Interception, loss and translocation of ^{85}Sr, ^{103}Ru and ^{134}Cs in the rice plants sprayed with a mixed RI solution

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Abstract. Interception, loss and translocation of ^{85}Sr, ^{103}Ru and ^{134}Cs in rice plants were investigated through a greenhouse experiment in which the whole aboveground plant parts were exposed to radioactive spray at 6 different growth stages. Showing little difference among radionuclides, the interception factor tended to increase as the plant grew to maturity. The highest observed factor was 0.94. The fractions of the intercepted activity that remained in rice plants at harvest were 0.19~0.42 for ^{85}Sr, 0.23~0.62 for ^{103}Ru and 0.11~0.69 for ^{134}Cs, depending on application times. The translocation factors for hulled seeds were in the range of 5.8×10^{-4}~3.2×10^{-2} for ^{85}Sr, 1.6×10^{-4}~7.6×10^{-3} for ^{103}Ru and 3.2×10^{-2}~2.0×10^{-1} for ^{134}Cs indicating the highest mobility of ^{134}Cs. The greatest translocation factor of every radionuclide came when plants were contaminated at the active seed growth stage. It was indicated that weathering loss and translocation would not greatly depend on the rain frequency if it differs by a factor of less than 2. Based on the experimental results, the concentrations of ^{85}Sr, ^{90}Sr, ^{103}Ru, ^{106}Ru, ^{134}Cs and ^{137}Cs in hulled rice seeds at harvest were estimated for their deposition at different growth stages

1. INTRODUCTION

Rice is one of the most important food crops in the world and as high as 12% of the national area is used as paddy fields in Korea [1]. Radiostrontium, radioruthenium and radiocesium can be deposited onto crop fields in a comparatively large amount after an accidental release from nuclear facilities [2]. If such deposition occurs during the growing season of crop plants, they shall be directly contaminated with radioactivity. It is well known that direct contamination of the plant's aerial part generally results in a higher food-chain radiation dose than does root uptake of radionuclides from contaminated soil [3,4].

A number of experiments concerning direct plant contamination have been made with various food crops like wheat, barley, grasses, lettuce, beans, fruits and so on [5-10]. Little work, however, has been done with rice. In most experiments, radioactive solutions were applied to crop plants using a spray or nebulizer to simulate the plant contamination via dry deposition of fine and highly soluble radioactive particulates or via wet deposition in light rain [5,6,9].

In this study, the direct contamination pathway of radiostrontium, radioruthenium and radiocesium in rice plants were investigated through a greenhouse experiment in which rice plants at different growth stages were sprayed with a radioactive solution containing ^{85}Sr, ^{103}Ru and ^{134}Cs. Based on the results obtained, radionuclide concentrations in rice seeds were predicted for unit deposition at different stages.

2. MATERIALS AND METHODS

2.1 Rice culture

Rice seedlings were transplanted to flooded culture boxes in mid May. The culture boxes, installed in a greenhouse, were 0.6 m wide, 0.6 m long and 1.0 m high. Soil in the top 15 cm layer was an acidic sandy loam. The planting density was 12 hills per box with 4 plants per hill. Agricultural practices such as irrigation, fertilization and disease control were made as required. All windows were removed to let as much wind as possible blow in.

2.2 Radionuclide application

The radionuclide application was made at 6 different times of 37, 65, 87, 100, 114 and 132 days after transplanting. The heading, that is, ear emergence began 92 days after transplanting. A solution containing career-free ^{85}Sr, ^{103}Ru and ^{134}Cs (47, 70 and 17 kBq per ml, respectively, as of the harvest day) was applied using a home spray to the whole aboveground parts of the rice plants in an exposure box mounted onto the culture box. The exposure box was 0.9 m wide, 0.9 m long and 1.3 m high.

The spraying height was about 0.5~0.7 m above the plant canopy and a total of 31 shots were given for each application with 3 shots to the 9 divisions of the planting area and one additional shot to the 4 divisions at the corners. It took about 15 ml of the solution and 16 s to complete the spraying. The soil surface in the culture box was covered with absorbent paper to prevent radionuclide deposition onto the soil.

Rain was simulated for the contaminated plants by sprinkling tap water from about 0.5 m above the plant canopy at the rate of 4.5~6.0 l per box every 3~5 days depending on the month. For the applications made 65 and 114 days after transplanting, the test with a rain simulation in half the above-mentioned frequency was also carried out. The first rain was simulated 3 days after each radionuclide application.

2.3 Sampling and measurement

Three hours after the radionuclide application, the absorbent paper was removed and 6 hills of the rice plants were cut out. The remaining 6 hills of the plants were grown to maturity and harvested 149 days after transplanting. Plant and paper samples were air-dried in the greenhouse for longer than 3 weeks and the dried plants were separated into straw, chaff and hulled seeds. Dried straw and absorbent paper were cut into small pieces using scissors.

The radionuclide concentrations in the samples were determined by γ-spectrometry using a HPGe detector (EG&G ORTEC). The detection time was 0.5~2 h depending on the sample activity. Counting error was less than 10% in 2σ. All the concentrations were decay-corrected to harvest time.

3. RESULTS AND DISCUSSION

3.1 Plant interception

Plant interception of the applied activity was quantified with the interception factor, which was defined as the fraction of the total deposition (onto plant plus absorbent paper) that was deposited onto the whole aboveground plant parts. Table 1 gives the biomass of the aboveground parts and the interception factors of ^{85}Sr, ^{103}Ru and ^{134}Cs varying with the times of radionuclide application.

Table 1. Interception factors of ^{85}Sr, ^{103}Ru and ^{134}Cs applied at different growth stages of rice plants

Application time		Biomass (kg-dry m^{-2})		Interception factor [c]		
DAT [a]	Growth stage	Total [b]	Ear	^{85}Sr	^{103}Ru	^{134}Cs
37	Tillering	0.08	-	0.48 (-)	0.47 (-)	0.48 (-)
65	Elongation	0.39	-	0.80 (-)	0.79 (-)	0.80 (-)
87	Booting	0.93	-	0.88 (-)	0.88 (-)	0.88 (-)
100	Milky ripe	1.04	0.11	0.87 (0.05)	0.87 (0.05)	0.88 (0.06)
114	Dough ripe	1.70	0.47	0.94 (0.19)	0.93 (0.19)	0.94 (0.19)
132	Yellow ripe	1.91	0.86	0.94 (0.16)	0.94 (0.16)	0.94 (0.16)

[a] Days after transplanting

[b] The whole aboveground parts

[c] Values in parentheses denote interception factors for ears.

There was little difference in the interception factor among radionucldies. Rauret *et al.* [7] also observed no difference in the interception factor between ^{85}Sr and ^{134}Cs, which were applied to lettuce plants in the form of aerosol. The interception factor increased with increasing biomass as the plants grew to maturity. It increased rather rapidly till the elongation stage, after which it increased very slowly and stayed around 0.9 since the booting stage. Similar trends were also found in other crops [11-13]. It was highest at 114 and 132 days after transplanting, although many leaves were dried up then. This can be explained by the relatively great depositions onto the ears on those days as shown in Table 1.

Plant interception may depend on the planting density. The planting density in this experiment was 33 hills m^{-2} being 20~30% higher than a normal density in the real rice field [14]. Thus, the interception factor might be more or less overestimated in this experiment and a somewhat conservative assessment could be expected with the present data. This effect seems to be more direct when the deposition occurs at the early growth stage.

3.2 Remaining fraction at harvest

Figure 1 shows the fraction of the intercepted activity that remained in the whole aboveground plant parts at harvest. The remaining fraction increased with increasing time intervals between transplanting and radionuclide application. It was in the range of 0.19~0.42, 0.23~0.62 and 0.11~0.69 for ^{85}Sr, ^{103}Ru and ^{134}Cs, respectively.

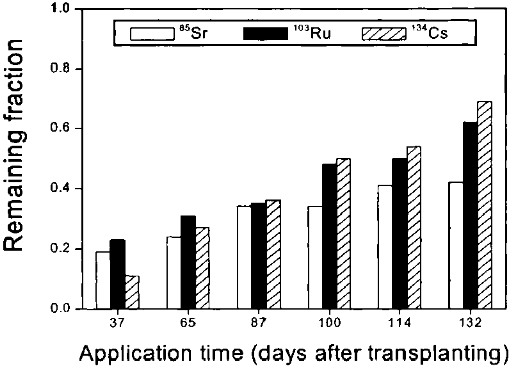

Figure 1. Fractions of the intercepted activity that remained in rice plants at harvest (149 days after transplanting).

The remaining fraction is determined by the activity loss resulting mainly from the environmental weathering by rain and wind [8,15]. The magnitude of this loss of a radionuclide would depend on an interaction of many factors including its solubility, strength of the adsorption and the degree of permeation into the inner flesh and secretion to the exterior. The loss was most rapid after the latest application with 31~58% of the intercepted activity being removed in 17 days. This is partly attributable to the fact that most activity, not entering the interior, stays on the leaf surface during the early phase after the application.

Table 2 gives the weathering half-lives of ^{85}Sr, ^{103}Ru and ^{134}Cs calculated with data in Figure 1 assuming that they do not change with time since deposition. Half-lives of ^{85}Sr and, to a lesser degree, ^{103}Ru tended to be shorter for the later application. This kind of time-dependence was, however, not clear in ^{134}Cs. ^{85}Sr had much shorter half-lives than ^{103}Ru and ^{134}Cs for the latest three applications. This suggests that adsorption strength or permeability of ^{85}Sr might be comparatively low during the earlier phase after the application or that leachability of the absorbed ^{85}Sr might be comparatively high during the same phase. Aarkrog [6] also found that the weathering half-life of ^{85}Sr was shorter than that of ^{134}Cs in some grain crops for a decontamination period not longer than about 70 days.

Table 2. Weathering half-lives of ^{85}Sr, ^{103}Ru and ^{134}Cs applied at different growth stages of rice plants

Application time		Duration of weathering (d)	Weathering half-life (d)		
DAT	Growth stage		^{85}Sr	^{103}Ru	^{134}Cs
37	Tillering	112	47	53	36
65	Elongation	84	40	50	44
87	Booting	62	40	41	42
100	Milky ripe	49	32	46	49
114	Dough ripe	35	27	35	39
132	Yellow ripe	17	14	24	32

3.3 Translocation to seeds

Translocation to the edible part was quantified with the translocation factor, which was defined as the fraction of the total remaining activity that was contained in hulled seeds at harvest. Figure 2 shows ^{85}Sr, ^{103}Ru and ^{134}Cs translocation factors for different times of their application. The translocation factor of ^{134}Cs was greater than those of ^{85}Sr and ^{103}Ru indicating that ^{134}Cs was the most mobile of the three radionuclides in rice plants. Similar tendencies for the mobility difference were also found in many other crop species [8,16,17].

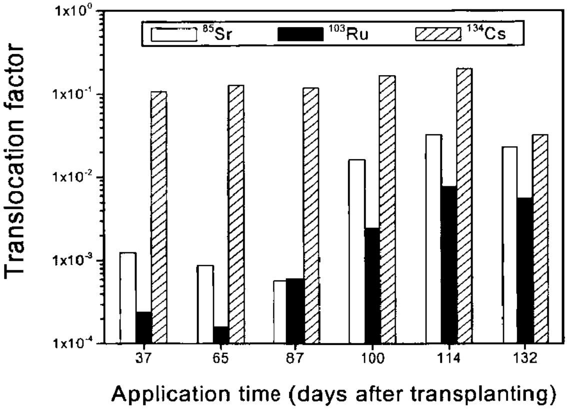

Figure 2. Translocation factors of ^{85}Sr, ^{103}Ru and ^{134}Cs for hulled rice seeds.

Translocation factors of the three radionuclides were highest when they were applied 114 days after transplanting, that is, at the stage of active seed growth. The translocation factor varied with application times by a factor of only about 6 for ^{134}Cs but by a factor of as high as 50 for ^{85}Sr and ^{103}Ru.

The patterns of the variation for ^{85}Sr and ^{103}Ru indicate that chaff-to-seed translocation contributes much more to their seed concentrations compared with leaf-to-seed translocation. On the other hand, it is indicative of an active leaf-to-seed translocation of ^{134}Cs that ^{134}Cs translocation factors for the earliest three applications, which were performed at the pre-heading stage, were not much lower than the highest. These different behaviors of the radionuclides are in general agreement with the results of wheat and barley experiments by Aarkrog [16]

3.4 Effect of rain frequency

Table 3 gives remaining fractions and translocation factors of ^{85}Sr, ^{103}Ru and ^{134}Cs under the rain simulated in a normal frequency and in half the normal frequency.

Table 3. Remaining fractions and translocation factors under the rain simulated in two different frequencies

Application time (DAT)	Rain frequency	Remaining fraction			Translocation factor		
		^{85}Sr	^{103}Ru	^{134}Cs	^{85}Sr	^{103}Ru	^{134}Cs
65	Normal	0.24	0.31	0.27	8.7×10^{-4}	1.6×10^{-4}	1.3×10^{-1}
	Half	0.30	0.39	0.29	9.0×10^{-4}	1.3×10^{-4}	1.3×10^{-1}
114	Normal	0.41	0.50	0.54	3.2×10^{-2}	7.6×10^{-3}	2.0×10^{-1}
	Half	0.40	0.49	0.55	2.9×10^{-2}	6.1×10^{-3}	1.8×10^{-1}

The remaining fraction was not different between two kinds of the rain simulation except that the more frequent rain resulted in slightly smaller remaining fractions of ^{85}Sr and ^{103}Ru applied 65 days after transplanting than the less frequent rain. Similarly, Middleton [18] showed that the removal of ^{89}Sr from wheat, potato and cabbage plants due to rain was greater than that for ^{137}Cs. The difference in translocation factor between two kinds of the rain simulation was found only in ^{103}Ru, which had a little bit higher translocation factors under the more frequent rain.

From these facts, it may be expected that the difference in the total precipitation due to different rain frequency would not cause a greatly different loss and translocation of ^{85}Sr, ^{103}Ru and ^{134}Cs in rice plants if the rain frequency differs by a factor of less than 2.

3.5 Prediction of seed concentrations

Based on the present experimental data, radionuclide concentrations in hulled rice seeds at harvest were predicted for the deposition onto the rice-growing field in the level of 1 Bq of each nuclide per m^2. The yield of hulled rice seeds was assumed to be 0.5 kg m^{-2} [1]. Table 4 shows the results of the prediction.

Table 4. Radionuclide concentrations in hulled rice seeds at harvest predicted for a deposition of 1 Bq m^{-2} for each nuclide

Deposition time		Radionuclide concentration in rice seeds (Bq kg^{-1}-dry)					
DAT	Growth stage	^{85}Sr	^{90}Sr	^{103}Ru	^{106}Ru	^{134}Cs	^{137}Cs
37	Tillering	6.7×10^{-5}	2.2×10^{-4}	7.3×10^{-6}	4.2×10^{-5}	1.1×10^{-2}	1.2×10^{-2}
65	Elongation	1.3×10^{-4}	3.2×10^{-4}	1.8×10^{-5}	6.7×10^{-5}	5.0×10^{-2}	5.4×10^{-2}
87	Booting	1.8×10^{-4}	3.4×10^{-4}	1.3×10^{-4}	3.3×10^{-4}	7.1×10^{-2}	7.4×10^{-2}
100	Milky ripe	5.7×10^{-3}	9.7×10^{-3}	8.7×10^{-4}	1.9×10^{-3}	1.4×10^{-1}	1.5×10^{-1}
114	Dough ripe	1.7×10^{-2}	2.5×10^{-2}	3.8×10^{-3}	6.6×10^{-3}	2.0×10^{-1}	2.0×10^{-1}
132	Yellow ripe	1.5×10^{-2}	1.8×10^{-2}	4.8×10^{-3}	6.3×10^{-3}	4.1×10^{-2}	4.2×10^{-2}

The concentration decreases in the order of radiocesium > radiostrontium ≥ radioruthenium. This is the same order as that for the translocation factor. It means that the translocation factor played a critical role in determining the concentration differences.

The concentration of ^{103}Ru, which has a comparatively short half life of 40 days, increases with a increasing time interval between transplanting and deposition. Concentrations of the others are, however, highest when they are deposited around 114 days after transplanting, that is, at the stage of active seed growth. The variation in the seed concentration with deposition time is greatest in ^{103}Ru and smallest in ^{137}Cs. The variation with radionuclides tends to decrease as deposition approaches harvest.

4. CONCLUSION

Interception, loss and translocation of ^{85}Sr, ^{103}Ru and ^{134}Cs to be deposited onto rice plants at different growth stages were investigated through a greenhouse experiment. The dependence of interception and translocation factors on the deposition time was relatively great. The translocation factor showed a great variation with radionuclides but the interception factor showed little variation. Patterns of the time-dependent variation and the difference among radionuclides are in reasonable agreement with those for other crop species in many previous works.

The obtained data can be utilized in predicting the radionuclide concentrations in rice seeds at the time of an accidental deposition during the growing season. They may be comparatively well applied to the deposition of fine and highly soluble particulates or to the deposition in light rain. It needs to be also noted that prediction using the present data can result in an overestimation of the seed concentration because they were produced under a higher planting density and a weaker wind effect than in real rice fields.

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