DOI: 10.15669/pnst.4.60

Progress in Nuclear Science and Technology
Volume 4 (2014) pp. 60-63

ARTICLE

Development of internal dosimetry evaluation code for chronic exposure after intake of radionuclides

Masanori Kimura[a*], Sakae Kinase[a,b] and Shinji Hato[b,c]

[a]*Japan Atomic Energy Agency, 2-4 Shirakata, Tokai-mura, Naka-gun, Ibaraki-ken, 319-1195, Japan;* [b]*Ibaraki University, 2-1-1 Bunkyo. Mito, Ibaraki-ken, 310-8512, Japan;* [c]*Visible Information Center, 440 Muramatsu Tokai-mura, Naka-gun, Ibaraki-ken, 319-1112, Japan*

The Fukushima Daiichi nuclear power plant accident resulted in a release of radionuclides to the environment and in the large land contamination. The national government and local governments implemented urgent protective actions to reduce internal exposure from ingestion of foods and tap water or inhalation of radionuclides after the accident. However, there has been some concern in evaluating internal exposure due to chronic intakes. In the present study, DSYS-chronic code was developed in order to evaluate internal exposure due to chronic intakes after the accident. The code can treat internal dosimetry for chronic exposure due to continuous and discontinuous intake. To validate the code, the results of equilibrium values or the dose coefficients for ^{137}Cs and ^{131}I due to continuous intake were compared with those of the International Commission of Radiation Protection (ICRP) Publ.78, MONDAL3 code and INDES code. It was found that the evaluated values in DSYS-chronic code are in good agreement with the values of them.

Keywords: Fukushima; nuclear accident; chronic exposure; internal dose; protective action

1. Introduction

The Fukushima Daiichi nuclear power plant accident occurred on March 11, 2011 and resulted in a release of radionuclides to the environment and in the large land contamination. The public had ingested potentially contaminated foods and tap water or inhaled radionuclides in the atmosphere until the national government and local governments implemented urgent protective actions after the accident. There has been some concern in evaluating internal exposure due to continuous intake. For an episodic intake or a daily intake of the same total activity, the resulting whole-body activity at the end of the period is significantly different [1]. Therefore, dose assessment of internal exposure due to acute intake cannot be applied to the accident. It is important to develop internal dosimetry code to calculate retention or excretion functions and internal dose coefficients for chronic exposure.

In 2004, the Japan Atomic Energy Agency (JAEA) developed DSYS (Dose System) code that evaluates the internal doses for organ or tissue based on dosimetric and biokinetic models of the ICRP [2-3]. DSYS code is applied to the environmental consequence assessment in a nuclear emergency using a Level 3 Probabilistic Safety Assessment (PSA) code, the Off-site Consequence Analysis code for Atmospheric Release in Reactor Accident (OSCAAR) [4], while it cannot treat internal dosimetry for chronic exposure. In the present study, the authors enhanced the functions of DSYS code and developed DSYS-chronic code that can evaluate internal exposure due to continuous and discontinuous intake.

2. Material and methods

2.1. DSYS code

DSYS code can treat internal dosimetry for acute exposure using GI-tract model, respiratory tract model, and biokinetic and bioassay models for ICRP Publ. 30, 56, 67, 69, 71 and 72. It consists of four calculation modules, such as Depo, Predat, SEE and Dose. **Figure 1** shows the construction of DSYS code and data flow. Each module has the following functions.

· Depo

Calculating the fraction of the inhaled particles deposited in each respiratory tract region based on the human respiratory tract model of the ICRP Publ.66.

· Predat

Editing the input data of DSYS using databases on nuclear data and biokinetic data based on the ICRP Publ.30, 38, 56, 67, 69 and 71.

· SEE

Calculating specific effective energy (SEE) for each age-group (3 months, 1 year, 5 years, 10 year, 15 years

*Corresponding author. Email: kimura.masanori@jaea.go.jp

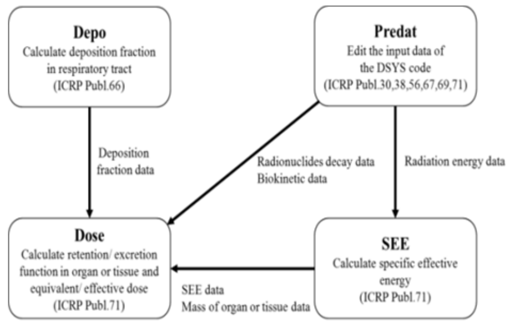

Figure 1. The construction of the DSYS code and out data flow.

and the adult).

- Dose

Calculating retention or excretion functions, or the committed effective dose and equivalent doses to organ or tissue due to inhalation, ingestion and injection based on the output data of the Depo, Predat and SEE.

DSYS code can evaluate the following items.

- Internal doses due to inhalation, ingestion and injection for approximately 700 nuclides excluding noble gases or nuclides without biokinetic models.
- Age-dependent doses to members of the Public (3 months, 1 year, 5 years, 10 years, 15 years and the adult).
- Time-dependent internal dose coefficients, retention values in the body and excretion values in urinary or faecal.

2.2. Development of DSYS-chronic code

2.2.1 Biokinetic models for acute and chronic intakes

In DSYS code, internal doses due to acute intake can be evaluated by the amount of radionuclides retained in tissue or organ and SEE for each age-group. GI-tract model, respiratory tract model, and biokinetic and bioassay models have compartment models using first-order kinetics equation referred as Eq. (1).

$$\frac{d\mathbf{q}}{dt} = \mathbf{A} \cdot \mathbf{q}, \quad \mathbf{q}(t=0) = \mathbf{q}_0 \qquad (1)$$

where

$\mathbf{q}$ = the vector of the amount of radionuclides retained in each compartment at time t after intake (Bq)

$\mathbf{A}$ = the matrix of the transfer coefficients between compartments and decay constant of radionuclides (1/d)

$\mathbf{q}_0$ = the vector of initial values (Bq)

In the present study, DSYS code was enhanced to evaluate internal exposure due to chronic intakes using Eq.(2). Consequently, DSYS-chronic code has equivalent function of DSYS code and can evaluate internal exposure due to acute and chronic intakes.

$$\frac{d\mathbf{q}}{dt} = \mathbf{A} \cdot \mathbf{q} + \dot{\mathbf{I}}, \ \mathbf{q}(t=0) = 0 \qquad (2)$$

where

$\mathbf{q}$ = the vector of the amount of radionuclides retained in each compartment at time t after intake (Bq)

$\mathbf{A}$ = the matrix of the transfer coefficients between compartments and decay constant of radionuclides (1/d)

$\dot{\mathbf{I}}$ = the vector of external feed for chronic intakes (Bq/day) (=d×f)

d = deposition fraction using respiratory tract model of the ICRP Publ.66

f = the intake amount of radionuclides depended on intake time t

2.2.2 Validation of DSYS-chronic code

(a) Constant intakes

To validate DSYS-chronic code for evaluating chronic exposure, the equilibrium values (Bq) for continuous intake of ^{137}Cs and ^{131}I were evaluated by DSYS-chronic code and were compared with those valued at ICRP Publ.78 [5], MONDAL3 code [6] and INDES code[a]. ICRP Publ.78 gives equilibrium values after a year for continuous inhalation at a rate of 1 Bq/y (1/365 Bq/d). In the present study, the equilibrium values were calculated under the following condition described by ICRP Publ.78 (**Table 1**).

Table 1. The detail of the calculation condition.

Items	Condition
Nuclides	^{137}Cs, ^{131}I
Age	20 y
Intake pathway	inhalation (AMAD 5 μm, type:F)
f_1 values	1.0 (^{137}Cs, ^{131}I)
Intake pattern	1 Bq/y for a year, total amounts: 1Bq

(b) Patterned intakes

DSYS-chronic code can evaluate for the chronic exposure using the intake pattern of a linear equation. In the present study, predicted values (Bq) of the thyroid or whole-body and inhalation dose coefficients for patterned intake of ^{137}Cs and ^{131}I were evaluated by using DSYS-chronic code under the condition of **Table 2** and were compared with those of INDES code.

Table 2. The detail of the calculation condition for continuous intake.

Items	Condition
Nuclides	^{137}Cs, ^{131}I
Age	1 y
Intake pathway	Inhalation (AMAD 1 μm, type:F)
Intake pattern	(t + 1) Bq for a year (0<t<365 days), Total amounts: 66977.5Bq

2.3. Evaluation for discontinuous intake

DSYS-chronic code can evaluate for the chronic exposure due to discontinuous intakes. In the present study, while the existing chronic exposure codes cannot treat assessment for discontinuous intake and the calculation results cannot be compared, predicted values (Bq) of stomach and whole-body, and the effective dose coefficients for discontinuous intake of ^{137}Cs were evaluated by using DSYS-chronic code under the condition of **Table 3**.

[a] developed by the Science and Technology Agency in Japan (formerly the Ministry of Education, Culture, Sports, Science and Technology).

Table 3. The detail of the calculation condition for discontinuous intake.

Items	Condition
Nuclides	^{137}Cs
Age	1 year
Intake pathway	Ingestion
Intake pattern	100 (Bq/day): 0-10 day
	20 (Bq/day): 25-50 day
	10 (Bq/day): 50-100 day
	10 (Bq/day): 1000-1150 day
	Total amounts: 3500 (Bq)

Table 4. Equilibrium values for continuous intake of ^{137}Cs and ^{131}I.

Equilibrium values (Bq)		DSYS-chronic	ICRP Publ.78	MONDAL3	INDES
^{137}Cs	Whole body	1.7×10^{-1}	1.9×10^{-1}	1.7×10^{-1}	1.7×10^{-1}
	Excretion in urine	9.5×10^{-4}	1.0×10^{-3}	9.5×10^{-4}	9.5×10^{-4}
^{131}I	Thyroid	4.1×10^{-3}	4.1×10^{-3}	4.1×10^{-3}	4.1×10^{-3}
	Excretion in urine	8.9×10^{-4}	8.5×10^{-4}	8.5×10^{-4}	8.9×10^{-4}

3. Results and discussion

3.1. Validation of DSYS-chronic code

3.1.1 Constant intake

Table 4 shows the calculation results of the equilibrium values (Bq) for continuous intake of ^{137}Cs and ^{131}I. It can be seen from the table that equilibrium values of ^{131}I and ^{137}Cs evaluated in DSYS-chronic code are in good agreement with those evaluated by ICRP Publ.78, MONDAL3 code and INDES code.

3.1.2 Patterned intake

Figure 2 shows predicted values of ^{131}I of the thyroid and ^{137}Cs of whole-body. It can be seen from the figure that predicted values of ^{131}I and ^{137}Cs evaluated in DSYS-chronic code are in good agreement with those evaluated by INDES code. **Table 5** shows calculated inhalation dose coefficients for ^{137}Cs and ^{131}I using DSYS-chronic code and INDES code. It was found that the dose coefficients of organ or tissue for ^{131}I and ^{137}Cs evaluated in DSYS-chronic code are also in good agreement with those evaluated by INDES code.

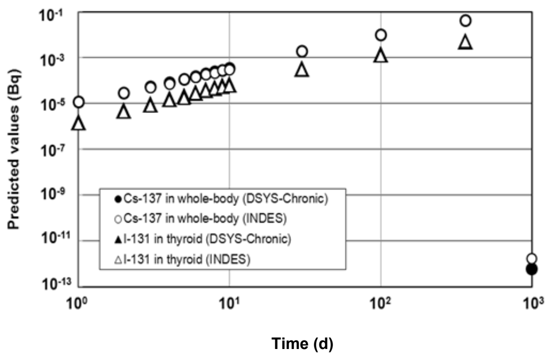

Figure 2. Predicted values (Bq) of the thyroid or whole-body for patterned chronic intakes of ^{137}Cs and ^{131}I.

Table 5. Inhalation dose coefficients (Equivalent dose to age 70 years).

Chronic intakes (t+1, 0<t<365)	Dose coefficient (Sv/Bq)			
	^{137}Cs		^{131}I	
equivalent/effective dose	DSYS-chronic	INDES	DSYS-chronic	INDES
Adrenals	3.9×10^{-9}	3.9×10^{-9}	1.2×10^{-10}	1.2×10^{-10}
Bladder Wall	4.2×10^{-9}	4.2×10^{-9}	5.5×10^{-10}	5.5×10^{-10}
Bone Surface	3.8×10^{-9}	3.8×10^{-9}	1.8×10^{-10}	1.8×10^{-10}
Brain	3.6×10^{-9}	3.6×10^{-9}	1.5×10^{-10}	1.5×10^{-10}
Breast	3.2×10^{-9}	3.2×10^{-9}	1.6×10^{-10}	1.6×10^{-10}
Oesophagus	3.9×10^{-9}	3.8×10^{-9}	6.9×10^{-10}	6.9×10^{-10}
ST Wall	3.8×10^{-9}	3.8×10^{-9}	3.1×10^{-10}	3.0×10^{-10}
SI Wall	4.0×10^{-9}	4.0×10^{-9}	1.1×10^{-10}	1.1×10^{-10}
ULI Wall	6.2×10^{-9}	6.1×10^{-9}	2.8×10^{-10}	2.8×10^{-10}
LLI Wall	1.0×10^{-8}	1.0×10^{-8}	5.7×10^{-10}	5.6×10^{-10}
Colon	8.0×10^{-9}	8.0×10^{-9}	4.1×10^{-10}	4.0×10^{-10}
Kidneys	3.8×10^{-9}	3.8×10^{-9}	1.0×10^{-10}	1.0×10^{-10}
Liver	3.8×10^{-9}	3.8×10^{-9}	1.2×10^{-10}	1.2×10^{-10}
Muscle	3.6×10^{-9}	3.6×10^{-9}	2.6×10^{-10}	2.6×10^{-10}
Ovaries	4.1×10^{-9}	4.1×10^{-9}	1.1×10^{-10}	1.1×10^{-10}
Pancreas	3.9×10^{-9}	4.0×10^{-9}	1.2×10^{-10}	1.2×10^{-10}
Red Marrow	3.5×10^{-9}	3.5×10^{-9}	1.4×10^{-10}	1.4×10^{-10}
ET Airways	2.3×10^{-8}	2.3×10^{-8}	1.3×10^{-8}	1.3×10^{-8}
Lungs	3.7×10^{-9}	3.7×10^{-9}	2.7×10^{-10}	2.6×10^{-10}
Skin	3.2×10^{-9}	3.2×10^{-9}	1.3×10^{-10}	1.2×10^{-10}
Spleen	3.8×10^{-9}	3.8×10^{-9}	1.2×10^{-10}	1.1×10^{-10}
Testes	3.5×10^{-9}	3.5×10^{-9}	8.7×10^{-11}	8.7×10^{-11}
Thymus	3.9×10^{-9}	3.8×10^{-9}	6.9×10^{-10}	6.9×10^{-10}
Thyroid	3.9×10^{-9}	3.9×10^{-9}	1.3×10^{-6}	1.2×10^{-6}
Uterus	4.0×10^{-9}	4.0×10^{-9}	1.1×10^{-10}	1.1×10^{-10}
Remainder	1.3×10^{-8}	1.3×10^{-8}	2.4×10^{-10}	2.3×10^{-10}
Effective dose	4.8×10^{-9}	4.8×10^{-9}	6.3×10^{-8}	6.2×10^{-8}

3.2. Evaluation for discontinuous intake

In **Figure 3 (a)**, predicted values (Bq) of ^{137}Cs of the stomach are similar to the intake pattern because the ingested radionuclides transfer to the content of the stomach in the ingestion model. **Figure 3 (b)** shows predicted values (Bq) of ^{137}Cs of whole body. The values were little change until 100 days and then decreased until 1000 days. After that, it increased drastically by chronic intakes from 1000 days and decreased after 1150 days. **Figure 3 (c)** shows predicted values of the effective dose coefficients that are normalized by the total intake during the period. It increased loosely and was almost constant after 100 days. After that, it increased drastically from 1000 days and was constant after 1150 days. In this case, it was found that predicted values of ^{137}Cs of whole-body drastically increased and decreased for intake after the elapse of considerable time since last intake.

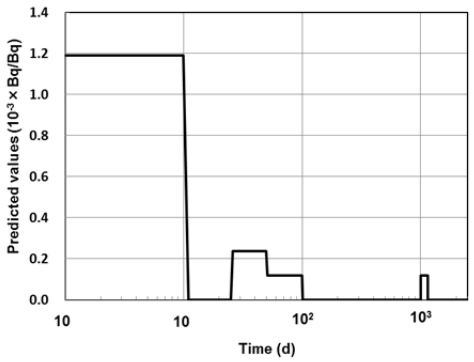

Figure 3 (a). Predicted values of the stomach.

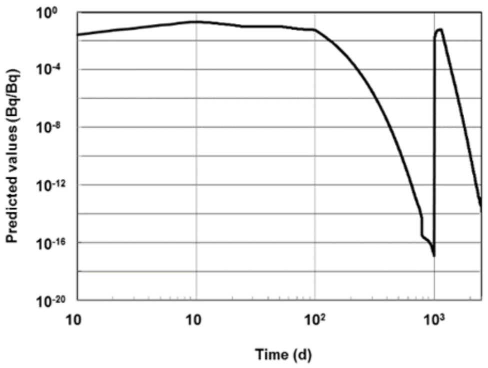

Figure 3 (b). Predicted values of the whole-body.

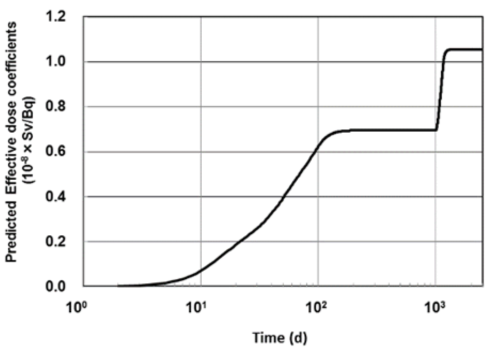

Figure 3 (c). Predicted values of the effective dose coefficients during the period of intake.

4. Conclusion

To evaluate internal exposure due to chronic intakes after the Fukushima Daiichi nuclear power plant accident, internal dosimetry code, DSYS-chronic, was developed. The code can evaluate internal exposure due to continuous and discontinuous intake. The result of equilibrium values for continuous intake or the dose coefficients for ^{137}Cs and ^{131}I using DSYS-chronic code were compared with those of the ICRP Publ.78, MONDAL3 code and INDES code. It was found that these values are also in good agreement. It was also found that predicted values of ^{137}Cs of whole-body drastically increased and decreased for intake after the elapse of considerable time since last intake.

References

[1] International Commission on Radiological Protection, Application of the commission’s recommendations to the protection of people living in long-term contaminated areas after a nuclear accident or a radiation emergency, ICRP Publication 111, *Annals of the ICRP* 39 (3), (2009).

[2] S. Hato and T. Homma, *Internal Dose Coefficients for Off-site Radiological Consequence Analysis of Nuclear Reactor Accidents,* JAERI-Data/Code 2005-006, Japan Atomic Energy Research Institute, (2005). [in Japanese]

[3] S. Hato, M. Terakado. K. Tomita and T. Homma, *User’s Manual of DSYS-GUI: The Calculation System of Internal Dose Coefficients*, JAEA-Data/Code 2008-031, Japan Atomic Energy Agency, (2009). [in Japanese]

[4] T. Homma, K. Tomita and S. Hato, Uncertainty and sensitivity studies with the probabilistic accident consequence assessment code OSCAAR, *Nuclear Engineering and Technology* 37 (3) (2005), pp. 245-258.

[5] International Commission on Radiological Protection, Individual monitoring for internal exposure of workers, ICRP Publication 78, *Annals of the ICRP* 27 (3-4), (1997).

[6] N. Ishigure, M. Matsumoto, T. Nakano and H. Enomoto, *Monitoring to Dose Calculation (M ONDAL)*, National Institute of Radiological Sci ences, (http://www.nirs.go.jp/db/anzendb/RPD/m ondal3.php).