**Supplement**

The International Commission on Radiological Protection (ICRP) defined that cancer detriment can be calculated as:

(1)

where is the nominal lifetime risk, is the lethality fraction, is the quality of life and is the relative life lost (values for , and can be found in Table S.1). We can therefore evaluate each parameter in the equation and to find out the effects of these parameters on cancer detriment.

**Nominal Lifetime Risk Calculation**

Nominal lifetime risk from a specific cancer can be calculated by three slightly different methods (Thomas et al., 1991). They are called risk of exposure induced cancer incidence (REIC), excess lifetime risk (ELR) and lifetime attributable risk (LAR) which is an approximation to REIC. All methods have been used by different organisations and individual authors, for examples, REIC, ELR and LAR have been used by UNSCEAR, BEIR Committees (National Research Council 1988, 1990) respectively in their previous publications. The mathematical formulas of the three methods can be expressed as:

(2)

(3)

(4)

where, (a) is the incidence rate from cause *c* at age a, is the incidence rate from cause *c* at age *a*, when receiving dose *d* (Sv) at age *e*. *e*=age-at-exposure (years), *L*=latency period (years), and *att* is the attained age.

For a population with a mixture of ages, the quantities calculated above can also be averaged over a population by taking a weighted average of the effect calculated for each age. For example,

(5)

where is age-sex specific population size in each corresponding age group, and  are the age lower and upper limit in the population. The same methodology can be applied to calculate LAR and ELR.

A comparison of three different types of lifetime risk calculation is illustrated in Figure S1, showing that at low doses below about 0.4 Sv, the LAR and REIC agree well. The LAR increases linearly with dose, but REIC and ELR become smaller than LAR as dose increases. In ICRP Publication 103 (ICRP 2007), the lifetime risk was calculated as REIC at 0.1 Sv and multiplied by 10. This is equivalent to LAR at 1 Sv since the difference between REIC and LAR at 0.1 Sv is negligible as shown in Figure S1 and the LAR is linear in relation to radiation dose for solid cancer.

The lifetime risk calculations use the survival function without radiation exposure: S(a) and with radiation exposure *d* at a given age e: *S(a|e,d)*. They can be calculated using the Kaplan-Meier method:

(6)

(7)

The difference between these survival functions is illustrated in Figure S.2. The above survival functions are modelled based on all-cause mortality rate , and µ which is the all-cause mortality rate plus incidence rate from cancers at age *a*, when receiving dose *d* (Sv) at age *e*. µcan be calculated as:

(8)

or

(9)

where is the all cancer incidence rate at age *a*, and are the excess relative risk and excess absolute risk for all cancers, although the contribution from radiation induced cancers would be negligibly small if the calculations were performed at low dose level, and REIC can be approximated by LAR. However, there might be people living with cancers which were caused by non-radiation risk factors; these patients may undergo medical treatments such as radiotherapy and no longer represent a general population for the risk assessment purpose, and therefore should be removed from the survival curves. For a complete cancer-free survival curve which takes out both mortality and extra cancer incidence from the population, should be replaced by {, where is the all-cancer death rate. Figure S.3 illustrates the survival curve S(a) with and without adjustment of cancer incidence.

For solid cancer except breast cancer, and are modelled using data from Japanese atomic bomb survivors:

(10)

(11)

where *e* is age-at-exposure and *a* is age-at-risk; are model coefficients which are listed in Tables S2 and S3.

For breast cancer, the model is based on the pooled analysis by Preston et al (2002):

(12)

(13)

Demographic data, such as all causes mortality rate, all cancer mortality rate, all cancer incidence rate and specific cancer incidence rate from ICRP are used for the calculation (ICRP Publication 103, Tables A.4.10–A.4.17).

**Lethality Fraction and Quality of Life Factor**

In Equation (1), is the lethality fraction and is defined by:

(14)

where is 0 for skin, 0.2 for thyroid and 0.1 for all other sites. The values have changed somewhat over the years. In this analysis, we have set all to zero and =1, and examined the effect of these changes on detriment.

**Relative Years of Life Lost**

The loss of life expectancy due to a particular cancer *c* () is defined as the difference between the expectation of life for an individual exposed at age *e* and that of an unexposed individual, assuming that the latency for cancer *c* is *L* and individual in both cases has survived up to age *a*:

= (15)

where S(a|e) and *S(a|e,d)* are survival functions without radiation exposure and with radiation exposure *d* at a given age *e*. The *S(a|e,d)* takes account of radiation induced cancer incidence for this particular cancer *c*. Years of life lost among exposure-induced can be calculated as,

(16)

For a mixed age population, the weighted average of years of life lost can also be calculated. The relative life lost used in the equation is the ratio of the above quantity for a specific cancer over that of all cancer combined. In ICRP Publication 103, the average number of years of life lost for all cancers was equal to 15 years, as was the case in Publication 60 (ICRP 1991). Factor reflects the relative cancer free life lost varying from less than 1 for cancers occurring late in life (0.71 for bladder cancer or 0.80 for lung cancer) to more than 1 for cancers occurring early in life (1.29 for thyroid or breast cancer). In the sensitivity analysis, we assumed a simplified scenario and set all =1, i.e., the years of life lost for every type of cancer are the same as that for all cancers. The effect of the change on detriment can be examined accordingly.

Table S1. Values of parameters for the lethality fraction, minimum quality of life, quality of life and relative cancer-free life lost as used in ICRP Publication 103.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| site | ICRP lethality (k) |  | ICRP quality of life (q) | Relative cancer-free life lost (l) |
| Oesophagus | 0.93 | 0.1 | 0.937 | 0.87 |
| Stomach | 0.83 | 0.1 | 0.847 | 0.88 |
| Colon | 0.48 | 0.1 | 0.532 | 0.97 |
| Liver | 0.95 | 0.1 | 0.955 | 0.88 |
| Lung | 0.89 | 0.1 | 0.901 | 0.80 |
| Bone | 0.45 | 0.1 | 0.505 | 1.00 |
| Skin | 0.002 | 0.1 | 0.002 | 1.00 |
| Breast | 0.29 | 0.1 | 0.361 | 1.29 |
| Ovary | 0.57 | 0.1 | 0.613 | 1.12 |
| Bladder | 0.29 | 0.1 | 0.361 | 0.71 |
| Thyroid | 0.07 | 0.2 | 0.256 | 1.29 |
| Bone Marrow | 0.67 | 0.1 | 0.703 | 1.63 |
| Other Solid | 0.49 | 0.1 | 0.541 | 1.03 |
| Gonads | 0.80 | 0.1 | 0.820 | 1.32 |

Table S2. Excess Relative Risk (ERR) model coefficients.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Site | sex | (ERR per Gy at age 70 for exposure at age 30) | (coefficient for age-at-exposure)# | (coefficient for age-at-risk) |
| All solid | M  F | 0.35  0.58 | –0.18 | –1.65 |
| Oesophagus | M  F | 0.40  0.65 | –0.18 | –1.65 |
| Stomach | M  F | 0.23  0.38 | –0.18 | –1.65 |
| Colon | M  F | 0.68  0.33 | –0.18 | –1.65 |
| Liver | M  F | 0.25  0.40 | –0.18 | –1.65 |
| Lung | M  F | 0.29  1.36 | 0.157 | –1.65 |
| Ovary | F | 0.32 | –0.18 | –1.65 |
| Bladder | M  F | 0.67  1.10 | –0.18 | –1.65 |
| Thyroid | M  F | 0.53  1.05 | –0.82 | 0.00 |
| Other | M  F | 0.22  0.17 | –0.42 | –1.65 |

# The values in this column are derived from the 4th column of Table A.4.6 in ICRP Publication 103 (age at exposure: % change in ERR per decade increase)

No ERR model was provided for breast cancer.

Table S3. Excess Absolute Risk (EAR) model coefficients.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Site | sex | (Excess deaths per 10000 persons per year per Gy at age 70 for exposure at age 30) | (coefficient for age-at-exposure)# | (coefficient for age-at-risk) |
| All solid | M  F | 43.20  59.83 | –0.27 | 2.38 |
| Oesophagus | M  F | 0.48  0.66 | 0.49 | 2.38 |
| Stomach | M  F | 6.63  9.18 | –0.27 | 2.38 |
| Colon | M  F | 5.76  2.40 | –0.27 | 2.38 |
| Liver | M  F | 4.18  1.30 | –0.27 | 2.38 |
| Lung | M  F | 6.47  8.97 | 0.01 | 4.25 |
| Ovary | F | 1.47 | –0.27 | 2.38 |
| Bladder | M  F | 2.00  2.77 | –0.116 | 6.39 |
| Breast | F | 10 | –0.49 | 3.5 (a ≤50)  1.0 (a >50) |
| Other | M  F | 7.55  10.45 | –0.27 | 2.38 |

# The values in this column are derived from the 4th column of Table A.4.7 in ICRP Publication 103 (Age at exposure: % change in EAR per decade increase).

No EAR model was provided for thyroid cancer.

Figure S1. Comparison of three types of lifetime risk calculation for all solid cancers combined.

Figure S2. Survival curves for S(a) and S(a|e,d=1Sv), calculated for solid cancers of Euro-American male.

Figure S3. Survival curves S(a), with and without adjustment of cancer incidence, calculated for solid cancers of Euro-American male.