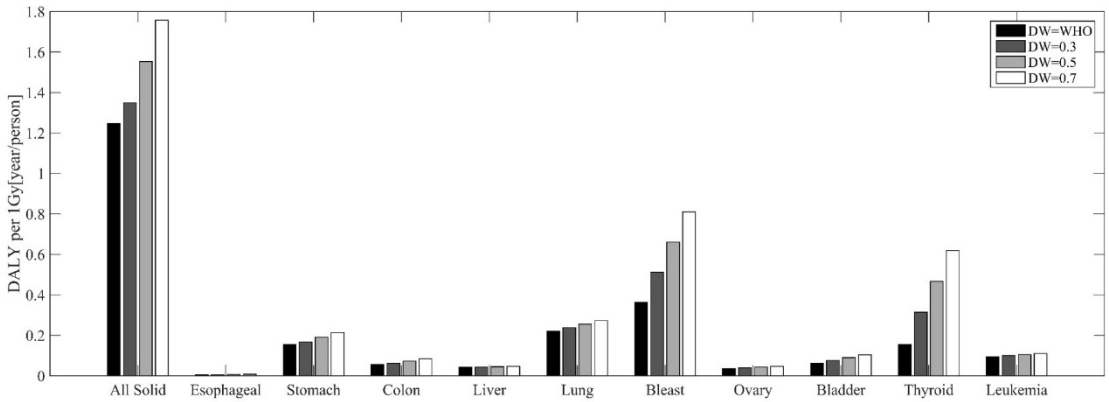

Figure 6. DALY with different DW values (Japanese Women)

In men, the DALYs of colon cancer became larger than those of lung cancer with increasing DW. In women, the DALY of thyroid cancer exceeded that of lung cancer with increasing DW. These results suggested ways to reduce DALY. In men, it was an effective measure to reduce the lung cancer incident rate. In women, exploring a measure to increase QOL could be effective because the YLD of breast and thyroid cancer was higher.

DALY in the case of chronic exposure

The preceding DALY indicated an average among the constituent ages of the population acutely exposed at 1 Gy. Radiation cancer risk was higher at a younger age. Figure 7 shows the dependence of DALY on age-at-exposure at 1 Gy for Japanese population. In Figure 7, the higher DALY at age 47 were attributed to the age population distribution in Japan (Figure 1).

People are always chronically exposed to natural radiation in their lifetimes, and radiation workers are exposed in radiation control area. Table 7 shows the results of DALY of all cancers in the case of a chronic exposure situation.

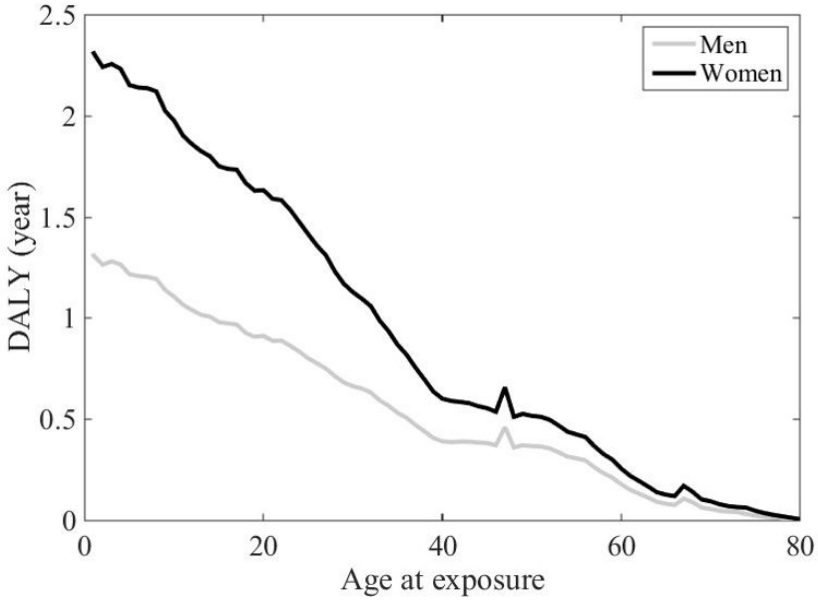

Figure 7. Dependence of DALY on age-at-exposure for Japanese population at an acute exposure to 1 Gy

Table 7. Calculated results of DALY of all cancers in case of chronic exposure situations

Dose	Sex	DALY per person (year)	Colletcive Dose (mGy)	DALY per person per 1Gy (year)
1mGy/year	M	0.07	81	0.81
	F	0.11	87	1.28
5mGy/year (age 18 to 64)	M	0.15	230	0.65
	F	0.29	230	1.27
20mGy/year (age 18 to 64)	M	0.60	920	0.65
	F	1.17	920	1.27

DALY for baseline cancer in Japan

Cancers are caused not only by radiation but also by many factors in a normal lifestyle, for example, smoking, food, and ultraviolet exposure. We then calculated the DALY of cancer incidence and mortality for the Japanese baseline to compare with the radiation cancer risk. We calculated DALY of baseline cancer using Eq. (16) using the cancer incidence baseline λ_i. Table 8 illustrates the results of DALY per person for each cancer site for the Japanese baseline.

$$DALY_{baseline} = \frac{1}{\sum_0^g N(a)} \left(\int_0^g \lambda_i(a) \cdot RC(a) \cdot N(a) \cdot LE(a) da + DW \cdot YD \int_0^g \lambda_i(a) \cdot N(a)\, da \right) \quad (16)$$

Table 8. Calculation results of DALY for each cancer site in the Japanese baseline per person

Cancer Sites	Men			Women		
	DALY per men	% of total DALY	% of YLL in DALY	DALY per women	% of total DALY	% of YLL in DALY
All Sites	4.8	100%	88%	3.5	100%	85%
All Solid Sites	4.3	89%	88%	3.4	97%	84%
Esophagus	0.22	4.6%	98%	0.05	1.3%	97%
Stomach	0.66	14%	81%	0.39	11%	84%
Colon	0.29	6.1%	75%	0.33	9.4%	80%
Liver	0.47	10%	97%	0.25	7.1%	97%
Lung	1.0	20%	98%	0.44	12%	97%
Breast	-	-	-	0.40	11%	78%
Ovary	-	-	-	0.14	4.1%	96%
Bladder	0.07	1.5%	80%	0.04	1.2%	91%
Thryoid	0.05	0.9%	83%	0.07	2.1%	59%
Other Solid Sites	1.5	32%	86%	1.3	37%	85%
Leukemia	0.50	11%	98%	0.10	2.7%	98%

DALY for all cancers in the Japanese baseline was 4.8 in men and 3.5 in women. Comparing the DALY of cancer between chronic lifetime exposure cases with 1mGy/year and all cancers in the Japanese baseline, the ratios of DALY were 1.5% in men and 3.1% in women.

These results may not apply to non-Japanese people. DALY differed from cancer incidence, mortality baseline, and the survival fraction exceeding 5 years as well as the disability weight and the mean years of disability. These results would depend on the Japanese genetic background and lifestyle and health care standards. However, these results may be useful if one considers an alternative measure of radiation risk to the ICRP detriment.

Conclusion

We calculated the DALY of radiation cancer risk as a measure of risk. DALY can be a practical tool that can compare many types of diseases encountered in common public health, although DALY for cancer sites was similar to the radiation detriment without leukemia. Moreover, the calculated results of DALY can provide information to identify the components that should be reduced in terms of public health. DALY may be a promising risk measure for effective radiation protection.

Acknowledgement

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Appendix. A

We find in terms of the 5-years relative survival fraction (*SF*) the value of the mean years of disability (*YD*). For this calculation, we assumed that relative survival rates R depend on time since diagnosis *t* as in Eq. (A-1)[10]

$$R(t) = exp[-t \cdot h] \tag{A-1}$$

Here, *R* (t) is relative survivals rates for each cancer sites, *h* is mortality rates (death/year) and *t* is time since diagnosis (year).

For these calculations, we use *SF* given in Table.6 and assumed that cancer mortality rate *h* depend on age at diagnosis and are equal to

$$h = -0.2 \times \log SF \tag{A-2}$$

Here, $\log SF$ is 5 years relative mortality rates, 0.2 is revised coefficient of transformation of $\log SF$ to 1 year relative mortality rate.

Here, to calculate *YD*, substitute *R* for 0.5 in Eq (A-1).

$$0.5 = exp[-YD \cdot h] \tag{A-3}$$

Solve equation for *YD*

$$YD = -\frac{\log(0.5)}{h} \tag{A-4}$$

Substitute *h* for Eq. (A-2) in Eq. (A-4) and express by the sign *SF*

$$YD = -\frac{log2}{(0.2 \times \log SF)}$$