INSTITUTE OF DEFENSE ACQUISITION PROGRAM

JAMS JOURNAL OF ADVANCES IN MILITARY STUDIES

2025, Vol. 8, No. 1, 37–56.

https://doi.org/10.37944/jams.v8i1.273

Rethinking dosimeter assignment for military radiation safety: Focusing on comparative performance of thermoluminescent dosimeters (TLDs) and electronic personal dosimeters (EPDs) under portable x–ray exposure

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ABSTRACT

The increasing use of portable X–ray generators in military operations—particularly for explosive detection and counter–terrorism—has highlighted the need for a radiation safety strategy tailored to field–based, low–dose environments. This study evaluates the performance of thermoluminescent dosimeters (TLDs) and electronic personal dosimeters (EPDs) under controlled pulsed X–ray conditions using the XRS–3 generator, focusing on their sensitivity, dose–response characteristics, and operational suitability in military contexts. The results showed that while TLDs exhibited high accuracy in cumulative dose tracking, they failed to detect radiation beyond 3 meters or at low pulse counts. In contrast, EPDs—although they showed some inconsistencies in cumulative dose measurements under low–dose conditions—successfully detected radiation at all distances and pulse settings. Their ability to provide immediate feedback and detect fluctuations in real time makes them more suitable for dynamic radiation monitoring in military field environments. The study provides a solid foundation for revising current military dosimetry protocols in current military radiation safety management practices.

Keywords : personal dosimeter, thermoluminescent dosimeter (TLD), electronic personal dosimeter (EPD), military radiation safety, portable X–ray generators

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Ⅰ. Introduction

The number of institutions using radiation-emitting devices in the Republic of Korea rose by about 30% between 2018 and 2023. Although this growth indicates increased demand for X-ray technologies, it does not guarantee enhanced safety practices. Many facilities, despite meeting regulatory standards, lack real-time monitoring—resulting in serious gaps such as no immediate exposure alerts, outdated dosimetry access, and inadequate emergency protocols. Actually recent cases of unexpected overexposure, such as the 2019 incident involving outsourced civilian workers at Seoul Semiconductor and the 2024 radiation accident involving two workers from a private electronics company who received doses of 28.5 and 94 Sv, respectively, underscore that radiation risks are not merely theoretical, but manifest in actual field conditions (Nuclear Safety and Security Commission, 2019; Nuclear Safety and Security Commission, 2024).

Thus, using portable X-ray generators is essential for effective radiation monitoring in industrial, security, and military applications (e.g., Ho et al., 2024). These devices are widely used in nondestructive imaging applications, including explosive detection, hazardous material identification, and structural analysis. Their high mobility, short exposure time, and high-resolution imaging capabilities make them indispensable tools for field operations (i.e., Henderson, Mark, Rawlings, & Robson, 2022; Shinde, Mali, & Thekkuttu, 2022). However, despite their advantages, X-ray exposure poses a potential risk to operators and radiation protection guidelines are often impractical in military operations confined spaces maintaining the safety distances and the need for rapid mobility. These risks are exacerbated by a combination of operational constraints and structural characteristics unique to military settings. Such environments typically involve confined spaces, frequent use of radiation-emitting devices in unpredictable, non-fixed combat zones, and high personnel turnover, which may lead to reduced operator proficiency and inconsistent equipment handling. For instance, portable X-ray generators are often deployed in dynamic tactical contexts such as tunnel-like structures, makeshift barricades, or exposed terrain during explosive ordnance disposal (EOD) and counterterrorism missions, where standard radiation shielding and fixed monitoring systems are infeasible. These non-standardized and unpredictable operating conditions significantly hinder consistent exposure monitoring and timely intervention, thereby increasing the likelihood of unnoticed radiation incidents.

In this sense, personal dosimeters are key elements of radiation safety systems and are typically divided into passive and active types. Passive dosimeters, such as thermoluminescent dosimeters (TLDs), accumulate exposure data over time but require post-use processing to retrieve results. This delay prevents real-time detection, hindering timely response in dynamic environments. During equipment failures or operational errors, undetected cumulative exposure may occur, heightening the risk of prolonged, unnoticed radiation dose. But, electronic personal dosimeters (EPDs) as active dosimeters deliver real-time dose readings and instant feedback, improving safety and situational awareness in dynamic settings. Each type has unique strengths and limitations; thus, selection should align with operational needs. However, current regulations mandate passive dosimeters even in low-risk registered institutions where real-time monitoring could offer greater effectiveness.

To bridge the gap between regulatory standards and actual exposure conditions in military environments, the present study compares the performance of TLDs and EPDs under controlled low-dose X-ray exposure. Military personnel frequently operate portable X-ray generators, such as the XRS-3—classified as registered devices—with low exposure risk but high need for real-time monitoring. Based on the experimental findings, our study proposes practical guidelines for selecting appropriate dosimeters in military radiation operations. By aligning dosimeter choice with specific exposure risks and operational demands, the approach seeks to strengthen radiation safety within the Ministry of National Defense and reduce risks from unexpected exposures, such as abnormal activations of portable X-ray generators. This study fills a significant gap in the current literature by providing a comparative evaluation of dosimeter performance under low-dose, pulsed X-ray conditions. Through empirical testing of both TLDs and EPDs, it offers practical guidance for military applications and baseline data for selecting appropriate dosimeters in non-military low-dose environments.

Ⅱ. Related study

To ensure functional suitability regarding pulse X-ray exposure conditions in the experimental evaluation, we first compare the key technical and operational features by two dosimeter types of TLD and EPD (Table 1).

〈Table 1〉 Comparison between Thermoluminescent Dosimeters (TLDs) and Electronic Personal Dosimeters (EPDs)

Category	TLD (Passive Dosimeter)	EPD (Active Dosimeter)
Dosimeter Type	Passive	Active
Monitoring Capability	Not real-time;post-exposure readout required	Real-time dose and dose rate display with alarm
Dose Readout Method	Requires separate TLD reader and annealing process	Direct digital readout

Category	TLD (Passive Dosimeter)	EPD (Active Dosimeter)
Reusability	Reusable after annealing; limited by physical degradation over repeated use	Highly reusable; minimal maintenance; battery-based operation
Response to Low Dose	Limited sensitivity; often fails to detect low-dose radiation below detection threshold (LLD)	High sensitivity; capable of detecting subtle fluctuations in low-dose conditions
Response to Pulsed X-rays	Prone to underestimation due to integration delays and pulse width limits	Stable performance with digital signal integration even under nanosecond pulse durations
Regulatory Status	Widely approved and used in regulated dose tracking	Increasingly accepted in Japan, Switzerland, UK as legal dosimeters in various operational settings

Thermoluminescent dosimeters (TLDs), a common type of passive dosimeter, are widely valued for their high accuracy and stability in cumulative dose assessment. Their strength lies in precisely recording long-term radiation exposure, making them suitable for retrospective monitoring. However, their inability to provide real-time data limits their use in situations requiring immediate response, especially in military settings where sudden radiation surges demand instant feedback (Oliveira, 2017). In contrast, electronic personal dosimeters (EPDs), representing active dosimeters, offer real-time dose monitoring and alarm functions. When preset thresholds are exceeded, they trigger alerts, enabling rapid response to hazardous conditions (Yadav et al., 2024). These capabilities are particularly beneficial in environments with unpredictable radiation fluctuations. Recent advancements further enhance EPD functionality. Moon et al. (2021) present models with integrated position-tracking systems, while Luszik-Bhadra (2007) and McCaffrey, Shen, and Downton (2008) demonstrated EPDs' ability to detect dose rates below the sensitivity threshold of passive dosimeters. Additionally, Lee, Kim, and Lim (2015) found that modern EPDs often report slightly higher dose values than TLDs under the same conditions, offering a conservative safety margin.

Several studies have compared the strengths and limitations of passive and active dosimeters. Kry et al. (2020) and the ICRP (1997) noted that while TLDs are reliable for long-term dose tracking, their lack of immediate feedback makes them less effective in emergencies or low-dose environments. Moon et al. (2021) highlighted the advantages of EPDs in such settings, particularly their ability to support rapid evacuation through real-time alarms. These observations are supported by international reviews such as IAEA-TECDOC-1564, which confirmed EPD effectiveness across various operational environments. As a result, countries including Japan, Switzerland, and the UK have formally adopted EPDs as legal dosimeters in select institutional contexts.

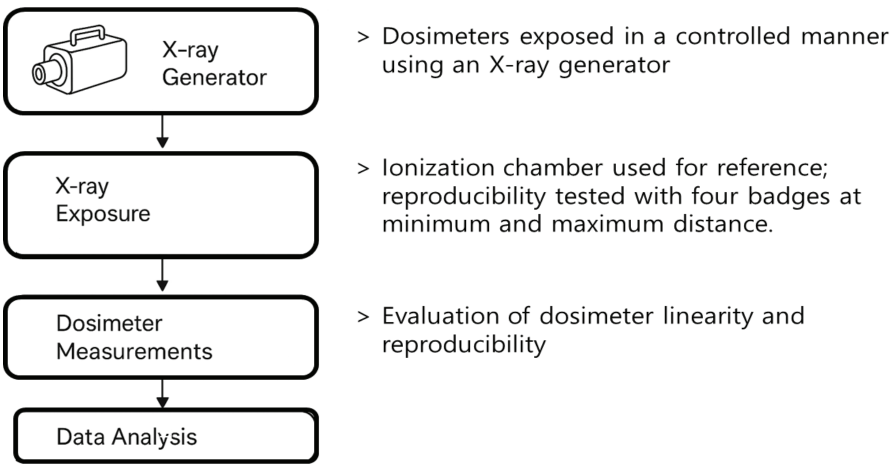
A key factor in dosimeter selection is the type of radiation source. Towers (2024) and Bolognese-

Milsztajn et al. (2004) found that TLDs may show nonlinearity or underestimate dose under pulsed X-ray exposure due to delayed charge-trapping mechanisms. Golden Engineering (2018) also reported that portable generators like the XRS-3 typically emit pulses of 20–50 ns—durations often too short for standard TLD readers to capture accurately. As a result, TLDs may miss or under-record doses in low-pulse or short-exposure conditions. In contrast, EPDs, which use digital signal integration, are less affected by pulse duration and provide more consistent readings under pulsed radiation. These findings highlight the importance of aligning dosimeter capabilities with the temporal and energetic characteristics of the radiation source. Real-world incidents reinforce these concerns. Reports by Korea's Nuclear Safety and Security Commission (NSSC) from 2019 and 2024 documented risks stemming from delayed radiation detection, underscoring the need for real-time monitoring in field operations. Previous studies have primarily examined nuclear power plants and medical facilities, where radiation exposure patterns differ significantly. In contrast, comparative evaluations targeting military use of portable X-ray generators remain limited. This gap underscores the need to validate the performance of TLDs and EPDs under military-specific conditions—particularly in low-dose, pulsed X-ray environments like those produced by the XRS-3.

Ⅲ. Experimental Methods

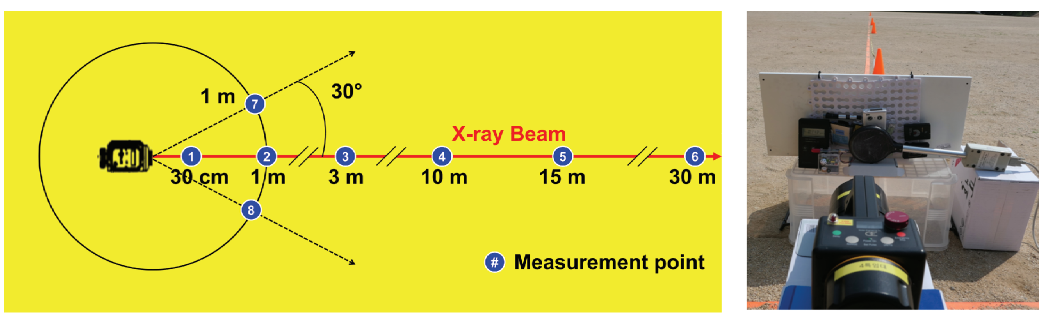
3.1 Overview of the experimental design

The experiment was designed to assess and compare the cumulative dose response and real-time detection capabilities of TLDs and EPDs under low-dose portable X-ray exposure. All tests were conducted using an XRS-3 generator in an open, controlled environment to meet radiation safety standards. As shown in Figure 1, the procedure included generator setup, exposure distance selection, dosimeter placement, X-ray irradiation, reference dose measurement, and data analysis. This structure enabled a systematic comparison of dosimeter performance under varying low-dose conditions.



〈Figure 1〉 Schematic diagram of experimental procedures

Measurement points were set at 30 cm, 1 m, 3 m, 10 m, 15 m, and 30 m along the primary beam axis. These distances were chosen based on the manufacturer's safety guidelines and typical field working positions. Figure 2 illustrates the spatial layout, including the beam direction and dosimeter placements.



Note. The X-ray beam path and measurement points (left) and the placement of measurement equipments for radiation evaluation (right).

〈Figure 2〉 Experimental setup and equipment

At each measurement point, the TLDs and EPDs were exposed to X-rays under 5-and 10-pulse conditions, and a calibrated ionization chamber was used to measure reference exposure doses. To account for angular scatter, additional measurements were taken 30° off-axis at a distance of 1m. Each test condition (distance × pulse count) was repeated three times to ensure reliability. The TLDs were retrieved after a 24-h stabilization period and processed using a Panasonic UD-716 reader (Ipe, 2021), whereas the

EPDs provided real-time dose readings during irradiation. Three TLDs and two EPDs were deployed at each point to minimize device-related variability and enable cross-validation of the measurement results. All dosimeters were placed perpendicular to the beam path and securely fixed to minimize positional deviation. The ionization chamber-based dose values were later used as baseline reference data for performance comparison across devices.

3.2 Dosimeters and reference instrumentation

This study used one TLD and three EPD models—Rad-60, Trudose, and DMC3000. These EPDs are commonly used in industrial and military radiation monitoring, each offering unique features in energy range, dose display, and update rate. Table 2 summarizes their technical specifications, emphasizing key differences relevant to military field use.

〈Table 2〉 Comparison of TLD, Rad-60, Trudose, and DMC3000 dosimeters

Feature	TLD	Rad-60
Manufacturer	Panasonic	Rados
Dimensions (cm)	8.5 x 2.2 x 1.9	7.8 x 6.7 x 2.2
Weight (g)	22	85 (With battery)
Radiation Type	X-rays, Gamma rays	X-rays, Gamma rays
Energy Range	10 keV - 10 MeV	60 KeV - 3 MeV
Display dose	1 µSv -10 Sv	1 µSv - 10 Sv
Display rate	-	5 µSv/h - 3 Sv/h
Feature	**Trudose**	**DMC3000**
Manufacturer	Thermofisher Scientific	Mirion
Dimensions (cm)	8.6 x 3.2 x 1.8	9 x 6 x 2.3
Weight (g)	114 (With battery)	90 (With battery)
Radiation Type	X-rays, Gamma rays	X-rays, Gamma rays
Energy Range	16 keV - 3 MeV	15 KeV - 7 MeV
Display dose	1 µSv -10 Sv	1 µSv - 10 Sv
Display rate	10 µSv/h - 10 Sv/h	10 µSv/h - 3 Sv/h

Data source: Panasonic, Rados, Thermofisher Scientific, Mirion.

In addition to the dosimeters, a calibrated Radcal 2026C ionization chamber was employed as the reference instrument for this study. The ionization chamber is widely regarded as a reliable standard for ambient and spatial dose assessments, owing to its ability to generate precise real-time dose measurements by collecting the ionization current in a gas-filled chamber. During testing, it was placed on the same axis as the dosimeters and the X-ray source to maintain a consistent exposure geometry across all pulse and distance conditions. The measurements obtained using the ionization chamber served as reference values for evaluating the accuracy and performance of the TLD and EPD models.

3.3 Radiation source and pre-verification of the XRS-3 generator

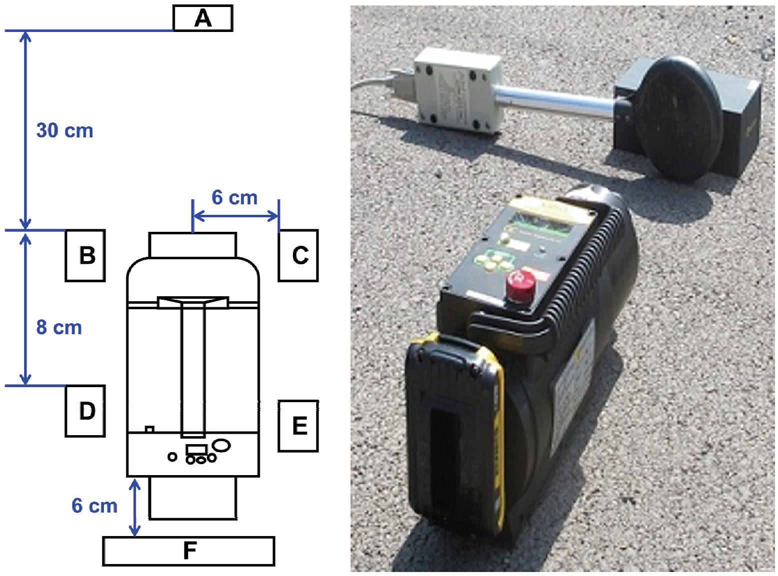
An XRS-3 portable X-ray generator was used as the primary source of radiation. This device emits pulsed X-rays at a peak voltage of up to 270 kVp with a pulse duration ranging from 25 to 50 ns. Its high-energy output, compact size, and portability make it suitable for military and security applications. The key technical specifications of the XRS-3 are summarized in Table 3.

〈Table 3〉 Specifications of XRS-3 Portable X-ray Generator

Specification	XRS-3
Dimensions (L x W x H / cm)	40.6 x 11.5 x 10
Weight (including hattery / kg)	5.7
Maximum Voltage (kVp)	270
X-ray Current (mA)	0.25
X-ray Pulse Width (ns)	20
X-ray Source Size (mm)	3
Dose per Pulse (at 30 cm)	2.6-3.6 mR/pulse
Pulse Rate	15 pulses/sec

Data Source: XRS-3 Operator's Manual.

To ensure the reliability of the experimental conditions and validate the operational safety of the device, a pre-verification test was conducted prior to dosimeter testing. Radiation leakage was measured using a calibrated Radcal 2026C ionization chamber under 10-pulse condition at six predefined positions (A—F) around the XRS-3. The measurement positions included the front, sides, and rear of the generator, as shown in Figure 3.



Data Source: Golden Engineering.

〈Figure 3〉 Predefined measurement positions and actual setup for radiation leakage evaluation around the XRS-3 portable X-ray generator

The measured exposure levels are listed in Table 4. The highest radiation dose was recorded at Position A, directly in front of the beam port, with a value of 30.42 mR,—well within the allowable safety range of 25–35 mR. All other positions recorded significantly lower values, with Position F at the rear showing only 0.01 mR, far below the threshold limit of 0.7 mR. These results confirmed that the XRS-3 generator operates within acceptable radiation safety limits and can be reliably used for controlled exposure studies involving personal dosimeters

〈Table 4〉 Results of radiation leakage measurement for XRS-3 verification

Position	Pulses	Allowable Limit (mR)	Measured exposure (mR)
A	10	25–35	30.42
B	10	≤ 4.5	1.08
C	10	≤ 4.5	1.19
D	10	≤ 1.5	0.20
E	10	≤ 1.5	0.22
F	10	≤ 0.7	0.01

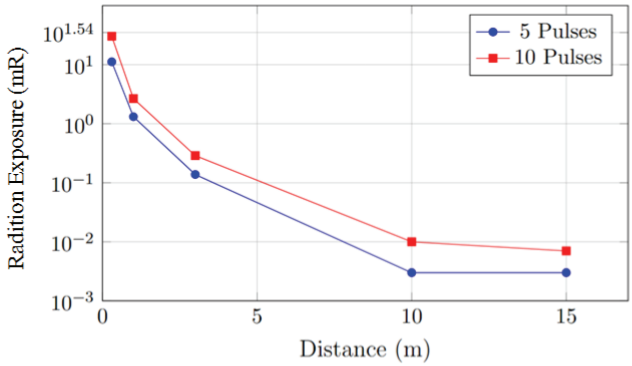
This validation procedure ensured that subsequent measurements using TLDs and EPDs were performed under safe and consistent radiation conditions, enabling an accurate performance comparison across all dosimeter types.

Ⅳ. Results

We focus on the spatial characteristics of radiation exposure around the XRS-3 portable X-ray generator, using a calibrated ionization chamber to establish baseline exposure levels at various distances and pulse settings. These measurements provide a reference framework for evaluating personal dosimeter performance. The results indicate limited radiation risk beyond a certain distance, highlighting the greater practical value of real-time radiation monitoring systems compared to long-term cumulative dose tracking in low-dose operational environments. Additionally, our study presents a comparative analysis of TLDs and EPDs regarding cumulative dose measurements, dose response characteristics, linearity, and reproducibility.

4.1 Measured Radiation Exposure at Various Distances

The radiation exposure from the XRS-3 device was measured at varying distances using an ionization chamber to evaluate the spatial distribution under different operational conditions. Measurements were conducted under 5- and 10-pulse settings, with each setting repeated three times, and the results served as baseline reference values for subsequent comparisons of the TLD and EPD performance. The data are summarized in Figure 4.



Distance (m)	5 Pulse (Avg, mR)	10 Pulses (Avg, mR)	Relative Decrease (5 Pulses)	Relative Decrease (10 Pulses)
0.3	11.173	30.2	–	–
1	1.312	2.668	88.26%	91.17%
3	0.138	0.288	98.77%	99.05%
10	0.003	0.010	99.97%	99.95%
15	0.003	0.007	99.97%	99.98%
30	–	–	–	–
30°, 1m (Left)	0.026	0.053	–	–
30°, 1m (Right)	0.025	0.051	–	–

Nore. "-" indicates values below the minimum detectable dose of TLD or cases in which the EPD failed to accumulate the dose.

〈Figure 4〉 Logarithmic Trends in Radiation Exposure with Increasing Distance

The results showed a substantial decrease in exposure with increasing distance, generally following the inverse squared law. Increasing the pulse count from 5 to 10 led to a proportional increase in dose across all distances—approximately two-fold at 1 m and nearly three-fold at 30 cm—indicating that shorter distances were more sensitive to pulse variations due to beam divergence or localized scattering effects. Exposure measurements taken at a 30° angle and 1 m recorded values of 0.025 mR (5 pulses) and 0.053 mR (10 pulses), respectively, both far below the 10 mR typically delivered in a standard chest X-ray. This suggests minimal radiation risk even at distances significantly shorter than the manufacturer's recommended safety buffer zones (30 m front, 6 m sides, and 3 m rear) and reinforces the importance of distance in minimizing exposure. In this context, long-term cumulative dose tracking may be unnecessary for registered personnel to maintain standard working distances. Instead, real-time monitoring systems should be prioritized to detect abnormal equipment behavior or operator errors, thereby enabling immediate corrective action.

4.2 Comparison between EPDs and TLDs

Following three cumulative exposures under 5- and 10-pulse conditions using the XRS-3, the cumulative doses were measured using TLDs and EPDs (Rad-60 and Trudose) at varying distances (Table 5).

〈Table 5〉 Results of measuring radiation dose by distances with TLD and EPD

Point	5 Pulse x 3 times			10 Pulse x 3 times		
	Rad-60(μSv)	Trudose(μSv)	TLD(mSv)	Rad-60(μSv)	Trudose(μSv)	TLD(mSv)
30 cm	2	0.3	0.23	1	0.7	0.53
1 m	-	0.35	0.045	1	0.7	0.08
3 m	-	0.35	-	-	0.7	-
10 m	-	0.3	-	-	0.7	-
15 m	-	0.2	-	-	0.3	-
30 m	-	0.05	-	-	0.1	-
30°, 1 m (Left)	-	0.3	-	-	0.7	-
30°, 1 m (Right)	-	0.35	-	-	0.65	-

Note. "-" indicates values below the minimum detectable dose of TLD or cases where the EPD failed to accumulate the dose.

As presented in Table 5, the EPDs (Trudose) successfully detected the dose values at all the measured distances and pulse settings, demonstrating a consistent and proportional increase in the measured dose with increasing pulse count. In contrast, the TLDs recorded dose values only at 30 cm and 1 m, where the delivered dose exceeded the lower limit of detection (LLD), making it difficult to confirm the dose-response trend under broader conditions.

A key distinction emerged in distance-based sensitivity. While TLDs were effective at close range (within 1 m), they failed to register doses beyond 3 m due to their detection threshold. In contrast, the Trudose EPD measured doses at distances up to 30 m and at 30° oblique angles, demonstrating superior sensitivity to low-level and scattered radiation. This indicates that although TLDs can provide accurate cumulative dose estimates under sufficient exposure, EPDs offer significantly broader spatial responsiveness, making them better suited for real-time monitoring in complex radiation environments. Additionally, performance varied across EPD models. While the Trudose consistently responded under low-dose conditions, the Rad-60 EPD, which has a higher energy detection threshold of 60 keV, failed to detect the X-rays generated by the XRS-3 generator. This outcome underscores the importance of selecting dosimeters based not only on category but also on specific technical specifications and operational compatibility.

The EPDs (Trudose and DMC3000) began registering dose values as early as the 2-pulse setting and maintained a stable linear response up to 90 pulses. However, the TLDs did not detect measurable doses until the pulse count exceeded 20 and showed a distinct response only after 50 pulses, with a sharp increase observed at 90. These findings have important implications for practical applications. The ability of EPDs to detect subtle changes from low-pulse exposures indicates a higher responsiveness to environmental fluctuations. Under field conditions, where radiation exposure may be scattered or intermittent, this responsiveness allows for earlier detection and immediate response, thereby—enhancing accident prevention and operational safety. When benchmarked against reference values measured by the calibrated ionization chamber, the TLD readings showed greater alignment at short distances, reaffirming their reliability for cumulative dose assessments. However, their lack of real-time feedback and inability to register transient exposures render them unsuitable for dynamic field operations.

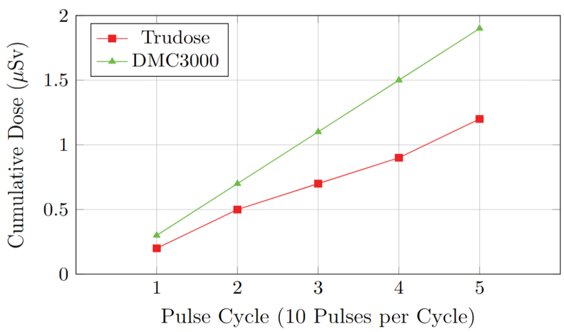
〈Table 6〉 Results of measured dose by TLD and EPDs across pulse counts

Pulse counts	TLD (mSv)	Trudose (μSv)	DMC3000 (μSv)
1	–	0	0
2	–	0.1	0.1
5	–	0.1	0.2
10	–	0.2	0.3
20	0.05	0.5	0.7
50	0.08	1.2	1.8
90	0.18	2.1	3.5

Note. "-" indicates values below the minimum detectable dose of TLD

4.3 Linearity and Reproducibility Testing of EPDs

The performance of the EPDs was further evaluated using tests designed to assess their linearity and reproducibility under controlled low-dose X-ray conditions. As presented in Figure 5, both devices exhibited a consistent linear increase in the cumulative dose when exposed to successive 10-pulse cycles, demonstrating strong proportionality between the exposure frequency and recorded dose. DMC3000 showed slightly higher readings across all cycles, however, the dose increments in both devices remained stable and predictable.

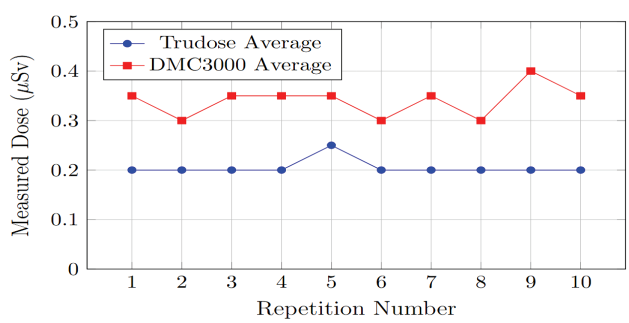


Cycle (10 Pulses)	Trudose (μSv)	DMC3000 (μSv)
1	0.2	0.3
2	0.5	0.7
3	0.7	1.1
4	0.9	1.5
5	1.2	1.9

〈Figure 5〉 Cumulative dose trends per cycle

In addition, Figure 6 present the results of 10 repeated measurements under identical exposure settings. The Trudose dosimeter maintained a near-constant dose reading of approximately 0.2 μSv per repetition, with a standard deviation of 0.016 μSv. The DMC3000 EPD produced similarly consistent results, averaging 0.34 μSv with a standard deviation of 0.032 μSv. These findings confirm the high reproducibility of both devices across multiple trials.

Repetition	Trudose (μSv)			DMC3000 (μSv)		
	#1	#2	Avg.	#1	#2	Avg.
1	0.2	0.2	0.2	0.3	0.4	0.35
2	0.2	0.2	0.2	0.3	0.3	0.3
3	0.2	0.2	0.2	0.3	0.4	0.35
4	0.2	0.2	0.2	0.3	0.4	0.35
5	0.3	0.2	0.25	0.3	0.4	0.35
6	0.2	0.2	0.2	0.3	0.3	0.3
7	0.2	0.2	0.2	0.3	0.4	0.35
8	0.2	0.2	0.2	0.3	0.3	0.3
9	0.2	0.2	0.2	0.3	0.4	0.35
10	0.2	0.2	0.2	0.3	0.4	0.35
Mean			0.21			0.34
Std. Dev.			0.016			0.032



〈Figure 6〉 Comparison of average measured doses for Trudose and DMC3000 across 10 repetitions

In summary, the consistent linearity and high reproducibility of EPDs confirm their reliability as radiation monitoring tools in low-dose environments. This is particularly significant in military contexts, where radiation workers often operate in portable or mobile settings rather than fixed facilities. In dynamic environments, the ability to provide real-time, accurate, and stable dose readings is critical for ensuring operational safety. These results validate EPDs as effective monitoring instruments and often the only practical solution for radiation safety management among military personnel. For field operators using portable X-ray generators in transient settings, EPDs offer a unique capability for real-time exposure detection, enabling immediate responses and reinforcing frontline radiation safety protocols.

Ⅴ. Conclusion and implications for Radiation Safety Management

This study compared the performance of TLDs and EPDs in an operational environment involving portable X-ray generating devices, focusing on their sensitivity, accuracy, and applicability in military settings. Given the complex nature of such environments, which are—characterized by irregular deployment sites, spatial constraints, and frequent personnel turnover,—radiation safety management poses unique challenges. These findings highlight the complementary strengths and limitations of both dosimeter types, emphasizing the importance of selecting appropriate monitoring tools based on specific operational risks, considering the stark contrast between personnel who routinely handle radiation-emitting devices in licensed facilities and those who operate such equipment intermittently during field-based missions such as counter-terrorism drills. TLDs demonstrated high accuracy and reliability in cumulative dose assessments, making them well-suited for long-term radiation exposure tracking (e.g., Aswal & Chandra, 2024) in licensed institutions. However, their limited sensitivity to low-dose radiation and delayed readout process restrict their effectiveness in environments requiring immediate feedback. Specifically, TLDs failed to register radiation doses at low pulse counts and beyond 3 meters, limiting their utility for real-time monitoring applications. Conversely, EPDs exhibited superior low-dose sensitivity and real-time monitoring capabilities, enabling the immediate detection of exposure fluctuations. They successfully recorded radiation doses across all the tested pulse counts and distances, demonstrating their effectiveness in operational settings where low-level exposure monitoring is critical. Nonetheless, the minor discrepancies observed in EPDs under high pulse conditions suggest the need for further validation of cumulative dose accuracy, especially during ultra-short exposure events.

Accordingly, a differentiated approach for radiation safety management is warranted. TLDs should be maintained for use in licensed institutions where cumulative dose tracking and regulatory compliance are prioritized. However, the mandatory use of TLDs in registered institutions—where the exposure risks are minimal and intermittent—should be reconsidered. Instead, prioritizing EPDs in such settings would enable more effective real-time monitoring and a rapid response to potential exposure events, while alleviating the administrative burden placed on the military's sole dose assessment center. The parallel use of TLDs and EPDs is the most comprehensive strategy for radiation safety. However, imposing mandatory dosimeter usage on personnel operating portable X-ray devices—who are not legally required to wear them—may be excessive in certain contexts. As previously discussed, this approach increases the workload of the single dose-reading institution within the military, potentially limiting a focused oversight of higher-risk licensed facilities.

Given resource allocation and budgetary constraints, personnel in licensed institutions will continue to comply with existing Nuclear Safety Act regulations, including the mandatory use of TLDs, while EPDs are recommended as an additional measure. For personnel in registered institutions, radiation safety management can be enhanced by prioritizing EPDs for real-time monitoring, moving away from the current mandatory TLD requirement under military radiation safety directives. This approach will enable early detection of unintended exposure for radiation workers in registered institutions, minimizing risks associated with radiation incidents. Additionally, it will streamline military radiation dose assessments, reduce administrative burdens, and allow for a stronger focus on exposure management in licensed institutions, where radiation levels are typically higher.

Consequently, our study examined whether EPDs could be a more suitable alternative to TLDs for preventive monitoring in specific environments. The experimental results provide strong evidence supporting the prioritization of EPDs as a practical and responsive dosimetry solution for military personnel involved in portable X-ray operations. To enhance radiation safety strategies, future research should validate these findings under various field conditions, utilizing different X-ray sources and varying background radiation levels. Ongoing research into the long-term reliability of EPDs and their integration into military protocols is essential for advancing radiation protection practices in defense operations. By strategically employing both TLDs and EPDs based on operational needs, military radiation safety management can be optimized to balance cumulative dose assessment with real-time monitoring, ensuring compliance and protection for radiation workers in diverse field environments.

Acknowledgement

This study is based entirely on data obtained through experimental research conducted by the authors. All interpretations, implications, and recommendations derived from the results were solely written by the authors without any assistance from AI. ChatGPT was used as a language tool strictly for improving

clarity in English grammar, word choice, and sentence refinement. Even in such cases, all AI-generated suggestions were carefully reviewed and revised by the authors to ensure accuracy and fidelity to the intended meaning.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Author contributions

Conceptualization: HSC, JP, GC, Literature review: HSC, JP, KK, Resources and Data curation: HSC, JP, Investigation and Methodology: HSC and JP, Writing (Original Draft): HSC and KK, Project administration and Supervision: HSC, KK.

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원 고 접 수 일 2025년 02월 28일
원 고 수 정 일 2025년 05월 07일
게 재 확 정 일 2025년 05월 16일

IDAP 광운대학교 방위사업연구소
INSTITUTE OF DEFENSE ACQUISITION PROGRAM

JAMS JOURNAL OF ADVANCES IN MILITARY STUDIES

2025, Vol. 8, No. 1, 37-56.

https://doi.org/10.37944/jams.v8i1.273

군 방사선 안전을 위한 선량계 배정의 재검토: 휴대용 X선 노출 하에서 열발광 선량계(TLD)와 전자 개인 선량계(EPD)의 성능 비교

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국문초록

최근 군 작전 환경(폭발물 탐지, 대테러 작전 등)에서 휴대용 X선 발생장치 활용이 증가하면서 현장 중심의 저선량 방사선 노출 환경에 적합한 방사선 안전 관리의 필요성이 높아지고 있다. 본 연구는 저선량 펄스형 방사선 환경을 모사한 조건에서 군에서 가장 널리 사용되는 X선 발생장치인 XRS-3 장비를 활용하여 열형광선량계(TLD)와 전자개인선량계(EPD)의 감도, 선량 반응 특성, 그리고 군 작전 환경에서의 운용 적합성을 비교・평가하였다. 실험 결과, TLD는 누적선량 추적에 있어 높은 정확도를 보였으나, 3m 이상의 거리 또는 낮은 펄스 조건에서는 방사선 검출에 실패하였다. 반면, EPD는 저선량 조건에서 누적선량 측정값의 정확도는 일부 한계가 있었으나 모든 이격 거리 및 펄스 조건에서 방사선을 검출하는 데 성공하였다. 특히, 선량 변화를 실시간으로 감지하고 사용자에게 즉각 피드백을 제공하는 특성은 야전에서 동적 방사선 모니터링에 더 적합한 장점으로 작용한다. 본 연구는 펄스형 저선량 환경에서 선량계 성능을 실증적으로 검증함으로써 기존 문헌의 공백을 보완하고, 현행 군 방사선 안전 관리 방안의 효과적이고 합리적인 개선을 위한 실질적 근거를 제공한다.

주제어 : 개인선량계, 열형광선량계(TLD), 전자개인선량계(EPD), 군 방사선 안전, 휴대용 X선 발생장치

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