Development of a Novel Measurement System and Methods for Radionuclide-Contaminated Wounds

Authors: Wang, Ms. Wei, Wang, Yujian, Dr. Xinglong Li, Dr. HongChao Pang, Dr. Zhiping Luo, wang, Ms. wei

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Abstract

Due to the lack of devices and methods for measuring internal contamination caused by radionuclides in wounds that may occur during spent fuel reprocessing and radioisotope production, we developed a novel non-contact measurement system for radionuclide-contaminated wounds featuring improved resolution, moderate size, and ease of clinical application. This system employs imaging and energy spectroscopy measurement technologies to quantify the amount and distribution of contamination retained in wounds. With this system, we established a measurement method to estimate the retention depth and activity of nuclides in injured tissue by exploiting differences in the absorption attenuation coefficients of X/γ rays emitted by retained nuclides at various thicknesses of the injured limb. This method enables identification of retained nuclides in wounds, measurement of nuclide depth and activity in different wound types, and determination of radioactive contamination distribution characteristics, thereby fundamentally solving the problem of measuring radionuclide-contaminated wound characteristics. This study is of great significance for advancing existing technology for radionuclide-contaminated wounds worldwide, improving internal irradiation monitoring and evaluation systems, and enhancing occupational health protection for radiation workers.

Full Text

Preamble

Development of a New Measurement System for Radionuclide-Contaminated Wounds and Its Measurement Methods

Wei Wang[1], Yujian Wang[1], Xinglong Li[1], Hongchao Pang[1], Zhiping Luo[1]
[1] China Institute of Atomic Energy, Beijing, 102413

Abstract: Due to the current lack of devices and methods for measuring internal contamination from radionuclides in wounds that may occur during spent fuel reprocessing and radioisotope production, we developed a novel non-contact measurement system for radionuclide-contaminated wounds featuring improved resolution, moderate size, and clinical applicability. This system employs imaging and energy spectroscopy technologies to quantify the amount and distribution of contamination retained in wounds. Using this system, we established a measurement method to estimate the retention depth and activity of nuclides in injured tissue by leveraging differences in the absorption attenuation coefficients of X/γ rays emitted by retained nuclides through varying tissue thicknesses. This enables identification of retained nuclides in wounds, measurement of nuclide depth and activity across different wound types, and determination of radioactive contamination distribution characteristics in wounds, thereby fundamentally solving the problem of characterizing radionuclide-contaminated wounds. This study significantly advances the current state of radionuclide-contaminated wound measurement technology both domestically and internationally, improves the internal irradiation monitoring and evaluation system, and enhances occupational health protection for radiation workers.

Keywords: Radionuclide-contaminated wounds, Retention and distribution measurements, Internal radiation

1 Introduction

During the manufacturing, maintenance, and recycling of nuclear fuel assemblies [1] and in radioisotope production [2], various injuries (such as punctures, cuts, explosions, and acid burns) frequently occur, allowing radionuclides to enter the human body. Over 90% of radioactive injury events involve the arms and hands (primarily fingers) through puncture wounds and chemical burns [3]. Compared to inhalation or ingestion, intake via contaminated wounds bypasses the skin' s defensive barrier and delivers radioactive isotopes directly into the bloodstream, where they can be transported to vital organs such as the liver and bones [4]. Even relatively small amounts of intake can result in high effective doses from internal irradiation. Furthermore, long-term retention of certain insoluble nuclides at wound sites may induce local tissue cancer.

Therefore, detailed and accurate measurement of radionuclide-contaminated wounds must be performed promptly after trauma occurs [5].

Detection methods for radionuclide-contaminated wounds can be broadly categorized into indirect and direct measurement technologies [6-7]. Indirect measurement techniques obtain pollutant types and concentrations at wound sites through offline analysis of wound samples, primarily including alpha particle detection and X-ray fluorescence analysis. While these methods offer rapid measurement, they suffer from sampling representativeness issues due to the inability to predict contamination distribution characteristics. Additionally, sampling increases patient pain and risks secondary infection. Direct measurement technologies [8-10] identify radiation emitted by residual nuclides at wound sites through direct detection, supplemented by effective measurement methodologies to obtain activity and depth information. These methods primarily include alpha/beta ray measurement analysis and X/γ ray measurement analysis, representing non-contact online measurement that is simple, direct, and avoids wound sampling to reduce infection risk. Among these, the X/γ ray measurement analysis method leverages the strong penetration capability of gamma/X-rays emitted by residual nuclides, enabling detection of deep wound contamination while overcoming measurement difficulties caused by preliminary medical cleaning or blood obstruction at wound surfaces. This method has advanced rapidly in recent years. In addition to traditional high-purity germanium (HPGe), NaI, or CsI detectors, yttrium aluminum perovskite (YAP:Ce) detectors [11] based on cerium-activated crystals have emerged for detecting radionuclide-contaminated wounds, broadening the energy range for wound radioactivity measurement and nuclide identification while improving measurement effectiveness.

Current research reveals that existing measurement technologies for radionuclide-contaminated wounds are limited to identifying residual nuclide types and determining surface contamination activity. For larger, deeper wounds requiring targeted medical intervention (such as surgical removal) even after initial cleaning, it is necessary to accurately locate and quantify the distribution characteristics of radionuclide contamination in a timely manner.

Currently, there is a lack of effective measurement methods and no commercially available specialized equipment. The common approach involves staged measurements using two or more detectors of different sizes: first, a large-volume probe with poor resolution roughly determines the contamination range, followed by a small, high-sensitivity probe to scan and identify the maximum contamination point for residual activity measurement. Identification of the maximum contamination point relies primarily on observing changes in detector count rate. This method is inefficient for locating wound contamination distribution, complex, time-consuming, labor-intensive, and prone to human measurement errors.

Integrating measurement of wound contamination retention and distribution represents a current challenge in detection technology for radionuclide-contaminated wounds.

This work establishes a new non-contact measurement system for radionuclide-contaminated wounds featuring improved resolution, moderate size, and clinical applicability. The system combines imaging and energy spectroscopy measurement to assess wound contamination retention and distribution. Based on the principle of coded aperture imaging, it measures the distribution characteristics of radionuclide-contaminated wounds, supplemented by a direct measurement method for retention based on X/γ energy spectroscopy analysis. This achieves comprehensive detection of radionuclide-contaminated wound characteristics, addresses shortcomings in existing measurement technologies, and enhances practical applicability.

2 Methods

2.1 Measurement of Distribution Characteristics of Radionuclide-Contaminated Wound Retention

We employ the principle of coded aperture imaging [12] to measure the distribution characteristics of radionuclide-contaminated wound retention. A coded aperture imaging system [13] typically consists of position-sensitive detectors and collimators made of heavy metals with specific coding patterns. The imaging process comprises encoding and image reconstruction stages. During encoding, the superimposed projection formed by radiation from the source passing through the coded aperture collimator onto the position-sensitive detector is processed into a coded image through signal processing. This coded image is then reconstructed using decoding algorithms to ultimately restore the radiation source distribution image. Figure 1 [Figure 1: see original paper] presents a simplified mathematical model of the coded aperture imaging principle.

Figure 1 Schematic diagram of the mathematical model process for coded aperture imaging.

Let $f(r_0)$ be the radioactive intensity of the radiation source at position r_0, and $h(r_a)$ be the imaging coding function, with a value of 1 for perforated elements and 0 for unperforated elements. The total number of particles detected by the detector at position r_i, denoted as $P(r_i)$, can be expressed as:

$$P(r_i) = \int_{r_0} f(r_0) \cdot h(r_a) \cdot \cos\theta \cdot C(\theta)\, dr_0 \tag{1}$$

where $C(\theta)$ is the collimation factor of the coded aperture, which can be ignored when the collimator thickness is thin. θ represents the angle of ray deviation when incident light passes through the imaging system, calculated as $\arctan(|r_i - r_0|/Z)$. This is the fundamental reason for the difference between near-field and far-field imaging in coded aperture systems. For far-field imaging, distance a tends toward infinity and $\theta \approx 0$. At this point, equation (1) exhibits perfect autocorrelation and can be simplified into a convolution operation, enabling high-quality radiation source image reconstruction through deconvolution. However, detecting the distribution characteristics of radionuclide-contaminated wounds belongs to near-field imaging, which differs from conventional gamma camera applications. In this case, a cannot be ignored. Due to the $\cos\theta$ term, equation (1) does not maintain autocorrelation and cannot directly reconstruct images through convolution, as this would lead to image artifacts [14]. For near-field imaging, calibration methods such as coded aperture collimator centralization must be used to eliminate artifacts, and appropriate reconstruction algorithms must be selected to improve image quality and accuracy [15].

Image reconstruction algorithms for coded aperture imaging primarily include correlation decoding algorithms and the Maximum Likelihood Expectation Maximization (MLEM) algorithm [16]. The MLEM algorithm [17] first assumes an initial source distribution, calculates the projection of the assumed source, compares it with actual imaging results, and iteratively corrects the source distribution multiple times based on the difference until it approaches the true distribution. Given its effectiveness in suppressing noise and improving signal-to-noise ratio, this work employs the MLEM algorithm to reconstruct wound contamination distribution images. The iterative formula of MLEM is as follows [18]:

$$x_j^{(k+1)} = x_j^{(k)} \cdot \frac{\sum_i a_{ij} \cdot \frac{y_i}{\sum_j a_{ij} x_j^{(k)}}}{\sum_i a_{ij}} \tag{2}$$

where x_j represents the reconstructed image weight of the j-th pixel in the radiation source plane; y_i represents the actual photon count received by the i-th pixel in the detector plane; a_{ij} is the system response matrix, representing the probability that radiation emitted by the j-th pixel of the source plane is received by the i-th pixel of the detector plane; and k represents the number of iterations.

2.2 Measurement of Depth and Activity of Radionuclide-Contaminated Wound Retention

By leveraging the energy spectroscopy recognition and analysis capabilities of the new radionuclide-contaminated wound measurement system, the retention depth and activity of nuclides in injured limbs can be estimated based on differences in absorption attenuation coefficients of X/γ rays through varying tissue thicknesses.

The measurement of retention depth and activity is based on preliminary measurements that have identified and determined the category of residual radioactive isotopes at the wound site. First, a soft tissue-equivalent material is used to simulate injured limbs for detection efficiency calibration of the measurement system.

A standard point source with known activity representing the retained nuclide is placed beneath different thicknesses of soft tissue-equivalent material coating to measure the net count rate (cps) of the characteristic X/γ-ray full-energy peak emitted by the point source. Measurement conditions and duration are kept constant for each configuration. The full-energy peak efficiency for characteristic X/γ rays emitted by the point source under different thicknesses of soft tissue-equivalent material coating is calculated by:

$$\varepsilon = \frac{\text{cps}}{S \cdot \eta} \tag{3}$$

where S is the source activity and η is the branching ratio of the full-energy peak. Exponential fitting of these results yields calibration curves and fitting relationships for the system across different thicknesses of soft tissue-equivalent material coating, thereby determining the linear attenuation coefficient μ of the soft tissue-equivalent material for the characteristic X/γ rays of the retained nuclide.

For puncture wounds with unknown contamination retention depth, assuming the contamination retention depth is d and the injured limb thickness is C, energy spectroscopy analysis and measurement are performed on suspected puncture contamination hotspots based on the wound contamination distribution characteristics determined by the measurement system. Measurements are conducted from both directions of the limb surface directly above and below the suspected puncture contamination hotspot (hereinafter referred to as positive and negative directions) while keeping measurement conditions and duration constant. The net count rates of the retained nuclide' s characteristic X/γ-ray full-energy peak, N_1 and N_2, satisfy:

$$N_1 = \varepsilon_0 \cdot S \cdot \eta \cdot e^{-\mu d} \tag{4}$$

$$N_2 = \varepsilon_0 \cdot S \cdot \eta \cdot e^{-\mu(C-d)} \tag{5}$$

where ε_0 represents the net count rate of the full-energy peak for the detector measuring characteristic X/γ rays of retained nuclides without tissue absorption in the positive and negative directions, respectively. Comparing equation (4) with equation (5) yields:

$$\frac{N_1}{N_2} = e^{-2\mu d + \mu C} \tag{6}$$

Considering the isotropy of the radioactive source, ε_0 is assumed to be approximately equal in both directions. The above equation can be simplified as:

$$d = \frac{C}{2} - \frac{1}{2\mu} \ln \frac{N_1}{N_2} \tag{7}$$

By substituting the attenuation coefficient μ determined through calibration into equation (7), the depth d of pollutant retention in the wound can be inferred. Combined with the system detection efficiency calibration relationship and equation (3), the pollutant retention activity S in the wound can be finally determined.

3 System Design

3.1 Detector Selection

We selected a position-sensitive cadmium zinc telluride (CZT) detector as the fundamental detector for the radionuclide-contaminated wound measurement system. CZT can operate at room temperature without refrigeration, offers high stopping power, and provides good energy resolution across a wide energy range from tens of keV to 1.5 MeV. Pixelated CZT detectors employ microelectronic photolithography technology to achieve segmented electrode design on the crystal, effectively recording the location of energy deposition through extremely small square metal electrodes. Additionally, due to the small-pixel effect, the low-energy tail phenomenon in pixelated CZT detectors is effectively mitigated, enhancing energy resolution capability. Figure 2 [Figure 2: see original paper] shows the MPS-256B pixelated CZT detector selected for actual development, featuring a crystal pixel size of 1.6 mm × 1.6 mm × 5.0 mm, an overall size of 25.6 mm × 25.6 mm × 5.0 mm, and a total of 16 × 16 channels.

Figure 2 MPS-256B pixelated CZT detector.

3.2 Design of Coded Aperture Collimator

(1) Basic Coding Method and Structural Design

To accommodate the CZT detector size and effectively improve transmittance, a Modified Uniformly Redundant Array (MURA) was selected as the basic coding method for the imaging system collimator. From the perspective of maximizing imaging system sensitivity while satisfying MURA coding rules, the effective sensitive detection area of the detector should be fully utilized. Therefore, the collimator coding function was selected as MURA (13 × 13), corresponding to an effective detection area of 20.8 mm × 20.8 mm for the CZT detector, with 169 pixels actually used. Additionally, to expand the field of view, increase the spatial detection range for gamma rays, and ensure the detector surface can receive a complete projection of the coding pattern, the MURA array was extended by one cycle in all directions to form a nested MURA coded aperture collimator.

(2) Design of Imaging Performance Indicators

The performance indicators of the coded aperture imaging system primarily include imaging angular resolution and imaging field of view. Figure 3 [Figure 3: see original paper] shows schematic diagrams of the Full Coded Field of View (FCFOV) and angular resolution Δ for the nested MURA coded aperture imaging system.

Figure 3 FCFOV and angular resolution (Δ) of the nested MURA coded aperture imaging system.

The FCFOV and angular resolution are given by:

$$\mathrm{FCFOV} = \arctan\left(\frac{b \times d_m}{a \times D_d}\right) \tag{8}$$

$$\Delta\theta = \arctan\left(\frac{\lambda}{a + b}\right) \tag{9}$$

where d_m is the edge length of the effective sensitive detection area of the detector, D_d is the edge length of the aperture of the nested coded aperture collimator, and b is the edge length of the basic coded aperture collimator. λ is the geometric resolution of the coded aperture collimator, meaning that when two ideal point sources (P1 and P2) in space are separated by λ and reconstructed through the coded aperture collimator, the center distance between the reconstructed images equals exactly the Full Width at Half Maximum (FWHM) of the system' s Point Spread Function (PSF). Equations (8) and (9) show that the full field of view and angular resolution are mutually constrained and cannot be improved simultaneously. However, for near-field imaging, these two imaging indicators can be balanced by adjusting distance a to meet application requirements. In this design, imaging effectiveness for wound contamination is prioritized, with system angular resolution Δ designed to be less than 5°. Secondly, while ensuring angular resolution, adjusting distance a maximizes the imaging field of view and improves imaging efficiency.

(3) Design of Practical Performance Indicators

Considering that radioactive contamination activity levels in wound retention are generally low (approximately 10^4 Bq), imaging efficiency should be maximized to reduce measurement time, and the imaging field of view should be expanded to minimize the number of measurements. Therefore, the distance $(a + b)$ between the source plane and detector plane is limited to less than 10 cm. Additionally, considering the manufacturing difficulty of the coded aperture collimator, the designed collimator aperture should be greater than or equal to 1 mm.

Taking these factors into account, the final design parameters and specifications for the radionuclide-contaminated wound measurement system are determined as shown in Table 1 . The actual coded aperture collimator fabricated using 3D printing is shown in Figure 4 [Figure 4: see original paper]. The 3D printing substrate material is resin, which is filled into the coded aperture made of pure tungsten material to provide self-supporting capability for the coded board collimator.

Table 1 Design parameters and specifications of the radionuclide-contaminated wound measurement system

System Component	Design Parameter	Value
Coded aperture collimator	Basic size	1.3 mm × 1.3 mm × 4 mm
	Size after nesting	16.9 mm × 16.9 mm × 4 mm

System Component	Design Parameter	Value
	Aperture size	32.5 mm × 32.5 mm × 4 mm
	Material	W (Purity 99%)
Detector	Basic size	25.6 mm × 25.6 mm × 5 mm
	Pixel size	1.6 mm × 1.6 mm × 5 mm
	Material	Pixelated CZT
Geometry	Vertical distance a (source to collimator)	88.67 mm
	Vertical distance b (collimator to detector)	88.67 mm
Performance	FCFOV	3.92°
	Angular resolution Δ	<5°

Figure 4 Physical picture of the coded aperture collimator.

3.3 Electronic System Design

The electronic design scheme of the radionuclide-contaminated wound measurement system is shown in Figure 5 Figure 5: see original paper. The high-voltage power supply provides negative bias voltage to the CZT detector after filtering. The anode pixel signals from the CZT are amplified and filtered by a dedicated ASIC chip (SRE4002) designed for reading pixelated CZT detector signals, which generates trigger signals, hit channel number signals, and channel address signals based on the comparator circuit output. Simultaneously, amplitude analog signals from the corresponding channels are output.

The amplified analog signals, ASIC output event address signals, and hit channel number signals are transmitted to the STM32H743 microcontroller board. The STM32H743 board transmits the collected data to a computer for data processing and image generation via Ethernet in a specific format. The designed electronic module is divided into three parts: the SRE4002 control and data transmission module, the microcontroller control and power management module, and the high-voltage and RC filtering circuit module, as shown in Figures 5(b)-(d).

Figure 5 System electronics design scheme and electronic modules.

3.4 System Implementation

The prototype of the radionuclide-contaminated wound measurement system and its performance testing bench were fabricated according to Table 1, as shown in Figure 6 Figure 6: see original paper. To improve signal-to-noise ratio and imaging performance, the CZT detector and its supporting electronic module are sequentially placed at the bottom of a tungsten shielding enclosure measuring 47 mm × 47 mm × 36 mm with a wall thickness of 4 mm, with a pre-designed coded aperture collimator installed at the front end, as shown in Figure 6(b). To block light and resist environmental electromagnetic interference, the shielding enclosure and other electronic module components are housed in a 1 mm-thick aluminum shell, forming an integrated system structure with the experimental testing bench.

Figure 6 Appearance of the radionuclide-contaminated wound measurement system.

4 Experimental Testing and Result Analysis

4.1 Experimental Testing of Distribution Characteristics of Radionuclide-Contaminated Wound Retention

(1) Imaging Function Test

Three ^{241}Am standard point sources (two with activity of 3.0×10^4 Bq and one with 2.589×10^4 Bq) were placed simultaneously on the surface of soft tissue-equivalent material (density = 1.08 g/cm^3, composition: H 10%, C 12.5%, N 3.50%, O 74%) and at depths of 15 mm, 25 mm, and 30 mm to test the imaging function of the measurement system. Each measurement ensured sampling of 7000 effective imaging events, and images were reconstructed using the MLEM algorithm with a system response matrix calculated from simulated values. The detector plane was divided into 169 pixels, the source plane within the theoretical imaging full field of view was divided into 2704 pixels, and the number of iterations was set to 50. The imaging results are shown in Figure 7 [Figure 7: see original paper].

Figure 7 Imaging effect of ^{241}Am standard point source under different soft tissue-equivalent material coating thicknesses.

The results demonstrate that soft tissue-equivalent material coatings up to 30 mm do not affect the system' s imaging performance. Thus, for wounds with ^{241}Am contamination at depths within a 30 mm soft tissue layer, the system can effectively measure wound contamination distribution. Figure 8 [Figure 8: see original paper] shows the imaging effect after optical superposition of a single ^{241}Am standard point source with an actual hand limb.

Figure 8 Actual imaging effect of ^{241}Am standard single point source.

(2) Imaging Performance Testing

The imaging performance indicators, including angular resolution, FCFOV, and positioning accuracy of the radionuclide-contaminated wound measurement system, were tested using a ^{241}Am standard point source (2×10^4 Bq). The MLEM algorithm was used for image reconstruction with a system response matrix calculated from simulated values, and the number of iterations was set to 50. During testing, the ^{241}Am standard point source was moved along the horizontal X-axis and vertical Y-axis in 10 mm increments. Each measurement ensured sampling of 3700 valid imaging events, and the average FWHM obtained from Gaussian fitting of each reconstructed point source image was used as the measured system angular resolution value. The peak position range from Gaussian fitting of each reconstructed point source image served as the measured FCFOV value, and the peak position was compared with the actual point source position to determine system positioning accuracy. The test results are shown in Table 2 .

Table 2 Experimental test results of system imaging angular resolution, FCFOV, and positioning accuracy

Axis	Actual Location (mm)	Angular Resolution (°)	Reconstructed Position (pixels)	Positioning Accuracy (mm)
X-axis	10	4.15	13	2.5
	20	3.98	25	2.2
	30	4.05	38	2.8
	40	4.12	50	2.3
Y-axis	10	3.95	12	2.1
	20	3.88	24	2.4
	30	4.02	37	2.6
	40	4.08	49	2.2

Averaging the horizontal X-axis and vertical Y-axis angular resolutions from Table 2 yields a measured system angular resolution of approximately 4.02°. Linear fitting of the actual and reconstructed positions of point sources along the X and Y axes provides the average actual distance corresponding to unit pixels in both directions. Combined with the pixel division number in the imaging field plane (52×52), the measured imaging field of view for the system is approximately 99.16 mm $\times$ 92.31 mm. Comparison between actual and reconstructed point source positions shows that system positioning accuracy is within 3 mm. These indicators have achieved the theoretical design goals and can basically meet the practical requirements for wound imaging measurement.

(3) Imaging Efficiency Test

The imaging efficiency of the radionuclide-contaminated wound measurement system was tested using a ^{241}Am standard point source (2×10^4 Bq). The MLEM algorithm was used for image reconstruction with a system response matrix calculated from simulated values and 50 iterations. During testing, the ^{241}Am standard point source was imaged at 5 mm intervals along both horizontal X-axis and vertical Y-axis directions. The signal-to-noise ratio of reconstructed images was calculated at different sampling data volumes to evaluate reconstruction quality and determine imaging efficiency. Additionally, since iteration number also affects reconstruction quality, different iteration numbers were applied to each dataset for image reconstruction. The test results are shown in Table 3 , which presents the average signal-to-noise ratio of reconstructed point sources for the same iteration number and sampling data volume.

Table 3 Experimental test results of system imaging efficiency

Iterations	Data Volume (events)	SNR
20	1000	12.3
20	2000	18.7
20	3500	19.2
20	5000	19.5
10	3500	15.6
30	3500	18.9
50	3500	19.1

As shown in Table 3, for the ^{241}Am standard point source with constant sampling data volume, the signal-to-noise ratio is lowest when the iteration number is set to 20. Therefore, the optimal iteration number is considered to be around 20, as excessive iterations increase noise peaks. With constant iteration number, the decreasing trend of the reconstructed point source signal-to-noise ratio flattens when sampling data exceeds 2000 events, indicating high imaging quality has been achieved. Therefore, a minimum of 2000 sampling events is considered sufficient to meet imaging quality requirements. Additionally, the time required to collect 3500 events from the ^{241}Am standard point source is 2-4 minutes, with 2 minutes corresponding to sampling when the point source is at the field-of-view center and 4 minutes at the edge. Thus, the sampling time required to ensure a minimum of 2000 events is approximately 2 minutes.

(4) Energy Spectroscopy Performance Testing

To achieve identification of contaminated nuclides in wounds and quantitative estimation of their retention depth and activity, the energy spectroscopy performance of the developed measurement system was tested. To improve system energy resolution, four gamma standard point sources—^{241}Am (59.54 keV), ^{57}Co (121.78 keV, 244.7 keV), ^{152}Eu (344.3 keV), and ^{137}Cs (661.66 keV)—were used to calibrate the energy of all 169 channels in the CZT crystal. Figure 9 [Figure 9: see original paper] shows the accumulated energy spectra of ^{241}Am, ^{133}Ba, and ^{137}Cs across all channels after calibration.

Analysis using energy spectroscopy software reveals that the energy resolution (FWHM) is approximately 8.43% for the ^{241}Am 59.5 keV full-energy peak, 2.28% for the ^{133}Ba 356 keV full-energy peak, and 2.1% for the ^{137}Cs 662 keV full-energy peak.

Figure 9 Energy spectra of the radionuclide-contaminated wound measurement system.

4.2 Experimental Testing of Retention Depth and Activity in Radionuclide-Contaminated Wounds

(1) System Detection Efficiency Calibration

Using puncture by the typical nuclide ^{241}Am as an example, a soft tissue-equivalent material (= 1.08 g/cm^3, H 10%, C 12.5%, N 3.50%, O 74%) was used to simulate an injured limb. A ^{241}Am standard point source (2.589×10^4 Bq) was placed beneath different thicknesses of soft tissue-equivalent material, and the measurement system recorded the net count rate (cps) of the ^{241}Am 59.5 keV full-energy peak. During measurement, the system probe was positioned as close as possible to the soft tissue-equivalent material surface, with the ^{241}Am standard point source center aligned with the detection crystal center, while maintaining constant measurement conditions. Each measurement lasted 180 seconds. The system calibration curve $\varepsilon(d)$ was calculated from cps data and is shown in Figure 10 [Figure 10: see original paper]. The branching ratio for ^{241}Am 59.5 keV is 35.9%, and the fitting relationship satisfies equation (10):

$$\varepsilon = 0.0093 \cdot e^{-0.044 \cdot d} \quad (10)$$

From Figure 10 and equation (10), the linear attenuation coefficient μ of the soft tissue-equivalent material for ^{241}Am 59.5 keV rays is approximately 0.044/mm.

Figure 10 Calibration curve of ^{241}Am 59.5 keV ($\varepsilon \sim d$) system.

(2) Measurement and Verification of Retention Depth and Activity

Method validation was conducted using ^{241}Am contaminants with known activity of 2.589×10^4 Bq trapped at depths of 9.68 mm, 17.82 mm, 27.93 mm, and 8.14 mm below the surface of an injured limb with thickness 36.13 mm. First, the radionuclide-contaminated wound measurement system determined the wound contamination distribution characteristics. The system probe was then adjusted to be as close as possible to the injured limb surface, ensuring the suspected puncture contamination hotspot position from imaging measurement was aligned with the detection crystal center. The net count rate of the ^{241}Am 59.5 keV full-energy peak was measured from both positive and negative directions, with each measurement lasting 180 seconds. Equation (7) was used to estimate the depth of radioactive contamination retention from the measurement results, and the $\varepsilon(d)$ fitting relationship from equation (10) together with equation (3) were used to estimate the retention activity. The measurement and verification results are shown in Table 4 .

Table 4 Measurement and verification results of retention depth and activity

True Depth (mm)	True Activity (Bq)	Net Count Rate (cps)	Estimated Depth (mm)	Depth Deviation (%)	Estimated Activity (Bq)	Activity Deviation (%)
9.68	2.589E+04	45.2	9.21	-4.9	2.512E+04	-3.0
17.82	2.589E+04	28.7	17.34	-2.7	2.468E+04	-4.7
27.93	2.589E+04	15.3	28.52	+2.1	2.721E+04	+5.1
8.14	2.589E+04	48.9	8.51	+4.5	2.703E+04	+4.4

These results demonstrate that using soft tissue-equivalent materials to approximate injured limbs, the method for estimating ^{241}Am contamination depth and retention activity is feasible. After verification, the deviation in calculated wound contamination retention depth is within 5%, and the relative deviation in wound retention activity is also within 5%, both within acceptable ranges.

5 Conclusion

In response to the current lack of effective measurement devices and methods for retention and distribution of radionuclide-contaminated wounds, this work has established a new non-contact measurement system featuring improved resolution, moderate size, and clinical applicability by combining imaging and energy spectroscopy measurement. The system can identify residual nuclides in wounds, measure the depth and activity of nuclides in different wound types, and determine the location and distribution characteristics of radioactive contamination in injured tissue. Testing shows the system achieves an imaging angular resolution of approximately 4.02°, an imaging field of view of 99.16 mm × 92.31 mm, positioning accuracy better than 3 mm, and imaging efficiency of about 2 minutes for a ^{241}Am standard point source (2×10^4 Bq). The energy resolution (FWHM) is approximately 8.43% at 59.5 keV. These indicators basically meet the measurement requirements for wound radioactive contamination.

Furthermore, by fully leveraging the system's energy spectroscopy measurement capabilities, we established a method to estimate the depth and activity of residual nuclides in injured limbs based on differences in X/γ ray absorption attenuation coefficients through varying tissue thicknesses. This method has been verified to be simple, practical, and reliable, with measurement deviations for both wound contamination depth and activity within acceptable ranges, demonstrating high clinical practicality.

The new radionuclide-contaminated wound measurement system and method developed in this work effectively solve the problem of measuring and rapidly reconstructing distribution characteristics of radionuclide-contaminated wounds, advancing the current state of measurement technology both domestically and internationally. The system is suitable not only for rapid detection of radionuclide-contaminated wounds in post-reprocessing and isotope production fields but also for post-injury clinical medical measurement. It provides an effective basis for evaluating local and internal irradiation doses from wound intake and for selecting medical treatment and disposal methods.

This work supplements and improves the domestic radiation monitoring and evaluation system and is significant for increasing industry awareness of internal irradiation hazards from radionuclide-contaminated wounds and for effectively enhancing occupational health protection for radiation workers.

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Note: Figure translations are in progress. See original paper for figures.