Review of health effects models for Level 3 PSA

Seunghee Lee[a*], Juyoul Kim [a], Seokjung Han [b]
[a] *FNC Technology Co., Ltd., 32F, 13,Heungdeok 1-ro, Giheung-gu, Yongin, Korea*
[b]*Korea Atomic Energy Research Institute, 150, Dukjin-dong, Yuseong-Gu, Daejeon, Korea, 305-353*
[*]*Corresponding author: seunghee0505@fnctech.com*

1. Introduction

As a part of Level 3 Probabilistic Safety Assessment (PSA), health effects estimations have been performed with MELCOR Accident Consequence Code System (MACCS) in Korea. However, as the health risk model in MACCS was developed based on specific data of Unite States, there are lots of limitations to apply it. So, there has been a demand for improving the health risk model.

For several decades, many international organizations have developed health risk models. Especially, as radiation-induced cancer is an important part among health effects, development has been focused on cancer risk model. This paper reviewed the cancer risk models of international agencies; United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), National Academy of Sciences (NAS) and International Commission on Radiological Protection (ICRP). Moreover, as pre-research for improving the health risk model in Korea, this paper analyzed the three methodologies and specific details in modeling.

2. Methods and Results

2.1 Mathematical risk model

Cancer risk model have been developed by using the epidemiological information. There are two types in epidemiological model: Excess Relative Risk (ERR) model and Excess Absolute Risk (EAR) model. As multiplicative model, ERR assumes that radiation-induced cancer risk is proportional to the baseline rate (natural cancer rate), whereas EAR model, as additive model, represents a constant increase of cancer risk from radiation exposure regardless of baseline rate.

ERR and EAR model have forms as below.

$$\lambda_e = \lambda_u(1 + \mathrm{ERR}) = \lambda_u + \lambda_u \cdot \mathrm{ERR}$$

or

$$\lambda_e = \lambda_u + \mathrm{EAR}$$

λ_i is the cancer mortality or incidence rate after radiation exposure. λ_u is the baseline cancer mortality or incidence rate without radiation. In case of ERR model, the excess risk from radiation exposure is a multiplication of ERR and baseline rate.

The ERR and EAR models are defined with dose-response model f(d) and modification function $g(a, e, s)$, where $g(a, e, s)$ is exponential function of attained age, exposure age and gender. f(d) and $g(a, e, s)$ are determined based on epidemiological data like Japanese atomic bomb survivors lifespan study (LSS). Lifetime risk estimation can be calculated by integrating the value of ERR or EAR for lifetime. The lifetime risk is expressed as a function of the exposure age and gender of exposed person.

2.2 UNSCEAR model

UNSCEAR developed cancer mortality and incidence risk model for leukemia and solid cancer. Especially, the cancer incidence risk model of solid cancer varied with organs; esophagus, stomach, colon, liver, lung, bone, skin, female breast, urinary bladder, brain and central nervous system, thyroid and the rest organs. The risk models were fundamentally based on A-bomb survivor cancer mortality data for the period of 1950-2000 and A-bomb survivor cancer incidence data for 1958-1998. The dose-response models for leukemia and all solid cancer mortality were linear-quadratic function and for solid cancer incidence were linear function except bone cancer (linear-quadratic) and non-melanoma skin cancer (quadratic-exponential). Generally, when the dose-response model is assumed as linear function, Dose and Dose Rate Effectiveness Factor (DDREF) is applied for adjusting its overestimates at low dose. UNSCEAR model determined the value of DDREF as 1, and it was used to modify the risk at low dose. The ERR and EAR models are as follow [1].

For leukemia mortality and incidence,

$$ERR = (\alpha D + \beta D^2) \cdot exp[\kappa_1 \cdot ln(a)]$$
$$EAR = (\alpha D + \beta D^2) \cdot exp[\kappa_1 \cdot 1_{g=female} + \kappa_2 \cdot ln(a - e)]$$

For solid cancer mortality,

$$ERR = (\alpha D + \beta D^2) \cdot exp[\kappa_1 \cdot 1_{g=female} + \kappa_2 \cdot ln(a - e) + \kappa_3 \cdot ln(a)]$$
$$EAR = (\alpha D + \beta D^2) \cdot exp[\kappa_1 \cdot ln(a - e) + \kappa_2 \cdot ln(a)]$$

For solid cancer incidence,

$$ERR\ or\ EAR = (\alpha D) \cdot exp[\kappa_1 \cdot 1_{g=female} + \kappa_2 \cdot ln(a - e) + \kappa_3 \cdot ln(a) + \kappa_4 \cdot ln(e)]$$

where D is dose [Sv], a is attained age, e is exposure age. The parameters, α, β, κ, are defined for each organs in solid cancer incidence model. The lifetime cancer risk estimate used 100% ERR model and 100% EAR model. The measure of lifetime risk was the Excess Cancer Death (ECD), Risk of Exposure-Induced Death (REID), Year of Life Lost (YLL) and Year of Life Loss per Radiation-Induced Cancer (YLLRIC)

2.3 NAS model (BEIR VII)

NAS presented radiation-induced cancer risk model though Biological Effects of Ionizing Radiation VII (BEIR VII) report in 2006. BEIR VII model modified BEIR V model and was based on A-bomb survivor mortality data for the period 1950-2000 and A-bomb survivor cancer incidence data for the period 1958-1998. The modeling was performed for leukemia and solid. As there was little information of the mortality data, the BEIR VII model firstly developed cancer incidence risk model, and then induced cancer mortality risk model by modifying the incidence model. The cancer incidence risk models are as below.

For leukemia,

$$ERR\ or\ EAR = \beta_s \mathrm{D}(1+\theta \mathrm{D}) \cdot exp[\gamma e^* + \delta \log\left(\frac{t}{25}\right) + \phi e^* log\left(\frac{\mathrm{t}}{25}\right)]$$

Where s is gender, t is the period after exposure, e^* is adjusted exposure age $e^* = \begin{cases} \frac{e-30}{10}, & e < 30 \\ 0, & e \geq 30 \end{cases}$. The leukemia model assumed linear-quadratic dose response model. When the lifetime risk of leukemia was calculated, 70% ERR + 30% EAR was applied.

For solid cancer, modeled organs were stomach, colon, liver, lung, breast, prostate, uterus, ovary, bladder, thyroid and other organs. Female breast and thyroid risk model were developed separately. As the solid cancer models assumed linear dose-response model, DDREF was applied as 1.5.

Solid cancer : 70% ERR + 30% EAR
(lung model - 30% ERR + 30% EAR)

$$\mathrm{ERR\ or\ EAR} = \beta_s D \cdot \exp(re^*) \cdot \frac{a}{60}^{\eta}$$

Female breast : 100% EAR

$$\mathrm{EAR} = 9.9\mathrm{D} \cdot \exp[-0.05(\mathrm{e}-25)] \cdot \frac{a}{50}^{\eta}$$

Thyroid : 100% ERR

$$\mathrm{ERR} = \begin{cases} 0.53D \cdot \exp[-0.083(e-30)], & for\ males \\ 1.05D \cdot \exp[-0.083(e-30)], & for\ females \end{cases}$$

where the unit of D in female breast and thyroid model is Gy not Sv.

In cancer mortality risk model, ERR model is same with cancer incidence risk model. However, EAR model is induced by multiplying EAR of incidence risk model by λ_m/λ_i, where λ_m is cancer mortality rate, λ_i is cancer incidence rate of evaluation group. For calculating lifetime risk, BEIR VII used Lifetime Attributable Risk (LAR) and drew the lifetime risk function of exposure age and gender [2].

2.4 ICRP model

ICRP developed cancer incidence risk models for leukemia and solid cancer in ICRP publication 103. In advance, ICRP had developed cancer mortality risk models in ICRP publication 60. The cancer incidence risk models of ICRP publication 103 are as below.

For leukemia model,

$$EAR = (\alpha D + \beta D^2) \cdot exp[\kappa_1 \cdot ln(a-25)]$$

where A-bomb survivor data for 1950-1987 was used and the dose-response model was assumed linear-quadratic function. As leukemia incidence model use only 100% EAR model, there is no ERR model.

For solid cancer model,

$$ERR\ or\ EAR = (1+tg)\kappa_d D \cdot exp[-g_e(e-30) + g_a\, ln\left(\frac{a}{70}\right)]$$

The source data was from A-bomb survivor from 1958 to 1998. Even though the equation was same, the parameters were different for ERR and EAR model. The modeled organs were esophagus, stomach, colon, liver, lung, breast, ovary, bladder, thyroid and other organs. The solid cancer risk model used a linear dose response, decreasing risk at low dose to half of that (DDREF=2). For LAR calculation to estimate lifetime risk, the risk model was applied as 100 % ERR model for thyroid cancer, 100% EAR model for breast cancer, 30% ERR + 70% EAR model for lung cancer and 50% ERR + 50% EAR model for the rest cancer [3].

2.4 Comparison and summary

The radiation-induced cancer risk models of UNSCEAR, ICRP and NAS (BEIR VII) were summarized in Table I. All models of three organizations were based on ERR and EAR model which were composed of a multiplication of dose-response model and modification function. As epidemiological models, they were developed basically based on A-bomb survivor data of Japan. However, as the main data and its projection methods were slightly

different among these models, the mathematical models were also different.

Table I: Problem Description

	UNSCEAR (2006)	NAS BEIR VII (2006)	ICRP Publication 103 (2007)
Risk model	Cancer Incidence, Cancer Mortality	Cancer Incidence, Cancer Mortality	Cancer Incidence*
Organ	Leukemia, Solid cancer**	Leukemia, Solid cancer **	Leukemia, Solid cancer **
Dose-response model	Leukemia : linear-quadratic Solid cancer : linear-quadratic (mortality), linear (incidence***)	Leukemia : linear-quadratic Solid cancer : linear	Leukemia : linear-quadratic Solid cancer : linear
DDREF	1	1.5	2

* The cancer mortality models were already developed in ICRP Publication 60
** The solid cancer models vary with organs.
*** except for bone cancer(linear-quadratic) and non-melanoma skin cancer(quadratic-exponential)

3. Conclusions

International agencies have developed radiation-induced cancer risk model reflecting the recent A-bomb survivor LSS data. This paper reviewed the recent cancer risk model of UNSCEAR, NAS and ICRP. All three models were based on ERR and EAR model in the form of a multiplication of dose-response model and modification function. Lifetime risk was calculated as a function of exposure age and gender.

In future, cancer risk models of other organizations like U.S.NRC, U.S.EPA and European Commission (EC) will be analyzed, and the results will be used as preliminary data to improve the health risk model in Korea.

ACKNOWLEDGMENTS

This work was supported by the Nuclear Research & Development Program of the National Research Foundation grant funded by the Ministry of Science, ICT and Future Planning, Republic of Korea.

REFERENCES

[1] UNSCEAR, Effect of Ionizing Radiation UNSCEAR 2006 Report, Volume 1 with Scientific Annex A, 2008.
[2] National Research Council of the National Academies, Health Risks from Exposure to Low Levels of Ionizing Radiation: BEIR VII-Phase 2, 2006.
[3] ICRP, The 2007 Recommendations of the International Commission on Radiological Protection, ICRP Publication 103, Ann. ICRP 37, 2-4, 2007.