Nuclear Instruments and Methods in Physics Research A ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Novel methods for estimating 3D distributions of radioactive isotopes in materials

Y. Iwamoto [a],*, J. Kataoka [a], A. Kishimoto [a], T. Nishiyama [a], T. Taya [a], H. Okochi [a],
H. Ogata [a], S. Yamamoto [b]

[a] *Research Institute for Science and Engineering, Waseda University, Shinjuku, Tokyo 169-8555, Japan*
[b] *Nagoya University Graduate School of Medicine, 1-1-20, Daikominami, Higashi-ku, Nagoya-shi, Aichi 461-8673, Japan*

ARTICLE INFO

Article history:
Received 5 November 2015
Received in revised form
15 March 2016
Accepted 29 March 2016

Keywords:
3D distribution
Environmental monitoring
Decontamination
Gamma camera

ABSTRACT

In recent years, various gamma-ray visualization techniques, or gamma cameras, have been proposed. These techniques are extremely effective for identifying “hot spots” or regions where radioactive isotopes are accumulated. Examples of such would be nuclear-disaster-affected areas such as Fukushima or the vicinity of nuclear reactors. However, the images acquired with a gamma camera do not include distance information between radioactive isotopes and the camera, and hence are “degenerated” in the direction of the isotopes. Moreover, depth information in the images is lost when the isotopes are embedded in materials, such as water, sand, and concrete. Here, we propose two methods of obtaining depth information of radioactive isotopes embedded in materials by comparing (1) their spectra and (2) images of incident gamma rays scattered by the materials and direct gamma rays. In the first method, the spectra of radioactive isotopes and the ratios of scattered to direct gamma rays are obtained. We verify experimentally that the ratio increases with increasing depth, as predicted by simulations. Although the method using energy spectra has been studied for a long time, an advantage of our method is the use of low-energy (50–150 keV) photons as scattered gamma rays. In the second method, the spatial extent of images obtained for direct and scattered gamma rays is compared. By performing detailed Monte Carlo simulations using Geant4, we verify that the spatial extent of the position where gamma rays are scattered increases with increasing depth. To demonstrate this, we are developing various gamma cameras to compare low-energy (scattered) gamma-ray images with fully photo-absorbed gamma-ray images. We also demonstrate that the 3D reconstruction of isotopes/hotspots is possible with our proposed methods. These methods have potential applications in the medical fields, and in severe environments such as the nuclear-disaster-affected areas in Fukushima.

1. Introduction

Radioactive isotopes released from the Fukushima Daiichi Nuclear Plant persist in the environment at Fukushima. Consequently, various gamma camera technologies, such as Compton camera [1–4], pinhole cameras [5] and coded mask cameras [6], have been proposed to assist the decontamination efforts. However, images acquired by a gamma camera do not include distance information between the source of radioactive isotope and the camera, since an image is a projection from 3D to 2D, thus leaving uncertainty in the camera gaze direction. One popular technique used to determine the depth distribution of radioactive isotopes is the Scraper plate. However, this method has the disadvantage that it requires a long sampling time to measure the radioactive substance distribution, with consequent extended exposure of the user to radiation. Furthermore, several years after a nuclear contamination event, the radioactive isotopes infiltrate deep into the ground. There are also other approaches to obtaining depth information of radioactive isotopes, namely, the photopeak-to-valley method [7–10]. This method generally defines the energy band before the photopeak as a valley. In this study, we focused on the scattering of gamma rays by their surrounding materials to estimate the depth of a radioactive source, an approach suggested by previous works [7–11]. In particular, we try to use low-energy photons as much as possible to extract gamma rays scattered inside the material. Below we propose two nondestructive methods for obtaining the depth distributions of radioactive isotopes in their surrounding materials using energy spectra and images as independent probes of depth information.

---

* Corresponding author.
E-mail address: y.iwamoto0805@ruri.waseda.jp (Y. Iwamoto).

http://dx.doi.org/10.1016/j.nima.2016.03.098
0168-9002/© 2016 Elsevier B.V. All rights reserved.

Please cite this article as: Y. Iwamoto, et al., Nuclear Instruments & Methods in Physics Research A (2016), http://dx.doi.org/10.1016/j.nima.2016.03.098

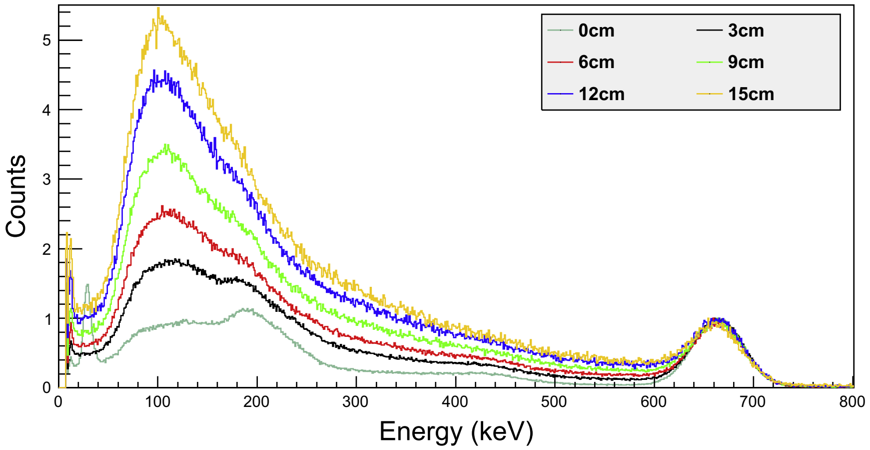

Fig. 1. Energy spectra measured with survey meter of a ^{137}Cs source embedded various depths of concrete, and normalized by the number of events at 662 keV.

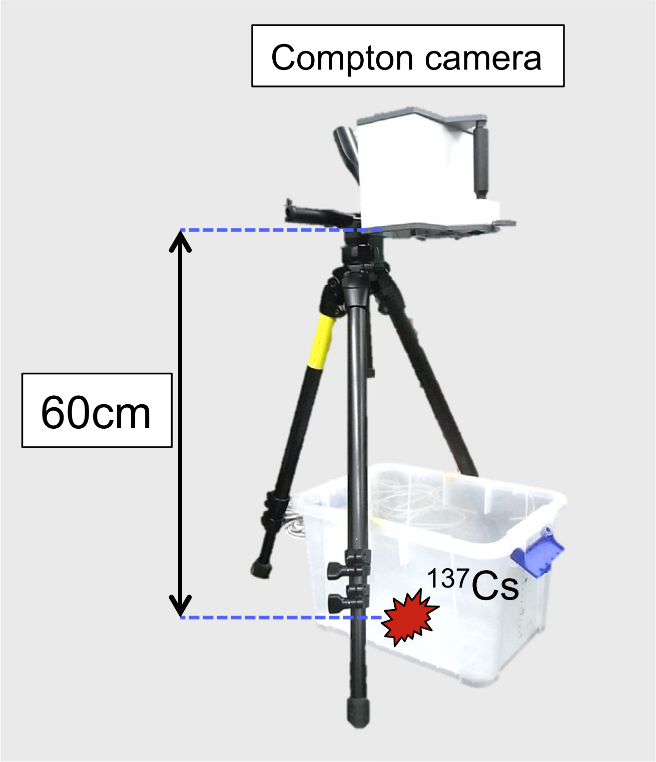

Fig. 2. Experimental configuration of the first method.

2. Compton camera and pinhole camera

2.1. Compton camera

A Compton Camera is well known as a gamma camera restricting an arrival direction of gamma rays using Compton kinematics. The Compton camera used in our experiments is specifically designed for the Fukushima decontamination operations. The construction is lightweight (2.5 kg) and compact (14 × 15 × 16 cm^3) [1,2], and is thus a portable device that is easy to use outside when controlled by a laptop PC. Both the scatterer and the absorber are made of Ce-doped $Gd_3Al_2Ga_3O_{12}$ (Ce:GAGG) scintillator [12] optically coupled to an 8 × 8 large monolithic TSV-MPPC array [1]. The detection part of the Compton camera consists of 2 × 2 blocks. The one block consists of 11 × 11 × 2 arrays of 2.0 × 2.0 × 4.0 mm^3 pixels (scatterer) and 11 × 11 × 10 arrays of 2.0 × 2.0 × 2.0 mm^3 pixels (absorber). The distance between the scatterer and the absorber is fixed to 12 mm .

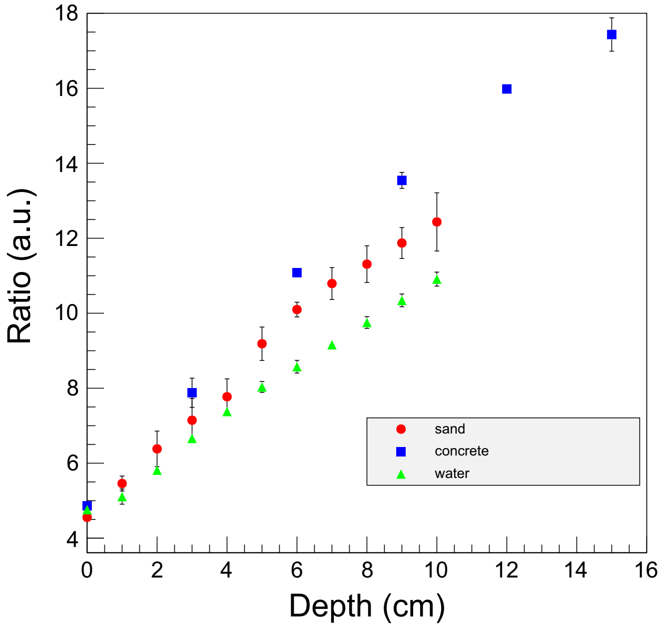

Fig. 3. Relationship between depth and ratio.

The angular resolution evaluated by angular resolution measure (ARM) is ~8° (FWHM) at 662 keV. The Compton camera also has a high intrinsic efficiency of 0.45% for 662 keV gamma rays immediately in front of the detector. These features allow rapid identification of radioactive isotopes. However, our Compton camera can only produce images using photons of high energies, >200 keV, because the scatterer of the Compton camera will fully photo-absorb low-energy gamma rays without producing Compton scattering.

2.2. Pinhole camera

The structure of a pinhole camera is extremely simple, and suited to the imaging of low-energy gamma rays below 200 keV. The detection part of the pinhole camera used in this research consists of Ce:GAGG scintillator of 42 × 42 arrays of 0.5 × 0.5 × 3 mm^3 pixels and an 8 × 8 large monolithic TSV-MPPC array. The

Please cite this article as: Y. Iwamoto, et al., Nuclear Instruments & Methods in Physics Research A (2016), http://dx.doi.org/10.1016/j.nima.2016.03.098