Using Experimental Transfer Factors to Estimate the Ratio between the Committed Effective Dose from Ingestion of Radio-tellurium to that of Radio-cesium Released by the Fukushima Daiichi Nuclear Power Plant Accident

Tomoyuki TAKAHASHI,*1, # Keiko FUJIWARA,*1 Tadatoshi KINOUCHI,*1 Satoshi FUKUTANI,*1 and Sentaro TAKAHASHI*1

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Tellurium (Te) isotopes were released into the environment with other radioactive isotopes including cesium (Cs) and iodine (I) as a result of the accident at the Fukushima Daiichi Nuclear Power Plant. There is a possibility that the ingestion of Te-127m and Te-129m with foods may cause a significant internal radiation dose for the public because the half-lives of these isotopes are relatively long 109 and 33.6 days, respectively. Data on the transfer of Te from cultivated soil to plants through roots is essential to estimate the contribution of radioactive Te to the internal radiation dose in the public. However, little is known about transfer of Te from soil to plants in the ecosystem. Therefore, we previously estimated transfer factors for stable Te and Cs from soil to radish and komatsuna by experiments. In the present study, we calculated ratios of committed effective dose for radioactive Te to radioactive Cs by using our experimentally estimated transfer factors for stable Te and Cs as well as those reported by the IAEA. Ratios calculated with transfer factors estimated by the IAEA report were two orders of magnitude higher than those calculated with our measured transfer factors. These results suggest that the committed effective dose from ingestion of radioactive Te is probably considerably lower than the dose based on IAEA results.

KEY WORDS: soil-to-plant transfer factor, tellurium, cesium, committed effective dose, Fukushima nuclear power plant accident.

I INTRODUCTION

The Fukushima Daiichi Nuclear Power Plant (FDNPP) accident in 2011 caused the release of large amounts of tellurium (Te) isotopes and various other radionuclides, including cesium (Cs) and iodine (I), into the environment.1) Owing to the large amount of Te-127m and Te-129m and their relatively long half-lives (109 and 33.6 days), these isotopes could have contributed to the internal radiation doses of public through ingestion of foods harvested in the contaminated area during an early period following the accident.

Considerable experimental data are available on behavior in the environment for radionuclides that have been thought to have health effects on human beings (e.g., Cs-137 and I-131). However, only limited information is available on the environmental behaviors of some radionuclides, including isotopes of Te. The transfer factor (TF) of a radionuclide from soil to plant is required to determine internal radiation doses through agricultural products. Only one TF for Te is given in the International Atomic Energy Agency Technical Report Series No. 472 (TRS 472),2) and only a few researchers have noticed the importance of the environmental behavior of Te after the FDNPP accident.3)

It is well known that TF values vary largely depending on many environmental conditions such as the kinds of plant and soil. Therefore, it is difficult to estimate committed effective dose accurately by using few experimental data on TF. For this reason, we focused on the ratio between the TF of Te and that of Cs and experimentally determined the TF values of Te and Cs from soil to radish (Raphanus sativus var. sativus) and to komatsuna (Brassica rapa var. perviridis).4) This approach is a first step for accurate estimation of committed effective dose by radioactive Te.

In the present study, the ratio between the committed effective doses from the ingestion of radioactive Te and that of radioactive Cs released by the FDNPP accident was estimated by using the TF values of Te and Cs measured in our previous study. In addition, we compared the ratio with that calculated by using the TFs reported in the IAEA TRS 472. These ratios indicate whether internal exposure pathway by ingestion of radioactive Te contribute to total internal radiation dose or not.

II MATERIALS AND METHODS

1. Activity ratio between radionuclides

To estimate the committed effective dose due to oral ingestion of leafy vegetables contaminated by the root uptake...
of radionuclides, it is necessary to estimate their concentration in the soil. In this study, we focused on comparison of the committed effective doses of Te and Cs; therefore, we used the radioactivity ratio of each of them in soil.

The Nuclear and Industrial Safety Agency reported that during the FDNPP accident the amounts of released radioactive Te-127m and Te-129m were $1.1 \times 10^{14}$ Bq and $3.3 \times 10^{15}$ Bq.\(^1\) SCHAURT ET AL.\(^6\) estimated that the amounts of Te-127m and Te-129m in the nuclear fuel assemblies a day after reactor scram were $3.58 \times 10^{14}$ Bq and $1.18 \times 10^{15}$ Bq. From these values, we assumed that the radioactivity ratio between Te-127m and Te-129m was 1:3 on March 11, 2011.

After reactor scram were 3.58 × 10\(^{14}\) Bq and 1.18 × 10\(^{15}\) Bq. The average radioactivity ratios of Te-129m to Cs-137 in the nuclear fuel assemblies a day were 3.8 × 10\(^{-2}\) and 1.5 × 10\(^{-2}\), respectively. These dates were determined based on the average radioactivity ratios of Cs-134 to Cs-137 of radionuclides, it is necessary to estimate their concentration in the soil. In this study, we focused on comparison of the committed effective doses of Te and Cs; therefore, we used the radioactivity ratio of each of them in soil.

We estimated the radioactivity ratio of Te-129m to Cs-137 between Te-127m and Te-129m was 1:3 on March 11, 2011.

SCHWANTES ET AL.\(^3\) reported a detailed deposition map of Te-129m within the 80 km radius of the FDNPP, and suggested that the radioactivity ratio of Te-129m to Cs-137 for the southern coastal area (area A) and the whole area (area B) on a normalized date (June 14, 2011) were 1.49 and 0.17, respectively. These dates were determined based on the average radioactivity ratios of Te-129m to Cs-137 was 0.91 on June 14, 2011.

In this study, we assumed the harvest dates of the leafy and root vegetables were April 30 and October 30, 2011, respectively. These dates were determined based on the growing period of the vegetables.

To estimate the committed effective dose due to oral ingestion of Te-129m to that of Cs-137 using the above radioactivity ratios. In addition, SAIJO ET AL.\(^6\) reported that the average radioactivity ratio of Cs-134 to Cs-137 was 0.91 on June 14, 2011.

We estimated the committed effective dose due to oral ingestion of Te-129m to that of Cs-137 using the above radioactivity ratios. In addition, SAIJO ET AL.\(^6\) reported that the average radioactivity ratio of Cs-134 to Cs-137 was 0.91 on June 14, 2011.

In this study, we assumed the harvest dates of the leafy and root vegetables were April 30 and October 30, 2011, respectively. These dates were determined based on the growing period of the vegetables.
ingestion of leafy and root vegetables contaminated by root uptake, we estimated the doses for area A and area B on the assumption that the Cs-137 concentration in the soil was 10 Bq/g. This assumption was made for easier understanding of the results and this concentration does not affect the ratios of the committed effective dose. We assumed that harvest and ingestion dates of each vegetable were the same for a conservative approach.

The estimated radioactivity concentrations in each vegetable are shown in Table 4. Concentrations of Te-127m and Te-129m in area A were higher than those in area B, due to differences in the soil concentration ratio. Cs-134 and Cs-137 concentrations in vegetables determined using TF values from our previous study were higher than those determined using TF values reported in TRS 472. In addition, Te-127m and Te-129m concentrations determined using TF values from our previous study were lower than those determined using TF values reported in TRS 472.

2. Estimation of the committed effective dose

In the present study, a single ingestion dose was assumed, following a conservative approach to determine the ratio of committed effective dose due to ingestion of radioactive Cs to that of radioactive Te. This approach was used because the half-lives of Te-127m and Te-129m are shorter than those of Cs-134 and Cs-137.

For example, the ratios of the committed effective dose of Te-127m to Cs-137 of single vegetable ingestion were estimated using the following equation.

$$ R = \frac{C_{\text{Cs-137}}}{C_{\text{Te-127m}}} \frac{\varepsilon(Te-127m)}{\varepsilon(Cs-137)} $$

Here, $R$ (-) is the ratio of the committed effective dose of Te-127m to Cs-137, $C_{\text{Te-127m}}$ (Bq/g) and $C_{\text{Cs-137}}$ (Bq/g) are the concentration of Te-127m to Cs-137 in food, respectively, and $\varepsilon(Te-127m)$ (Sv/Bq) and $\varepsilon(Cs-137)$ (Sv/Bq) are the dose coefficient of Te-127m and Cs-137, respectively.

Ratios of the committed effective dose for each nuclide to Cs-137 and of (Te-127m + Te-129m) to (Cs-134 + Cs-137) after single ingestion of leafy vegetables calculated with the TFs from TRS 472 and experimental data are shown in Tables 5 and 6, respectively. In addition, those after single ingestion of root vegetables calculated with the TFs from TRS 472 and experimental data are shown in Tables 7 and 8, respectively.

Ratios of the committed effective dose of (Te-127m + Te-129m) to (Cs-134 + Cs-137) after ingestion are larger for younger people. As shown in Tables 5 and 6, the ratios after single ingestion of leafy vegetables for three-month-old child in area A were 4.7 × 10^2 using values from TRS 472 and 3.5 × 10^2 using values from our experimental data. The ratios after single ingestion of leafy vegetables for adult in area A were 4.4 × 10^0 using values from TRS 472 and 3.2 × 10^{-2} using values from our experimental data. The same trends were observed for area B and after ingestion of root vegetables in both areas.

### Table 4 Estimated concentrations* in plants on the day of harvest.

| TF       | Area | Part | $^{134}$Cs | $^{137}$Cs | $^{129}$mTe | $^{130}$Te |
|----------|------|------|-----------|------------|-------------|-------------|
| TRS 472  | A    | Leaf | 3.8 × 10^{-1} | 3.6 × 10^{-1} | 7.7 × 10^{-1} | 1.1 × 10^{-1} |
|          |      | Root | 1.5 × 10^{-1} | 1.2 × 10^{-1} | 2.4 × 10^{-1} | 2.6 × 10^{-1} |
|          | B    | Leaf | 3.8 × 10^{-1} | 3.6 × 10^{-1} | 8.8 × 10^{-1} | 1.3 × 10^{-1} |
|          |      | Root | 1.5 × 10^{-1} | 1.2 × 10^{-1} | 2.8 × 10^{-1} | 3.0 × 10^{-1} |
| Our      | A    | Leaf | 1.2 × 10^{-2} | 1.1 × 10^{-2} | 6.9 × 10^{-3} | 1.0 × 10^{-2} |
|          |      | Root | 1.0 × 10^{-2} | 8.2 × 10^{-3} | 1.9 × 10^{-3} | 2.0 × 10^{-3} |
| experimental data |   | Leaf | 1.2 × 10^{-2} | 1.1 × 10^{-2} | 7.9 × 10^{-3} | 1.2 × 10^{-3} |
|          | B    | Root | 1.0 × 10^{-2} | 8.2 × 10^{-3} | 2.1 × 10^{-2} | 2.3 × 10^{-3} |

* Each value is expressed in Bq/g when the $^{137}$Cs concentration in the soil was assumed to be 10 Bq/g.

**“Area A” refers to the southern coastal area with high $^{129}$mTe/$^{137}$Cs ratios; “area B” refers to the whole area with average $^{129}$mTe/$^{137}$Cs ratios.

### Table 5 Ratios of the committed effective dose of each nuclide to $^{137}$Cs after single ingestion of leafy vegetables, calculated with the transfer factors of TRS 472.

| Area | Nuclide | 3 months | 1 year | 5 years | 10 years | 15 years | Adult |
|------|---------|----------|--------|---------|----------|----------|-------|
| A    | $^{134}$Cs/$^{137}$Cs | 1.2 × 10^0 | 1.3 × 10^0 | 1.3 × 10^0 | 1.3 × 10^0 | 1.4 × 10^0 | 1.4 × 10^0 |
|      | $^{129}$mTe/$^{137}$Cs | 3.9 × 10^{-1} | 3.0 × 10^{-1} | 2.0 × 10^{-1} | 1.1 × 10^{-1} | 4.7 × 10^{-1} | 3.6 × 10^{-1} |
|      | $^{130}$Te/$^{137}$Cs | 6.2 × 10^{-1} | 5.9 × 10^{-1} | 3.7 × 10^{-1} | 2.0 × 10^{-1} | 8.9 × 10^{-2} | 6.8 × 10^{-2} |
| A    | $^{129}$mTe/($^{137}$Cs + $^{134}$Cs) | 4.7 × 10^{-1} | 4.0 × 10^{-1} | 2.5 × 10^{-1} | 1.3 × 10^{-1} | 5.7 × 10^{-2} | 4.4 × 10^{-2} |
|      | $^{130}$Te/($^{137}$Cs + $^{134}$Cs) | 4.5 × 10^{-1} | 3.5 × 10^{-1} | 2.3 × 10^{-1} | 1.2 × 10^{-1} | 5.3 × 10^{-2} | 4.1 × 10^{-2} |
| B    | $^{129}$mTe/$^{137}$Cs | 7.1 × 10^{-1} | 6.8 × 10^{-1} | 4.2 × 10^{-1} | 2.2 × 10^{-1} | 1.0 × 10^{-1} | 7.8 × 10^{-2} |
|      | $^{130}$Te/($^{137}$Cs + $^{134}$Cs) | 5.5 × 10^{-1} | 4.5 × 10^{-1} | 2.9 × 10^{-1} | 1.5 × 10^{-1} | 6.5 × 10^{-2} | 5.0 × 10^{-2} |

* “Area A” refers to the southern coastal area with high $^{129}$mTe/$^{137}$Cs ratios; “area B” refers to the whole area with average $^{129}$mTe/$^{137}$Cs ratios. In this estimation, the transfer factor of TRS 472 was used. The date of harvest was assumed as April 30, 2011.
Table 6  Ratios of the committed effective dose of each nuclide to $^{137}$Cs by continuous ingestion of leafy vegetables during one year since harvest, calculated with transfer factors determined by our experimental data.

| Area* | Nuclide | 3 months | 1 year  | 5 years | 10 years | 15 years | Adult     |
|-------|---------|----------|---------|---------|----------|----------|-----------|
| A, B  | $^{131}$Cs/$^{137}$Cs | $1.0 \times 10^{-3}$ | $1.1 \times 10^{-3}$ | $1.1 \times 10^{-3}$ | $1.1 \times 10^{-3}$ | $1.2 \times 10^{-3}$ | $1.2 \times 10^{-3}$ |
|       | $^{129m+131m}$Te/$^{137}$Cs | $4.6 \times 10^{-4}$ | $3.5 \times 10^{-4}$ | $2.3 \times 10^{-4}$ | $1.2 \times 10^{-4}$ | $5.4 \times 10^{-5}$ | $4.2 \times 10^{-4}$ |
| A     | $^{129m}$Te/$^{137}$Cs | $2.5 \times 10^{-4}$ | $2.4 \times 10^{-4}$ | $1.5 \times 10^{-4}$ | $7.8 \times 10^{-5}$ | $3.6 \times 10^{-5}$ | $2.7 \times 10^{-4}$ |
|       | $^{127m+129m}$Te/$^{137}$Cs | $3.5 \times 10^{-4}$ | $2.8 \times 10^{-4}$ | $1.8 \times 10^{-4}$ | $9.4 \times 10^{-5}$ | $4.1 \times 10^{-5}$ | $3.2 \times 10^{-4}$ |
| B     | $^{129m}$Te/$^{137}$Cs | $5.3 \times 10^{-4}$ | $4.0 \times 10^{-4}$ | $2.7 \times 10^{-4}$ | $1.4 \times 10^{-4}$ | $6.2 \times 10^{-5}$ | $4.8 \times 10^{-4}$ |
|       | $^{127m+129m}$Te/$^{137}$Cs | $2.8 \times 10^{-4}$ | $2.7 \times 10^{-4}$ | $1.7 \times 10^{-4}$ | $8.9 \times 10^{-5}$ | $4.1 \times 10^{-5}$ | $3.1 \times 10^{-4}$ |
|       | $^{127m}$Te/$^{137}$Cs | $4.0 \times 10^{-4}$ | $3.2 \times 10^{-4}$ | $2.1 \times 10^{-4}$ | $1.1 \times 10^{-4}$ | $4.7 \times 10^{-5}$ | $3.6 \times 10^{-4}$ |

* “Area A” refers to the southern coastal area with high $^{129m+131m}$Te/$^{137}$Cs ratios; “area B” refers to the whole area with average $^{129m+131m}$Te/$^{137}$Cs ratios. In this estimation, transfer factors determined by our previous study were used. The date of harvest was assumed as April 30, 2011.

Table 7  Ratios of the committed effective dose for each nuclide to $^{137}$Cs after the single ingestion of root vegetable, calculated with the transfer factors of TRS 472.

| Area* | Nuclide | 3 months | 1 year  | 5 years | 10 years | 15 years | Adult     |
|-------|---------|----------|---------|---------|----------|----------|-----------|
| A, B  | $^{131}$Cs/$^{137}$Cs | $1.0 \times 10^{-3}$ | $1.1 \times 10^{-3}$ | $1.1 \times 10^{-3}$ | $1.1 \times 10^{-3}$ | $1.2 \times 10^{-3}$ | $1.2 \times 10^{-3}$ |
|       | $^{129m+131m}$Te/$^{137}$Cs | $3.2 \times 10^{-4}$ | $2.4 \times 10^{-4}$ | $1.6 \times 10^{-4}$ | $8.4 \times 10^{-5}$ | $3.7 \times 10^{-5}$ | $2.9 \times 10^{-4}$ |
| A     | $^{129m}$Te/$^{137}$Cs | $3.7 \times 10^{-4}$ | $3.5 \times 10^{-4}$ | $2.2 \times 10^{-4}$ | $1.2 \times 10^{-4}$ | $5.2 \times 10^{-5}$ | $4.0 \times 10^{-4}$ |
|       | $^{127m+129m}$Te/$^{137}$Cs | $1.8 \times 10^{-4}$ | $1.3 \times 10^{-4}$ | $8.7 \times 10^{-5}$ | $4.5 \times 10^{-5}$ | $1.9 \times 10^{-5}$ | $1.5 \times 10^{-4}$ |
| B     | $^{129m}$Te/$^{137}$Cs | $3.6 \times 10^{-4}$ | $2.8 \times 10^{-4}$ | $1.8 \times 10^{-4}$ | $9.6 \times 10^{-5}$ | $4.3 \times 10^{-5}$ | $3.3 \times 10^{-4}$ |
|       | $^{127m+129m}$Te/$^{137}$Cs | $4.2 \times 10^{-4}$ | $4.0 \times 10^{-4}$ | $2.5 \times 10^{-4}$ | $1.3 \times 10^{-4}$ | $6.0 \times 10^{-5}$ | $4.6 \times 10^{-4}$ |
|       | $^{127m}$Te/$^{137}$Cs | $2.0 \times 10^{-4}$ | $1.5 \times 10^{-4}$ | $9.9 \times 10^{-5}$ | $5.1 \times 10^{-5}$ | $2.2 \times 10^{-5}$ | $1.7 \times 10^{-4}$ |

* “Area A” refers to the southern coastal area with high $^{129m+131m}$Te/$^{137}$Cs ratios; area B refers to the whole area with average $^{129m+131m}$Te/$^{137}$Cs ratios. In this estimation, the transfer factor of TRS 472 was used. The date of harvest was assumed as October 30, 2011.

These results show that ratios calculated with TF values from TRS 472 are two orders of magnitude higher than those calculated with values from our experimental data. These results indicate that the committed effective dose for radioactive Te may be considerably lower than that calculated with the TFs from TRS 472. However, as shown in Table 2, the transfer and distribution of Cs and Te vary among kinds of plant and soil, leading to a large range of TF values. In order to estimate the internal radiation dose more accurately, it is necessary to examine the TFs in various soils and choose the most suitable value.

IV CONCLUSIONS

Ratios of committed effective dose of radioactive Te to radioactive Cs calculated with TF reported in TRS 472 were two orders of magnitude higher than those calculated with values of our previously obtained experimental data. This indicated that the committed effective dose of radioactive Te may be considerably lower than that calculated on the basis of values reported in TRS 472. However, the results are based on the experimental data for root vegetable and leafy vegetable. In order to estimate the internal radiation dose more accurately, it is necessary to obtain TFs in a large variety of soils and plants such as rice which is the staple food of the Japanese. It is important to carry out experiments using different soils.
to obtain more reliable transfer factors of Te and to reveal the mechanisms of migration of Te from these soils to plants.

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