Article

Evaluation of ^{109}Cd Detection Performance of a Real-Time RI Imaging System for Plant Research

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In this study, real-time imaging using γ -emitting nuclide, ^{109}Cd , was studied and sensitivity and resolution of the system we developed was evaluated. When RI was applied to the plant, the radiation from the RI distributed throughout the plant was converted to visible light by a scintillator. Then, this weak light was multiplied by a micro-channel plate (MCP) and photographed by a charge-coupled device (CCD) camera. ^{109}Cd emits 88 keV γ -rays together with 22 keV X-rays, and therefore it is necessary to investigate effective condition for designing an observation system for the measurement of radiation from ^{109}Cd . Analysis was performed to determine which rays, γ -rays or X-rays, were mainly detected by this system and the optimal scintillator thickness for imaging ^{109}Cd was investigated. Then the sensitivity and resolution of the system was evaluated.

Key Words : evaluation of detector performance, plant, radioisotope imaging,
cadmium-109, scintillator, Monte Carlo simulation

1. Introduction

Observing how ions are absorbed by plants and transported within the plant sample provides very important information for plant research. We developed an imaging system for real-time observation of the nutrient uptake by the root and translocation to up-ground part of the plant¹⁾⁻³⁾. In the previous studies, imaging was performed mainly using β -emitting nuclides, such as ^{32}P , ^{35}S , ^{14}C , and ^{45}Ca ^{4),5)}. In this study, imaging using γ -emitting nuclide, ^{109}Cd , was studied and the sensitivity and resolution of the system was evaluated.

Cadmium is well known as a poisonous element for the human. After zinc smelting in mining operations and application to industrial products, this metal element has been thrown away into the environment, resulting in accumulation in soils such as rice fields. The uptake and accumulation of cadmium by rice and other crops during their growth period in contaminated fields causes a problem in crop production. However, little is known about the uptake manner of Cd by plants.

In this study, we tried to observe the absorption process of ^{109}Cd by the plant from a culture solution using the real-time RI imaging system we developed. The principle of the imaging system was as follows; when an RI was ab-

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Fig. 1 Schematic illustration of real-time imaging system.

When RI was applied to the plant, the radiation from the RI distributed throughout the plant was first converted to visible light by a scintillator. Then, this weak light was multiplied by a micro-channel plate (MCP) and photographed by a charge-coupled device (CCD) camera.

sorbed from roots, RI emitted γ -rays and the radiation from the RI in the plant was converted by a CsI(Tl) scintillator to visible light. Then this weak scintillation light was electronically multiplied by a MCP with a GaAsP photoelectric surface and photographed by a charge-coupled device (CCD) camera. The ultra-sensitive camera system consisted of an MCP and a CCD camera was a Hamamatsu Photonics image-intensifier unit. A series of CCD images was analyzed by a software AQUACOSMOS developed by Hamamatsu photonics, Co. Japan. Figure 1 showed the schematic illustration of the system.

In the previous studies, the imaging was successfully performed using β -emitting nuclides such as ^{32}P , ^{35}S , ^{45}Ca , and ^{14}C . In this study, ^{109}Cd was employed for imaging, which emits γ -rays, to observe the absorption process of Cd by the plant. The decay of ^{109}Cd is as follows:

^{109}Cd emits 88 keV γ -rays and 22 keV X-rays, therefore first of all, the detection performance

of the system for these rays was evaluated. A simulation study was also carried out to identify major rays detected by the system as well as to evaluate the resolution to obtain the optimum thickness of ^{109}Cd scintillator.

2. Experiment A

First, sensitivity measurements were performed. 10 kBq/5 μL of ^{109}Cd solution was mounted on a filter paper as a spot source for measurement. The relation between the counting efficiency of the scintillator and its thickness was measured using this spot source. The scintillator was prepared by depositing CsI(Tl) on a fiber-optic plate, which was then grown into a needle-like crystal (hereinafter referred to as FOS). The filling factor of the CsI(Tl) scintillator was 80%. Radiation was detected by the scintillator on the fiber-optic plate. Radiation counts were measured for five types of FOSs with different thicknesses of scintillators, 10, 25, 50, 100 and 200 μm .

Fig. 2 Relation between scintillator thickness and an image intensity. 10 kBq/ $5\mu\text{L}$ of ^{109}Cd solution was mounted on a filter paper as a spot source for measurement. Then the scintillator with different thickness, ranged from 10 to 200 μm , was used to measure the radioactivity counts. The pseudo-color was employed in the image of the spots according to the intensity of radioactivity.

3. Result A

Figure 2 showed the relation between scintillator thickness and radioactivity counts. The vertical axis was the relative radioactivity and the horizontal axis was the scintillator thickness. The detection counts were increased logarithmically as the thickness of the scintillator was increased.

4. Experiment B

We investigated the following points ; the intensity of detected radiation ; the resolution of imaging ; the scintillator and the sample thickness and the shielding material for the measurements.

4.1 Counting curve calculation and resolution evaluation

In case of β -ray, after the conversion to light by the scintillator, the light was emitted along with the trajectory of the β -ray and almost all

the β -rays entering the scintillator was detected. However, when γ -rays or X-rays was entered into the scintillator, the intensity of the radiation that passes within the materials was expressed by a probabilistic expression.

The absorption coefficient of γ -rays and X-rays has generally the following relationship to the radiation energy E , showing the degree of interaction between photons and material :

$$\mu = aE^{-b} \quad (1)$$

The transmittance p , which is a probabilistic figure and related to the intensity of detected radiation, is expressed by the following equation as a function of the scintillator thickness d :

$$p = \exp(-\mu d) \quad (2)$$

With high radiation energy and a very thin scintillator, most of the radiation is transmitted through the scintillator without interacting with the material, resulting in a decreased de-

Fig. 3 Simulation model of flight path of radiation.

Simulation was performed by Monte Carlo method from X(γ)-ray emission to detection by a scintillator.

tection count of radiation. Since the absorption coefficient and the radiation energy are the main factors for this decrease, it is possible to estimate the radiation energy from the feature of the decrease. Absorption coefficient in the scintillator was obtained from the NIMS (National Institute for Materials Science) database.

A Monte Carlo simulation was performed to estimate the detection count, using the following conditions and steps. Figure 3 showed the simulation model for the flight paths of radiation and fluorescence.

- Emission of radiation was assumed to be uniform in all spatial directions (the incident angle θ and the azimuth angle ψ are generated by random numbers)
- The probability of transmission of X(γ)-rays was calculated using equation (2), where $d = d_0 \cos \theta$ and d_0 = thickness of the scintillator (absorption coefficient μ was 73.36 cm^{-1} for 22 keV and 10.16 cm^{-1} for 88 keV.
- Calculation of the radiation counts according to the irradiated position (X, Y) were

performed based on the probabilistic treatment of the X(γ)-ray transmittance. The spread of scintillation light which varies with the luminous position and the direction of the light within the scintillator was not considered because the scintillator was grown into a needle-like shape.

The above calculation was repeated 2880 times for each scintillator, with five different thicknesses of the scintillator, to obtain count curves. Microsoft Excel was used for calculation.

4.2 Influence of the sample thickness and the shielding material

The influence of the sample thickness and the shielding material was investigated. In an actual measurement system there was self-absorption in the sample. In the imaging system, the front surface of the scintillator was covered with a $50 \mu\text{m}$ aluminum plate to prevent LED light, which was irradiated to the sample, from entering the CCD camera's lens⁷⁾. Therefore, the radioactivity counts and resolution of the

Fig. 4 Outline of Monte Carlo simulation

measurement system with the above-mentioned conditions was evaluated by the simulation study. Figure 4 indicated the outline of the Monte Carlo simulation process. The position in the depth and direction of the radiation emitted from the RI, was generated by uniform random numbers. This processing enabled the probabilistic evaluation of the detected counting rate and resolution considering the self-absorption both in the sample and in the light shielding plate, which was a $50\ \mu\text{m}$ aluminum plate inserted between the sample and the scintillator.

5. Result B

5.1 Counting curve calculation and resolution evaluation

Figure 5 showed the relationship between the scintillation thickness and the radiation count which was obtained from the Monte Carlo simulation. The solid line with $\square$ mark showed the radiation count for X-ray energy of 22 keV and the solid line with $\times$ mark showed the radiation count for γ -ray energy of 88 keV. Two dashed lines with $\circ$ and $*$ marks showed

Fig. 5 Comparison between simulation and experimental counting of spot test.

Counting rates by scintillators with different thickness was simulated based on single point radiation source without considering an Al foil and sample thickness.

The left axis is resolution that were calculated from the counting radius of 50% efficiency and the right axis is counting rate.

The counting curve pattern was superposed to the actual counting ($\triangle$) curve.

resolutions that were calculated from the counting radius of 50% efficiency.

The plotted values of $\triangle$ marks on the dashed line were proportional to the plotted values in Fig. 2, which were measured by the experiment. Comparing the actual counting rate with that of simulated one, the counting curve of 22 keV radiation derived by the simulation agreed well with the 22 keV curve obtained from measurement, indicating that 22 keV X-rays were mainly detected. Also according to the simulation, the resolution for 22 keV X-rays was $10\ \mu\text{m}$ to $200\ \mu\text{m}$, which was probably enough for our imaging requirements for a whole plant.

5.2 Impact of the sample thickness and the shielding material

Figure 6 showed the results of the simulation

Fig. 6 Simulation results for 22 keV X-ray imaging of experimental condition.

Counting rate by scintillators with different thickness was simulated, based on self absorption by a sample (0.25 mm in thickness) as well as decrease by an Al foil (0.05 mm).

This is a case of simulation when a sample thickness was 0.25 mm and an aluminum shield thickness was 0.05 mm.

when a sample thickness was 0.25 mm and an aluminum shield thickness was 0.05 mm to indicate the relation between the scintillator thickness and the radiation count. The decrease in

overall count was only 15 to 20% for 22 keV, showing the satisfactory range for detection efficiency compared with counting rate of Fig. 5. The resolution increased as the scintillator thickness increased, reaching plateau over 0.1 mm of thickness. Generally, in the case of β -rays, the resolution tends to be higher with thinner scintillator, but in the case of X-rays, the tendency was opposite. The possible reason for this is that because the X-rays entering perpendicularly to the surface have short ranges in the scintillator, therefore, the number of the detected X-rays is decreased. As a result, X-rays with larger incident angles, which were the major factors in the resolution degradation, are preferentially detected. This indicates that the resolution cannot be improved by decreasing the thickness of the scintillator.

6. Discussion

Imaging of rice grains was performed using an FOS with a scintillator of 0.1 mm in thickness. Figure 7 showed the image of four rice grains that accumulated ^{109}Cd , after applying

Fig. 7 ^{109}Cd imaging in rice grains.

Upper right figure is a picture of the rice grains for imaging. The pseudo-color was employed in the image according to the intensity of radioactivity.

^{109}Cd to the culture solution containing $0.9\ \mu\text{M}$ of Cd. The image shown in Fig. 7 are the accumulated image for 10 minutes. Resolution of the image obtained was not enough, but each one of rice grain was able to distinguish. We expect that higher resolution can be obtained by improving the method of sample setting and measurement method considering the shape and the thickness of the sample.

7. Conclusions

In this study we studied the imaging condition of a γ -ray-emitting nuclide, ^{109}Cd , by the real time imaging system developed and evaluated the resolution and counting rates. ^{109}Cd emits 22 keV X-rays as well as 88 keV γ -rays, and therefore it was necessary to investigate efficient conditions for the measurement of the radiation emitted from ^{109}Cd . Through an experimental and simulation analysis it was shown that 22 keV X-ray was mainly detected and optimal thickness of the scintillator was discussed. It was also shown that 22 keV X-rays was able to detect efficiently by the system and the resolution was sufficient when a scintillator thickness was 0.1 mm. ^{109}Cd imaging in a rice grain was obtained by accumulating the image for 10 minutes with a scintillator of 0.1 mm in thickness.

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要 旨

植物の研究のためのリアルタイム RI イメージングシステムの
 ^{109}Cd 検出性能評価

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今回, ^{109}Cd γ 線放出核種のイメージングを検討し, 感度・解像度の評価を行った。 ^{109}Cd は 88 keV の γ 線を放出すると同時に 22 keV の X 線なども放出するため, ^{109}Cd の放射線計測における観測系設計の効率的な条件を検討する必要がある。そこで, 本システムにおいて主にどの放射線を検出しているかの分析を行い, 最適なシンチレータ厚の検討を行った。その結果, 本システムにおいては 22 keV の X 線が効率的に検出されることが確認され, ^{109}Cd の良好なイメージングのための知見が得られた。

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