Evaluation of Effective Dose Coefficient with Variation of Absorption Fraction in Gastrointestinal System for Ingestion of Radiocesium

Mochamad Adhiraga PRATAMA,*1 Shogo TAKAHARA*1 and Shinji HATO*2

(Received on December 22, 2016)
(Accepted on May 19, 2017)

The purpose of this study is to identify the significance of the change in the intestinal absorption rate values the \( f_1 \) value to the change of ingestion dose coefficient following an acute intake of \(^{134}\text{Cs}\) and \(^{137}\text{Cs}\). This study also attempted to provide a simple calculation method of ingestion dose coefficients given a specific value of \( f_1 \) and age groups by using linear regression models. In the range of 0–1, 10 different values of \( f_1 \) for 1-year, 5-year-old, and the adult group were chosen and used in a separate calculation by using, a biokinetic compartment model, DCAL. It was found that the lower values of \( f_1 \) lead to a significant decrease of the committed effective dose coefficient for an adult. Oppositely for children, the decrease of the coefficient was not as significant. This study also suggests that the significance of dose coefficient change due to the variation of \( f_1 \) substantially depends on the biological half-life of the radionuclide, the fraction of absorbed energy and the mass of organs and tissues in human body.

KEY WORDS: effective dose coefficient, intestinal absorption, cesium.

I INTRODUCTION

Following Fukushima Daiichi Nuclear Power Plant Accident, a substantial amount of radiocesium has released and contaminated the environment. Consequently, the living organisms within the contaminated area were under threat of radiation exposure externally and internally. The deposited radionuclide on the ground surface which, thereafter, is up-taken by agricultural commodities and also direct deposition and resuspension of radionuclide on food commodities contribute a significant amount to internal radiation exposure.\(^1,2\)

According to a study, it was estimated that the maximum total exposure dose through inhalation and ingestion on residents in Fukushima Prefecture in the 5th month after the accident was 13 µSv/month.\(^3\) Breaking down the estimate, the contribution from ingestion pathway was estimated to be about 50% of the total dose. In addition, according to the results of a survey on radiocesium body burden of residents in Fukushima, it was found that the maximum activity in a participant to be 270 Bq.\(^4\) Furthermore, the effective dose of radiocesium in the diet decreased over time as shown by a study that reported the dose was 1.18 µSv/month in September 2011 then dropped to 0.44 µSv/month in March 2012.\(^5\) The most recent survey from Ministry of Health, Labor and Welfare in September 2015 reported that the radiation dose from dietary intake was 0.0125 µSv/month.\(^6\) These studies and reports suggest that though the exposure through ingestion was not sufficiently high to cause acute effect, it still poses a long-term radiological risk so that the evaluation of internal dosimetry needs to be addressed appropriately.

To estimate the dose after ingestion intake of a radionuclide, committed effective dose coefficient per unit intake, which are recommended by the International Commission on Radiological Protection (ICRP),\(^7,12\) plays an important role to convert the amount of radioactivity entering the body through ingestion in Becquerel to the effective dose unit in Sievert. These age-dependent coefficients depend on body and organ masses, excretion rates from the urinary bladder and absorption fraction of ingested radionuclide from the gastrointestinal system.\(^8,9\) ICRP publication 71 and 72 provide the values of \( f_1 \) and taking account on the pathway of exposure (inhalation or ingestion) and the age of receptor (infant, 1, 5, 10, 15 and 20 years old).\(^11,12\) Moreover, these publications suggest that the absorption fraction of ingested cesium absorbed directly into the blood \( f_1 \) is set to be 1 which means that all the cesium entering small intestine would be absorbed. This suggestion is made under an assumption that the characteristic of dietary source that contains ingested cesium has no effect on the intestinal absorption fraction.

However, this assumption is valid only to soluble form, if cesium adsorbed onto specific dietary source as the relatively insoluble form such as soils and irradiated fuel fragments, assessors cannot adopt this assumption. Table 1 shows the \( f_1 \) values for various dietary source which are obtained from \textit{in-vivo} or \textit{in-vitro} experiments. As shown in this table, it is

---

*1 Nuclear Safety Research Center, Japan Atomic Energy Agency; 2–4 Sirakata-Sirane, Tokai-mura, Naka-gun, Ibaraki 319–1195, Japan. E-mail: pratama.mochamadadhira@gmail.com
*2 Visible Information Center, Inc.; 440 Muramatsu, Tokai-mura, Naka-gun, Ibaraki 319–1112, Japan.
generally accepted that radiocesium ingested as a soluble form is well absorbed in the gastrointestinal tracts of humans and animals. Results from controlled studies on human subjects indicate that orally administered soluble radiocesium is rapidly and almost completely absorbed. Furthermore, radiocesium in foodstuffs is equally available for absorption in humans and animals. By contrast, previous studies clearly indicate that insoluble radiocesium such as that adsorbed on soils tends to be unavailable for absorption in the gastrointestinal tract compared with the soluble form and other foodstuffs such as meats and grass. Therefore, if we try to assess the doses from ingestion of insoluble dietary radiocesium through ingestion which is based on the various values of $f_1$. A biokinetic model, the Dose and Risk Calculation software (DCAL), developed by Oak Ridge National Laboratory, was used to calculate the committed effective dose coefficient. In addition, the change of the coefficient value under the variation of age and $f_1$ will be shown in this paper.

## II MATERIAL AND METHODS

### 2.1 Gastrointestinal Tract Model

DCAL is a biokinetic compartment model based on the recommendation of ICRP publication 30. The gastrointestinal tract of a human is represented as four compartments, namely stomach, small intestine, upper large intestine, lower large intestine (Fig. 1). Compartment lower large intestine is in charge on excreting radionuclide from the human body in feces form, whereas the absorption of radionuclide occurs in the small intestine compartment which is connected to blood compartment. The radionuclide absorbed by blood is circulated to the whole body which, in this model, is divided into two part, total body $A$, and total body $B$ compartment. Finally, thorough bladder compartment, it is excreted together with urine.

In general, the mass balance, $M_i$, radionuclide activity in compartment $i$ is governed by the following equation:

$$\frac{dM_i}{dt} = I - K_{ij} M_i - K_{id} M_d. \quad (1)$$

Where $I$ is the input of radionuclide from the previous compartment (Bq/day), $K_{ij}$ is transfer rate of radionuclide from

---

**Table 1** The value of $f_1$ for radioactive Cs from various types of dietary sources.

| In vivo or In vitro experiment | Dietary source | Species | $f_1$ | Ref. |
|-------------------------------|----------------|--------|-------|------|
| **In vivo**                   |                |        |       |      |
| CsCl                          | human          | 0.85   | (13)  |      |
| CsCl                          | human          | 0.89   | (14)  |      |
| CsCl                          | sheep          | 0.84   | (15)  |      |
| CsCl                          | sheep          | 0.87   | (16, 17) | (16, 17) |
| CsCl                          | sheep          | 0.78   | (17)  |      |
| CsCl                          | sheep          | 0.84   | (17)  |      |
| CsCl                          | cattle         | 0.71   | (17)  |      |
| Grass hay                     | sheep          | 0.73   | (17)  |      |
| Clover hay                    | sheep          | 0.76   | (17)  |      |
| Upland Grass                  | sheep          | 0.88   | (15)  |      |
| Pasture grass                 | cattle         | 0.23   | (16, 17) | (16, 17) |
| Calluna Vulgaris              | sheep          | 0.67   | (15)  |      |
| Venison                       | human          | 0.78   | (18)  |      |
| Lowland peat soil             | sheep          | 0.03   | (17, 19) | (17, 19) |
| Silty soil                    | sheep          | 0.13   | (15, 17) | (15, 17) |
| Alluvial gley soil            | Sheep          | 0.19   | (17, 19) | (17, 19) |
| Peaty podzol soil             | Sheep          | 0.20   | (17)  |      |
| Peaty podzol soil             | Sheep          | 0.02   | (17)  |      |
| Insoluble fallout particle     | human          | 0.032  | (14)  |      |
| Insoluble irradiated fuel particle | rat          | 0.075  | (20)  |      |
| **In vitro**                  |                |        |       |      |
| Savannah River Site soil      | enzymolysis procedure | 0.060–0.38 | (21) |      |
| Winkle with soil              | enzymolysis procedure | 0.13–0.63 | (22) |      |
| Alfalfa with soil             | enzymolysis procedure | 0.18   | (23)  |      |
| Soil                          | enzymolysis procedure | 0.047–0.064 | (24) |      |
In this study, we construct 3 age groups, namely 1-year-old, 5-year-old, and adult group. Noted that some of parameters such as transfer rate from stomach to small intestine \((K_{25})\) and transfer rate from upper large intestine to lower large intestine \((K_{34})\) could be calculated based on the relationship between the transfer rate from the small intestine to the upper large intestine \((K_{23})\) and \(f_i\) as written in the following equation:

\[
K_{23} = (f_i; K_{23})(1 - f_i).
\]

Where \(f_i\) is the fraction of a specific radionuclide absorbed by the blood. The value of this fraction is 0–1 depending on the element and form of the radionuclide. The values of parameters used in this model are shown in Table 2. In this study, we construct 3 age groups, namely 1-year-old, 5-year-old, and adult group. Noted that some of parameters such as distribution to BODY A and B, biological half life \((K_{56} \text{ and } K_{57})\) and urination rate \((K_u)\) are age dependent. Thus, a specific value of those parameters which was provided in ICRP 67, was set to each age group.

![Fig. 1 Structure of the biokinetic model suggested in ICRP Publication 30 and 56.](image)

### 2.2 Dosimetry

At First, the equivalent dose rate \((\overline{H}_i)\) at age \(t\) in target organ \(T\) after radionuclide intake at age \(t_0\) was calculated according to ICRP Publication 56 by the following equation:

\[
\overline{H}_i(t, t_0) = \sum_j q_j(t, t_0) \cdot \text{SEE}(T \leftrightarrow S; t).
\]

Where \(q_j\) is the activity of radionuclide in compartment or tissue \(S\) \((\text{Bq})\) whereas \(\text{SEE}\) is the specific energy deposited in target organ \(T\) per nuclear transformation in source region \(S\) at time \(t\).

\(\text{SEE}\) is calculated by the following equation:

\[
\text{SEE}(T \leftrightarrow S; t) = \frac{Y \cdot E \cdot W \cdot AF(T \leftrightarrow S; t)}{m(T)},
\]

where \(E\) is the energy of a discrete radiation emitted by the radionuclide with intensity \(Y\) per nuclear transformation, \(m(T)\) is the mass of the target tissue \(T\) at age \(t\). Tissue masses for adults are provided in ICRP 23 (1975) (Reference Man) whereas for children, age-dependent organ masses are based on a report by Cristy and Eckerman (1987). \(W\) is the radiation-weighting factor, \(AF(T \leftrightarrow S; t)\) is the quantity representing the fraction of the energy \(E\) emitted in \(S\) that is absorbed in \(T\) for an individual of age \(t\).

According to a method proposed by Cristy and Eckerman (1987), \(AF(T \leftrightarrow S; t)\) could be calculated by the following equation:

\[
AF(T \leftrightarrow S; t) = \frac{1}{m(T)} \sum_j w_j \cdot \left( \sum \frac{\text{wt}_j}{m(E_j)} \right).
\]

Where \(j\) indexes the collisions in region \(V\) experienced by the \(j\)th photon, \(V\) is the volume of the region over which the fluence is averaged, \(w_j\) is the statistical weight of the photon entering the \(j\)th collision, \(\mu(E)\) is the linear attenuation coefficient at energy \(E\), and \(E_j\) is the initial energy of each photon emitted from \(S\).

The total committed equivalent dose at age \(t\) due to the intake of radionuclide at age \(t\), was calculated by the following equation:

*Table 2 Parameters value for the biokinetic model of radiocesium ingestion.*

| Parameter | Definition | Unit | 1 y | 5 y | Adult | Ref |
|-----------|------------|------|-----|-----|-------|-----|
| \(K_{12}\) | Transfer rate from stomach to small intestine | /day | 24 | | | (7) |
| \(K_{25}\) | Transfer rate from small intestine to upper large intestine | /day | 6 | | | (7) |
| \(K_{34}\) | Transfer rate from upper large intestine to lower large intestine | /day | 1.8 | | | (7) |
| \(K_d\) | Defecation rate | /day | 1 | | | (7) |
| \(K_{56}\) | Distribution rate from blood to total body A | % | – | 45 | 10 | (8) |
| \(K_{57}\) | Distribution rate from blood to total body B | % | 100 | 55 | 90 | (8) |
| \(R_a\) | Half life of radionuclide in total body A | Day | – | 9.1 | 2 | (8) |
| \(R_b\) | Half life of radionuclide in total body B | Day | 13 | 30 | 110 | (8) |
| \(K_{10}\) | Transfer rate from body A to Upper Large Intestine | % | 20% of \(R_b\) | | | (37) |
| \(K_{11}\) | Transfer rate from body B to Upper Large Intestine | % | 20% of \(R_b\) | | | (37) |
| \(K_{12}\) | Transfer rate from body A to Bladder | % | 80% of \(R_b\) | | | (37) |
| \(K_{13}\) | Transfer rate from body B to Bladder | % | 80% of \(R_b\) | | | (37) |
| \(K_u\) | Urination rate | /day | 32 | 12 | 12 | (9) |
\[ H_f(t - t_0) = \int_{t_0}^{t} H_f(t - t') dt \]  \hspace{1cm} (6)

The value of \( t \) depends on the age of the receptor. For an adult, the value was set to be 50 and for children, the value was 70. This is based on the assumption that adulthood and childhood were spent about 50 and 20 years, respectively. For children, it was assumed that the initial exposure occurred right before the first year of childhood started. Thus, the committed equivalent dose was calculated for the entire adulthood and childhood, 70 years. Afterward, the committed effective dose coefficient at age \( t \) due to the intake of radionuclide at age \( t_0 \) is:

\[ E(t - t_0) = \sum_{J=1}^{12} H_J W_J + W_{\text{remainder}} H_{\text{remainder}} \]  \hspace{1cm} (7)

Where \( W_J \) is the specific weighting factor for 12 organs according to ICRP Publication 71. Table 3 shows 12 organs and their specific weighting factors. \( W_{\text{remainder}} \) is the weighting factor for the rest of the organs which the value was 0.05 and \( H_{\text{remainder}} \) is the equivalent dose for the remainder organs. If \( H_{\text{max}} \) is the maximum committed equivalent dose to the 12 organs and \( H_f \) is the maximum committed equivalent dose among the remainder organs, the equivalent dose rate in the remainder organs is:

\[ H_{\text{remainder}}(t, t_0) = \frac{\sum_{J=1}^{12} M_J(t) H_J(t, t_0)}{\sum_{J=1}^{12} M_J(t)} W_{\text{remainder}} H_{\text{remainder}} \]  \hspace{1cm} (8)

If \( H_f > H_{\text{max}} \):

\[ H_{\text{remainder}}(t, t_0) = 0.5 \left[ \sum_{J=1}^{12} M_J(t) H_J(t, t_0) \right] \]

\[ + H_f(t, t_0) W_{\text{remainder}} H_{\text{remainder}} \]  \hspace{1cm} (9)

| Organ or tissue | Weighting factor (\( w_J \)) |
|-----------------|-----------------------------|
| Gonads\(^{(1)}\) | 0.20                        |
| Bone marrow (red) | 0.12                      |
| Colon            | 0.12                        |
| Lungs\(^{(2)}\)  | 0.12                        |
| Stomach          | 0.12                        |
| Bladder          | 0.05                        |
| Breast           | 0.05                        |
| Liver            | 0.05                        |
| Oesophagus       | 0.05                        |
| Thyroid          | 0.05                        |
| Skin             | 0.01                        |
| Bone surface     | 0.01                        |
| Remainder\(^{(3)}\) | 0.05                     |

\(^{(1)}\) Dose coefficients are given in ICRP Publication for both ovaries and testes, the higher of which is used for the calculation of effective dose.

\(^{(2)}\) Thoracic airways.

\(^{(3)}\) The remainder is composed of the following ten additional tissues and organs: adrenals, brain, extrathoracic airways, small intestine, kidneys, muscle, pancreas, spleen, thymus, and uterus.

Where \( M_r \) is the mass of the remainder organs. The more detailed explanation of internal dose calculation is provided in ICRP Publication 71.

It has to be noted that for the case where the radionuclide intake occurs during pre-adult age, the age-dependent parameters continuously change throughout the growth period. The values of age-dependent parameters for specific ages provided in ICRP’s series on doses to members of the public from intake of radionuclides were interpolated to obtain a set of continuous parameter values throughout the growth period.

Although the equivalent dose for colon and esophagus are components in the calculation of effective dose as shown in Table 3, biokinetic compartment model does not take into account these organs. According to ICRP Publication 71, the equivalent dose for esophagus is assumed to be equal to that for thymus. In addition, the equivalent dose for colon is calculated as the weight-average of the upper large intestine and lower large intestine using following equation:

\[ H_{\text{colon}} = 0.57 \times H_{\text{ULI}} + 0.43 \times H_{\text{LLI}}. \]  \hspace{1cm} (10)

Where \( H_{\text{ULI}} \) is the equivalent dose for colon, \( H_{\text{ULI}} \) is the equivalent dose for upper large intestine, and \( H_{\text{LHI}} \) is the equivalent dose for the lower large intestine.

### III RESULTS AND DISCUSSIONS

#### 3.1 The Effect of Change in Value of \( f_1 \) on Equivalent and Effective Dose Coefficient

As could be seen in Table 1, the value of \( f_1 \) for cesium attached in soil is in the range from 0.047 to 0.18. Thus, for simplification purpose, the value of 0.1 was chosen to represent the ingested soil pathway. Fig. 2 shows the equivalent dose for 1 and 5-year-old children and adult for each organ and tissues based on the calculation using DCAL. Only little differences were found between the dose coefficient given by DCAL (\( f_1 = 1 \)) and those of ICRP 72. The relative difference for \(^{134}\)Cs were in the range of 0.011–0.019 whereas for \(^{137}\)Cs, they were in the range of 0.008–0.046. It could be seen in the figure that the equivalent dose coefficient to the colon which consists of the upper large intestine and the lower large intestine for the 1 and 5-year-old groups significantly stands out compared to the other organs and tissues. The values are even magnified substantially when the \( f_1 = 0.1 \). This is understandable since the lower value of \( f_1 \) means that the large intestine receives a larger flux of a radionuclide from the small intestine. In addition, the upper large intestine also receives flux of radionuclide from the human body due to excretion mechanism. Consequently, if the organ receives more influx of radionuclide, the radiation dose also becomes larger. For the adult group, on the other hand, the difference in the dose coefficient to the colon compared to other organs is not as significant as those for the 1 and 5-year-old groups.

The results in Fig. 2 may indicate that the lower large intestine plays an important key for determining the effective dose coefficient due to its magnitude of the equivalent dose coefficient. The weighing factor of upper and lower large intestine that is used for calculating effective dose coefficient is...
Mochamad Adhiraga Pratama, Shogo Takahara and Shinji Hato

relatively larger than the other organs and tissues, it increases the effect of equivalent dose in the lower large intestine to total effective dose. As shown in Table 3, considering the weighting value of this organ could reach 2.4–12 times larger than the other organs, and also considering the equivalent dose of the lower large intestine magnifies when the value of $f_1$ decreases due to the increase of radionuclide influx from the small intestine, the total effective dose coefficient for 1 and 5-year-old children under the condition of $f_1 = 0.1$ is only slightly smaller than the coefficient under the condition of $f_1 = 1$. On the other hand, as seen in Fig. 2, the effective dose for the adult group significantly smaller under the condition where the value of $f_1 = 0.1$. The biological half life of radiocesium in organs and tissues for adult is substantially larger than that of 1 and 5-year-old groups. When the change of radionuclide influx to organs and tissues due to the change of $f_1$ occurs, the longer biological half life significantly enhances the change of the effective dose. The role of biological half life is discussed in detailed in the next section.

3.2 The Dynamic of $f_1$, Biological Half Life and Absorbed Energy on Determining Equivalent Dose

In Fig. 2, it could be seen that for almost all organs in all age-groups, the equivalent doses are larger when $f_1 = 1$ except for the colon which consists of the upper large intestine and lower large intestine. Interestingly, the equivalent dose to the colon for 1 and 5-year-old groups is larger when $f_1 = 1$. Based on Eq. (3) and Eq. (4), the equivalent dose to the colon ($H_{CL}$) is consisted by two components, (1) the dose due to the activity of radionuclide inside the colon, $H_{CL}^{(CL)} (CL \leftarrow CL)$ and (2) the dose due to the activity from the surrounding organs and tissues, $H_{CL}^{(OR)} (CL \leftarrow OT)$. These components are affected by $f_1$ which determines the amount of radionuclide flux to the colon and to the organs and tissues, biological half life of the radionuclide in organs and tissues ($R$), and absorbed energy from the other surrounding organs ($SE$) in Eq. (3) as described in the following relationship.

$$H_{CL}^{(CL)} = (1 - f_1) q_{CL}^{(CL)} (t, t_0). SSE(\text{CL} \leftarrow CL)$$

$$H_{CL}^{(OR)} = f_1 q_{OR}^{(CL)} (t, t_0). SSE(\text{CL} \leftarrow OT)$$

$$q_{CL}^{(CL)} (t) = q_{OR}^{(CL)} (t_0) \exp (-\frac{\ln 2}{R} \cdot t)$$

The value of $f_1$ is the key that governs the amount of...
radionuclides entering blood, colon, organs and body tissues. The smaller the value of \( f_1 \) means the smaller amount of the absorbed radionuclide into the blood and the larger amount of radionuclide flux to the colon. Consequently, it increases the equivalent dose to the colon and since the blood transports the absorbed radionuclide to organs and tissues, the smaller value of \( f_1 \) decreases their equivalent dose.

As described in Eq. (4), the value of SEE is determined by \( AF \) whose value for adult is smaller than that of 1 and 5 year-old groups. In addition, since mass of organ that become larger over the growth period is a denominator, together with \( AF \) cause the SEE of adult is smaller than that of children. As a result, with the same amount of \(^{137}\text{Cs} \) intake, the equivalent dose for children is larger than that of adult.

Furthermore, the biological half life of a radionuclide in the human body which directly determine the value of \( q_{OT} \) also plays as a key parameter for determining the amount of equivalent and effective dose. Fig. 3 shows the accumulation of \(^{137}\text{Cs} \) activity \( \int M \) versus time in the upper large intestine for the 1-year-old group (Fig. 3a) and adult group (Fig. 3b) and the body tissues for the 1-year-old group (Fig. 3c) and adult group (Fig. 3d). In Fig. 3a and Fig. 3b, it can be seen that the radionuclide is accumulated more when \( f_1 = 0.1 \). This is an obvious since 90% of \(^{137}\text{Cs} \) entering the intestine is not absorbed to the blood and passed into the colon. It also can be observed that there is no significant difference between the accumulation for 1-year-old group and adult group. This is because the retention time of \(^{137}\text{Cs} \) in the colon is not age dependent.

In contrast, Fig. 3c and Fig. 3d shows that \(^{137}\text{Cs} \) is more accumulated in the body tissue when \( f_1 = 1 \). This is because almost 100% of \(^{137}\text{Cs} \) entering the small intestine is absorbed to blood and distributed to organs and tissues. It also could be seen that the accumulation is significantly larger in the adult group compared to that of the 1-year-old group. This is because the half life of \(^{137}\text{Cs} \) in body tissue of adult is substantially longer. According to ICRP Publication 56, the retention time of \(^{137}\text{Cs} \) in the body of an adult can be 10 times longer than in the body of a 1-year-old child. Consequently, the longer the half life, the smaller the out flux of \(^{137}\text{Cs} \) from organs and tissues at any time \( t \). Therefore, the more \(^{137}\text{Cs} \) is accumulated in adult’s organs and tissues.

The accumulation of \(^{137}\text{Cs} \) in organs and tissues results an increase of the radiation received by the colon. Thus, \( H_{\text{CL}} (CL \leftarrow OT) \) is larger when \( f_1 = 1 \) than that of when \( f_1 = 0.1 \). For 1 and 5-year-old groups, (Figs. 3a and 3b), however, it seems that the increase of \( H_{\text{CL}} (CL \leftarrow OT) \) is not as significant as the decrease of \( H_{\text{CL}} (CL \leftarrow CL) \) when \( f_1 \) was changed from 0.1 to 1. Consequently, \( H_{\text{CL}} \) for 1 and 5-year-old groups is larger when \( f_1 = 0.1 \). Oppositely, for the adult group, the increase of \( H_{\text{CL}} (CL \leftarrow OT) \) when \( f_1 \) was changed from 0.1 to 1 seems to be much more significant to the decrease of \( H_{\text{CL}} (CL \leftarrow CL) \). As a result, \( H_{\text{CL}} \) for the adult group is larger when \( f_1 = 1 \) compared to that of when \( f_1 = 0.1 \).

These results may address the concern on the radiation risk of children that are orally exposed by the attached radiocesium on soil particles when they play outdoor. On one hand, most of the attached radiocesium in soils are not absorbed by the small intestine and passed to the colon due to its small value of

**Fig. 3** The activities of \(^{137}\text{Cs} \) in the upper large intestine and the body tissues at time \( t \) to \( t \) were summed and the curve of \( \int_0^t M \) versus time for each organ was created. Figs. 3a and 3b show the accumulated \(^{137}\text{Cs} \) activities in the upper large intestine for the 1 year old group and adult group respectively. Figs. 3c and 3d show the accumulated activities in body tissue (summation of compartment BODY A and BODY B) for the 1-year old group and adult group, respectively.
$f_1$ and on the other hand, for children’s colon, $H_{c2}$ ($CL \rightarrow CL$) plays more significant role for determining the equivalent dose for colon. Thus it can be suggested that by ingesting the attached radiocesium in soil particles, children’s colon will be more affected compared to that of adult.

### 3.3 Committed Effective Dose Versus $f_1$

For the calculation in this section, the value of $f_1$ was diversified into 11 values from 0, 0.1, 0.2, 0.3, 0.4, and so on until it reached 1. Here, if complete absorption is indicated from the small intestine into the body fluids, in the same manner of ICRP Publication 67, the calculations of Eq. (2) were performed using a value of 0.99 for the value of $f_1$ for technical reasons. Thereafter, in separated calculation, each of these values was set in DCAL and as a result, the relationship between the committed effective dose and the value of $f_1$ is presented in Fig. 4. In the case of the small value of $f_1 (<0.4)$, for both $^{134}$Cs and $^{137}$Cs, the dose coefficient for the adult group is lower than those for 1 and 5-year-old groups. Oppositely, as the $f_1$ value increases, the dose coefficient for adult becomes larger than 5-year-old group at $f_1 = 0.5$ and become larger than 1-year-old group at $f_1 = 0.8$ for $^{134}$Cs and $f_1 = 0.9$ for $^{137}$Cs.

In this particular case, the values of committed effective dose coefficient depend on the mass and volume of organs and tissues and, as previously mentioned in section 3.2, the biological half life. As can be seen in Eqs. (3) and (4), the mass of organ and tissues is the denominator of the equation. In addition, the volume of organs and tissues also has a role as a denominator for calculation of fraction absorbed energy by organs as written in Eq. (5). Thus, the larger mass and volume directly causes the lower equivalent dose and, thus, the lower effective dose as an indirect consequence. The mass and volume of organs and tissue naturally increase along with maturation process. The lower large intestine, for example, its mass and

![Fig. 4](image-url)
volume are 8 times larger at age 20 compared to that of a year old. This substantial development of mass and volume of organs contributes to the cause of high dose coefficient of 1 and 5-year-old groups, at small values of \( f_1 \).

Along with the increase of \( f_1 \), biological half life becomes the most dominant factor in determining committed effective dose coefficient. Though the denominator (mass and volume) is larger, an adult has a longer biological half life for cesium. Consequently, the activity of radionuclide in organs and tissues decreases slower than those of the activity in organs of 1 and 5-year-old groups. As a result, the exposure would occur for a longer period. Moreover, under a large \( f_1 \) value, the radionuclide is more uniformly distributed in all organs and tissues. Hence, each of these organs and tissues is exposed by the larger amount of radiation. Thus, the committed effective dose coefficient for an adult has larger values under the condition where \( f_1 \) is larger.

This study shows that the characteristic dietary source containing cesium significantly determines the intestinal absorption rate as well as the committed effective dose coefficient. Since there is a high possibility that dietary source other than food or soil has a specific value of \( f_1 \), linear regression analysis on committed effective dose coefficient with \( f_1 \) as a predictor was made in order to simplify the calculation process so that the coefficient could be determined easily without using biokinetic model (Table 4). Linear regression method was chosen as it provides the best fit to the dose coefficient data in Table 4. It can be seen that the regression results achieve a good \( r^2 \) indicating that the equations are reliable to estimate committed effective dose coefficient which corresponds to a specific value of \( f_1 \).

Note that the ICRP is currently revising the biokinetic model and this revision is not yet complete. Therefore, once the models and coefficients are prepared, it may be necessary to assess the doses from the ingestion pathway based on the new model.

**IV CONCLUSIONS**

This study shows the significance of intestinal absorption rate related to the dietary source of the ingested cesium to the committed effective and equivalent dose coefficient. It was found that when the dietary source of the ingested cesium is soil, which has small intestinal absorption rate, the committed effective and equivalent dose coefficient become lower compared to that when the host dietary source is food. However, the significance of the change of the coefficient varies depending on age. It was observed that the dose coefficient is significantly lower for an adult when the value of \( f_1 \) is small compared to those of the dose coefficient for 5-year-old children and 1-year-old children respectively. Moreover, mass and volumes of the organs, the biological half life of the radionuclide and the absorbed energy fraction plays some important role in determining the change of dose coefficient due to the change of \( f_1 \).

Finally, this study suggests that the characteristic of the dietary source of the ingested cesium required to be examined before estimating committed effective and equivalent dose. As a particular dietary source might have a different value \( f_1 \) to the others, in order to improve the accuracy and representativeness of committed effective and equivalent dose, more investigation of \( f_1 \) value from various dietary source (vegetables, rice, meat, fruit, etc.) as well as various condition (pH, CEC, soil structure, etc.) are necessary. However, as seen in fig. 4, for practical purpose, a conservative value of \( f_1 = 1 \) is still reliable considering that it results the largest dose coefficient which gives a space for safety factor. The more accurate value of \( f_1 \) is indeed required when dealing with the realistic dose assessment for individual or when conducting a detailed epidemiological study. In addition, such a detailed study on the biological half life of radionuclide is necessary considering its importance to the equivalent and effective dose coefficient. This because its value may depend on several factors such as sex, individual physiological condition, and the presence of other constituents in the body. The significance of these factors to the uncertainty of dose coefficient estimation needs further studies.

**REFERENCES**

1) IAEA; Testing of environmental transfer models using Chernobyl fallout data from the Iput River catchment area, Bryansk Region, Russian Federation: Report of the Dose Reconstruction Working Group of BIOMASS Theme 2, IAEA-BIOMASS-4 (2003).

2) K. Tensho, K. L. Yeh and S. Mitsui; The uptake of strontium and cesium by plants from soil with special reference to the unusual cesium uptake by lowland rice and its mechanism, *Soil Sci. Plant Nutr.*, 6 (4), 176–183 (1961). doi: 10.1080/00380768.1961.1043094.

3) A. Koizumi, K. Harada, H. Nisoe, A. Adachi, Y. Fubu, T. Hitomi and H. Ishikawa; Preliminary assessment of ecological exposure of adult residents in Fukushima Prefecture to radioactive cesium through ingestion and

| Age category | Committed effective dose coefficients as a function of \( f_1 \) (nSv/Bq) |
|--------------|---------------------------------------------------------------|
|              | \( Cs \)                                                    | \( ^{207}Cs \)                      |
| 1 year       | \( E(70) = 7.010 \cdot f_1 + 8.773 \)                       | \( E(70) = 3.590 \cdot f_1 + 8.827 \) |
|              | \( R^2 = 0.998 \)                                           | \( R^2 = 0.999 \)                  |
| 5 year       | \( E(70) = 8.493 \cdot f_1 + 4.754 \)                       | \( E(70) = 5.167 \cdot f_1 + 4.548 \) |
|              | \( R^2 = 0.999 \)                                           | \( R^2 = 0.999 \)                  |
| Adult        | \( E(70) = 17.81 \cdot f_1 + 1.528 \)                       | \( E(70) = 12.36 \cdot f_1 + 1.309 \) |
|              | \( R^2 = 0.999 \)                                           | \( R^2 = 1 \)                      |
inhalation. *Environ. Health Prev. Med.*, 17 (4), 292–298 (2012). http://doi.org/10.1007/s12199-011-0251-9.

4) R. Hayano, M. Tsukabora, M. Miyazaki, H. Sato, K. Sato and Y. Sakuma; Internal radionuclides contamination of adults and children in Fukushima 7 to 20 months after the Fukushima NPP accident as measured by extensive whole-body-counter survey. *Proc. Jpn. Acad.*, Ser. B 2013, 89, 157–163 (2013).

5) M. Murakami and T. Oki; Estimated Intake of Radionuclides and Health Risks for the Citizens of Fukushima City, Tokyo, and Osaka after the 2011 Nuclear Accident. *PLoS ONE*, 9 (11), e112791 (2014). doi: 10.1371/journal.pone.0112791.

6) Ministry of Health, Labor, and Welfare of Japan; The Result of Survey on Dietary Intake of Radionuclides –Part 2 Ingestion Dose. Available at: http://www.mhlw.go.jp/stf/houdou/0000126025.html, Accessed 20 June 2016.

7) ICRP; Limits for Intakes of Radionuclides by Workers; ICRP Publication 30 (Part 1). *Ann. ICRP*, 2 (3–4) (1979).

8) ICRP; Age-dependent Doses to Members of the Public from Intake of Radionuclides–Part 1. ICRP Publication 56, *Ann. ICRP*, 20 (2) (1990).

9) ICRP; Age-dependent Dose to Members of the Public from Intake of Radionuclides–Part 2 Ingestion Dose Coefficients. ICRP Publication 67, *Ann. ICRP*, 23 (3/4) (1993).

10) ICRP; Age-dependent Dose to Members of the Public from Intake of Radionuclides–Part 3 Ingestion Dose Coefficients. ICRP Publication 69, *Ann. ICRP*, 25 (1) (1995).

11) ICRP; Age-dependent Doses to Members of the Public from Intake of Radionuclides–Part 4 Inhalation Dose Coefficients. ICRP Publication 71, *Ann. ICRP*, 25 (3–4) (1995).

12) ICRP; Age-dependent Doses to the Member of the Public from Intake of Radionuclides–Part 5 Compilation of Ingestion and Inhalation Coefficients. ICRP Publication 72, *Ann. ICRP*, 25 (1) (1995).

13) N. Yamagata, K. Iwashima, T. Nagai, K. Watari and T. Ainuma; *In vivo* experiment on the metabolism of Cs in human blood with reference to rubidium and potassium. *J. Radiol. Res.*, 7 (1), 29–46 (1996).

14) G. V. Leroy, J. H. Rust and R. J. Hasterlik; The consequences of ingestion by man of real and simulated fallout. *Health Phys.*, 12 (4), 449–473 (1966).

15) N. A. Beresford, R. W. Mayes, B. J. Howard, H. F. Eyres, C. S. Lamb, C. L. Barnett and M. G. Segal; The bioavailability of different forms of radionuclides for transfer across the gut of ruminants. *Radiat. Prot. Dosim.*, 41 (2–4), 87–91 (1992).

16) N. A. Beresford, R. W. Mayes, C. L. Barnett, P. J. Maceachern and N. M. J. Crout; Variation in the metabolism of radionuclides between individual sheep. *Radiat. Environ. Biophys.*, 37, 277–281 (1998).

17) N. A Beresford, R. W. Mayes, A. J. Cooke, C. L. Barnett, B. J. Howard, C. S. Lamb and G. P. L. Naylor; The importance of source-dependent bioavailability in determining the transfer of ingested radionuclides to ruminant-derived food products. *Environ. Sci. Technol.*, 34 (21), 4455–4462 (2000).

18) K. Henrichs, H. G. Paretzke, G. Voigt and D. Berg; Measurements of Cs absorption and retention in man. *Health Phys.*, 57 (4), 571–578 (1989).

19) A. I. Cooke, N. Green, D. L. Rimmer, T. E. Weekes, B. T. Wilkins, N. A. Beresford and J. D. Fenwick; Absorption of radionuclides by sheep after ingestion of contaminated soils. *Sci. Total Environ.*, 192 (1), 21–29 (1996).

20) R. J. Talbot, D. Newton and M. G. Segal; Gastrointestinal absorption by rats of 137Cs and 88Sr from U3O8 fuel particles: implications for radiation doses to man after a nuclear accident. *Radiat. Prot. Dosim.*, 50 (1), 39–43 (1993).

21) K. M. Ellickson, C. J. Schopfer and P. J. Lioy; The bioaccessibility of low level radionuclides from two Savannah river site soils. *Health Phys.*, 83 (4), 476–484 (2002).

22) W. A. McKay and S. D. Memmott; An investigation of the availability of 137Cs and 239 + 240Pu for gut absorption in winkles following cooking and in vitro simulated gastrointestinal digestion. *Food Addit. Contaminants,*, 8 (6), 781–786 (1991).

23) S. C. Sheppard, W. G. Evenden and W. J. Schwartz; Ingested soil: bioavailability of sorbed lead, cadmium, cesium, iodine, and mercury. *J. Environ. Qual.*, 24 (3), 498–505 (1995).

24) S. Takahara, M. Ikegami, M. Yoneda, H. Kondo, A. Ishizaki, M. Iijima, Y. Shimada and Y. Matsui; Bioaccessibility of Fukushima accident-derived Cs in soils and the contribution of soil ingestion to radiation doses in children. *Risk Anal.*, 37 (7), 1256–1267 (2017).

25) B. Rossor, S. H. Cohn and H. Spencer; Cs-137 Metabolism in man. *Radiat. Res.*, 19 (4), 643–654 (1963).

26) USEPA; Guidelines for Exposure Assessment. U. S. Environmental Protection Agency, Risk Assessment Forum, Washington, DC, EPA/600/Z-92/001, (1992).

27) D. J. Paustenbach; The practice of exposure assessment: a state-of-the-art review. *J Toxicol. Environ. Health B Crit Rev*, 3 (3), 179–291 (2000).

28) IAEA; Actions to Protect the Public in an Emergency due to Severe Conditions at a Light Water Reactor; EPR-NPP-PPA (2013).

29) E. Calabrese; Improving the scientific foundations for estimating health risks from the Fukushima incident. *Proc. Natl. Acad. Sci. USA.*, 108 (49), 19447–19448 (2011).

30) Fukushima City Assembly; Minutes of the regular meeting of Fukushima City Assembly, 2011; No. 4 9-December. (in Japanese) Available at: http://www.city.fukushima.jp/voices/, Accessed 22 June 2016.

31) Fukushima Prefectural Assembly; Minutes of the regular meeting of Fukushima Prefectural Assembly, 2012; No. 4, 27-February. (in Japanese) Available at: http://www.kaigiroku.net/kensaku/fukushima/fukushima.html, Accessed 22 June 2016.

32) M. Cristy and K. F. Eckerman; Specific Absorbed Fractions of Energy at Various Ages from Internal Photon
Sources, ORNL/TM-8381/V1-V7, Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA (1987).

33) K. F. ECKERM, R. W. LEGGETT, M. CRIST, C. B. NELSON, J. C. RYMAIN, A. L. SIOREN and R. C. WARD; User’s Guide to the DCAL System, ORNL/TM-2001/190, Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA (2006).

34) M. CRIST; Mathematical phantoms representing children of various ages for use in estimates of internal dose. ORNL/NUREG/TM-367, Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA (1980).

35) ICRP; Human Alimentary Tract Model for Radiological Protection, ICRP Publication 100, Ann. ICRP, 36 (1–2) (2006).

36) ICRP; Occupational Intakes of Radionuclides: Part 1. ICRP Publication 130, Ann. ICRP, 44 (2) (2015).

37) ICRP; Dose Coefficients for Intakes of Radionuclides by Workers. ICRP Publication 68, Ann. ICRP, 24 (4) (1994).

Mochamad Adhiraga Pratama
Mochamad Adhiraga Pratama is a postdoctoral researcher in Japan Atomic Energy Agency. His research focuses on the dynamic of radioactive substances in municipal sewer systems and the risk assessment after internal exposure of members of the public. His published works deal with modeling of radioesium movement in the environment and risk analysis of organochlorine pesticide contamination in the aquatic environment. He received both his B.Eng. and M.Eng. in environmental engineering from Bandung Institute of Technology and his Dr. Eng. in environmental engineering from Kyoto University.

E-mail: pratama.mochamadadhiraga@jaea.go.jp