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ARTICLE

Radiological Risk Assessment for Therapeutic Use of ^{131}I Based on 2D Monte Carlo Analysis

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In recent years, use of ^{131}I in therapeutic nuclear medicine has been increased rapidly due to the increased detection rate of thyroid cancers. The associated radiological risks of workers and other individuals are affected by several uncertain variables such as radioactivity used, distance, time and frequency of exposure situations and the probabilistic risk assessment (PRA) is often used in the risk assessments. The two-dimensional Monte Carlo Analysis (2D MCA), which is one of the advanced approaches for PRA, is applied to assess risk associated with the therapeutic uses of ^{131}I in Korea. Exposures to workers during inpatient care and to members of the public, specifically family members, after release of patients were considered in both normal and accidental situations. In order to identify important variables to the risks, sensitivity analyses were performed as well.

KEYWORDS: ^{131}I, probabilistic risk assessments, variability and uncertainty, 2D MCA, sensitivity analysis

I. Introduction

In Korea, the most common therapeutic nuclear medicine is the treatment of thyroid cancers using ^{131}I. In recent years, the number of patients treated with this procedure has increased approximately 30%.[1)] On the other side of attractive utility in curing thyroid diseases, radioiodine, specifically ^{131}I, carry unfavorable characteristics in the radiological protection view point: it is volatile and very soluble, it emits several gamma rays per disintegration and its half-life is relatively long compared to other radiopharmaceuticals. Therefore it causes exposures of other persons, hospital staff during inpatient and members of the public when released from the hospital, both externally and internally for an extended period of time. The International Commission on Radiological Protection (ICRP) recommendded that the decision to hospitalize or release a patient should be determined on an individual basis.[2)] Practices regarding the release of patients after therapy with unsealed radionuclide vary from country to country. These situations call for studies on risk assessments for therapeutic uses of radioiodine.

Since late 1980s, calls for increased consideration of variability and uncertainty in risk assessments, combined with advances in computational speed and capability, motivated a greater shift toward the use of probabilistic risk assessment (PRA).[4)] PRA provides quantitative estimates of risk with their uncertainty.

In this paper, assessment of risks associated with therapeutic uses of ^{131}I based on circumstance in Korea was performed using two-dimensional Monte Carlo Analysis (2D MCA). The 2D MCA is one of the advanced methods for PRA by considering stochastic variability and uncertainty resulting from lack of knowledge. By considering the whole tasks involved (receipt, administration, inpatient care, disposal and release patient), the risks were estimated for the worker during inpatient care and a family member after release of patients in both normal and accidental situations.

II. Materials and Method

1. Framework for Risk Assessment

The overall framework for the risk evaluation, including risk definition, exposure model and scenario used in this study is based on the U.S. Nuclear Regulatory Commission (USNRC).[5)] The risk is defined as the sum of the products of the frequency and consequence pairs over the possible states.

$$Risk = \sum (Frequency_i \times Consequences_i) \qquad (1)$$

where the summation is over all possible states *i.* The state of system is description of its physical condition and its environment. The frequency of each sequence is the frequency of the initiating event times the probability of the safety function states for the sequences such as access control, confinement and shielding. The brief flow chart for risk assessment is shown in **Fig. 1.**

2. Exposure Pathways and Scenarios

The exposure models and scenarios used in this study largely follow those of USNRC[5)]. In normal situations, according to the expert consultation, typically one of the health care staff enters the therapy ward one time during the patient's stay. He or she may stay around 0.2h at around 1m from the patient. The dominant exposure pathway is external irradiation because the room air is well ventilated and cautions are paid to avoid contamination during the visit. Two models of staff behavior were applied.

There are however chances of accidental exposure. This could occur if the patient nauseated and vomit. Referring to experiences in domestic hospitals, it is estimated that 1

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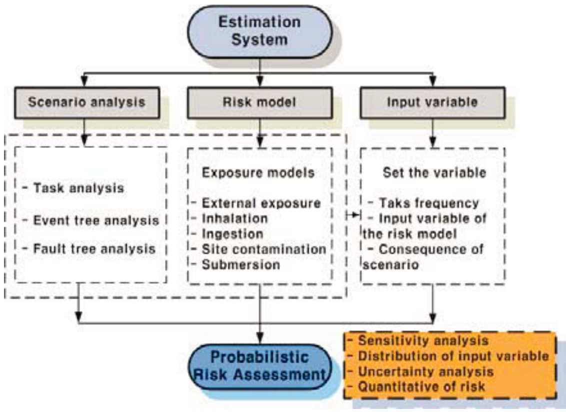


Fig. 1 The flow chart for risk assessment.

percent of patients cause this event.

Upon this event, multiple exposure pathways including external exposure, submersion exposure and internal exposure from inhalation and ingestion could involve. A major contamination and a minor one were considered.

For exposure of the members of the public after release of the patients, only risks to family members are considered. We assumed a patient after normal release stays close to a family member from 1 m for 3 hours a day for 20 days in normal situation.

As an accidental case, the patient is inadvertently released from hospital and then stays with a family member at 1m for 9 hours. Another case involves contamination due to spill of urine or vomit with low probability.

3. Evaluation of Input Parameters

The term "parameter" is used to reflect two concepts.[6,7] The first refers to the variability which is constant characterizing the probability density function (PDF) of a variable. The second refers to uncertainty which is a lack of knowledge about the PDFs. For example, if the random variable X is known to be normally distributed with mean μ and standard deviation σ, the characterizing constants μ and σ are called parameters which are subject to uncertainties. Variability is usually not reducible by further measurements, while uncertainty from other sources may be reduced by further measurements. Therefore, differentiating between variability and other types of uncertainty in risk assessment helps decision-makers to focus on appropriate uncertainty reduction measures.[8,9] The characteristics of input parameters applied in this study are shown in **Table 1** only for occupational exposures in normal situations.

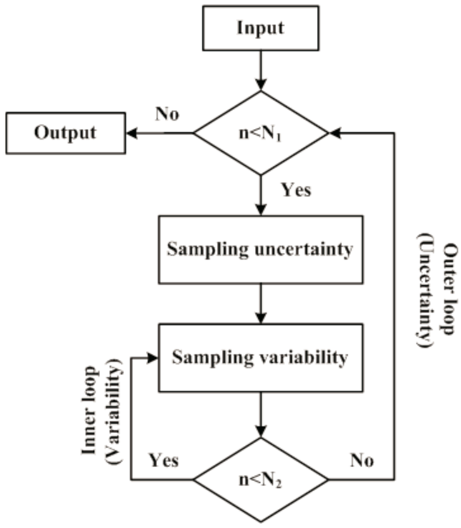


Fig. 2 Illustration of 2D Monte Carlo simulation process.

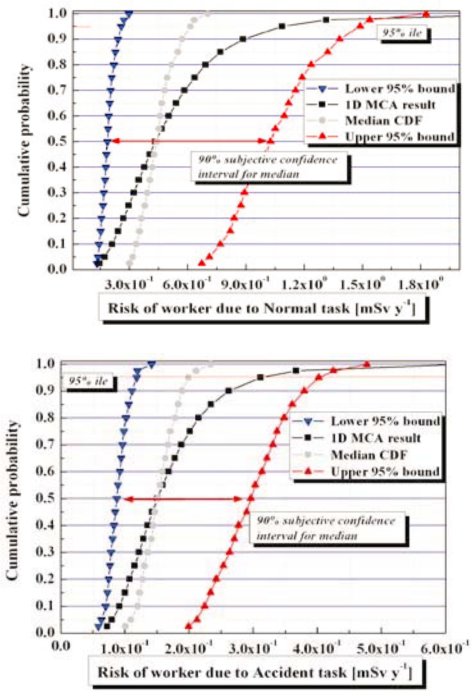
4. Two-dimensional Monte Carlo analysis

The 2D MCA is used with an uncertainty analysis that requires variability to be distinguished from other types of uncertainty.[10] The PDFs used to describe the variability in a variable has some certain degree of uncertainties. For example, variability in the frequency of treatments can be presented by a lognormal distribution but the parameters of this distribution, the mean and the standard deviation, are inferred to have triangle and uniform PDFs, respectively. The 2D MCA is performed using the PDFs of V-type (variability) and U-type (uncertainty). The flow chart for the 2D MCA process is presented in **Fig. 2**. A total of 250 cumulative distribution functions (CDFs) were generated using the software packages Crystal Ball.

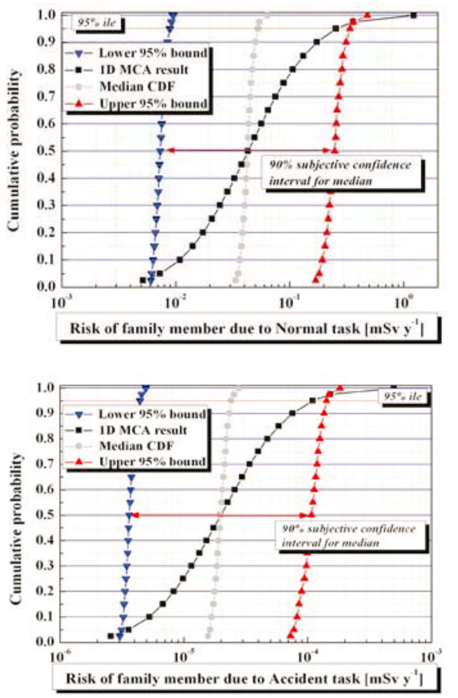
The number of runs was 100,000 for the inner loop and 250 for the outer loop. The resulting risks are expressed in terms of annual radiation doses.

Table 1 Variability and uncertainty of parameters for worker exposure model in normal situations

Parameter		Frequency [y^{-1}]		Time [h]		Distance [m]		Activity[GBq]	
		Mean	STDEV	Mean	STDEV	Mean	STDEV	Mean	STDEV
Variability	PDF	Lognormal		Lognormal		Lognormal		Lognormal	
(V-type)		115.3	6.1	0.2	0.02	1.0	0.25	6.78	0.89
	PDF	Triangle	Uniform	Triangle	Uniform	Triangle	Uniform	Triangle	Uniform
Uncertainty	Min	103.78	5.5	0.18	0.018	0.9	0.225	6.1	0.8
(U-type)	Mode	115.31	-	0.2	-	1	-	6.78	-
	Max	126.84	6.73	0.22	0.022	1.1	0.275	7.46	0.98

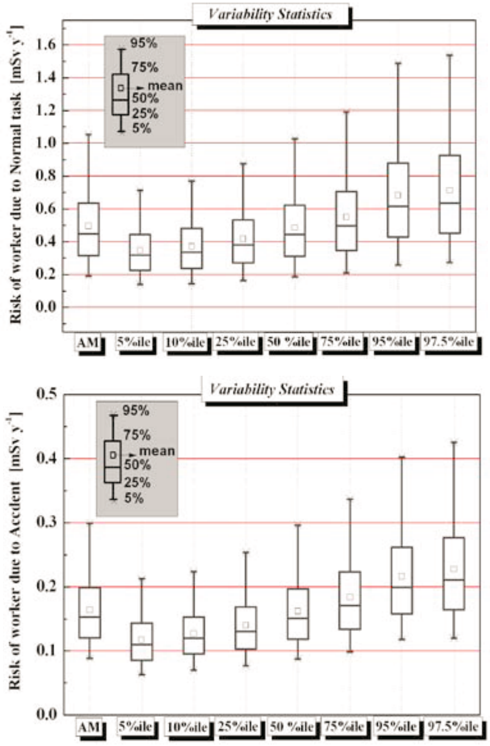


(a) Worker

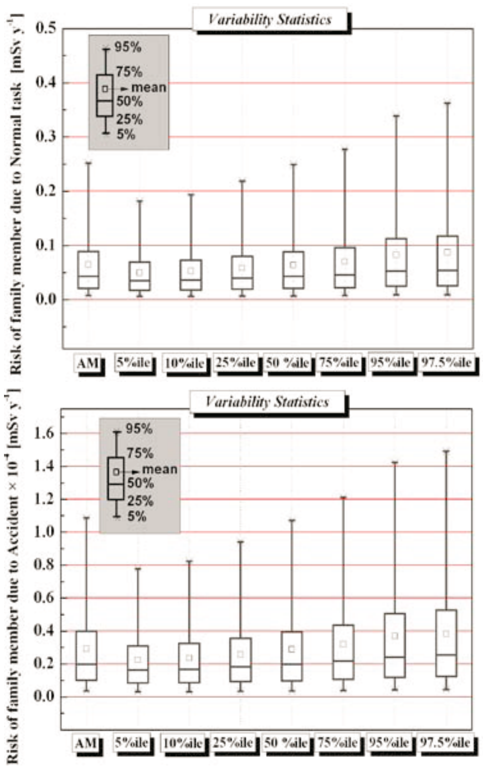


(b) Family member

Fig. 3 90% confidence interval of radiological risk in normal and accidental situations. (a) worker, (b) family member.



(a) Worker



(b) Family member

Fig. 4 Statistical summary for variability of radiological risk in normal and accident situations. (a) worker, (b) family member. The presented are 90% confidence intervals for arithmetic mean (AM) and selected percentiles of the risk distribution.

III. Results and Discussion

Figure 3 shows the 90% confidence interval for the median of annual doses resulting from the 2D MCA, where the results of 1D MCA are shown for comparison. While the 1D MCA provides a single distribution of estimated risk, the 2D MCA yields a series of distributions, from which credible

Table 2 Summary of the radiological risk from 2D MCA and 1D MCA for normal and accident situations

2D MCA	Distribution of expected dose [mSv y^{-1}]				
Percentile	Receptor	5%	Mean	Median	95%
		Normal situations			
2.5th	Worker	1.34E-01	3.41E-01	3.03E-01	6.74E-01
	Family	6.07E-03	5.51E-02	3.37E-02	1.70E-01
50th	Worker	1.87E-01	5.02E-01	4.42E-01	1.03E+00
	Family	7.33E-03	7.58E-02	4.30E-02	2.49E-01
97.5th	Worker	2.73E-01	7.39E-01	6.35E-01	1.54E+00
	Family	9.20E-03	1.06E-01	5.44E-02	3.63E-01
1D MCA	Worker	1.73E-01	5.09E-01	4.35E-01	1.09E+00
	Family	7.36E-03	7.78E-02	4.33E-02	2.56E-01
		Accident situations			
2.5th	Worker	5.88E-02	1.11E-01	1.05E-01	1.99E-01
	Family	3.03E-06	2.42E-05	1.57E-05	7.29E-05
50th	Worker	8.72-02	1.66E-01	1.51E-01	2.96E-01
	Family	3.62E-06	3.36E-05	1.98E-05	1.07E-04
97.5th	Worker	1.20E-01	2.34E-01	2.11E-01	4.25E-01
	Family	4.56E-06	4.55E-05	2.55E-05	1.49E-04
1D MCA	Worker	7.99E-02	1.68E-01	1.51E-01	3.12E-01
	Family	3.60E-06	3.42E-05	1.99E-05	1.10E-04

intervals can be calculated for each percentile of the CDF.

Table 2 summaries the radiological risks assessed by 2D MCA and again compares with those from 1D MCA. For 2D MCA results, characteristic values for the distributions are given for the lower(2.5th), median(50th) and the higher(97.5th) estimates. Here the advantage of 2D MCA is identified: the 1D MCA only gives that, for example, the median dose to workers is 0.435 mSv/y for normal situations while the 2D MCA provides further information saying that the 90% confidence interval of median dose is (0.187, 1.03) mSv/y.

In Table 2, it is noted that the risks of accident are lower than those of normal situations, particularly for the family member. This does not mean the doses are low in case of an accident happens but means the doses weighted by the probability of the events are low. Once an accident happens, the dose is significantly higher than normal ones. For example, given an accident happened in the hospital, the conditional dose to a specific individual worker involved in the accident could be around 100 times of the value in Table 2, i.e. the median would be around 17mSv, because the probability of such an accident is around 1%.

Figure 4 shows the statistical summary for variability of radiological risk from 2D MCA which presents 90% confidence intervals for each percentile.

Sensitivity analysis was performed on each of the parameters to determine which variables most strongly influence the risk estimate. For the accident scenario for workers, the sensitive parameters are in the order as follows: distance(0.80), occupational factor(0.40), activity(0.32) and working time(0.17).

IV. Conclusion

The risks involved in use of ^{131}I in thyroid cancer therapy procedures were estimated for worker during inpatient care and for the family member after release in both normal and accidental situations using the 2D MCA approach. The 2D MCA provides further insight for the underlying uncertainty of risk estimates by giving possible variations of outcome distribution rather than a single distribution. Hence, 2D MCA is particularly valuable when our knowledge or experience for the tasks is insufficient.

Acknowledgments

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