



Radioactivity Retention of Liquid Iodine-131 in Residual Syringes: Implications for Radiation Exposure and Radioactive Waste Management in Radiopharmaceutical Preparation

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Abstract

Residual radioactivity in syringes used during the preparation of liquid iodine-131 radiopharmaceuticals may contribute to avoidable radiation exposure and increase the radioactive waste burden. Although radioactivity retention in syringes has been reported for several radiopharmaceutical preparations, safety-oriented evaluations of residual iodine-131 activity in liquid formulations remain limited. This study aimed to investigate the relationship between residual radioactivity retention and radiation exposure rates in syringes following liquid iodine-131 preparation and to assess the implications for radioactive waste management. This experimental study used sodium iodide labeled with iodine-131 (Na^{131}I) in liquid form. Initial and residual syringe activities were measured using a radionuclide dose calibrator, while ambient dose equivalent rates were measured using a gamma radiation survey meter. Residual activity, percentage radioactivity retention, radiation dose rate, and estimated decay-in-storage duration were analyzed descriptively. Pearson's correlation analysis and simple linear regression were performed to evaluate the relationship between radioactivity retention and measured radiation dose rates. Sequential rinsing with water for injection and 0.9% sodium chloride solution was evaluated as an approach to reducing residual radioactivity. Mean residual syringe activity increased from 0.270 ± 0.012 mCi at an initial activity concentration of 5 mCi/mL to 0.435 ± 0.016 mCi at 15 mCi/mL. Radioactivity retention increased from $12.90 \pm 0.63\%$ to $20.97 \pm 0.74\%$, accompanied by an increase in the measured radiation dose rate from 2.703 ± 0.102 to 4.131 ± 0.237 $\mu\text{Sv/h}$. Radioactivity retention exhibited a strong positive correlation with the radiation dose rate (Pearson's $r = 0.9412$, $R^2 = 0.8858$, $p < 0.0001$). Sequential rinsing reduced the measured dose rate from 4.160 ± 0.186 to 1.329 ± 0.034 $\mu\text{Sv/h}$ using water for injection and from 4.190 ± 0.117 to 1.314 ± 0.023 $\mu\text{Sv/h}$ using 0.9% sodium chloride solution. These findings demonstrate a strong association between residual syringe radioactivity and measured radiation dose rates following liquid iodine-131 preparation, highlighting the contribution of residual activity to the initial radioactive waste burden. Controlled rinsing procedures may help reduce residual syringe activity and support radiation protection, contamination control, and radioactive waste management practices in nuclear medicine facilities.

INTRODUCTION

Iodine-131 remains an important radionuclide in nuclear medicine, particularly for the treatment and follow-up of thyroid-related disorders, including differentiated thyroid cancer and hyperthyroidism, as well as selected diagnostic applications (Haugen et al., 2016; Nguyen et al., 2024). In clinical radiopharmacy practice, iodine-131 is frequently supplied as sodium iodide (Na^{131}I) in liquid form and dispensed into patient-specific activities according to

established institutional radiopharmacy procedures. The preparation of liquid iodine-131 radiopharmaceuticals requires accurate radioactivity measurements, consistent measurement and handling geometries, effective contamination control, appropriate radiation shielding, comprehensive documentation, and proper radioactive waste management (Hung, 1997; Gillings et al., 2021; Wadsley et al., 2023).

One of the technical and radiation safety concerns associated with radiopharmaceutical preparation is residual radioactivity in syringes, vials, and other preparation devices. Residual syringe activity, commonly described in terms of radioactivity retention, refers to the amount or proportion of radioactive activity remaining within a syringe after the radiopharmaceutical has been transferred or dispensed. This phenomenon is relevant not only to the accuracy of activity transfer and the amount of activity delivered but also to radiation protection, as retained radioactivity constitutes a residual radiation source that may contribute to occupational radiation exposure and increase the radioactive waste burden (Keskinetepe & Özer, 2005; Stavrou et al., 2016).

Previous studies have investigated residual radioactivity and the adsorption of radiopharmaceutical compounds onto syringe and container surfaces, particularly in technetium-99m-based diagnostic radiopharmaceutical preparations (Gunasekera et al., 2001; Mushtaq et al., 2008; Swanson et al., 2013; Galbraith et al., 2015; Kvaternik et al., 2020). Residual activity may be influenced by several factors, including the physicochemical properties of the radiopharmaceutical, activity concentration, syringe material, residual dead-space volume, interactions with container surfaces, contact duration, and rinsing or flushing procedures (Stopar et al., 2007; Ladrière et al., 2024). However, comprehensive safety-oriented investigations specifically addressing residual syringe radioactivity during liquid iodine-131 preparation remain limited.

The radiation safety implications of residual iodine-131 activity are particularly significant because iodine-131 emits both beta particles and gamma photons and has a physical half-life of approximately 8.02 days, necessitating appropriate radiation protection measures and radioactive waste management procedures. Radioactive waste generated during iodine-131 preparation, including contaminated syringes and associated materials, must be appropriately segregated, shielded, monitored, documented, and managed through decay-in-storage procedures, where permitted, until the waste satisfies applicable clearance or release criteria established by institutional policies and regulatory authorities (IAEA, 2009; ICRP, 2007). Consequently, minimizing residual syringe radioactivity during radiopharmaceutical preparation represents a potential preventive strategy for reducing avoidable radiation exposure and supporting the radiation protection principle of keeping exposures as low as reasonably achievable (ALARA).

Although radioactivity retention is frequently discussed as a technical issue associated with incomplete activity transfer, its relationship with measured radiation dose rates and the resulting radioactive waste burden warrants further investigation. Therefore, this study aimed to evaluate the relationship between radioactivity retention in syringes following liquid iodine-131 preparation and the associated radiation dose rates, while assessing the implications of residual activity reduction for radioactive waste management. Specifically, the study sought to (1) quantify residual syringe activity and percentage radioactivity retention at different activity concentrations; (2) measure radiation dose rates associated with residual syringe radioactivity;

(3) determine the correlation between radioactivity retention and measured radiation dose rates; (4) evaluate the effectiveness of sequential rinsing procedures in reducing residual radioactivity and radiation dose rates; and (5) estimate the decay-in-storage duration required for radioactive syringe waste under specified release criteria. The findings are expected to advance understanding of radiation safety considerations in radiopharmaceutical preparation, provide evidence to inform practical radiopharmacy procedures, and support the application of the ALARA principle in nuclear medicine facilities.

METHOD

Study design

This study employed an experimental design to evaluate residual syringe radioactivity during liquid iodine-131 radiopharmaceutical preparation at the nuclear medicine radiopharmacy facility of Dr. Kariadi General Hospital, Semarang, Indonesia. All experimental procedures were conducted in accordance with institutional standard operating procedures and radiation safety requirements. The analysis focused on residual syringe activity, percentage radioactivity retention, radiation dose rate, and estimated decay-in-storage duration. No patient-related clinical procedures or imaging evaluations were included in the study.

Radiopharmaceutical material and instruments

The evaluated radiopharmaceutical was liquid sodium iodide iodine-131. Radioactivity was measured using a dose calibrator, while radiation exposure rate from residual syringes was measured using a gamma survey meter. Activity measurement using a dose calibrator was performed because reliable activity measurement is essential in nuclear medicine and radiopharmaceutical preparation (Bergeron & Cessna, 2018).

The main evaluated variables were initial syringe activity, residual syringe activity, percentage radioactivity retention, radiation exposure rate, and estimated decay-storage time of residual syringe waste.

Definition and calculation of radioactivity retention

Radioactivity retention was defined as the percentage of activity remaining in the syringe after the liquid iodine-131 preparation had been transferred out of the syringe. Radioactivity retention was calculated using the following equation:

Radioactivity retention (%) = (Residual syringe activity / Initial syringe activity) × 100
Initial activity and residual syringe activity were measured using a dose calibrator. Residual syringe activity was then used as the basis for evaluating activity loss, radiation exposure rate, and radioactive waste implications.

Evaluation of residual syringe activity and exposure rate

The initial safety evaluation included liquid iodine-131 samples at three concentration levels: 5, 10, and 15 mCi/mL. For each concentration level, five independent observations were obtained. Residual activity, radioactivity retention, radiation exposure rate, and estimated decay-storage time were summarized as mean ± standard deviation, as shown in Table 1.

Radiation exposure rate was measured from residual syringes using a gamma survey meter under standardized measurement conditions. The exposure rate was expressed in µSv/h. The relationship between percentage radioactivity retention and radiation exposure rate was evaluated using the 15 independent observations from the concentration-test data set, as presented in Figure 1.

Evaluation of sequential rinsing

Sequential rinsing was evaluated as an approach to reduce residual syringe activity and radiation exposure rate. Water for injection and 0.9% sodium chloride were used as rinsing solutions. Radiation exposure rate was measured before rinsing and after each rinsing stage. Because the rinsing dataset represented repeated measurements from the same syringes, it was interpreted as a stage-wise reduction pattern rather than as independent observations for correlation analysis. The stage-wise reduction of radiation exposure rate after sequential rinsing is summarized in Table 2 and visualized in Figure 2.

Estimated decay-storage time

The radioactive waste implication was assessed using estimated decay-storage time based on residual activity. The estimation used the physical decay equation for iodine-131. The decay constant used in this calculation was 0.0864 day^{-1} . The estimated time required for residual activity concentration to reach a reference clearance level was calculated using the following equation:

$$t = \ln (A_0/10) / 0.0864$$

where t is estimated decay-storage time in days, A_0 is the initial specific activity of residual waste in Bq/g, and 10 represents the reference clearance level in Bq/g used in this calculation. This value should be adjusted according to the applicable institutional or regulatory clearance criterion when implemented in a specific facility.

Statistical analysis

Quantitative data were presented as mean $\pm$ standard deviation. Pearson correlation was used to evaluate the relationship between radioactivity retention and radiation exposure rate. Simple linear regression was performed to describe the association between these two variables. The regression slope, intercept, coefficient of determination (R^2), and p-value were reported. Statistical significance was set at $p < 0.05$. Statistical analysis and graph preparation were performed using GraphPad Prism 10.

RESULTS AND DISCUSSION

Residual syringe activity and radiation safety parameters

Residual syringe activity increased across the evaluated concentration levels. At 5 mCi/mL, the residual activity was 0.270 ± 0.012 mCi, corresponding to $12.90 \pm 0.63\%$ radioactivity retention and an exposure rate of 2.703 ± 0.102 $\mu\text{Sv/h}$. At 10 mCi/mL, residual activity increased to 0.362 ± 0.023 mCi, with retention of $17.45 \pm 1.08\%$ and an exposure rate of 3.304 ± 0.100 $\mu\text{Sv/h}$. The highest residual burden was observed at 15 mCi/mL, with residual activity of 0.435 ± 0.016 mCi, retention of $20.97 \pm 0.74\%$, and an exposure rate of 4.131 ± 0.237 $\mu\text{Sv/h}$ (Table 1).

Table 1. Safety-oriented characteristics of residual syringe activity before sequential rinsing

Iodine-131 concentration (mCi/mL)	n	Residual activity (mCi)	Radioactivity retention (%)	Radiation exposure rate ($\mu\text{Sv/h}$)	Estimated decay-storage time (days)
5	5	0.270 ± 0.012	12.90 ± 0.63	2.703 ± 0.102	133.22 ± 0.52
10	5	0.362 ± 0.023	17.45 ± 1.08	3.304 ± 0.100	136.62 ± 0.75
15	5	0.435 ± 0.016	20.97 ± 0.74	4.131 ± 0.237	138.77 ± 0.42

The estimated decay-storage time also increased with increasing residual activity. The estimated decay-storage time was 133.22 ± 0.52 days at 5 mCi/mL, 136.62 ± 0.75 days at 10 mCi/mL, and 138.77 ± 0.42 days at 15 mCi/mL (Table 1). These findings indicate that residual syringe activity contributed not only to measurable radiation exposure but also to the initial radioactive waste burden.

Relationship between radioactivity retention and radiation exposure rate

A strong positive correlation was observed between radioactivity retention and radiation exposure rate in residual syringes (Figure 1). Pearson correlation analysis showed $r = 0.9412$ with a 95% confidence interval of 0.8283–0.9806 and $p < 0.0001$. Simple linear regression produced an R^2 value of 0.8858, indicating that approximately 88.58% of the variation in radiation exposure rate could be explained by radioactivity retention under the experimental measurement conditions.

The regression equation was:

$$Y = 0.1674x + 0.5156$$

where Y represents radiation exposure rate in $\mu\text{Sv/h}$ and X represents radioactivity retention in percent. The regression slope indicates that each 1% increase in radioactivity retention was associated with an estimated increase of 0.1674 $\mu\text{Sv/h}$ in radiation exposure rate under the measurement conditions used in this study.

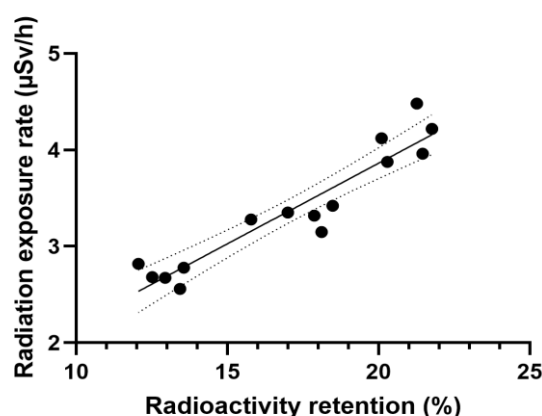


Figure 1. Relationship between radioactivity retention and radiation exposure rate in residual syringes after liquid iodine-131 preparation. Each point represents an independent residual syringe measurement from the concentration-test dataset. Radioactivity retention was strongly correlated with radiation exposure rate (Pearson $r = 0.9412$, 95% CI: 0.8283–0.9806, $R^2 = 0.8858$, $p < 0.0001$, $n = 15$). The solid line represents the linear regression fit, and the dotted lines represent the 95% confidence interval.

Reduction of radiation exposure rate after sequential rinsing

Sequential rinsing reduced radiation exposure rate in both rinsing-solution groups (Table 2 and Figure 2). In the water for injection group, the exposure rate decreased from 4.160 ± 0.186 $\mu\text{Sv/h}$ before rinsing to 2.319 ± 0.098 $\mu\text{Sv/h}$ after the first rinse, 1.822 ± 0.057 $\mu\text{Sv/h}$ after the second rinse, and 1.329 ± 0.034 $\mu\text{Sv/h}$ after the third rinse. This corresponded to a 68.05% reduction after the third rinse.

Table 2. Stage-wise reduction of radiation exposure rate after sequential rinsing

Rinsing solution	Rinsing stage	n	Radiation exposure rate ($\mu\text{Sv/h}$)	Reduction from baseline (%)
Water for injection	Before rinsing	5	4.160 ± 0.186	-
Water for injection	Rinse 1	5	2.319 ± 0.098	44.25
Water for injection	Rinse 2	5	1.822 ± 0.057	56.20
Water for injection	Rinse 3	5	1.329 ± 0.034	68.05
0.9% sodium chloride	Before rinsing	5	4.190 ± 0.117	-
0.9% sodium chloride	Rinse 1	5	2.319 ± 0.074	44.65
0.9% sodium chloride	Rinse 2	5	1.787 ± 0.014	57.35
0.9% sodium chloride	Rinse 3	5	1.314 ± 0.023	68.63

A similar reduction pattern was observed in the 0.9% sodium chloride group. The exposure rate decreased from $4.190 \pm 0.117 \mu\text{Sv/h}$ before rinsing to $2.319 \pm 0.074 \mu\text{Sv/h}$ after the first rinse, $1.787 \pm 0.014 \mu\text{Sv/h}$ after the second rinse, and $1.314 \pm 0.023 \mu\text{Sv/h}$ after the third rinse. This corresponded to a 68.63% reduction after the third rinse.

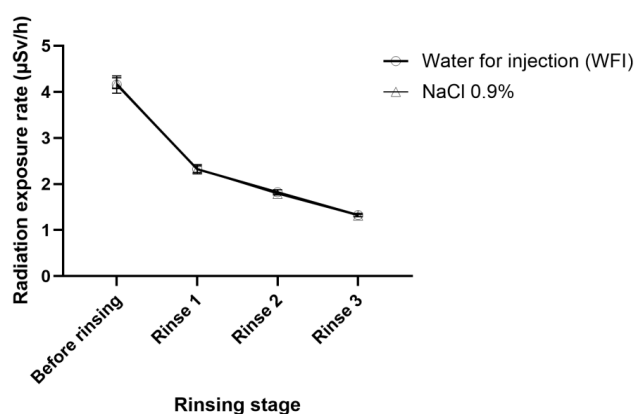


Figure 2. Stage-wise reduction of radiation exposure rate from residual syringes after sequential rinsing. Radiation exposure rate decreased progressively after each rinsing stage in both water for injection and 0.9% sodium chloride groups. Data are presented as mean $\pm$ standard deviation from five replicates per group. The reduction pattern indicates that sequential rinsing reduced the radiation burden of residual syringes regardless of rinsing solution type.

These results indicate that sequential rinsing reduced the radiation burden of residual syringes. The reduction pattern was similar between water for injection and 0.9% sodium chloride, suggesting that the main safety benefit was related to residual activity reduction through rinsing rather than to the specific rinsing solution.

Radioactive waste management implication

Higher residual syringe activity was associated with higher radiation exposure rate and longer estimated decay-storage time. Sequential rinsing reduced exposure rate and decreased the initial residual burden that entered the radioactive waste stream.

Reducing residual activity does not alter the physical half-life of iodine-131. However, it decreases the initial activity that must be managed as radioactive waste. This reduction may support safer temporary handling, segregation, shielding, monitoring, and decay-storage management of residual syringe waste.

This study demonstrated that residual syringe activity after liquid iodine-131 preparation was strongly associated with radiation exposure rate and contributed to the initial radioactive waste burden. These findings support the interpretation that radioactivity retention is not only a technical issue related to activity transfer, but also a radiation safety issue in radiopharmaceutical preparation.

The strong positive correlation between radioactivity retention and radiation exposure rate is consistent with the principle that higher residual activity contributes to a higher external radiation field around contaminated or radioactive preparation devices. In this study, radioactivity retention explained approximately 88.58% of the variation in measured exposure rate. This suggests that residual syringe activity is a relevant safety parameter that should be considered in radiopharmacy quality assurance and radioactive waste management.

Previous studies on syringe and container interactions have shown that residual activity may occur in radiopharmaceutical preparation and may be influenced by radiopharmaceutical type, syringe characteristics, dead volume, adsorption, and handling technique (Gunasekera et al., 2001; Stopar et al., 2007; Swanson et al., 2013; Kvaternik et al., 2020). Most published data have focused on technetium-99m radiopharmaceuticals, whereas the present study provides a specific safety-oriented perspective on liquid iodine-131 residual syringe activity.

The increase in radiation exposure rate at higher residual activity levels is relevant for occupational radiation protection. Residual syringes are commonly handled after preparation for segregation, shielding, monitoring, and decay storage. Even when measured exposure rates are manageable under controlled conditions, unnecessary residual activity should be minimized according to the ALARA principle (ICRP, 2007). In this context, residual syringe activity should be interpreted as a preventable contributor to occupational exposure and radioactive waste burden.

Sequential rinsing substantially reduced radiation exposure rate in both water for injection and 0.9% sodium chloride groups. The greatest reduction occurred after the first rinse, followed by further decreases after the second and third rinses. This pattern suggests that a considerable portion of residual activity may be associated with removable liquid residue or activity retained within the syringe dead volume. Similar observations have been reported in previous studies showing that rinsing or flushing procedures can reduce residual activity in preparation devices (Swanson et al., 2013; Ladriere et al., 2023).

The similarity between water for injection and 0.9% sodium chloride indicates that the observed reduction was primarily related to residual activity removal rather than to the specific rinsing solution. However, the choice of rinsing solution in routine practice must still follow institutional procedures, pharmaceutical compatibility, radiopharmaceutical quality requirements, and radiation safety approval. The findings of this study should therefore be interpreted as technical evidence supporting residual activity reduction, not as a standalone operational recommendation.

From a radioactive waste management perspective, the amount of residual activity determines the initial activity entering the waste stream. Two iodine-131 waste items with the same radionuclide will have the same physical half-life, but the item with higher initial activity will remain at a higher activity level and may require longer decay storage before meeting a defined release criterion. Therefore, reducing residual syringe activity at the preparation stage is a preventive waste-minimization strategy. This approach complements, but does not replace,

routine delay-and-decay waste management, radiation monitoring, and institutional release procedures (IAEA, 2009; IAEA, 2017).

The estimated decay-storage time in this study should be interpreted cautiously. It provides a conceptual estimate based on residual activity and a reference clearance value, but it should not replace actual radioactive waste monitoring. Actual release decisions must be based on applicable regulations, institutional standard operating procedures, calibrated measurement instruments, waste geometry, contamination status, and radiation safety officer approval. Facilities using different clearance criteria should recalculate decay-storage estimates according to their local regulatory framework.

This study also has practical implications for radiopharmacy quality systems. Good radiopharmacy practice emphasizes controlled preparation, documentation, equipment suitability, personnel competence, and radiation protection (Gillings et al., 2021). The present findings indicate that residual syringe activity measurement may serve as a useful internal quality indicator, particularly for liquid iodine-131 preparation. Monitoring residual activity could help identify handling conditions that increase activity retention and could support local validation of safer preparation practices.

This study has several limitations. First, the data were obtained under specific local conditions, including a particular radiopharmaceutical preparation setting, syringe type, measurement geometry, and institutional workflow. Therefore, the numerical values may not be directly generalizable to all nuclear medicine facilities. Second, the decay-storage time was estimated from residual activity and should not be interpreted as an actual serial decay monitoring result. Third, the rinsing data consisted of repeated measurements from the same syringes; therefore, they were interpreted as stage-wise reduction data rather than as independent observations for correlation analysis. Fourth, this study did not evaluate patient-administered activity or clinical outcomes, because the analysis focused specifically on residual syringe safety parameters (Barbosa et al., 2022).

Despite these limitations, this study provides a safety-oriented perspective on liquid iodine-131 radiopharmaceutical preparation. The findings show that residual syringe activity is strongly associated with exposure rate and contributes to radioactive waste burden. Reducing residual syringe activity may support radiation protection, contamination control, and radioactive waste management in nuclear medicine facilities. Future studies should validate these findings using different syringe types, preparation volumes, operators, facilities, and radioactive waste monitoring protocols.

CONCLUSION

Residual syringe radioactivity following liquid iodine-131 radiopharmaceutical preparation was strongly associated with measured radiation dose rates and contributed to the initial radioactive waste burden (Saha, 2004; Willegaignon et al., 2023). Sequential rinsing reduced radiation dose rates by approximately 68% after the third rinse in both the water-for-injection and 0.9% sodium chloride solution groups. These findings suggest that minimizing residual syringe radioactivity may enhance radiation protection, support contamination control, and improve radioactive waste management practices in nuclear medicine facilities. The implementation of rinsing procedures in routine clinical practice should be supported by local

validation, approved institutional protocols, supervision by appropriately authorized personnel, and compliance with applicable radiation safety regulations (Bly, 2023).

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