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Original article

Residual Radioactivity Concentration Analysis and Storage Period Calculation for Tc-99m Contaminated Medical Wastes

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ABSTRACT

Purpose: This study aimed to evaluate residual radioactivity concentrations in different types of medical radioactive waste contaminated with Tc-99m to determine optimal storage periods and develop efficient waste management strategies for nuclear medicine facilities. **Materials and Methods**: Radioactively contaminated waste generated from July 2022 to December 2024 was collected from radiation-controlled areas and categorized by waste type including glass vials, syringes, injection needles, and alcohol swabs. Radioactivity measurements were performed using a calibrated radioisotope dose calibrator, and mass measurements employed precision electronic balances. Adsorption rates and residual radioactivity concentrations were calculated for each waste category using standardized protocols. Storage periods were determined using radioactive decay formulas with a conservative safety factor of 1.2 applied to theoretical concentrations. **Results**: Significant variations in residual radioactivity were observed across waste types. Glass vials demonstrated the highest adsorption rate at 46% with residual activity of 1.7×10^{10}Bq, while syringes and needles retained 3% and 1% respectively. Despite low adsorption percentages, injection needles exhibited the highest mass-normalized radioactivity concentration at 4.81×10^{9} Bq/g due to minimal mass. Required storage periods ranged from 5.80 days for alcohol swabs to 6.68 days for glass vials, with needles requiring 6.50 days and syringes 6.15 days. All calculated periods remained within one week, making self-disposal feasible for short-lived radionuclides. **Conclusion**: This systematic evaluation provides quantitative, science-based guidelines for optimizing storage periods of Tc-99m contaminated medical waste. The methodology establishes a reference framework for developing self-disposal strategies for isotopes with half-lives under five days, contributing to more efficient and cost-effective radioactive waste management protocols in medical settings while ensuring regulatory compliance and public safety.

Key words Nuclear medicine, Tc-99m, Radioactive waste, Residual radioactivity concentration, Medical waste disposal

INTRODUCTION

The increasing use of radioactive isotopes in medical applications—such as nuclear medicine imaging (PET, SPECT), radiotherapy, and biomedical research—has significantly elevated the volume of radioactive medical waste. This surge necessitates the implementation of stringent management protocols to prevent environmental contamination and safeguard public health[1-3].

Medical radioactive waste encompasses diverse materials contaminated with radioisotopes used in clinical procedures. The predominant isotopes in nuclear medicine (F-18, Tc-99m, I-123, I-125, I-131 , Tl-201) generate various waste categories: spent radiopharmaceuticals, contaminated medical supplies (syringes, vials, needles, alcohol swabs), personal protective equipment, and clinical instruments. Although

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these materials typically exhibit short half-lives and low radiation emissions, they still necessitate rigorous safety protocols throughout the entire waste management process—from generation and storage to final disposal. This is particularly critical when radioactive materials are commingled with biological specimens or patient-derived fluids[4-10].

The management of radioactive waste is strictly regulated by national and international safety standards. Radioactive waste cannot be treated as general waste and must undergo rigorous processes, including safety assessments and environmental radiation impact evaluations, as stipulated in the Nuclear Safety Act[11]. Specifically, medical radioactive waste, except for reusable items such as patient gowns and tableware, is subject to regulatory control under the Nuclear Safety Act.

Radioactive waste disposal in Korea primarily occurs via two routes: direct self-disposal by licensed nuclear facility operators or delegated disposal through the Korea Radioactive Waste Agency (KORAD). The entrusted disposal process applies to low-and intermediate-level radioactive waste, which must comply with KORAD's radioactive waste delivery and receipt guidelines. In contrast, self-disposal is permitted only when waste meets specific criteria: radioactivity concentrations below allowable thresholds for each radionuclide, or projected annual radiation exposure doses below 10 μSv per individual and 1 man·Sv for the total population. Institutions intending to self-dispose of radioactive waste must submit a self-disposal plan for review by the Korea Institute of Nuclear Safety (KINS). Upon approval, the waste may be disposed of via incineration, landfill, or recycling[12-15].

Recent regulatory revisions permit institutions to submit five-year self-disposal plans for radionuclides with half-lives under five days. However, developing these plans requires specialized knowledge, precision measurement equipment, and trained personnel for assessing radioactive residuals and activity concentrations. Consequently, most medical institutions opt for entrusted disposal through authorized agencies.

This study aims to quantitatively assess residual radioactivity and activity concentrations across various categories of medical waste contaminated with Tc-99m. By doing so, it seeks to determine optimal self-disposal storage durations and propose scientifically grounded strategies for efficient and cost-effective radioactive waste management in clinical settings.

MATERIALS AND METHODS

1. Collection and Classification

Waste produced in radiation-controlled zones where radioisotopes are handled must be initially classified and managed as radioactive waste. In this study, contaminated waste generated between July 2022 and December 2024 was collected from such areas and categorized based on radionuclide half-life, waste type (combustible vs. non-combustible), and anticipated storage duration.

2. Encapsulation and Storage

After collection, volatile radioactive materials were sealed in leak-proof bags and stored in standardized 20 liters plastic containers specifically designed for medical radioactive waste. Each container was labeled with relevant information, including radiation symbols, radionuclide type, waste classification, date of generation, quantity, management number, intended disposal date, and measured surface dose rate(Fig. 1). Radioactive waste must be stored in shielded, easily decontaminated facilities with sufficient space allocated based on projected waste volume, while minimizing the storage period. Containers were stored in a Nuclear Safety Commission-approved radioactive waste storage facility with appropriate shielding and decontamination capabilities. Periodic inventory checks and container integrity inspections were conducted, along with surface and contamination measurements.

Fig. 1. The collected waste was sealed in 20 liters plastic medical waste containers, with radioactive waste labels (A) affixed for easy identification of the contents and quantity, and stored in the radioactive waste storage room (B).

3. Radioactivity and Mass Measurements

Radioactivity measurements were conducted using a radioisotope dose calibrator CRC-25R (Capintec, USA) in accordance with standardized calibration protocols. Before measurement, all nearby radiation sources were removed from the ionization chamber, followed by a full calibration procedure including auto-zeroing, background measurement, voltage verification, and data consistency checks. Accuracy verification used a standard Cs-137 source 3.599 MBq(Fig. 2). Mass measurements employed precision electronic balances MWⅡ-300H (CAS, Korea) calibrated with standard weights, with five measurements averaged for each sample.

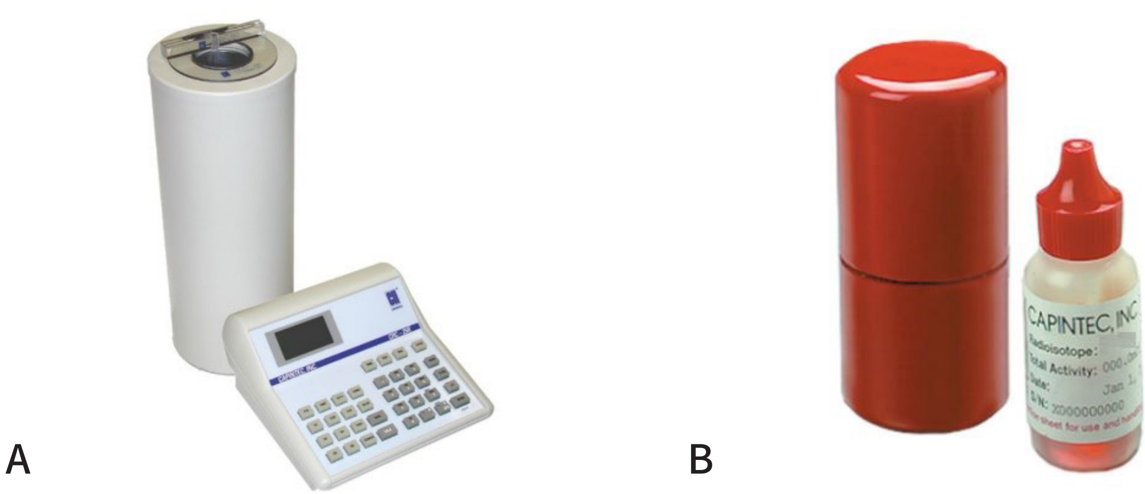


Fig. 2. The CRC-25R radioisotope dose calibrator (A) is employed to accurately measure the activity of various radionuclides, while a Cesium-137 calibration gamma standard source (B), emitting 662 keV gamma rays, is used to verify that the measurement accuracy remains within the specified limits.

4. Evaluation of radioactive material residue and Radioactivity concentration by waste type

4. 1. Glass Vials

At this institution, glass vials employed for eluting sodium pertechnetate from a generator, as well as for labeling and dispensing radioisotopes, are collected as non-combustible radioactive waste. These vials are sealed and stored without removing residual radioactivity. Therefore, assuming the maximum radioactivity (Amax:37 GBq) from one elution of the radioisotope generator is contaminating the glass vial. The vial adsorption rate (VAR) was calculated by measuring empty vial weight (V_0), vial with 5.2 ㎖ eluent (V_1), and vial with 2.6 ㎖ residual eluent (V_2)(Fig 3.):

$$VAR = (V2-V0) / (V1-V0) \times 100\% \quad \cdots\cdots\cdots \text{Eq. 1.}$$

Maximum potential residual radioactivity (VA) and radioactivity concentration (RA vial) were calculated as:

$$VA = Amax \times VAR \quad \cdots\cdots\cdots \text{Eq. 2.}$$

$$RA\ vial = VA / (V2-V0) \quad \cdots\cdots\cdots \text{Eq. 3.}$$

V_0 V_1 V_2

Fig. 3. The vial adsorption rate (VAR) was calculated by measuring the weight of the empty glass vial (V_0), the weight of the vial containing 5.2 ㎖ of eluent (V_1), and the weight of the vial with 2.6 ㎖ of eluent remaining (V_2).

4. 2. Syringes

Disposable 5 ㎖ syringes used for radiopharmaceutical administration were assessed by measuring empty syringe (S_0), syringe with 3 ㎖ saline (S_1), and post-use syringe (S_2) weights. The syringe adsorption rate (SAR) was calculated as(Fig 4.):

$$SAR = (S2-S0) / (S1-S0) \times 100\% \quad \cdots\cdots\cdots \text{Eq. 4.}$$

The residual radioactivity and volume in syringes used for labeling, distributing, and administering radiopharmaceuticals vary depending on the examination type. Therefore, assuming maximum radioisotope usage of 3.7 GBq (in 3 ㎖) contaminating the 5 ㎖ syringe, residual radioactivity (SA) and concentration (RA syringe) were determined:

$$SA = Amax \times SAR \quad \cdots\cdots\cdots \text{Eq. 5.}$$

$$RA\ syringe = SA / (S2-S0) \quad \cdots\cdots\cdots \text{Eq. 6.}$$

S_0 S_1 S_2

Fig. 4. The syringe adsorption rate (SAR) was calculated by measuring the weight of the empty 5 ㎖ disposable syringe (S_0), the weight of the syringe containing 3 ㎖ of saline (S_1), and the weight of the syringe after use (S_2).

4. 3. Injection Needles

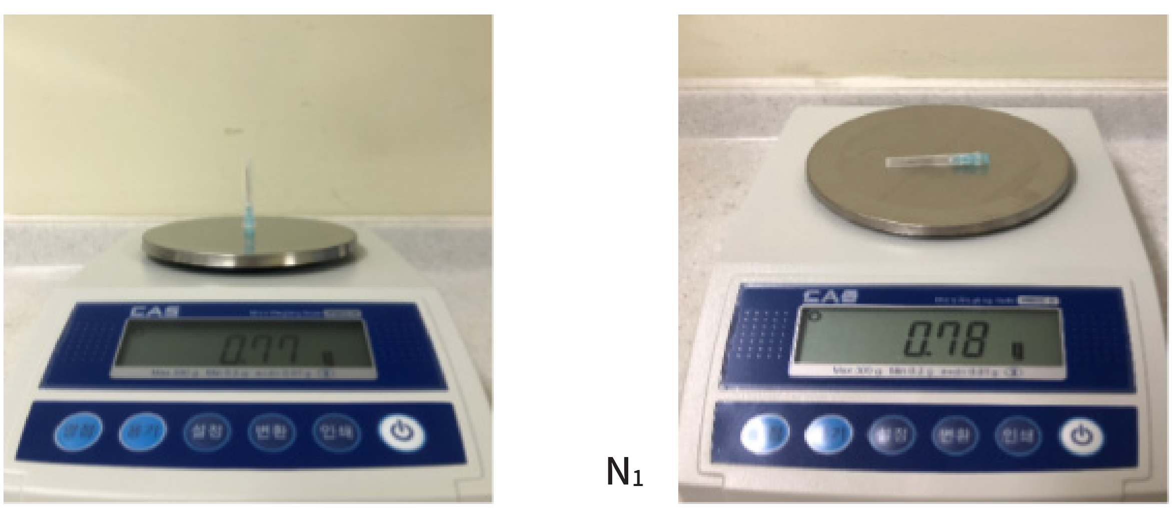
Needle evaluation involved measuring pre-use (N_0) and post-use (N_1) weights to calculate needle adsorption rate (NAR)(Fig 5.):

$$NAR = (N1-N0) / N0 \times 100\% \quad \cdots\cdots \text{Eq. 7.}$$

In this institution, after inserting a needle connected to a syringe into a vacuum glass vial containing radioisotopes, drawing the appropriate volume, and separating the syringe, the injection needle is collected and sealed as non-combustible medical radioactive waste. Therefore, Residual radioactivity (NA) and concentration (RA needle) calculations assumed maximum contamination of 3.7 GBq during radioisotope labeling, distribution, and radiopharmaceutical administration is contaminating the injection needle:

$$NA = Amax \times NAR \quad \cdots\cdots \text{Eq. 8.}$$

$$RA\ needle = NA / N1 \quad \cdots\cdots \text{Eq. 9.}$$



N_0 N_1

Fig. 5. The needle adsorption rate (NAR) was calculated by measuring the weight of the needle before (N_0) and after use(N_1).

4. 4. Alcohol Sponges

The quantity of alcohol sponges used per patient during hemostasis following intravenous radioisotope injection varies considerably, resulting in significant variability in measured residual radioactivity. For alcohol sponges used in patient procedures, residual radioactivity assessment required standardization due to variable usage patterns.

Thus, daily alcohol sponge usage was standardized to 1 pack, calculated from the maximum daily PET/CT and SPECT examinations (E_{max}). Per-patient sponge mass (DWperson) was calculated by measuring pre-use pack weight (D_0) and empty pack weight (D_1)(Fig 6.):

$$\text{DWperson} = (D0-D1) / \text{Emax} \quad \cdots\cdots\cdots\cdots\cdots \text{ Eq. 10.}$$

Since radiopharmaceutical administration in this institution uses catheters, the radioactivity of alcohol sponges contaminated with radioisotopes is minimal. Nevertheless, assuming the maximum radioisotope administered intravenously to one patient (Amax:1.11 GBq) contaminates the alcohol sponge, radioactivity concentration (RA alcohol sponge) was calculated as:

$$\text{RA alcohol sponge} = \text{Amax} / \text{DWperson} \quad \cdots\cdots\cdots\cdots\cdots \text{ Eq. 11.}$$

D_0

D_1

Fig. 6. The weight of disposable alcohol sponge used per person (DWperson) was calculated by measuring the weight of the alcohol sponge pack before use (D_0) and the weight of the empty pack after use (D_1).

RESULTS

1. Residual Radioactivity Analysis

The analysis of Tc-99m-contaminated medical waste revealed substantial variability in residual radioactivity across different waste types(Table 1). Glass vials exhibited the highest adsorption rate at 46%, corresponding to a residual activity of 1.7×10^{10} Bq. In contrast, syringes and injection needles retained only 3% and 1%, respectively. Despite their low adsorption rates, injection needles demonstrated the

Table 1. Residual radioactivity and concentration by waste type for Tc-99m

Waste Type	Initial Activity (Bq)	Adsorption Rate (%)	Residual Activity (Bq)	Mass (g)	Concentration (Bq/g)
Glass Vial	3.7×10^{10}	46	1.7×10^{10}	2.18	7.81×10^{9}
Syringe	3.7×10^{9}	3	1.12×10^{8}	0.06	1.86×10^{9}
Needle	3.7×10^{9}	1	4.81×10^{7}	0.01	4.81×10^{9}
Alcohol Swab	1.11×10^{9}	100	1.11×10^{9}	1.59	6.97×10^{8}

highest mass-normalized radioactivity concentration (4.81×10^9 Bq/g), primarily due to their minimal mass.

These findings regarding residual activity across waste types serve as the foundational input for calculating appropriate storage durations, as outlined below.

2. Storage Period Calculations

Required storage periods were calculated using the standard radioactive decay formula, $N = ln(I/I_0)/ln(0.5)$, where I_0 represents the initial radioactivity concentration, I is the permissible disposal threshold (100 Bq/g for Tc-99m), and N denotes the number of half-lives required for safe disposal. A conservative safety factor of 1.2 was applied to account for potential measurement uncertainties and regulatory margins (Table 2).

Among all waste types, glass vials required the longest storage duration at 6.68 days, followed by injection needles (6.50 days), syringes (6.15 days), and alcohol swabs (5.80 days).

Table 2. Required storage periods for Tc-99m contaminated waste

	Glass Vial	Syringe	Needle	Alcohol Swab
Adjusted Conc entration (Bq/g)*	9.37×10^9	2.23×10^9	5.77×10^9	8.37×10^8
Required H alf-lives (N)	26.48	24.41	25.78	23.00
Storage Period (Days)	6.68	6.15	6.50	5.80

* : With safety factor of 1.2 applied

DISCUSSION

This study addresses the critical need for quantitative data in medical radioactive waste management by offering scientifically grounded solutions for optimizing storage durations. Standardized protocols and calibrated instruments were employed to ensure methodological rigor, with particular emphasis on Tc-99m, which is used in approximately 85% of diagnostic nuclear medicine procedures.

The significance of this research is underscored by the current lack of quantitative data regarding residual radioactivity by waste type and accurate storage periods for self-disposal in Korea. The research reveals dramatic variations in adsorption rates and radioactivity concentrations among waste types. While glass vials demonstrated high adsorption rates (46%), injection needles showed remarkably low adsorption (1%) but exhibited the highest mass-normalized radioactivity concentration (4.81×10^9 Bq/g). This finding highlights that effective risk assessment of radioactive waste must go beyond simple adsorption rates and incorporate mass-normalized radioactivity concentrations to capture potential hazards accurately.

The study introduces a novel, data-driven framework for optimizing waste management that distinguishes it from prior research grounded primarily in regulatory or procedural analyses. While Kim et al. (2014) addressed legal standards and procedures for radioactive waste self-disposal, this study provides specific storage periods applicable in actual clinical settings, offering substantial practical value[9]. The results of this study can be directly utilized in establishing the 5-year self-disposal plans implemented by Korea's Nuclear Safety and Security Commission. Notably, by furnishing scientifically validated storage period calculations, the study may enhance the likelihood of regulatory approval and alleviate the administrative burden on healthcare institutions seeking to implement self-disposal protocols. Furthermore, the proposed methodology holds potential as standardized educational material for training personnel in radioactive waste management, compliance practices.

Several limitations must be acknowledged. First, the data were collected from a single institution, limiting the generalizability of the findings across facilities with differing operational procedures. Second, the study exclusively examined Tc-99m; additional validation is required for other commonly used radionuclides such as F-18 and I-131. Third, the validity of the conservative approach using a safety factor of 1.2 requires further evidence. While this factor accounts for measurement uncertainty and regulatory approval considerations, more sophisticated uncertainty analysis may be necessary.

Following IAEA guidelines permitting radioactive medical waste treatment as general waste after appropriate storage, this study enhances environmental efficiency by preventing unnecessary long-term storage and optimizing facility utilization. Ultimately, this research advances evidence-based practices in radioactive waste management and may enhance public confidence in the safety and oversight of nuclear medicine procedures.

CONCLUSION

This comprehensive evaluation of residual radioactivity levels in Tc-99m contaminated medical waste establishes quantitative benchmarks for optimizing storage durations and improving radioactive waste management strategies in clinical environments. The analysis revealed pronounced variation in both adsorption rates and mass-normalized radioactivity concentrations across waste types, including glass vials, syringes, injection needles, and alcohol swabs. Among these, glass vials displayed the highest residual activity and necessitated the longest storage duration, whereas alcohol swabs required the shortest retention time. By incorporating a conservative safety factors and applying precise radioactive decay modeling, the study determined optimal storage durations ranging from 5.80 to 6.68 days, depending on the waste category.

These findings offer actionable, data-informed guidance for the safe handling, interim storage, and disposal of short-lived radionuclides such as Tc-99m. The proposed approach contributes to the development of efficient, economically viable, and evidence-based radioactive waste management protocols tailored for clinical nuclear medicine environments. The methodology serves as a reference framework for developing self-disposal strategies for isotopes with half-lives under five days. Future studies should expand the methodology to include additional radionuclides and multi-institutional datasets, thereby enhancing the generalizability and regulatory utility of the proposed framework.

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