Comprehensive Radiation Dose Monitoring and Shielding Effectiveness Assessment in the Nuclear Medicine Hot Lab of INMAS, Pabna: Six Months Observation

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ABSTRACT

Background: Radiation protection in nuclear medicine hot lab is essential to minimize occupational exposure during handling of radiopharmaceuticals. Continuous monitoring of dose rates and evaluation of shielding effectiveness are necessary to maintain safe working environments.

Methods: A six-month observational study was conducted in the nuclear medicine hot lab at Institute of Nuclear Medicine and Allied Sciences (INMAS) Pabna. Monthly average dose rate measurements over six months and day-wise measurements during generator elution were recorded using a calibrated survey meter at 24-hour intervals across multiple locations including the fume hood (FH) surface, radial distances from the hood (0.15 m–1 m), inner and outer door surfaces of FH, post-dose handling area and corridor outside the hot lab. Dose attenuation and shielding effectiveness were analysed. Each location was selected to assess both high-risk zones and peripheral areas. Data were recorded in micro-Sieverts per hour (µSv/h).

Results: The highest monthly mean dose rate was observed at the fume hood surface (37.85 ± 1.29 µSv/h), while the lowest value was recorded in the corridor (0.29 ± 0.01 µSv/h). Dose rate decreased progressively with increasing distance from the source and a strong negative correlation ($r = -0.96$) was observed between distance and dose rate. The shielding was corrected using a consistent half-value layer (HVL) approach for ^{99m}Tc gamma photons. Based on the measured fume hood surface dose rates, approximately 1.27 mm lead is required to reduce the monthly mean dose rate to 2.0 µSv/h and about 1.34 mm lead is required to reduce the peak elution dose rate to the same target.

Conclusions: The results demonstrate effective radiation attenuation with distance and confirm that existing shielding and operational protocols maintain radiation exposure within acceptable safety limits. However, localized shielding enhancements near the fume hood may further improve radiation protection.

Keywords: Nuclear medicine, Radiation protection, Hot lab, Shielding effectiveness, Occupational exposure.

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INTRODUCTION

Ionizing radiation, while inherently hazardous, is indispensable in nuclear medicine for both diagnostic and therapeutic applications (1). Radiopharmaceuticals such as those derived from the molybdenum-99/technetium-99m (^{99}Mo/^{99m}Tc) generator are widely used in clinical practice due to their favourable physical and biological properties (2). The preparation, handling, and dispensing of these radiopharmaceuticals are typically performed in specialized facilities termed as nuclear medicine hot laboratories (3). These areas contain radioactive sources that can produce significant radiation fields if appropriate shielding and operational controls are not maintained. Ensuring radiation protection in such environments is essential to safeguard medical personnel and the surrounding environment. International radiation safety frameworks highlight three fundamental principles for medical exposure: justification of procedures, optimization of protection and adherence to recommended dose limits to minimize occupational exposure to ionizing radiation (4). Proper shielding design, adherence to operational protocols and routine radiation monitoring are therefore critical components of radiation safety programs in nuclear medicine departments (5). Continuous monitoring of radiation dose rates provides valuable information regarding spatial dose distribution and the effectiveness of shielding structures within hot laboratories (6). Observational measurements obtained under routine clinical conditions can help identify high-exposure zones, evaluate existing protective measures and guide improvements in radiation safety practices (7). The present study assessed radiation dose distribution in the hot lab of INMAS Pabna using both short-term measurements during generator elution and monthly monitoring over six months. In addition to descriptive analysis, the manuscript includes corrected half-value layer and shielding calculations derived directly from the measured dose-rate data in Table 1 and Table 3.

MATERIALS AND METHODS

Study design: This observational study was conducted from January to June 2025 in the nuclear medicine hot laboratory at INMAS Pabna, Bangladesh using a portable gas-filled ionizing radiation detector, Geiger-Muller (GM) (8). Measurements were taken at the fume hood surface, at radial distances of 0.15 m, 0.3 m, 0.6 m and 1 m from the source, at the inner and outer surfaces of the fume hood door, in the post-dose handling area and in the corridor outside the hot lab.

Radiation Measurement:

Radiation dose rate measurement was recorded using a handheld Geiger Muller survey meter, Ludlum 3000 and 3004 which has a wide operating range, typically from 0.00 µSv/h to 999 Sv/h and pocket dosimeter (15). The survey meter and the pocket dosimeter were calibrated by the Secondary Standard Dosimetry Laboratory (SSDL) of Institute of Nuclear Science and Technology (INST) from Atomic Energy Research Establishment (AERE), Savar, Dhaka. Day-wise measurements were recorded during generator elution over six consecutive days and monthly measurements were collected over six months. Radiation dose measurements were recorded at 24-hour intervals during routine radiopharmaceutical preparation and handling procedures over six months. ^{99}Mo-^{99m}Tc generator was chosen due to their optimum energy (140 Kev and 90% abundance) and short half-life i.e. 6 hours. (8)

Figure 1(a): Geiger Muller survey meter, Ludlum 3000. 1(b): Radiation Pocket Dosimeter.

Data Analysis:

In first case a single ^{99m}Tc generator was considered to observe the attenuation pattern for 6 days. Secondly a month averages were calculated to evaluate dose distribution patterns over six months. Radiation attenuation with distance was analysed and shielding calculations were performed.

Table 1: Day-Wise Dose Rate Measurements at Different Points from Generator during Elution (µSv/h)

Day	FH Surface	0.15 m	0.3 m	0.6 m	1 m	Inner Door Surface of FH	Outer Door Surface of FH	Post Dose	Corridor
Day-1	44.4	17.6	11.2	4.54	2.20	1.4	0.57	0.40	0.30
Day-2	31.5	13.0	8.7	3.90	1.30	0.88	0.50	0.30	0.30
Day-3	23.8	10.1	5.9	2.70	1.25	0.85	0.50	0.35	0.20
Day-4	18.2	7.8	4.7	2.50	1.15	0.43	0.40	0.40	0.30
Day-5	15.4	6.7	3.2	1.80	1.10	0.35	0.40	0.30	0.30
Day-6	11.2	4.5	2.8	1.30	0.97	0.33	0.35	0.30	0.30

Table 2: Descriptive Statistics for Day-Wise Dose Measurement (µSv/h) during Elution.

Dose	FH-Surface	0.15 m	0.3 m	0.6 m	1 m	Inner Door Surface of FH	Outer Door Surface of FH	Post Dose	Corridor
Mean	24.08	9.95	6.08	2.79	1.33	0.71	0.45	0.34	0.28
SD	12.20	4.75	3.29	1.23	0.44	0.42	0.08	0.05	0.04

Table 3: Monthly Dose Rate Measurements at Different Points (µSv/h).

Month	FH Surface	0.15 m	0.3 m	0.6 m	1 m	Inner Door Surface of FH	Outer Door Surface of FH	Post Dose	Corridor
January	38.6	15.0	9.8	4.1	2.0	1.20	0.52	0.35	0.30
February	36.1	14.0	8.9	3.9	1.8	1.10	0.50	0.34	0.30
March	39.3	15.5	9.9	4.3	2.6	1.25	0.55	0.36	0.31
April	38.9	14.8	9.8	4.2	2.0	1.21	0.51	0.33	0.28
May	36.7	14.1	9.0	3.9	1.9	1.10	0.50	0.33	0.29
June	37.5	14.3	8.9	4.0	1.9	1.11	0.51	0.32	0.28

Table 4: Descriptive Statistics for Monthly Dose Rate Measurement (µSv/h).

Dose	FH-Surface	0.15 m	0.3 m	0.6 m	1 m	Inner Door Surface of FH	Outer Door Surface of FH	Post Dose	Corridor
Mean	37.85	14.62	9.38	4.07	2.03	1.16	0.52	0.34	0.29
SD	1.29	0.58	0.50	0.16	0.29	0.07	0.02	0.01	0.01

RESULTS

Monthly Radiation Dose Distribution:

The measured dose-rate data demonstrate a clear spatial gradient around the generator. In the monthly dataset, the fume hood surface showed the highest mean dose rate (37.85 ± 1.29 µSv/h), followed by 14.62 ± 0.58 µSv/h at 0.15 m, 9.38 ± 0.50 µSv/h at 0.3 m, 4.07 ± 0.16 µSv/h at 0.6 m and 2.03 ± 0.29 µSv/h at 1 m. Peripheral locations remained low, with mean values of 1.16 ± 0.07 µSv/h at the inner door surface, 0.52 ± 0.02 µSv/h at the outer door surface, 0.34 ± 0.01 µSv/h in the post-dose area and 0.29 ± 0.01 µSv/h in the corridor.

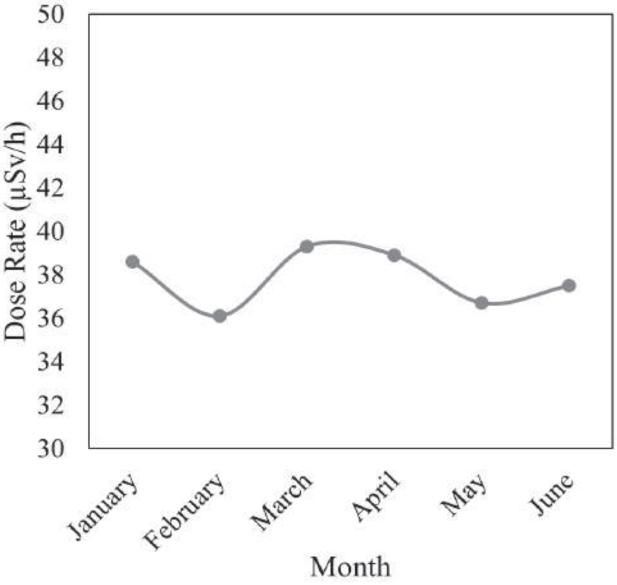

Figure 2: Monthly Dose Trend at Fume Hood Surface over a Six-Month Period

Radiation Dose Distribution during Generator Elution:

During generator elution, the maximum recorded dose rate was 44.4 µSv/h at the fume hood surface. The six-day mean at this location was 24.08 ± 12.20 µSv/h, decreasing to 9.95 ± 4.75 µSv/h at 0.15 m, 6.08 ± 3.29 µSv/h at 0.3 m, 2.79 ± 1.23 µSv/h at 0.6 m and 1.33 ± 0.44 µSv/h at 1 m. These findings are consistent with the expected reduction in dose rate as distance from the source increases.

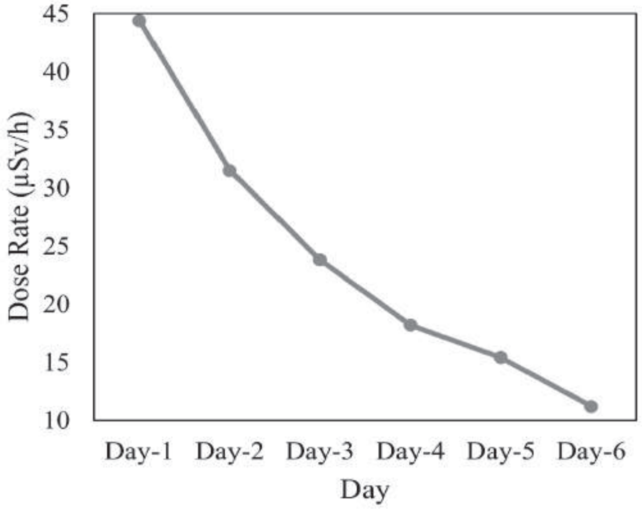

Figure 3: Dose-rate measurement at fume hood surface from generator during elution with generator day progress.

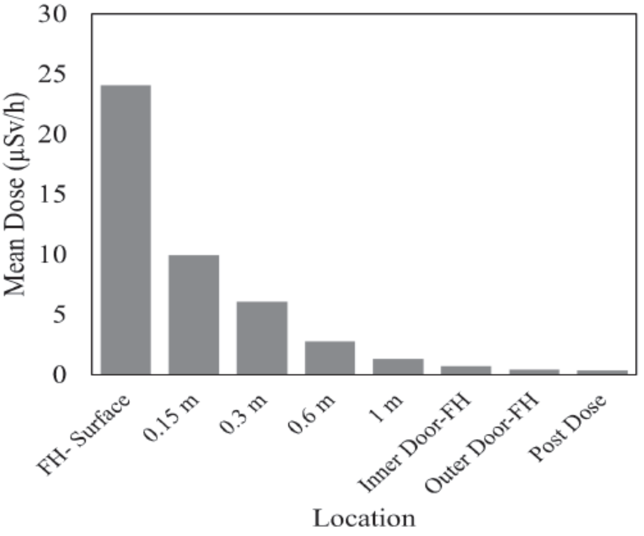

Figure 4: Dose-rate measurement at different location from generator during elution with generator day progress.

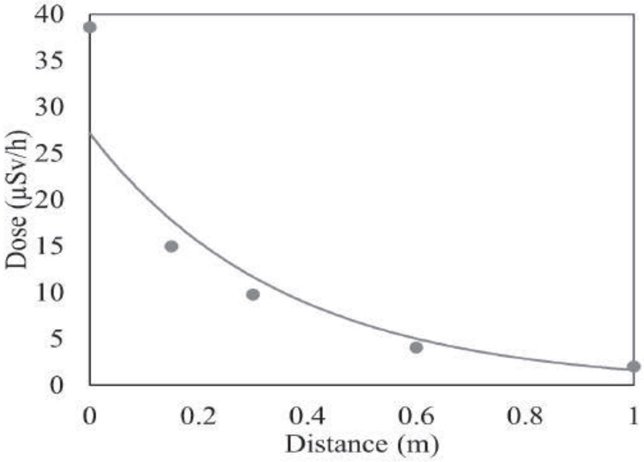

Figure 5: Dose-rate pattern at different places from the fume hood surface

Pearson correlation analysis was performed between distance from the source and measured radiation dose rate.

Table 5: Pearson Correlation between Distance from the Source and Measured Radiation Dose Rate.

Variable	Correlation (r)
Distance vs Dose Rate	-0.96

A strong negative correlation (r = −0.96) was observed between distance and radiation dose rate. This indicates that radiation exposure decreases sharply as the distance from the source increases. This finding is consistent with radiation physics principles where dose rate decreases with increasing distance from a radioactive source, commonly approximated by the inverse square law.

Half Value Layer (HVL) Shielding Calculation:

For ^{99m}Tc gamma photons (140 keV), the shielding calculation was corrected using a single consistent lead half-value layer (HVL) value of 0.3 mm. Because 0.3 mm is equivalent to 0.03 cm, the corresponding linear attenuation coefficient is obtained from the standard relation HVL = 0.693/μ.

$$\text{HVL} = 0.693/\mu$$

$$0.03\ \text{cm} = 0.693/\mu$$

$$\mu = 0.693/0.03 = 23.1\ \text{cm}^{-1}$$

The tenth-value layer (TVL) is then calculated from TVL = 2.303/μ. Substituting $\mu = 23.1\ \text{cm}^{-1}$ gives TVL = 0.0997 cm or approximately 1.0 mm.

Monthly mean dose rate at the FH surface:

Using the monthly mean fume hood surface dose rate from Table 4 as the initial intensity ($I_0 = 37.85$ μSv/h) and taking a target intensity of I = 2.0 μSv/h, the required number of half-value layers is:

$$n = \log_2(I_0/I)$$

$$n = \log_2(37.85/2.0)$$

$$n = \log_2(18.925) = 4.24$$

The required lead thickness is therefore:

$$x = n \times \text{HVL}$$

$$x = 4.24 \times 0.3\ \text{mm}$$

$$x = 1.27\ \text{mm lead}$$

Peak Elution Dose Rate at the FH Surface:

Using the highest measured elution dose rate from Table 1 ($I_0 = 44.4$ μSv/h) and the same target intensity (I = 2.0 μSv/h):

$$n = \log_2(44.4/2.0)$$

$$n = \log_2(22.2) = 4.47$$

$$x = 4.47 \times 0.3\ \text{mm} = 1.34\ \text{mm lead}$$

If a more conservative target of 1.0 μSv/h is selected for the peak elution condition, the required number of half-value layers becomes $\log_2(44.4/1.0) = 5.47$ and the corresponding lead thickness is 1.64 mm. Therefore, the measured data support a practical recommendation of about 1.5-2.0 mm additional localized lead shielding near the fume hood to provide a realistic safety margin.

Table 6: Shielding Summary for Lead at the Different Location

Location	Initial dose (μSv/h)	Target dose (μSv/h)	Required lead thickness
FH surface (monthly mean)	37.85	2.0	1.27 mm
FH surface (peak elution)	44.4	2.0	1.34 mm
FH surface (peak elution)	44.4	1.0	1.64 mm
0.15 m	14.62	2.0	0.86 mm
0.3 m	9.38	2.0	0.67 mm
0.6 m	4.07	2.0	0.31 mm
1 m	2.03	2.0	Negligible

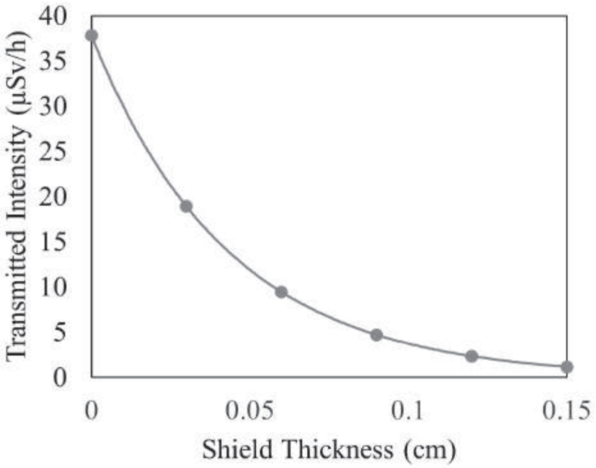

Figure 6: Attenuation of radiation dose by shielding thickness

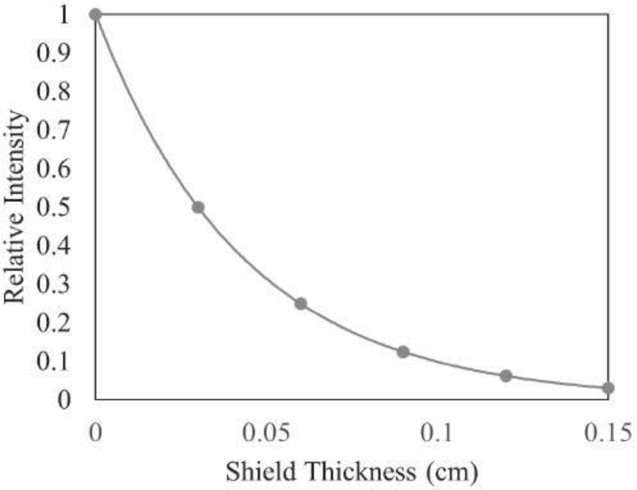

Figure 7: Attenuation of radiation dose by shielding thickness with HVL concept

DISCUSSION

This study evaluated radiation dose distribution and shielding effectiveness in a nuclear medicine hot laboratory using both short-term generator elution data and six-month monitoring results. The findings demonstrate a clear spatial variation in radiation dose, with the highest exposure observed at the fume hood (FH) surface and progressively lower values at increasing distances (8). The elevated dose rate at the FH surface reflects its role as the primary site for radiopharmaceutical preparation and generator handling. The peak elution dose (44.4 µSv/h) and monthly mean (37.85 ± 1.29 µSv/h) indicate that this area represents the most critical location for occupational exposure. Similar observations have been reported in nuclear medicine facilities, where handling zones consistently show higher radiation levels due to direct interaction with radioactive materials. The variation in dose rate during generator elution (Figure 3) is consistent with radionuclide decay and operational workflow (9). A significant reduction in dose rate with increasing distance was observed, supported by a strong negative correlation ($r = -0.96$) (10). As illustrated in Figures 4 and 5, dose rates decreased rapidly from the FH surface to 1 m, approaching near-background levels. This finding is consistent with the inverse square law and highlights distance as a simple and effective method for reducing radiation exposure (11). Such observations are in agreement with previous studies in nuclear medicine environments. The study also demonstrates that the existing shielding and laboratory design are effective in limiting radiation exposure to peripheral areas. Low dose rates recorded in the post-dose area and corridor (≤0.34 µSv/h) indicate that radiation is well confined within controlled zones. The attenuation observed across the fume hood door further supports the adequacy of installed shielding. These results suggest that current structural and operational measures are sufficient to maintain occupational exposure within recommended limits. Shielding analysis based on the half-value layer (HVL) concept showed that approximately 1.27–1.34 mm of lead is required to reduce FH surface dose rates to 2.0 µSv/h (12). The attenuation pattern (Figures 6 and 7) confirms the expected exponential reduction in radiation intensity with increasing shielding thickness (13, 14). From a practical perspective, the addition of approximately 1.5–2.0 mm localized lead shielding near the FH could further reduce exposure and provide an additional safety margin (5). This study has some limitations. Measurements were conducted in a single facility and focused on one type of radionuclide generator, which may limit generalizability. Additionally, individual staff dose monitoring was not included. However, the findings confirm that distance, shielding and proper laboratory design play key roles in radiation protection. Continuous monitoring and adherence to ALARA principles are essential to ensure sustained occupational safety in nuclear medicine hot laboratories (5, 15).

CONCLUSION

This study assesses radiation dose distribution and shielding effectiveness in a nuclear medicine hot laboratory, using both operational measurements and long-term monitoring data. It shows that radiation exposure significantly decreases with increased distance from the source, confirming the principles of radiation physics. The study identifies the fume hood surface as the primary radiation exposure zone, with surrounding areas demonstrating low dose rates. The findings indicate effective shielding design and lab layout that ensure compliance with safety standards. Shielding analysis suggests that minor increases in lead thickness (1.3–1.7 mm) can significantly lower radiation in critical areas. A recommendation for an additional 1.5–2.0 mm of localized shielding near the fume hood is proposed to optimize radiation protection. Overall, the radiation safety measures at INMAS Pabna are effective and follow international guidelines, though enhancements in shielding and adherence to ALARA principles are advised for improved safety in nuclear medicine facilities.

Funding

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Conflict of Interest

The authors declare no conflict of interest.

Ethical Approval

The study was conducted according to institutional radiation safety guidelines.

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