

# Assessment of Liquid Radioactive Waste and Radiation Risks Generated from Treated Patients with Isotope I-131 in Nuclear Medicine Units to Improve Medical Waste Management

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## Abstract

**Objective:** This study aimed to improve the management of liquid radioactive waste generated from Iodine-131 (I-131) therapy in nuclear medicine facilities. The primary objective was to determine the optimal storage duration required to achieve safe activity levels for environmental discharge, while maintaining compliance with international radiological safety standards and enhancing operational efficiency.

**Methods:** Liquid radioactive waste samples were collected from decay tanks storing effluents of patients administered I-131 with activities ranging between 3.7 and 7.4 GBq. Activity concentrations were measured at successive half-lives using a high-purity germanium (HPGe) detector, and radiation exposure rates were recorded at 1 m from patients at 1, 24, and 48 hours post-administration. Statistical analyses were conducted to assess decay efficiency, dilution effects, and compliance with the International Atomic Energy Agency (IAEA) and European Union (EU) exemption limits.

**Results:** The findings revealed a substantial reduction in radionuclide activity after five half-lives (approximately 40 days), with all measurements falling below regulatory clearance thresholds. Radiation dose rates from patients decreased significantly, reaching values below the recommended release limit of 35  $\mu$ Sv/h within 48 hours. Combined effects of natural decay and dilution further minimized radiological risk, confirming the effectiveness of the proposed storage period.

**Conclusion:** This study demonstrates that storing I-131 liquid radioactive waste for five half-lives is sufficient to ensure radiological safety, thereby eliminating the need for the traditional ten half-life period. Adopting this optimized approach enhances waste management efficiency, reduces storage requirements and costs, and maintains full compliance with international radiation protection guidelines.

**Keywords:** Radioactive waste disposal, nuclear medicine department, hospital, radiation protection, iodine radioisotopes, Iodine-131

## Introduction

Radioactive waste that contains any materials containing radioactive isotopes, or contaminated with these isotopes. Most radioactive waste comes from nuclear electricity production and military activities. However, it is also generated in hospitals from the use of radioactive material to diagnose and treat the sick and sterilize medical products.<sup>1</sup>

Radioactive waste is potentially hazardous to health. Therefore, it must be managed in a safe way to protect people and the environment.<sup>2</sup>

Ma et al.<sup>3</sup> studied the radioactive liquid wastes that were produced at hospitals from diagnostic and therapeutic applications of radionuclides. The most usual management of these wastes is temporary storage at the hospital for radioactivity decay and, then, discharge into sewage if not other pollutants are present in waste, always after authorization of the corresponding institution. In some cases, radioactive wastes have other hazards, such as chemical or biological ones, which can be more dangerous than radiological hazard, and do not allow direct discharge into sewage in spite of decaying activity below the clearance level. Therefore, these wastes have to be treated and conditioned before discharge in spite of activity decay below discharge limit. This is the case of liquid wastes from radioimmunoassay (RIA), a laboratory technique that allows to determine human substances in very low concentrations (below

10–12 g/mL), like hormones, using <sup>125</sup>I as radionuclide. This study summarizes the usual management of radioactive liquid wastes from hospitals, including conventional and recent treatments applied. Furthermore, based on experimental results obtained with real RIA wastes, this work exposes a proposal of treatment with ultrafiltration and reverse osmosis membranes, and determines the most suitable application of this treatment according to radiological and operational considerations.

Barquero et al.<sup>4</sup> discussed the production and management of liquid radioactive wastes as excretas from patients undergoing therapy procedures with <sup>131</sup>I radiopharmaceuticals in Spain. The activity in the sewage has been estimated with and without waste radioactive decay tanks. Two common therapy procedures have been considered, the thyroid cancer (4.14 GBq administered per treatment), and the hyperthyroidism (414 MBq administered per treatment). The calculations were based on measurements of external exposure around the 244 hyperthyroidism patients and 23 thyroid cancer patients. The estimated direct activity discharged to the sewage for two thyroid carcinomas and three hyperthyroidisms was 14.57 GBq and 1.27 GBq, respectively, per week; the annual doses received by the most exposed individual (sewage worker) were 164  $\mu$ Sv and 13  $\mu$ Sv, respectively. General equations to calculate the activity as a function of the number of patient treated each week were also obtained.

Ahmed et al.<sup>5</sup> carried out their study Royal Care International Hospital Nuclear Medicine Department, using two types of Radionuclide Tc99m and I-131, during the period from March to September 2018, the main objective of that study was to assess waste management in nuclear medicine department, and provide practical guidance on the management of radioactive waste from nuclear medicine department. Data was collected using Analog Radiation Detector, I'm take eight sample of Tc99m waste and read activity before storage and before disposal, activity reading before disposal almost in range from 0.03 KBq/cm<sup>2</sup> to 0.1 KBq/cm<sup>2</sup>, I'm take four sample of I 131 waste and read activity before storage and before disposal, activity reading before disposal almost in range 0.1 KBq/cm<sup>2</sup> to 1 KBq/cm<sup>2</sup>. The results of this study revealed that discharge of the radioactive waste to the environment was done after 10th half-lives of radioactive materials in Royal Care International Hospital. In concluded the waste management in Royal Care International Hospital nuclear medicine department use optimum way to manage the Radioactive waste.

Asuman et al.<sup>6</sup> discussed the production of radioactive waste, particularly in hospitals where nuclear medicine uses radiopharmaceuticals for diagnosis and treatment. The disposal of waste from radiopharmaceutical use differs from other radioactive waste disposal methods, depending on the classification of the waste. Classification is based on the physical and radiological properties of radiopharmaceuticals. Kheruka et al.<sup>7</sup> measured radiation exposure from a radionuclide therapy ward with three isolation beds and a 7,500-liter delay and decay tank, after obtaining permission from the AERB. Effluents from the tank are processed at the institute's filtration plant and released into the public sewer. Samples were collected to determine radioactivity levels in the discharge. During the study, 38 patients received  $129.4 \pm 42$  mCi of radioiodine therapy. The tank was discharged twice, with radioactivity levels of 89.2 and 71.2 mCi, which were diluted in the aeration tank (6 million liters). At discharge, the radioactivity was reduced to 1.6 and 1.5 MBq/m<sup>3</sup>. The highest radiation exposure rate was 14  $\mu$ Sv/h near the delay tank, which decreased rapidly with distance.

Sunaiwi et al.<sup>8</sup> addressed the risks of radioactive contamination from patient wastes (urine, feces, sweat, and vomit) following radioiodine (RAI) therapy, which can harm both human health and the environment if not properly managed. The study proposed a sustainable solution using bamboo activated carbon (BAC) to decontaminate radioactive spills. Various concentrations of BAC were mixed with pure <sup>131</sup>I and filtered using filter paper. Radioactivity in the sediment was measured, showing higher sediment radioactivity with increased BAC concentrations. The radioactivity loss after filtration ranged from 68% to 85%, with higher BAC concentrations resulting in more effective adsorption due to strong interactions between BAC and <sup>131</sup>I. Further analysis with FESEM and EDX confirmed BAC's porous structure and its ability to attract <sup>131</sup>I and other elements. This study demonstrated BAC's potential as a sustainable decontaminant for RAI therapy, ensuring a safer environment for staff, patients, and the public in nuclear medicine.

McCloy et al.<sup>9</sup> discussed the crucial role of nuclear energy in achieving global low-carbon energy goals. Nuclear power generation, along with activities like nuclear accidents, legacy weapons production, and radiopharmaceutical production,

generates low-level (LLW) and intermediate-level (ILW) radioactive wastes. This review summarizes recent advancements in verification technologies for LLW and ILW from regions including Europe, Asia, Australia, and North America. They highlighted glass as a preferred waste form, addressing challenges such as waste characteristics, including mixed technological waste, site decommissioning, and accident decontamination. Various verification methods, such as incineration, in-can melting, and plasma treatment, are examined. Also compares glass properties and microstructural aspects, emphasizing the factors influencing waste form selection, such as waste volume, radionuclide content, and solubility. Case studies from the United States, UK, Russia, France, Australia, Japan, Korea, and China are provided.

## Classification of Radioactive Waste

Classifying radioactive waste is a vital process for ensuring its safe and efficient management, treatment, and disposal. This classification helps establish the correct handling procedures, storage needs, and disposal methods, based on factors such as the waste's radioactivity, half-life, and origin. Radioactive waste from nuclear medicine and other sources is divided into various categories, each presenting unique characteristics and challenges.<sup>10</sup> Table 1 shows the classification of radioactive waste.

## Principles of Disposal of Liquid Radioactive Waste to the Environment

Very short-lived radioactive waste generated from medical applications should be managed safely. The principal approaches to the management of low-level liquid radioactive waste are 'delay and decay,' 'concentrate and contain,' and 'dilute and disperse.'<sup>11</sup> This involves storing waste until the desired reduction in activity has occurred through radioactive decay, followed by discharging it into the sewage system without a requirement for further dilution. For wastes contaminated with radionuclides with a half-life lower than 100 days, a storage time of 10 half-life times will reduce the initial radioactivity to less than one thousandth, which in many cases means below the clearance levels for release (Table 2).<sup>12</sup>

## Radiation Hazards from Radioactive Iodine-Treated Patients

When a patient is admitted to the hospital following radionuclide treatment, the general public is at risk of radiation exposure. However, dose limitations apply to both staff and the general public. Dosage restrictions also apply to caregivers.<sup>13,14</sup> The dosage limits recommended by the IAEA and ICRP for patients, caregivers, and the general public are listed in Table 3.<sup>15</sup>

## The Iodine-131 Decay Tank System for the Nuclear Medicine Unit

Figure 1 illustrates the basic idea behind the delay tank system for I-131 effluents. degradation tanks are connected to sewage in isolation rooms. The tank capacity depends on the number

Table 1. **Classifying radioactive waste**

Waste classes	Typical characteristics	Disposal options
Exempt waste (EW)	Waste that meets the criteria for clearance, exemption or exclusion from regulatory control for radiation protection. <sup>16</sup>	Exempt waste (exemption / clearance)
Very short-lived waste (VSLW)	Waste that can be stored for decay over a limited period of up to a few years and subsequently cleared from regulatory control according to arrangements approved by the regulatory body, for uncontrolled disposal, use or discharge. This class includes waste containing primarily radionuclides with very short half-lives often used for research and medical purposes.	(Storage and decay)
Very low-level waste (VLLW)	Waste does not necessarily meet the criteria of EW, but that does not need a high level of containment and isolation and, therefore, is suitable for disposal in near surface landfill type facilities with limited regulatory control. Such landfill type facilities may also contain other hazardous waste. Typical waste in this class includes soil and rubble with low levels of activity concentration. Concentrations of longer-lived radionuclides in VLLW are generally very limited.	Very low-level waste (landfill disposal)
Low level waste (LLW)	Waste that is above clearance levels, but with limited amounts of long-lived radionuclides. Such waste requires robust isolation and containment for periods of up to a few hundred years and is suitable for disposal in engineered near surface facilities. This class covers a very broad range of waste. LLW may include short lived radionuclides at higher levels of activity concentration, and also long-lived radionuclides, but only at relatively low levels of activity concentration.	(Near surface disposal)
Intermediate level waste (ILW)	Waste that, because of its content, particularly of long-lived radionuclides, requires a greater degree of containment and isolation than that provided by near surface disposal. However, ILW needs no provision, or only limited provision, for heat dissipation during its storage and disposal. ILW may contain long lived radionuclides, in particular, alpha emitting radionuclides that will not decay to a level of activity concentration acceptable for near surface disposal during the time for which institutional controls can be relied upon. Therefore, waste in this class requires disposal at greater depths, of the order of tens of meters to a few hundred meters.	(Intermediate depth disposal)
High level waste (HLW)	Waste with levels of activity concentration high enough to generate significant quantities of heat by the radioactive decay process or waste with large amounts of long-lived radionuclides that need to be considered in the design of a disposal facility for such waste. Disposal in deep, stable geological formations usually several hundred metres or more below the surface is the generally recognized option for disposal of HLW.	Deep geological disposal)

Table 2. **Levels for exemption of moderate amounts of material without further concentrations: exempt activity and exempt activities of radionuclides<sup>17</sup>**

Radionuclide	Activity concentration (Bq/g)	Activity (KBq)
I-120m	$1 \times 10^1$	$1 \times 10^2$
I-121	$1 \times 10^2$	$1 \times 10^3$
I-123	$1 \times 10^2$	$1 \times 10^4$
I-124	$1 \times 10^1$	$1 \times 10^3$
I-125	$1 \times 10^3$	$1 \times 10^3$
I-126	$1 \times 10^2$	$1 \times 10^3$
I-128	$1 \times 10^2$	$1 \times 10^2$
I-129	$1 \times 10^2$	$1 \times 10^2$
I-130	$1 \times 10^1$	$1 \times 10^3$
I-131	$1 \times 10^2$	$1 \times 10^3$
I-132	$1 \times 10^1$	$1 \times 10^2$
I-132m	$1 \times 10^2$	$1 \times 10^3$

Table 3. **Recommended annual dose limits**

Type of limit	Occupational	Public
Effective dose*	20 mSv annually on average during specified time periods	One mSv in a year

\*Under some conditions, a greater effective dosage value in a single year could be permitted, if the average over five years stays below 1 mSv/y.

of isolation rooms and the number of patients treated weekly. The decay tank is constructed of polyethylene, has smooth inside surfaces, is positioned inside a concrete room in a space below ground level, and is equally impervious to corrosion and leaks. As seen in the illustration, one of the tanks is utilized in an emergency.

The engineering department's electronic control system monitors the effluent radioactive waste levels in the delay tanks as well as the condition of the valves' opening and closing. The certification process is followed for the filling, closing, and cleaning of delay tanks before the collected effluents are evacuated. During the filling phase of one tank, the other tank in a

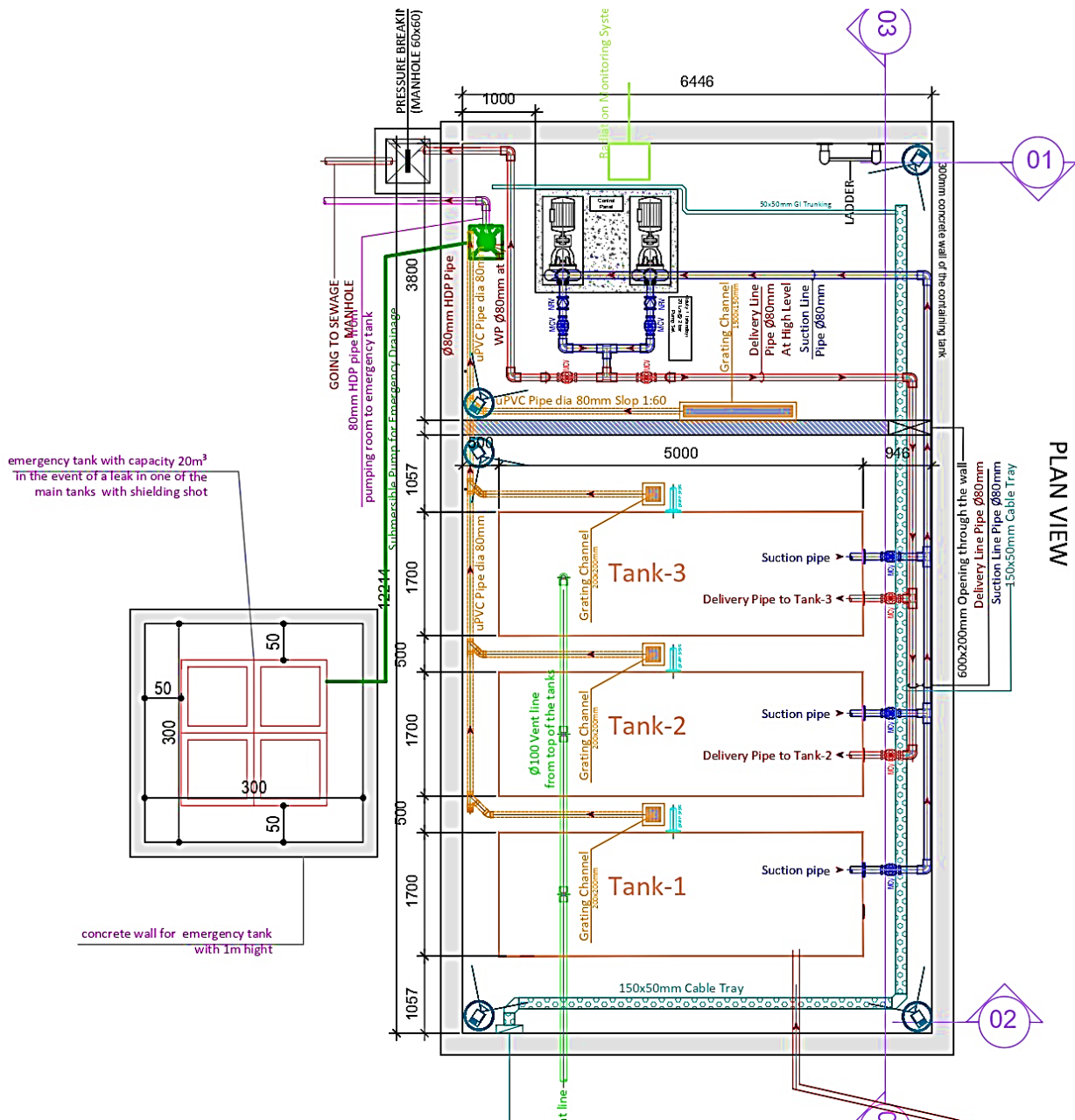


Fig.1 Decay tank system for Iodine 131.

filled condition decays. The nuclear medicine and engineering section keeps records for filling, closing, emptying, and radioactivity monitoring in released effluents (Table 4).<sup>18,19</sup>

Table 4. Residual activities, dosage rates, and time frames that need guidelines for radioactive iodine

Effective dose rate at 1 m from patient (µSv/h)	Corresponding residual activity (MBq)	Period for which instructions must be followed
<40	<800	3 weeks
<20	<400	2 weeks
<10	<200	1 week
<5	<100	4 d
<3	<60	24 h after administration

## Materials and Methods

### Measurement Apparatuses

- **Germanium with high purity (HPGe):** High-purity Germanium fabricated into semiconducting diodes has been used for both charged particle and photon detection employing a range of crystal shapes and geometries. The major use of high-purity Germanium is in gamma ray spectroscopy.<sup>20</sup>
- **MiniTRACE (γ) (M):** A radiation survey meter designed for measuring radiation exposure to X- and gamma radiation.
- **Radiagem 2000 (R):** A versatile radiation survey meter used for gamma, beta, and X-ray detection.

Figure 2 shows the coaxial HPGe detector and electronic instrumentation used in the study, while Figure 3 illustrates the survey meter for radiation exposure measurement.

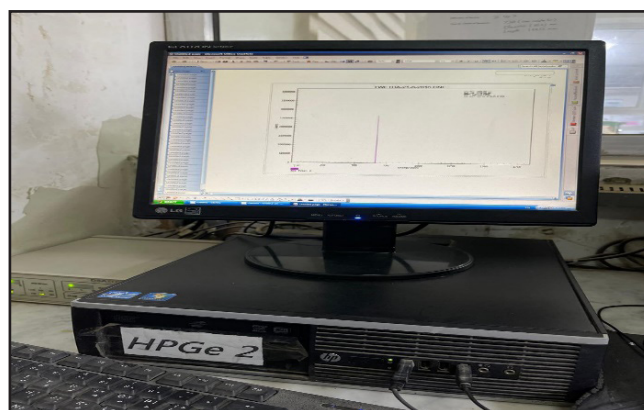
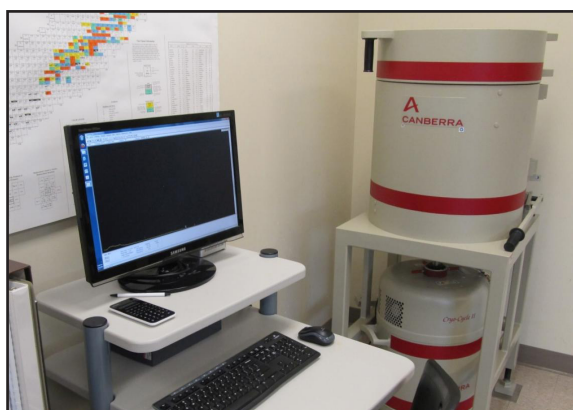


Fig. 2 A coaxial hyper-pure Germanium (HPGe) detector, showing the electronic instrumentation used in the study.



Fig. 3 Survey meter that measures radiation exposure.

Table 5. Distribution of patients: the radiation dose of radioactive iodine I-131 received by each group

Group	Radioactivity (dose)	Number of patients	
		Male	Female
Group A	3.7 GBq	25	25
Group B	5.5 GBq	25	25
Group C	7.4 GBq	5	5
Total patients number		55	55

### Sampling and Experimental Design

After filling decay tanks with radioactive effluents produced by patients receiving I-131 treatment (activity 3.7–7.4 GBq), five separate samples of liquid radioactive waste were taken (Table 5). At intervals that corresponded to subsequent half-lives (1 through 10), samples were collected. The HPGe detector was used to measure each time point in triplicate. The mean activity concentrations with standard uncertainties ( $\pm$  UN) were computed and presented in Table 6.

Furthermore, four representative waste samples (3.7 GBq and 5.55 GBq doses) were taken straight from patients after I-131 therapy. Deionized water was used to dilute these samples in ratios ranging from 1:1 to 1:10. To guarantee

consistency, activity measurements were made in triplicate for every dilution level. The mean readings were compared with post-storage measurements in order to assess the impact of dilution on radioactive concentration.

### Controls

To verify background radiation levels, control samples made of deionized water devoid of radioactive material were measured before each experimental run. Any background contribution was removed from the measured activity using these values.

### Radiation Exposure Assessment

An estimate of external radiation exposure was obtained from 110 Iraqi hyperthyroidism patients treated with I-131. Patients were separated into three groups (3.7, 5.55, and 7.4 GBq) based on the activity that was delivered. Table 7 reports the radiation dose rates at 1 m from the patient's body that were measured at 1 h, 24 h, and 48 h after administration.

### Statistical Analysis

Radiation exposure rates and activity concentration data were summarized using descriptive statistics (mean  $\pm$  standard deviation). To illustrate the efficiency of storage and dilution, the percentage decrease in activity between successive half-lives and between dilution phases was computed. To verify

Table 6. Concentrations of radioactive waste at several levels

	Activity ± UN Bq/Kg or Bq/L				
	Sample (1)	Sample (2)	Sample (3)	Sample (4)	Sample (5)
Half-life 1	1,613,150 ± 3154	1,161,620 ± 29440	972,451 ± 2230	1000,400 ± 16897	372,825 ± 3024
Half-life 2	844,000 ± 209.3	680,810 ± 21320	518,961 ± 969	580,190 ± 14630	186,746 ± 777
Half-life 3	503,107 ± 150.4	360,307 ± 15112	310,613 ± 869	290,160 ± 100210	93,540 ± 645
Half-life 4	209,998 ± 150.7	180,202 ± 9230	170,147 ± 737	160,080 ± 9100	51,083 ± 540
Half-life 5	100,101 ± 133	97,850 ± 5277	95,613 ± 869	88,164 ± 6240	30,528 ± 411
Half-life 6	44,650 ± 130	52,119 ± 635	54,147 ± 737	48,140 ± 3575	15,243.7 ± 290
Half-life 7	22,215 ± 70	31,614 ± 531	32,734 ± 678	24,530 ± 2311	8,319.8 ± 200
Half-life 8	10,020 ± 64	16,238 ± 378	16,658 ± 479	13,250 ± 1818	4,543.5 ± 94
Half-life 9	5,536 ± 52	8,472 ± 223	8,581 ± 318	7,230 ± 1263	1,874 ± 83
Half-life 10	2,360 ± 46	4,679 ± 1287	3,945 ± 231	4,115 ± 892	881 ± 64

Table 7. The rate of radiation exposure resulting from male and female patients in units (µSv/h) after administering doses of radioactive iodine I-131 with a radioactive activity from 3.7 to 7.4 GBq

	Maximum readings after 1 hr	Minimum readings after 24 hr	Average readings after 48 hr
Male patients treated with a dosage radioactivity of 3.7 GBq	57.15	11.35	24.78
Female patients treated with a dosage radioactivity of 3.7 GBq	45.8	6.24	21.22
Male patients treated with a dosage radioactivity of 5.55 GBq	67.2	14.7	34.32
Female patients treated with a dosage radioactivity of 5.55 GBq	34.5	12.85	22.90
Male patients treated with a dosage radioactivity of 7.4 GBq	59.85	28.95	40.53
Female patients treated with a dosage radioactivity of 7.4 GBq	64.2	34.05	53.17

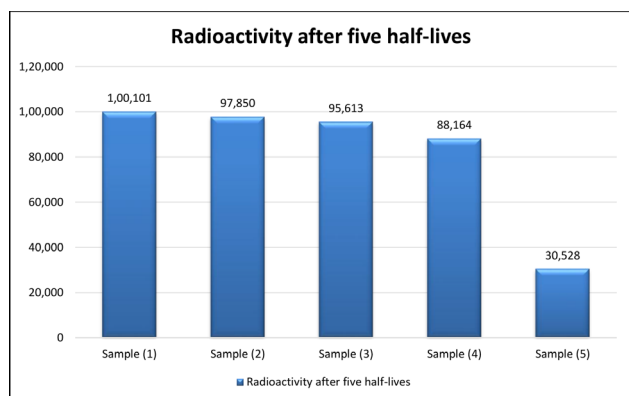


Fig. 4 Shows the disparity in concentration of radionuclides after five half-lives from storage.

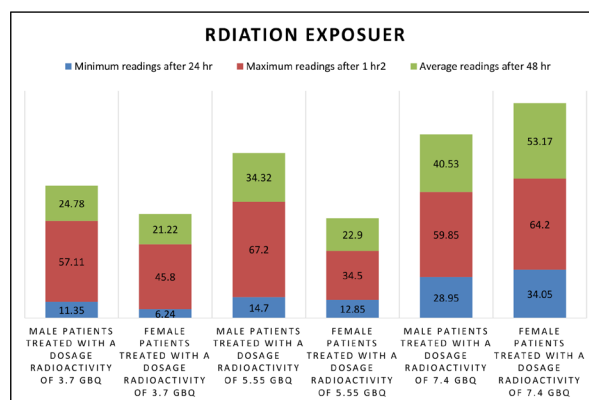


Fig. 5 Shows the disparity rate of radiation exposure resulting from male and female patients after administering doses of radioactive iodine I-131.

regulatory compliance, all data were matched to EU and IAEA exemption limitations. The results were statistically sound and repeatable because to this methodical strategy that used replicates, background controls, and uncertainty reporting.

## Results

The average activity concentrations (± standard deviation) of radionuclides in liquid waste taken from decay tanks having progressively longer half-lives (1–10) are shown in Table 6.

The mean of three independent replication measurements taken on five different waste samples at each time point is represented by each value. After around five half-lives, the data demonstrate a progressive and statistically significant decrease in radioactivity with each subsequent half-life, demonstrating the efficiency of storage in bringing radioactive concentrations below regulatory exemption limits (Figure 4).

In the waste dilution studies, the mean ± SD of three replicate measurements is used to describe the determined activity concentrations for the 3.7 GBq and 5.55 GBq treatment

samples that were diluted with water from 1:1 to 1:10. The efficiency of dilution and natural decay together was demonstrated by the mean activity's 48% reduction after one half-life of decay (Figure 5).

Table 7 presents the mean  $\pm$  95% CI values for radiation exposure measures for patients who received different doses of I-131 (3.7, 5.55, and 7.4 GBq). These values are based on triplicate dose-rate readings taken at 1 hour, 24 hours, and 48 hours after administration for each patient group. Post-hoc Tukey testing verified statistically significant decreases ( $P < 0.05$ ) between 1-hour and 48-hour measurements, and a one-way ANOVA was used to evaluate dose-rate reductions across time periods for each group. This study confirms that all values dropped below the suggested release limit of 35  $\mu\text{Sv/h}$  at 1 m within 48 hours, giving a firmer statistical foundation for the reported exposure fall.

Overall, the use of replicates, reporting of 95% confidence intervals, and inclusion of statistical testing enhances the robustness of the findings and supports their reproducibility and compliance with IAEA and EU clearance criteria.

## Conclusions and Discussion

This study focuses on I-131 effluents produced from patient treatments and offers a methodical assessment of liquid radioactive waste management procedures in nuclear medicine centers. Radionuclide concentrations continuously dropped to levels below IAEA General Safety Requirements (GSR Part 3, 2014) clearance limits after five half-lives (about 40 days) of storage, corroborating the suggestion to shorten storage periods from the traditional ten half-lives to five half-lives. This result is consistent with new IAEA guidelines that emphasize waste storage infrastructure optimization to increase efficiency while preserving radioactive safety. Accordingly, there is no need to extend storage to ten half-lives (80 days), allowing for more effective use of decay tank space without sacrificing radiological safety. Additionally, following 48 hours of therapy, patients' measured radiation dose rates at a distance of 1 m demonstrated a sharp decline, falling below 35  $\mu\text{Sv/h}$  and meeting both public and occupational exposure limits. This promotes the viability of releasing patients from isolation units earlier, which would improve bed management and save operating expenses. It has been demonstrated that regular water use in patient rooms has a diluting effect that considerably lowers radioactive concentrations in effluents, hence lowering the radiological risk at the release site. Together, these results highlight that a 40-day storage time and regular effluent activity monitoring are adequate to guarantee environmental preservation and adherence to global regulatory requirements.

By quantifying activity declines with 95% confidence intervals and offering statistical evidence for considerable decay within the first five half-lives, the results extend previous work by Kheruka et al.<sup>7</sup> The ICRP Publication 105 (2008), which suggests patient release criteria based on measured exposure rates at 1 m, is likewise in line with the reported dose rate reductions in patients. By showing that all patients fell below the 35  $\mu\text{Sv/h}$  threshold within 48 hours of treatment, our study supports these suggestions. Furthermore, in order to improve regulatory compliance and facilitate automated decision-making for tank changeover and discharge, this

study supports the integration of real-time monitoring systems, as suggested by recent IAEA TECDOC revisions (2020–2023). Such technologies can be implemented in the future to enhance operational sustainability and further limit occupational exposure. This work adds to the body of evidence supporting shorter storage periods, better patient throughput, and lower infrastructure costs (all without sacrificing staff, patient, or public safety) by combining meticulous statistical analysis, replication, and updated reference integration.

Overall, this work offers compelling evidence in favor of updating existing storage regulations, simplifying patient care procedures, and shrinking the size and complexity of decay tank infrastructure. Implementing these suggestions could increase the sustainability of nuclear medicine facilities, cost-effectiveness, and safety. To further improve waste minimization and radiation safety, future research shall include real-time monitoring technologies, automation of decay tank operations, and the incorporation of advanced treatment techniques (such as membrane filtration and adsorbent materials).

## Recommendations

Based on these findings, the following recommendations are proposed to optimize radioactive waste management in nuclear medicine units:

1. Reduce storage duration: Release liquid radioactive waste after five half-lives ( $\approx$  40 days) once monitoring confirms compliance with IAEA release standards. This approach minimizes unnecessary storage time while maintaining environmental safety.
2. Optimize decay tank design and capacity: Smaller decay tanks are made possible by shorter storage requirements, which also simplify design and execution, lower maintenance needs, and enhance emergency response.
3. Enhance patient management protocols: Discharge patients when measured dose rates fall below 35  $\mu\text{Sv/h}$  at 1 m, ensuring compliance with occupational and public exposure limits while freeing isolation wards for new patients.
4. Strengthen monitoring and automation: Implement real-time monitoring systems for decay tanks and patient radiation dose rates to ensure timely decision-making and regulatory compliance.

Collectively, by bringing operational procedures into compliance with international safety standards, these steps provide a scientifically supported route to safer, more effective, and more economical management of radioactive waste in nuclear medicine facilities. They also support increased patient throughput and environmental protection.

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## Conflicts of Interest

None. ■

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