

A Preliminary Study on the Applicability of 3D-Scan-Based Efficiency Calibration Method to Laboratory Analysis of Natural Radionuclides in Consumer Products

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1. Introduction

Radiation safety in consumer products is vital for public health, as demonstrated by the 2018 radon-emitting mattress incident in Korea. Conventional γ -ray spectroscopy, when calibrated with certified reference materials (CRMs), provides reliable accuracy if samples can be densely packed into standard containers and approximated as homogeneous samples. However, its applicability is limited for irregularly shaped or porous samples, where notable uncertainties remain.

To address this, a recent study proposed a 3D scan-based efficiency calibration method using Monte Carlo simulation, demonstrating improved geometric modeling [1]. However, that approach was developed without considering the practical constraints of laboratory-based HPGe (High Purity Germanium detector) measurements for low-level radioactivity, such as thick lead shielding and limited sample space.

In this context, this preliminary study examines the applicability of the 3D scan-based method under such laboratory conditions and seeks to identify additional factors that must be considered, with particular attention to cases where conventional γ -ray spectrometry shows limited reliability. In addition, differences in efficiency and radioactivity estimation are evaluated in comparison with the conventional approach, which assumes a homogeneous sample of average bulk density.

2. Methods and Results

In this study, a representative consumer product sample was selected, and then, the 3D scan-based method [1] was applied within the established laboratory analysis procedure for consumer products. Finally, the resulting efficiency and radioactivity estimation for the selected sample were compared with those obtained using the conventional approach.

2.1 Sample Selection

A driver component of shower device promoted for negative ion generation was chosen among radioactivity-suspected products, since surface contamination measured with a portable survey meter exceeded a certain fraction of the background level, thus warranting detailed radioactivity analysis. The sample, made of irregularly shaped plastic material, is

difficult to preprocess through conventional treatments such as crushing, grinding, or ashing. Without preprocessing, large voids would remain within the standard container, which is expected to cause significant errors when applying conventional method. Hence, this product was selected as the target sample of this study, and Fig. 1 shows the sample placed inside the standard container used for the analysis.

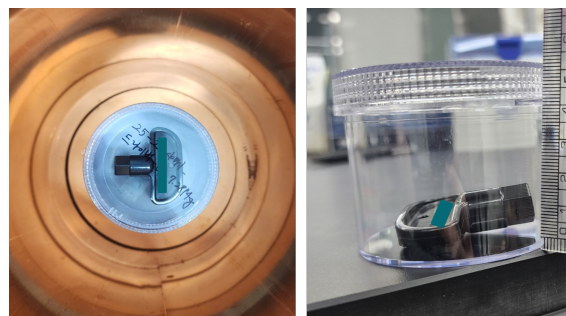


Fig. 1. Photographs of the selected sample placed inside the standard container: top view (left) and side view (right)

2.2 Application of the 3D scan based Method [1]

The proposed workflow of the previous study [1] consists of scan method selection, scan data acquisition, post-processing, tetrahedralization, and implementation of the sample model into the Monte Carlo radiation transportation code for efficiency calculation.

The 3D scanning was carried out using an arm-type laser scanning system in combination with Geomagic Design X software [3], consistent with the reference study [1]. The present sample was categorized as a rigid body smaller than the CMM (Coordinate Measurement Machine) radius [1]. Accordingly, it was scanned from multiple angles while being repositioned, and the resulting data were merged to obtain the final dataset. Because laboratory HPGe measurements require a short source-to-detector distance, accurate reproduction of the geometrical arrangement was crucial. To represent the realistic measurement condition in which the sample rests on the detector endcap, the setup including the plastic cap used for detector protection was also scanned to extract the height (Z) information.

Subsequent post-processing in Design X [3] included defect repair, hole filling, adjustment of polyfaces, and mesh deviation control, resulting in a refined 3D model. The resulting file (.stl) was converted to tetrahedral

elements files (.ele, .node) using TetGen [4]. These files were then imported into the detector model based on Geant4 code (version 11.2.2), where each tetrahedron was implemented using the G4Tet class to define the source term geometry [2]. This detector model was previously validated in the 300 ~ 1,000 keV energy range of main natural radionuclides using CRMs [5].

For source-to-detector alignment, the Z-direction placement was adjusted so that the minimum Z-value of the scanned data coincided with the plastic cap surface. In the XY-plane, the mean (X, Y) coordinates of the sample were aligned to the center of the detector endcap (0, 0), based on the assumption that the sample is placed at the central position on the top surface of the HPGe endcap during measurement. This geometrical arrangement, with the tetrahedralized sample placed on the plastic cap, is visualized in Geant4 (Fig. 2).

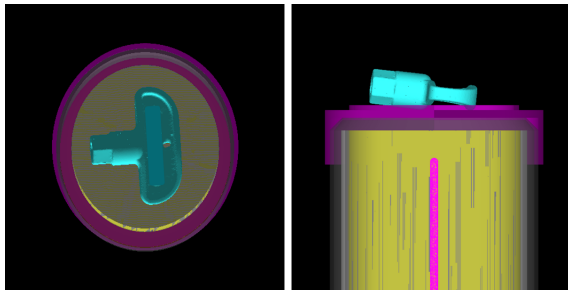


Fig. 2. Geant4 visualization of the sample placed on plastic cap covering the endcap: top view (left) and side view (right)

For efficiency calculations, the source term was defined such that gamma-ray emissions were isotropically sampled within the source volume. A homogeneous plastic was assumed for the sample material. The gamma emitters were set to daughter radionuclides typically used in natural radioactivity analysis, namely Pb-214 and Bi-214 for the U-238 series and Ac-228 for the Th-232 series. The resulting spectra were processed using GAMMAVISION software [6] to extract net peak counts for the energies of interest. Detection efficiency was then obtained by normalizing the net counts to the product of the number of simulated decays and emission yield, thereby enabling coincidence-summing corrections via simulation-based approach. The key gamma lines analyzed were 351.9, 609.3, and 911.2 keV, with the QBBC physics list and G4RadioactiveDecayPhysics model applied [2].

The efficiencies obtained through this process can be directly applied to radioactivity calculations, where the net counts from measurements are normalized by the counting time, emission yield, and the derived efficiencies. This application revealed that efficiencies are more strongly influenced by the source-detector geometrical modeling than in in-situ analyses, highlighting the need for refined geometry to ensure consistency between efficiency determination and net count measurement.

2.3 Comparison with the Conventional Method in Terms of Efficiency and Radioactivity Analysis

The sample was placed in a standard container for the measurement to compare detection efficiency and activity. In the conventional method, the sample was modeled as a cylinder with an average density, where the filling height was approximated by the maximum height obtained from the 3D scanned sample model. Comparative modeling results are illustrated in Fig. 3.

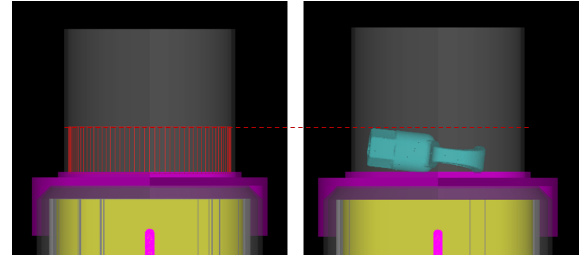


Fig. 3. Geant4 visualization of the sample in a standard container modeled as a cylindrical volume with average density (left) and as a 3D-scanned volume (right)

The results of radioactivity analysis were below the minimum detectable activity (MDA), indicating that the sample is not a radioactive consumer product requiring market withdrawal. Thus, instead of estimating radioactivity, the MDA values were calculated for comparison. The sample was not sealed for secular equilibrium prior to measurement, since the analysis focused on evaluation of MDA rather than radioactivity.

The results are summarized in Table I. For this sample, application of the 3D-scan-based method yielded efficiencies that were 9 ~ 10% higher than those obtained with the conventional method, depending on the energy. Conversely, the MDA values derived from the conventional method were 8 ~ 9% higher than those from the 3D-scan-based method. However, for 911keV gamma-rays of Ac-228, when the uncertainties were considered, the Zeta scores were below 3 – about 2.7 for efficiency and 1.1 for MDA, indicating that the difference between the two methods cannot be regarded as statistically significant.

Table I: Comparison of efficiencies and MDA values between the conventional and 3D-scan-based method

Radionuclide		Pb-214	Bi-214	Ac-228
Gamma Energy [keV]		351.9	609.3	911.2
Density [g/cc]	Conventional	0.152		
	3D scan	1.076		
Efficiency (Relative uncertainty, k=1, %)	Conventional	0.055 (1.08)	0.038 (1.14)	0.032 (3.24)
	3D scan	0.060 (1.11)	0.041 (1.17)	0.035 (3.26)
MDA[Bq/g] (Relative uncertainty, k=1, %)	Conventional	0.018 (1.57)	0.020 (1.70)	0.013 (5.81)
	3D scan	0.017 (1.59)	0.018 (1.72)	0.012 (5.82)

3. Conclusions

This study provides preliminary evidence that the 3D-scan-based modeling approach can improve the accuracy of HPGe efficiency calibration for irregularly shaped consumer products by more faithfully representing their geometry and material distribution. Although the present evaluation was limited to a single sample and quantitative verification of radioactivity could not be performed due to the minimum detectable activity (MDA) constraints, the results indicate the potential of this approach to enhance the reliability of radioactivity assessments, particularly for samples that are difficult to preprocess.

It should be noted that the observed differences may vary if the conventional approach employs a more carefully fitted simple geometry. Future work should refine the sample-detector geometry, expand testing to a wider variety of product types, verify the method using certified reference materials (CRMs) and actual radioactive samples, and develop practical radon-sealing techniques to support its broader application.

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